On the influence of effective stress and micro-structure on suffusion and suffosion

by

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Abstract

The research presented within this thesis covers the development of a flexible wall permeameter, and a parametric laboratory investigation of the factors influencing seepage-induced internal instability in gap-graded granular materials. A flexible wall permeameter comprising a double-walled triaxial cell, a seepage control system, and instrumentation, with a novel measurement of volume change, has been designed and built. The apparatus was successfully commissioned and the test procedure demonstrated to yield repeatable results. Two commissioning tests, 23 tests on eight glass beads gradations and 16 tests on ten soil gradations were conducted. All gap-graded gradations were reconstituted using the modified slurry deposition method, isotropically consolidated to a cell pressure between 50 and 150 kPa, and subsequently subject to upward multi-stage seepage flow.

Analysis of the test results identifies two distinct seepage-induced internal instability phenomena. First, migration of fine particles from a soil, termed suffusion, is characterised by a mass loss without change in volume, or with a small non-progressive change in volume, accompanied by an increase of hydraulic conductivity. Second, local or overall collapse of the soil structure, termed suffosion, is characterised by a seepage-induced mass loss, accompanied by a reduction in volume and a change in hydraulic conductivity. It is demonstrated that measurement of total volume change is necessary to avoid any mis-interpretation of the phenomenological response to seepage flow.

It was found that the differential pore water pressure at the onset of suffosion increases with increasing mean effective stress. The micro-structure of the specimen was found to influence the susceptibility to seepage-induced internal instability: the portion of non-load bearing fine particles appears a useful parameter to quantify the potential for suffusion, whereas the proposed state parameters are predictors of the relative susceptibility to suffosion. Although particle shape does not affect the suffusive response in a transitional clast-supported microstructure, sub-angular particles are found to yield a transitional micro-structure that is more resistant to suffosion than a similar micro-structure of spherical particles. A unified approach is presented to characterise suffosion.
Preface

Chapter 2. Versions of Sections 2.1 and 2.4.3 have been published as follows:


I was the lead author and lead investigator of the literature review for the above manuscript. R.J. Fannin was responsible for the conceptual formation, most notably of Fig. 2.5.

The remaining parts of this dissertation are original, unpublished, independent work of the author, P. Slangen.
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List of Acronyms

BT  sub-angular soil particles

DAQ  data acquisition system

DEM  discrete element modelling

DPT  differential pressure transducer

GB  glass beads

I-CHD  inflow constant-head device

ICOLD  International Committee on Large Dams

LVDT  linear variable differential transformer

MP  measurement port

O-CHD  outflow constant-head device

TDH  total dynamic head

TPT  total pressure transducer

UBC  the University of British Columbia
Glossary

α  stress reduction factor

$\Delta m_{inf}$  mass loss inferred from analysis of seepage regime and deformations

$\Delta m_{obs}$  mass loss established through forensic observations

$\Delta t$  duration of a stage of seepage flow

$\Delta u$  differential pore water pressure

$\Delta u_f$  differential pore water pressure at failure

$\Delta u_l$  differential pore water pressure at the last stage of seepage flow

$\Delta u_{so}$  differential pore water pressure at the onset of suffosion

$\Delta u_{su}$  differential pore water pressure at the onset of suffusion

$\Delta V$  volume change

$\Delta V_m$  volume change resulting from membrane compliance

$\Delta v_m$  membrane penetration per unit area

$\Delta V_t$  total measured volume change, including membrane compliance

$\varepsilon_a$  axial strain

$\varepsilon_{a,u}$  axial strain during isotropic unloading

$\varepsilon_v$  volumetric strain

$\varepsilon_{v,u}$  volumetric strain during isotropic unloading

$\gamma_s$  unit weight of solids

$\gamma_w$  unit weight of water

$\mu$  coefficient of static friction
\( \mu_w \)  dynamic viscosity of water

\( \phi \)  piezometric head

\( \Psi_f \)  inter-fine state parameter

\( \Psi_s \)  modified inter-coarse state parameter

\( \rho \)  density

\( \rho_s \)  density of solids

\( \rho_w \)  density of water

\( \sigma_c \)  cell pressure

\( \sigma_{vf}' \)  vertical effective stress on the fine particle fraction

\( \sigma_v' \)  vertical effective stress

\( A \)  projected particle area

\( a \)  threshold grain size ratio

\( A_m \)  soil surface covered by the membrane

\( AR \)  aspect ratio

\( A_s \)  specific surface of solids

\( B \)  area of convex hull

\( b \)  portion of load-bearing fine particles

\( C_c \)  coefficient of curvature

\( C_p \)  pore shape factor

\( C_t \)  tortuosity factor

\( C_u \)  coefficient of uniformity

\( Cx \)  convexity

\( D \)  specimen diameter

\( d \)  particle size

\( D' \)  particle size of the coarse component of a gap-graded gradation
$d'$ particle size of fine component of a gap-graded gradation

$D_{15}'/d_{85}'$ ratio of the particle size of the coarse fraction corresponding to the $15^{th}$ percent mass passing, and the particle size of the fine components corresponding to the $85^{th}$ percent mass passing

$D_{c,D95}$ constriction size corresponding to the $95^{th}$ percentile of the theoretical densest constriction curve for the coarse fraction

$d_{Fmax}^F$ maximum Feret diameter

$d_{Fmean}^F$ mean Feret diameter

$d_{Fmin}^F$ minimum Feret diameter

$e$ void ratio

$e_c$ void ratio at the end of consolidation

$e_{cub}$ void ratio corresponding to simple cubic fabric

$e_f$ inter-fine void ratio

$e_{f,max}^F$ maximum index void ratio of the fine fraction

$e_{f,min}^F$ minimum index void ratio of the fine fraction

$e_{max}$ maximum index void ratio

$e_{min}$ minimum index void ratio

$e_s$ inter-coarse void ratio

$e_{se}$ equivalent inter-coarse void ratio

$e_{s,max}^F$ maximum index void ratio of the coarse fraction

$e_{s,min}^F$ minimum index void ratio of the coarse fraction

$E_v$ average unit rate of volumetric deformation

$f$ function

$F_b$ buoyant force acting on the solids

$F_d$ drag acting on the solids

$F_g$ weight of the solids
\( F_r \) resultant force on the solids
\( g \) gravitational acceleration
\( G_s \) specific gravity of solids
\( i \) hydraulic gradient
\( k \) hydraulic conductivity
\( K_0 \) lateral earth pressure coefficient with zero lateral strain
\( k_i \) initial hydraulic conductivity
\( k_l \) hydraulic conductivity at the last stage of seepage flow
\( l \) specimen length
\( L_s \) length scale
\( n \) porosity
\( n_f \) inter-fine porosity
\( P \) projected perimeter
\( p' \) mean effective stress
\( p'_c \) mean effective stress at the end of consolidation
\( p'_f \) mean effective stress at failure
\( p'_{so} \) mean effective stress at the onset of suffosion
\( p'_{su} \) mean effective stress at the onset of suffusion
\( q \) deviatoric stress
\( R \) roundness
\( r_c \) sample correlation coefficient
\( R_d \) size disparity ratio
\( R_e \) Reynolds number
\( s \) standard deviation
\( s_{eq} \) equivalent coarse grain spacing constant
$S_f$ finer fraction content

$S'_f$ critical finer fraction content

$S_{LL}$ limit fine fraction content

$s_i$ standard deviation of base variable $z_i$

$s_x$ standard deviation of derived variable $z_x$

$S_m$ constant for proportionality of membrane penetration per unit area

$S_{OP}$ sphericity

$T$ temperature

$t$ time

$u$ pore water pressure

$V$ specimen volume

$v$ specific discharge

$v_s$ seepage velocity

$V_{p,c}$ volume of particles constituting the coarse fraction

$V_{p,f}$ volume of particles constituting the fine fraction

$v_{R_e=1}$ upper limit of specific discharge in Darcian flow regime

$V_v$ total volume of voids

$x$ arithmetic mean of $x$

$z$ $z$ coordinate

$z_i$ predicted value of variable $z_i$

$z_i$ base variable $z_i$
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Chapter 1

Introduction

Internal erosion is broadly defined as the migration of soil particles by seepage flow within earth structures, such as an embankment dam or its foundation. Statistical analysis established that internal erosion is the governing failure mode for approximately half of the failures of embankment dams (Foster et al., 2000). The contemporary design philosophy involves the construction of zoned embankment dams whereby filters and drains provide means of controlling the seepage flow through the embankment and preventing migration of particles between various zones of the embankment and its foundation (USBR, 2011). However, many existing embankment dams have not been provided with adequate filters and drains (ICOLD, 2013) and the safety assessment of these dams requires a fundamental understanding of the factors governing internal erosion. The European Working Group of International Committee on Large Dams (ICOLD) recently summarised the state-of-art of internal erosion in embankment dams (ICOLD, 2013) and proposed a framework for the safety assessment of embankment dams with respect to internal erosion, which was adopted from Fell and Fry (2007). For the assessment of the likelihood, and effect, of internal erosion, four phases are distinguished: (i) the initiation of internal erosion; (ii) the continuation of erosion; (iii) the progression of erosion to a larger zone; and (iv) the initiation of a breach in the structure. It is recommended to consider the following mechanisms through which internal erosion can initiate: erosion in concentrated leaks, such as cracks; backward, or retrogressive erosion of particles that are not retained by a downstream filter; contact erosion at the interface between two materials; and “suffusion” or “internal instability”, which is described as the transport of small particles by seepage flow through the pores of the coarser particles. A combination of empirical and physics-based tools are presented to determine the conditions at the onset, and subsequent progression, of the first three internal erosion mechanisms. In contrast, the description of the factors governing internal instability is minimal and is mainly of a qualitative nature. This investigation aims to address this knowledge gap and is an attempt to advance the fundamental understanding of seepage-induced internal instability.
Notably, Richards and Reddy (2007) and Moffat et al. (2011) recommend to distinguish between the seepage-induced internal instability phenomena of suffusion, “where the finer fraction of an internally unstable soil moves within the coarser fraction without any loss of matrix integrity or change in total volume” (Moffat et al., 2011), and suffosion, “where particle migration yields a reduction in total volume and a consequent potential for collapse of the soil matrix” (Moffat et al., 2011). Three factors controlling suffusion and suffosion are generally distinguished: material susceptibility, effective stress and hydraulic conditions (Garner and Fannin, 2010). The material susceptibility has historically been investigated by conducting laboratory tests. These investigations have yielded several useful empirical tools, which are exclusively based on the particle size distribution, to assess the susceptibility of materials to seepage-induced internal instability, without distinguishing between suffusion and suffosion (e.g. Burenkova, 1993; Kenney and Lau, 1985, 1986; Kezdi, 1979; Li, 2008, Sherard, 1979; Wan and Fell, 2008). Recently, Crawford-Flett (2014) confirmed a previous postulate that soils with a stable, coarse-particle dominated skeleton, exhibit a potential for suffusion (e.g. Kenney and Lau, 1985; Kezdi, 1979; Skempton and Brogan, 1994; Wittmann, 1978). Skempton and Brogan (1994) were one of the first researchers to specifically address the hydraulic conditions at the onset of seepage-induced internal instability, by subjecting gap-graded materials to upward seepage flow in a rigid wall permeameter. Research conducted at the University of British Columbia (UBC), using a rigid wall permeameter, indicated that the onset of seepage-induced internal instability was also controlled by the effective stress, in addition to the hydraulic conditions (Crawford-Flett, 2014, Li, 2008, Moffat, 2005). Chang and Zhang (2013), based on tests on one granular soil in a flexible wall permeameter, suggested that the onset and progression of suffosion is dependent on effective stress. Driven by the postulates regarding the role of the effective stress on the onset of seepage-induced internal instability, recent studies (Shire and O’Sullivan, 2013, Shire et al., 2014), using discrete element modelling (DEM), established that in certain gap-graded materials, the fine particles exhibit a smaller effective stress than the coarse particles.

Seepage-induced internal instability can thus be considered an emerging field of research, where the principle focus of investigation has shifted from the susceptibility of materials to the conditions at which seepage-induced internal instability initiates. The understanding of the factors governing seepage-induced internal instability has advanced to a largely qualitative appreciation of the role of the hydraulic conditions and the effective stress. A further advance to a quantitative approach is believed to be contingent on the generation and analysis of experimental data on seepage-induced internal instability, using suitable laboratory testing equipment, with control of the hydraulic conditions and effective stress.
1.1 Research hypotheses

The aim of this study is to establish causative relations between the factors governing seepage-induced internal instability. Four research hypotheses are proposed to achieve this aim.

Considering the visual observations of Moffat et al. (2011) that “significant voids in the specimen” associated with suffosion, developed in internally unstable materials, volume change is postulated to be a characteristic variable of seepage-induced internal instability. It is hypothesized that volume change can serve to distinguish between suffusion, which is associated with no volume change, and suffosion. The first hypothesis is proposed as follows:

Hypothesis no. 1: Volume change is a characteristic variable of seepage-induced internal instability and serves to distinguish between suffusion and suffosion.

The influence of effective stress on the onset of seepage-induced internal instability has mainly been established from tests in rigid wall permeameters (e.g. Li, 2008; Moffat, 2005), which exhibit shortcomings in the control of the effective stress. The recent advance towards the use of flexible wall permeameters (e.g. Bendahmane et al., 2008; Chang and Zhang, 2013; Ke and Takahashi, 2014b; Luo et al., 2012; Xiao and Shwiyhat, 2012), with better control of the effective stress state, enables a more thorough examination of the influence of effective stress on seepage-induced internal instability. Notwithstanding the influence of other factors, the second hypothesis is defined to advance the understanding of the influence of effective stress on the onset of suffosion:

Hypothesis no. 2: The onset of suffosion is dependent on effective stress.

Although suffusion has typically been attributed to the migration of fine particles from a stable coarse-particle-dominated skeleton, the causality between the soil micro-structure and suffosion has not been addressed. The third hypothesis has been defined to investigate the relation between the soil micro-structure and suffusion and suffosion:

Hypothesis no. 3: The micro-structure of internally unstable materials controls the phenomenological response to seepage flow.

Finally, considering the DEM work on gradations of spherical particles, and the generally recognised influence of the particle shape on the shear strength of soils, it seems prudent to examine the role of the particle shape on suffusion and suffosion. The fourth hypothesis is defined with the purpose of establishing a causative relation between particle shape and the susceptibility to seepage-induced internal instability:
Hypothesis no. 4: Gap-graded gradations of rounded particles are more susceptible to seepage-induced internal instability than identical gap-graded gradations of sub-angular particles.

1.2 Scope and objectives

The scope of this work is the laboratory element testing of reconstituted gap-graded granular materials. This laboratory investigation comprises a parametric sensitivity study where the dependent variable is the response of a material subject to seepage flow and effective stress. The independent material variables are the finer fraction content, ratio of the particle size of the coarse and fine fractions, and particle shape. The independent environmental variables are the mean effective stress and differential pore water pressure across the specimen. Five research objectives have been defined for this study, with the intend of partitioning the investigation in manageable projects. The research objectives of this study are:

1. To summarise the state-of-art of seepage-induced internal instability and in particular: factors controlling suffusion and suffosion; flexible wall permeameters used for seepage-induced internal instability testing; and the micro-structure of gap-graded materials.

2. To design a flexible wall permeameter, with control of effective stress and hydraulic load, and with measurement of volume change.

3. To commission the flexible wall permeameter and to assess the repeatability of the test procedure.

4. To determine the phenomenological response to seepage flow of tests on different gap-graded materials, subject to varying stress conditions.

5. To investigate the suitability of the volume change as a variable to quantify seepage-induced internal instability, and to determine the influence of effective stress, soil micro-structure, and particle shape on suffusion and suffosion.

1.3 Outline of the thesis

The investigation is addressed in seven chapters:

- Chapter One introduces the subject of seepage-induced internal instability, reports on recent advances and identifies knowledge gaps. Four research hypotheses are presented.

- Chapter Two summarises the state-of-art knowledge on seepage-induced internal instability, with particular focus on suffusion and suffosion, experimental investigations, the
micro-structure of gap-graded materials and the influence of the particle shape (research objective No. 1).

- Chapter Three describes the flexible wall permeameter, which has been developed for this study (research objective No. 2), the selection of the materials, and the test program.

- Chapter Four commences with the commissioning of the flexible wall permeameter. The results of the test program are subsequently presented, from which the repeatability of the test procedure is derived (research objective No. 3).

- Chapter Five presents the analysis of the test results, which yields the phenomenological response to seepage flow in each test (research objective No. 4).

- The research hypotheses are tested in Chapter 6 (research objective No. 5). Causative relations between the dependent variables are sought, and form the basis of a broader discussion on the factors governing suffusion and suffosion.

- Chapter Seven summarises important findings of this investigation, accentuates novel contributions, presents recommendations for future research and discusses implications for practice.
Chapter 2

Literature review

This Chapter summarises the state-of-art on seepage-induced internal instability (research objective No.1). First, distinct seepage-induced internal instability phenomena are identified and termed in Section 2.1, followed by a summary of the micro-structure of soils, including the role of the particle shape, in Section 2.2. Several important aspects of the seepage flow of water through a porous medium are summarised in Section 2.3. Advances in laboratory testing of internally unstable materials are summarised in Section 2.4, where a distinction is made between the two most common types of devices: rigid wall permeameters (Section 2.4.1) and flexible wall permeameters (Section 2.4.2). The main findings of the experimental work are summarised in Section 2.5. A reflection on the research hypotheses, in light of the literature review, is presented in Section 2.6. A summary of key aspects of the literature review is provided in Section 2.7.

2.1 Seepage-induced internal instability phenomena

There appears to be consensus in the literature that internal instability is a phenomenon whereby fine particles are transported from a non-plastic soil by seepage flow (see Table 2.1). A subtle distinction has been proposed between the migration of particles within a soil, and out of a soil (Kovacs, 1981). A more significant distinction has been made between a washed-out soil structure that remains intact, and one in which some form of destruction, or collapse, of the structure accompanies the seepage-induced migration of fine particles (e.g. Åberg, 1993; Burenkova, 1993; Garner and Sobkowicz, 2002; Kezdi, 1979; Li, 2008; Moffat et al., 2011; Richards and Reddy, 2007; Wittmann, 1978). Herein the term structure is used to take into account both the soil fabric and its stability, as suggested by Mitchell and Soga (2005); a more elaborate review of soil structure is presented in Section 2.2.

Various terms have been used to describe internal instability, with and without some form of collapse of the soil structure. More unfortunate is the use of the same term for each of these
distinct phenomena: suffosion has been used to describe both destructive (e.g. Burenkova, 1993; Garner and Sobkowicz, 2002; Moffat et al., 2011; Richards and Reddy, 2007) and non-destructive phenomena (e.g. Burenkova, 1993; Molenkamp et al., 1979; Wittmann, 1978) of seepage-induced internal instability (see Table 2.1). In contrast, suffusion has only been used to describe the non-destructive phenomenon of seepage-induced internal instability.

2.1.1 Experimental evidence of internal instability phenomena

Experimental evidence suggests that the three variables of (i) a measured value of mass loss, (ii) a measured value of volume change, and, (iii) a value of change in hydraulic conductivity, deduced from measurements of hydraulic gradient and flow rate, are sufficient to quantify, and hence distinguish between, seepage-induced instability phenomena:

- Skempton and Brogan (1994) report seepage-induced internal instability in a specimen of gap-graded sandy gravel subject to upward flow in a rigid-wall permeameter. The top surface of the specimen was unloaded. The linear relation between hydraulic gradient, $i$, and the specific discharge through the specimen to $i \leq 0.11$ (see Fig. 2.1) indicates a constant value of hydraulic conductivity. At $i > 0.11$, a disproportionate increase of seepage velocity with hydraulic gradient indicates an increase in hydraulic conductivity. At $i = 0.2$, there was “strong general piping of fines throughout”, but “[t]he gravel particles remain undisturbed.” The experimental findings are: (i) mass loss; (ii) no collapse of the soil structure and hence no volume change; and, (iii) an increase in hydraulic conductivity.

- Li (2008) reports seepage-induced internal instability in a specimen of gap-graded glass beads, subject to downward flow in a rigid-wall permeameter. The top surface of the specimen was loaded. The linear relation between hydraulic gradient and specific discharge to $i \leq 2.9$ (see Fig. 2.2) indicates a constant value of hydraulic conductivity. At $i > 2.9$, a disproportionate increase of discharge velocity with hydraulic gradient indicates an increase in hydraulic conductivity. “Negligible mass loss and axial displacement were observed during these flow stages […] Upon imposing a small increase in hydraulic gradient to $i = 3.2$, a modest amount of finer particles (6.9 %) was lost from the specimen […] A total downward axial displacement of 2.5 mm was measured, resulting in an axial strain of 2.6 %.” Thus, in contrast to the findings of Skempton and Brogan (1994), and notwithstanding the different hydraulic conditions, the experimental findings of Li (2008) are: (i) mass loss; (ii) contractive volume change associated with collapse of the soil structure; and, (iii) an increase in hydraulic conductivity.

In the classic description of piping by heave of sand, Terzaghi and Peck (1948) observe: “This process greatly increases the permeability of the sand […] and [t]he surface of the sand
then rises.” Accordingly, this seepage-induced instability phenomenon may be similarly quantified by the same three variables:

- Li (2008) reports seepage-induced instability of a specimen of broadly graded sand and gravel, subject to upward seepage flow in a rigid-wall permeameter. The top surface of the specimen was loaded. The linear relation between hydraulic gradient and discharge velocity to $i \leq 15$ (see Fig. 2.3) indicates a constant value of hydraulic conductivity. “Upon imposing an increase in hydraulic gradient to $i = 16.0$ [...] a large upward displacement of 4.2 mm was measured, resulting in a strain of 1.3 %.” The experimental findings are: (i) no mass loss; (ii) expansive volume change; and (iii) an increase in hydraulic conductivity.

2.1.2 Conceptual framework

In an internally unstable soil, the phenomenon whereby fine particles are transported by seepage flow and the soil structure remains intact, may be quantified by a mass loss, no change in volume and an increase in hydraulic conductivity (see Fig. 2.4a). The term suffusion has been commonly used to describe this non-destructive response (see Table 2.1), and its continued use is therefore advocated. In contrast, the internal instability phenomenon whereby the transport of fine particles by seepage flow is accompanied by a collapse of the soil structure, may be quantified by a mass loss, a volumetric contraction and a change in hydraulic conductivity (see Fig. 2.4b). It is a different response, and one with potential for unacceptable deformation, for which the term suffosion is recommended.

An internally stable soil may be either uniformly graded or broadly graded. In the presence of upward seepage flow, the instability phenomenon may be quantified by a volumetric expansion, accompanied by an increase in hydraulic conductivity (e.g. see Fig. 2.4c). The term fluidisation has been used to describe this response (Vardoulakis, 2004) and its continued use appears appropriate.

The recommendation to distinguish between the three phenomena of suffusion, suffosion and fluidisation, based on mass loss, volume change and change in hydraulic conductivity, is illustrated in a revised version of the Venn-diagram (see Fig. 2.5), originally proposed by Garner and Fannin (2010). The conceptual framework presented herein can thus successfully distinguish between the seepage-induced internal instability phenomena of suffusion and suffosion, in both a qualitative and a quantitative manner.
2.1.3 Concluding remarks

A conceptual framework is developed such that a distinction can be reasonably made between phenomenological responses based on mass loss and volume change, which can be measured directly, and change in hydraulic conductivity, which can be deduced from measurement of hydraulic gradient and flow rate. Recognising the important distinction between non-destructive and destructive phenomena in engineering practice, it is recommended that:

- suffusion be characterised as seepage-induced mass loss without change in volume, accompanied by an increase of hydraulic conductivity; and,
- suffosion be characterised as a seepage-induced mass loss accompanied by a reduction in volume and change in hydraulic conductivity; and,
- fluidisation be characterised as a seepage-induced volumetric expansion, accompanied by an increase in hydraulic conductivity, with no mass loss.

2.2 Micro-structure

Mitchell and Soga (2005) made an important distinction between soil fabric and soil structure: “[t]he term fabric refers to the arrangement of particles, particles groups and pore spaces in a soil.” Structure is used to refer to “the combined effects of fabric, composition, and inter-particle forces”, i.e. soil structure refers to the soil fabric and its stability. The term microstructure is used when considering aspects of the fabric and its stability on a particle level. In this study, fabric and particle arrangement will be used interchangeably to improve readability.

2.2.1 Micro-structures of gap-graded mixtures

A suitable starting point for the discussion on fabric and structure is the theoretical packing of equal-size spherical particles. The loosest theoretical fabric of equal-size spheres, for which the particles are in contact with each other, is the simple-cubic arrangement with a theoretical void ratio $e = 0.91$, and the densest theoretical fabric of equal-size spheres is the tetrahedral packing, with a theoretical void ratio $e = 0.35$. Several researchers have experimentally investigated the maximum and minimum densities of spheres and found that a stable fabric of equal-size spheres can only exist in a narrow range of void ratios. McGeary (1961) investigated the maximum possible density of equal-size spheres in a large container using mechanical vibration and obtained values of maximum packing densities $e_{min} = 0.60$. In their classic study, Scott and Kilgour

---

1The definition of micro-structure, as a particle arrangement and its stability, in this study, is thus distinct from the adjective “microstructured” used by Leroueil and Hight (2003) to characterise the mechanical behaviour of certain soils.

2It should be noted here that minimum and maximum void ratio values are variable and operator dependent; accordingly, Holtz et al. (2011) recommend considering $e_{min}$ and $e_{max}$ as minimum and maximum index void ratios, as at least theoretically, denser and looser states appear feasible. In this study, $e_{min}$ and $e_{max}$ are considered index
reported values for minimum and maximum densities of randomly packed steel balls of nearly perfect uniformity of \( \varepsilon_{\text{max}} = 0.67 \) and \( \varepsilon_{\text{min}} = 0.57 \), when correcting for the effect of the container diameter, using the elegant procedure proposed by Scott (1960). McGeary (1961) also investigated the maximum possible density of binary mixtures of discrete fine and coarse particle fractions and found that maximum densities could only be obtained by first placing and vibrating the coarse component to \( \varepsilon_{\text{min}} = 0.60 \), then placing the fine component, and vibrating again. The findings of McGeary (1961) demonstrate that the maximum density of binary mixtures of discrete fine and coarse particle fractions can only be attained if the ratio between the particle size of the coarse fraction \( (D') \) and the particle size of the fine fraction \( (d') \), is \( D'/d' > 10 \).

The concept of binary mixtures led Kenney and Lau (1985), and later Skempton and Brogan (1994), to the observation that seepage-induced internal instability is limited to a clast-supported micro-structure, which is characterised by a primary fabric of coarse particles. Clast-supported micro-structures were postulated to exhibit a potential for non-load bearing fine particles. In different appearances, Skempton and Brogan (1994), Kezdi (1979), Kenney and Lau (1985) and Wittmann (1978) presented equivalent expressions to determine the theoretical critical finer fraction content \( S_f^* \) above which a clast-supported micro-structure cannot exist. The definition of Kenney et al. (1985) is preferred for its simplicity:

\[
S_f^* = 1 - \frac{1}{1 + \varepsilon_s(1 - n_f)}
\]  

(2.1)

where \( \varepsilon_s \) is inter-coarse void ratio (see Eq. 2.2), and \( n_f \) is inter-fine porosity (see Eqs. 2.3 and 2.4).

The inter-coarse void ratio \( \varepsilon_s \) is defined as the void ratio of the coarse grains if the fine particles were considered voids (see Fig. 2.6):

\[
\varepsilon_s = \frac{V_v + V_{p,f}}{V_{p,c}} = \frac{V - V_{p,c}}{V_{p,c}} = \frac{e + S_f}{1 - S_f}
\]  

(2.2)

where \( V_v \) is total volume of voids, \( V_{p,f} \) is volume of particles constituting the fine fraction, \( V_{p,c} \) is volume of particles constituting the coarse fraction, \( V \) is specimen volume, and \( S_f \) is finer fraction content.

Similarly, in porous media with a high content of fine particles, the inter-fine void ratio, \( \varepsilon_f \) (see Fig. 2.6), can be calculated by ignoring the coarse particles:

void ratios that refer to the practically, as opposed to theoretically, densest and loosest states, respectively, of a granular material.
\[ ef = \frac{V_v}{V_{p,f}} = \frac{e}{S_f} \]  

(2.3)

The corresponding inter-fine porosity \( n_f \) can then be calculated using Eq. 2.4:

\[ n_f = \frac{ef}{1 + ef} \]  

(2.4)

In this thesis, the minimum and maximum index inter-coarse void ratios, \( e_{s,\text{min}} \) and \( e_{s,\text{max}} \), are defined as the void ratios corresponding to the practically densest and loosest void ratios, respectively, of a packing of only coarse particles. Similarly, the minimum and maximum index inter-fine void ratios, \( e_{f,\text{min}} \) and \( e_{f,\text{max}} \), are defined as the void ratios corresponding to the practically densest and loosest void ratios, respectively, of a packing of only fine particles.

Thevanayagam et al. (2002) proposed a micro-structure identification diagram as a “guide-line to determine the anticipated behavior of gap-graded granular mixtures”. The following five micro-structure “cases” were identified, based on void ratio and finer fraction content (see Fig. 2.7):

- Case i: “the fines are confined within the void spaces between the coarse grains with little contribution to supporting the coarse grain skeleton” (Thevanayagam et al., 2002). Accordingly, the coarse particle components has to yield a stable fabric with \( e_s < e_{s,\text{max}} \), which was postulated to be possible only if \( D'/d' > 6.5 \).

- Case ii: “[the fines] are partially supporting the coarse grain skeleton” (Thevanayagam et al., 2002). The limits for this case are not clearly defined, but Thevanayagam (1998) appears to suggest that \( e_s \approx e_{s,\text{max}} \).

- Case iii: “[the fines] partially separate the coarse grains” (Thevanayagam et al., 2002). The inter-coarse void ratio \( e_s > e_{s,\text{max}} \) indicates that the fine particles are partially supporting the coarse-particle dominated micro-structure.

- Case iv-1: “the coarse grains are fully dispersed in the in the fine grain matrix [...] the behavior of the soil mix is entirely governed by the fine grains” (Thevanayagam et al., 2002). A limiting finer fraction content \( S_{f,L} \) is proposed above which the coarse particles are fully dispersed in the fine particle matrix (see Eq. 2.5).

- Case iv-2: the coarse grains are partially dispersed and contribute as a reinforcing element if \( S_f^* < S_f < S_{f,L} \).

\(^{3}\)The specimen preparation technique influences the structure of the soil, related to the particle arrangement, composition and inter-particle forces, which governs the stress-strain response (e.g. Vaid and Sivathayalan 2000). It should be noted that the void ratio and finer fraction content do not quantify these characteristics of structure.
The limiting finer fraction content $S_{f,L}$ is determined based on geometrical considerations of a theoretical particle packing:

$$S_{f,L} = 1 - \frac{\pi(1 + e)}{6s^3_{eq}} = \frac{6s^3_{eq} - \pi}{6s^3_{eq} + \pi e_f} \quad (2.5)$$

where $s_{eq}$ is equivalent coarse grain spacing constant, which is defined as:

$$s_{eq} = 1 + \frac{ad'}{D'} \quad (2.6)$$

with the threshold grain size ratio $a = 10$, based on experimental observations of Roscoe (1970, as cited in Thevanayagam and Mohan, 2000), that the zone of influence of shearing in a uniform grained soil is about 10 times the grain size.

Thevanayagam et al. (2002) also defined the portion of the fine grains that are load bearing $b$, with $0 \leq b \leq 1$, to account for the secondary cushioning effects of the fines contributing to fabric stability in cases ii and iii: $b = 0$ indicates no contribution of the fines to the support of the coarse-grain skeleton and $b = 1$ indicates that all fines are actively contributing to the support of the coarse grain skeleton. The equivalent inter-coarse void ratio, $e_{se}$, which accounts for the contribution of the fine particles to the stability of the micro-structure, is introduced:

$$e_{se} = \frac{e + (1 - b)S_f}{1 - (1 - b)S_f} \quad (2.7)$$

Rahman et al. (2008) argued that $b$ is a function of both $S_f$ and the ratio $(D'/d')$, based on the findings of McGeary (1961) that the minimum void ratio of binary mixtures approaches a theoretical minimum void ratio only if $(D'/d') > 10$; mixtures with small particle ratios yielded significantly greater void ratios, which was attributed to the fine particles pushing the coarse particles apart.

Crawford-Flett (2014) constructed a micro-structure identification diagram, adapted from Thevanayagam et al. (2002), to investigate the potential for suffusion in gap-graded gradations of glass beads. The theoretical limits $e_{s,max} = e_{f,max} = 0.95$ and $e_{s,min} = e_{f,min} = 0.35$ were assumed to develop the diagram, which appear to yield too wide a range of void ratios considering to the experimental work of McGeary (1961), and Scott and Kilgour (1969). Crawford-Flett (2014) defined only three micro-structure types, instead of the five cases defined by Thevanayagam et al. (2002):

- A clast-supported coarse-particle dominated micro-structure with $e_s < e_{s,max}$, and $e_f > e_{f,max}$. “[A] significant portion of the finer particles will not be fixed in place by inter-particle contacts” (Crawford-Flett, 2014).
• Matrix-supported fine-particle dominated micro-structure with $e_f < e_{f,max}$, and $e_s > e_{s,max}$. “The coarser particles are therefore separated by the fixed matrix of finer particles” (Crawford-Flett 2014).

• Transitional micro-structure with $e_s < e_{s,max}$, and $e_f < e_{f,max}$. “Finer particles are in firm contact with coarser grains of the soil skeleton; therefore, both finer and coarser particles will contribute to stress transfer through in[ter]-particle contacts” (Crawford-Flett, 2014).

2.2.2 Particle shape

Measures of particle shape are presented in Section 2.2.2.1. It is followed by a summary of the influence of the particle shape on the stability of particle packings in Section 2.2.2.2.

2.2.2.1 Measures of particle shape

The state-of-practice description of the particle shape follows the approach of ASTM D2488-09a (ASTM, 2009), based on the charts provided by Powers (1953) and Krumbein and Sloss (1963), where particles are characterised according to four classes of roundness: angular, sub-angular, sub-rounded, and rounded. Altuhafi et al. (2013) demonstrate that this approach is somewhat subjective, and propose a new method based on measures of sphericity and convexity. The QicPic apparatus (Sympatec, 2008), which is based on a digital imaging technique, was used to obtain measures of sphericity and convexity. The convexity $C_x$ is defined as the ratio between the projected particle area $A$ and the sum of the projected particle area and the area of the convex hull ($A + B$) (see Fig. 2.8):

\[
C_x = \frac{A}{A + B} \tag{2.8}
\]

The sphericity $S_{QP}$ is defined as the ratio of the perimeter of a circle whose area equals the projected particle area, and the projected perimeter, $P$:

\[
S_{QP} = \frac{2\sqrt{\pi A}}{P} \tag{2.9}
\]

The equivalent particle shape used by ASTM D2488-09a (ASTM, 2009), can then be determined from a plot of $C_x$ versus $S_{QP}$ (see Fig. 2.9).

Additional useful parameters are the Feret diameter and the aspect ratio. The Feret diameter is measured as the distance between two tangents on opposite sides of the particle (see Fig. 2.8). The maximum, minimum, and mean Feret diameters are given by $d_{F,max}$, $d_{F,min}$ and $d_{F,mean}$, respectively. According to Altuhafi et al. (2013), $d_{F,min}$ is the measure that most closely corresponds to the particle size determined using sieving. The aspect ratio $AR$ is defined as the ratio between the Feret diameters, see Eq. 2.10.
\[
AR = \frac{dF_{\text{max}}}{dF_{\text{min}}} \tag{2.10}
\]

Aspect ratio, convexity and sphericity are typically reported as median values for a cumulative distribution by volume as \(AR_{50}, Cx_{50}\) and \(S_{QP50}\), respectively.

2.2.2.2 Role of particle shape

Although the particle shape greatly affects the engineering response of granular soils (Holtz et al., 2011), it has received little or no attention in the investigation of seepage-induced internal instability. The work of Casagrande on internal friction angles of granular soils (in Holtz et al., 2011) shows a substantial increase of internal friction angle for sub-angular particles compared to the internal friction angle of sub-rounded particles, reconstituted to the same void ratio. Youd (1973) demonstrates that minimum and maximum index void ratios, and the difference between minimum and maximum index void ratios, increase as the particles become more angular. Mitchell and Soga (2005), referring to Hagerty et al. (1993), note that “[..] angular glass beads are more susceptible to breakage than round glass beads.” Cho et al. (2006) note that angular particles yield a relatively looser packing, which exhibits a lower stiffness at small strains than a similar packing of rounded particles. Intermediate strain behaviour, associated with contact slippage or particle breakage, yielded higher compression and decompression indices of angular particles than rounded particles. At large strain behaviour, associated with particle rotation and contact slippage, increasing angularity was postulated to increase the resistance against particle rotation, yielding a greater shear resistance.

2.3 Seepage flow in granular materials

A review of seepage flow in granular media naturally starts with the pioneering work of Darcy (1856, as cited in Bear, 1972). From experiments, Darcy concluded that the specific discharge, \(v\), is proportional to the difference in piezometric head, \(\Delta\phi\), and inversely proportional to the specimen length, \(l\):

\[
v = k \frac{\Delta\phi}{l} \tag{2.11}
\]

where the coefficient of proportionality \(k\) is hydraulic conductivity.

Mitchell and Soga (2005) list three hypotheses to account for a deviation from Darcy’s law: 1) a non-Darcy flow regime; 2) particle migration; or 3) changes in specimen volume. The effect of non-Darcy flow is commonly, but erroneously, associated with the persistence of turbulent flow. Laminar flow occurs when a fluid flows in parallel layers, whereas lateral mixing of fluid particles between layers occurs in turbulent flow. Dybbs and Edwards (1984),
in their excellent review of flow of liquids in porous structures, note the existence of four flow regimes in porous media, based on the Reynolds number \( R_e \) (see Eq. 2.12):

1. The Darcy flow regime occurs at \( R_e < 1 \). The flow in this laminar, linear flow regime is dominated by the viscous forces.

2. The inertial flow regime initiates at \( 1 < R_e < 10 \) and persists to \( R_e \approx 150 \). The flow is laminar, but non-linear. The flow regime is sometimes referred to as the “Forchheimer” flow regime.

3. An unsteady laminar flow regime at Reynolds numbers between approximately 150 and 300. Unsteady flow occurs “in the form of laminar wake oscillations in the pores” (Dybbs and Edwards, 1984).


The Reynolds number \( R_e \) is the ratio of the inertial forces and the viscous forces of a flow:

\[
R_e = \frac{\rho_w v_s^2}{\mu_w v_s / L_s} = \frac{v_s L_s \rho_w}{\mu_w}
\]

where \( \rho_w \) is the density of water, \( \mu_w \) is the dynamic viscosity of water, \( v_s \) is the average seepage velocity through the pores (see Eq. 2.13), \( n \) is porosity, and \( L_s \) is a length scale.

The average seepage velocity through the pores \( v_s \) is defined as follows:

\[
v_s = \frac{v}{n}
\]

The Kozeny-Carman relation can be used to determine the saturated hydraulic conductivity of porous media for seepage regimes where Darcy’s law is valid. It is based on conceptual models of capillary tube flow for which the Navier-Stokes equation can be used. The relation is commonly held to be valid for granular materials, while its validity for fine grained soils, especially clays, is a subject of debate (e.g. Carrier, 2003; Chapuis and Aubertin, 2003, 2004; Hansen, 2004; Mitchell and Soga, 2005). In this study, the form presented by Mitchell and Soga (2005) is adopted:

\[
k = \frac{1}{C C_p} \frac{g}{\mu_w \rho_w A_s^2 G_s^2 (1 + e)}
\]

\(^4\)In this study, which primarily deals with laboratory investigations in a controlled environment, the water temperature \( T = 20 \, ^{\circ}C \) is constant, yielding \( \rho_w = 998.2 \, \text{kgm}^{-3} \), and \( \mu_w = 1.002 \times 10^{-3} \, \text{Nsm}^{-2} \).
where $g$ is gravitational acceleration, $C_t$ is tortuosity factor, $C_p$ is pore shape factor, $A_s$ is specific surface of solids and $G_s$ is specific gravity of solids.

Assuming constant values for viscosity and density of water and solids, which is a reasonable assumption in most geotechnical engineering applications, Eq. 2.14 establishes that the hydraulic conductivity increases with increasing void ratio, decreasing specific surface of the solids and decreasing tortuosity.

The interaction between the porous medium and fluid flow can also be appreciated by considering the forces acting on the solid particles of a porous medium, subject to seepage flow in a vertical direction, per unit volume of porous medium, with positive $z$ in a upward direction (after Bear, 1972):

- Weight of the solids $F_g$ acting in a downward direction is a function of the unit weight of the solids $\gamma_s$:
  \[ F_g = -\gamma_s(1-n) \]  \hfill (2.15)

- The buoyancy force $F_b$ is equal to the resultant of the liquid pressure $u$ acting on the solid particles:
  \[ F_b = -(1-n)\partial u/\partial z \]  \hfill (2.16)

Note that for the hydrostatic condition $\partial u/\partial z = \gamma_w$, the buoyancy force is equal the weight of the displaced fluid: $F_b = -\gamma_w(1-n)$.

- The drag force is derived from the available energy per unit fluid, $\phi$, which drives the fluid through the porous medium. This energy is dissipated as viscous friction at the solid-fluid interface which generates a drag on the solid matrix in the direction of fluid flow. The drag force $F_d$ of the fluid, at the solid-fluid interface, per unit volume of porous medium is:
  \[ F_d = -n\gamma_w\partial \phi/\partial z. \]  \hfill (2.17)

The resultant force $F_r$ per unit volume of porous medium acting on the solid matrix is then:

\[ F_r = F_g + F_b + F_d = - (\gamma_s - \gamma_w)(1-n) - \gamma_w \partial \phi/\partial z \]  \hfill (2.18)

The first term on the right-hand side of Eq. 2.18 is the specific submerged unit weight of the solid matrix, i.e. the weight of the solid particles and the buoyancy force on the solid particles in the hydrostatic condition. The second term in the right-hand side of Eq. 2.18 will be referred to as the seepage force per unit volume: it is the sum of the change of buoyancy, associated with the change of the pore water pressure distribution, and the drag force at the solid-fluid interface. The seepage force per unit volume is proportional to the hydraulic gradient $i = \partial \phi/\partial z$ across
the specimen and, in case of Darcy flow, proportional to the specific discharge \( v \). However, the measure of seepage force per unit volume does not correctly account for the seepage-induced changes of effective stress. This macro-scale effect can only be appreciated by integrating the seepage force per unit volume over the relevant volume of the soil. The pore water pressure is an appropriate measure for the seepage-induced changes of effective stress.

### 2.4 Experimental investigations of seepage-induced internal instability

#### 2.4.1 Rigid-wall permeameters

Historically, the susceptibility of a material to seepage-induced internal instability was tested in simple rigid wall permeameters, with constant head control. The susceptibility was determined based on mass loss and forensic analysis of the particle size distribution at the end of the test (e.g. Åberg [1993]; Kenney and Lau [1985]; USACE [1953]). The permeameter of Honjo et al. (1996) in addition permitted measurement of the axial deformation. The second generation of rigid wall permeameters included improved seepage control systems and monitoring of the pore water pressure distribution, using standpipes and measurement of the flow rate, to allow for the determination of hydraulic conductivity (e.g. Ke and Takahashi [2012]; Skempton and Brogan [1994]), often combined with measurement of mass loss and forensic analysis of the particle size distribution at the end of the test (e.g. Cividini et al., 2009; Lafleur et al., 1989; Sterpi, 2003; Wan and Fell, 2004; Wittmann, 1977). Most of these studies did not apply any vertical stress, although some applied a nominal top load (Åberg, 1993; Honjo et al., 1996; Kenney and Lau 1985). The third and most recent generation of rigid wall permeameters incorporated an axial loading system with measurement of the axial load at the top (Chapuis et al., 1996; and the small rigid wall permeameter of Li, 2008), or with measurement of the axial load at the top and bottom of the specimen (Moffat and Fannin, 2006; Sail et al., 2011).

#### 2.4.2 Flexible wall permeameters

Several flexible wall permeameters have been used to investigate seepage-induced internal instability (see Table 2.2). Molenkamp et al. (1979), Sanchez et al. (1983) and Sun (1989) used a flexible wall permeameter in an attempt to eliminate any preferential seepage flow paths along the soil-wall interface of a rigid-wall permeameter, in order to more confidently establish the susceptibility of materials. The ability to control the stress on the test specimen appealed to more recent investigators (e.g. Bendahmane et al., 2008; Chang and Zhang, 2011; Ke and Takahashi, 2014b; Luo et al., 2011; Xiao and Shiwiyhat, 2012), all of whom sought to investigate the conditions at the onset of instability. For this purpose, the hydraulic gradient, flow rate and eroded mass were monitored, typically in combination with deformation of the test speci-
imen, either by means of monitoring axial or volumetric deformations. Luo et al. (2012), and Ke and Takahashi (2014b), deduced volumetric deformation from local measurements using two and three pairs of strain gauges, respectively, whereas Chang and Zhang (2011) deduced radial deformation from planar deformations observed on digital photographs. Accordingly, the techniques yield an indirect determination of volume change of the specimen, through local measurements of deformation, which leads to substantial uncertainties in the measured values.

In contrast, it is common practice in triaxial shear testing of unsaturated soils to measure total volumetric deformation of the specimen by monitoring the cell fluid (e.g. Ng et al., 2002; Sharma, 1998; Wheeler, 1986; Yin, 2003).

### 2.4.3 Variables to quantify seepage-induced internal instability

Early investigations relied solely on change in the grain size distribution as an indicator of internal instability (e.g. Kenney and Lau, 1985; Molenkamp et al., 1979; USACE, 1953). Mass loss is commonly used to quantify internal instability: the loss may be characterised directly by collection of soil eroded from the specimen (e.g. Åberg, 1993; Adel et al., 1988; Bendahmane et al., 2008), else indirectly from change in gradation of the test specimen (e.g. Chapuis et al., 1996; Moffat et al., 2011; Wan and Fell, 2004). On occasion both methods have been used (e.g. Honjo et al., 1996; Lafleur et al., 1989; Li 2008). Kovacs (1981) first explicitly postulated that a change in local permeability accompanies the migration of fine particles out of a clast-supported micro-structure, which USACE (1953) had earlier alluded to. Lafleur et al. (1989) first used temporal and spatial changes in hydraulic conductivity, deduced from measurements of hydraulic gradient and flow rate, as indicators of internal instability. Although measurements of hydraulic gradient and flow rate are commonly recorded (e.g. Chapuis et al., 1996; Garner and Sobkowicz, 2002; Li, 2008; Moffat et al., 2011; Skempton and Brogan, 1994; Wan and Fell, 2004), it appears that changes in hydraulic conductivity are seldom reported in a systematic manner. Notably, Skempton and Brogan (1994), and later Li (2008), used measurements of hydraulic gradient and specific discharge to quantify the onset of instability. Despite an early appreciation for the possible rearrangement of soil structure in response to the onset of internal instability (e.g. Kezdi, 1979; Kovacs, 1981), measurement of deformation has not received the same widespread recognition that is given to measurement of mass loss, hydraulic gradient and flow rate. Only Honjo et al. (1996); Li (2008) and Moffat et al. (2011), in studies using a rigid-wall permeameter, report systematic measurements of axial deformation associated with seepage-induced internal instability. The recent development of a triaxial permeameter for investigation of internal instability has enabled the measurement of volumetric deformation (e.g. Chang and Zhang, 2011; Ke and Takahashi, 2014b; Luo et al., 2012; Xiao and Shwiyhat, 2012).
2.5 Factors governing seepage-induced internal instability

Early experimental investigations focused primarily on the susceptibility to seepage-induced internal instability of soils (e.g. USACE, 1953). Subsequent investigations established the role of the particle size distribution on the material susceptibility of granular materials, which has yielded several useful empirical tools, exclusively based on the particle size distribution, to determine the susceptibility to seepage-induced internal instability (e.g. Burenkova, 1993; Kenney and Lau, 1985, 1986; Kezdi, 1979; Sherard, 1979). Noteworthy is that these methods do not distinguish between the susceptibility to suffusion or suffosion. Chapuis (1992) demonstrated that the methods of Sherard (1979), Kezdi (1979) and Kenney and Lau (1985, 1986) essentially compare the secant slope of the particle size distribution with some limiting value. Li and Fannin (2008) proposed to combine the methods of Kenney and Lau (1985, 1986) and Kezdi (1979) to eliminate some of the conservatism in both methods. Wan and Fell (2008), following the work of Sun (1989), noted that the methods of Sherard (1979), Kenney and Lau (1985 1986) and Burenkova (1993) were conservative for sand and gravel soils with silty and clayey fines, and proposed a modification of the method of the method of Burenkova (1993). The recent findings of Crawford-Flett (2014) indicate that the “[p]lasticity in the fines component of widely-graded soils results in internally stable behaviour.”

Adel et al. (1988) first imposed a controlled, variable hydraulic load to determine the seepage velocity at which internal instability initiated. Skempton and Brogan (1994) established that the onset suffusion initiated at hydraulic gradients of approximately one order of magnitude smaller than the hydraulic gradient at which fluidisation occurs. The tests on glass beads of Crawford-Flett (2014) confirmed this finding and related the threshold hydraulic gradient to the sink velocity of the fine particles. The findings of Luo et al. (2012) suggest that the rate of particle migration increases with increasing hydraulic gradient.

Skempton and Brogan (1994) postulated that the fine particles exhibit a reduced effective stress, quantified by a reduction factor $\alpha$:

$$\alpha = \frac{\sigma_{vf}'}{\sigma_v'}$$

(2.19)

where $\sigma_{vf}'$ = vertical effective stress on the fine particle fraction and $\sigma_v'$ = vertical effective stress.

The work of Skempton and Brogan (1994) appears to have influenced Moffat (2005), who first systematically investigated the influence of the effective stress and hydraulic conditions on seepage-induced internal instability. Moffat (2005), using a rigid wall permeameter, identified suffosion in four gap-graded soils as a marked change in local hydraulic conductivity, typically
accompanied by a marked displacement. Although the progression of suffosion was observed to be temporally and spatially variable (Moffat et al., 2011), the onset of seepage-induced failure, associated with large deformations, occurred at a critical combination of hydraulic gradient and effective stress. The concept of a hydro-mechanical failure envelope (Moffat and Fannin, 2011) was introduced to quantify the conditions at failure. The findings of Li (2008), who tested soil and glass beads gradations in a rigid wall permeameter, appear to confirm the validity of the hydro-mechanical failure envelope. Li and Fannin (2012) noticed an apparent scale effect, when comparing the conditions at the onset of instability in a small permeameter and a large permeameter. However, the scale effect (see Appendix C.1) appears the unintended consequence of the reporting of test results in terms of the hydraulic gradient, instead of pore water pressures, which is a more suitable variable to quantify the seepage-induced change of effective stress (see also Section 2.3). The influence of effective stress on seepage-induced internal instability in clayey sand was established by Bendahmane et al. (2008), who, using a flexible wall permeameter, observed a decreasing rate of clay erosion with increasing confining stress. Chang and Zhang (2013), also using a flexible wall permeameter, investigated the progression of seepage-induced internal instability by consolidating one gap-graded gradation of soil to varying isotropic and anisotropic stress states, prior to imposing an incrementally increasing seepage flow. Chang and Zhang (2013) identified four phases in the erosion process: 1) a stable phase; 2) an initiation phase, in which some fine particles erode but the specimen deformation is limited; 3) a development phase, in which a large amount of fine particles washes out of the specimen, accompanied by large deformations; and 4) a failure phase. Comparison with the previously defined seepage-induced internal instability phenomena (see Section 2.1.3), suggests that the “initiation phase” is similar to suffusion, and that the “development phase” is similar to suffosion. The findings of Chang and Zhang (2013) indicate that the onset of suffusion, suffosion and failure, respectively, is dependent on the mean effective stress, the deviatoric stress and the hydraulic conditions. In contrast, Crawford-Flett (2014), in tests on two glass beads gradations with a lower finer fraction content, established that the onset of suffusion is independent of effective stress.

Ke and Takahashi (2014a) investigated the shear strength characteristics of an internally unstable soil that exhibited a substantial seepage-induced mass loss and volume change, which yielded a strength reduction in the drained triaxial test. This finding is in broad agreement with the previous finding of Ke and Takahashi (2012). Xiao and Shiwiyhat (2012) also reported a changed undrained shear strength in soils that exhibited seepage-induced internal instability.

Finally, Crawford-Flett (2014) proposed two additional necessary conditions for suffusion, in addition to the previously discussed hydraulic threshold. The particle detachment potential, quantified by $\alpha \approx 0$, was established in a clast-supported micro-structure, based on the results of
DEM (Shire and O’Sullivan, 2013) that in this micro-structure, $\alpha$ is indeed approximately zero. A transportation potential was established based on the concepts of a controlling constriction size $D_{c,D95}$ (after Kenney et al., 1984 and Indraratna et al., 2011), defined as the constriction size corresponding to the 95th percentile of the theoretical densest constriction curve for the coarse fraction, and $d_{85}$, defined as the particle size corresponding to the 85th percentile of the finer fraction of a gap-graded material. A gap-graded material is deemed susceptible to suffusion if:

$$\frac{D_{c,D95}}{d_{85}} > 1$$

(2.20)

2.6 Reflection on research hypotheses

In light of the literature review, the incomplete knowledge of the factors governing suffusion and suffosion, which was briefly alluded to in the introduction of the research hypotheses in Section 1.1, can be examined in greater detail. Herein, the knowledge gaps leading to the respective research hypothesis are discussed.

2.6.1 Hypothesis No. 1

The first research hypothesis was proposed as follows: Volume change is a characteristic variable of seepage-induced internal instability and serves to distinguish between suffusion and suffosion. A review of the literature on seepage-induced internal instability phenomena, identified volume change as one of three variables to characterise, and distinguish between, suffusion and suffosion (see Section 2.1.3). In experimental investigations using rigid wall permeameters (e.g. Chapuis et al., 1996; Crawford-Flett, 2014; Li, 2008; Moffat and Fannin, 2006; Sail et al., 2011), volume change could be inferred from the measurement of axial deformation. In the more recent experimental investigations using a flexible wall permeameter (e.g. Chang and Zhang, 2011; Ke and Takahashi, 2014b; Luo et al., 2012), volumetric deformation was deduced from local measurements of radial and axial strain. The disparity between the volume change as a variable to characterise, and distinguish between, suffusion and suffosion, and the indirect measurement of volume change in flexible wall permeameters, is addressed by research hypothesis No. 1.

2.6.2 Hypothesis No. 2

The second research hypothesis was proposed as follows: The onset of suffosion is dependent on effective stress. Crawford-Flett (2014) established that the onset of suffusion is independent of effective stress. In contrast, the findings of Moffat (2005) and Li (2008) indicated that failure in suffusive materials is governed by a critical combination of hydraulic gradient and effective stress. The experiments of Moffat (2005) and Li (2008) were conducted in a rigid wall permeameter, which exhibits obvious limitations in control of effective stresses. Recently,
Chang and Zhang (2013), based on tests on one granular soil gradation using a flexible wall permeameter, suggest that the onset of suffosion is dependent on mean effective stress. The general influence of effective stress on suffosion has thus predominantly been established using rigid wall permeameters, with limited control of effective stress, and it was broadly confirmed by tests using a flexible wall permeameter on only one soil gradation. Hypothesis No. 2 seeks to address the incomplete knowledge of the influence of the effective stress on the onset of suffosion.

2.6.3 Hypothesis No. 3

The third research hypothesis was proposed as follows: The micro-structure of internally unstable materials controls the phenomenological response to seepage flow. Several researchers (e.g. Kenney and Lau, 1985; Kezdi, 1979; Skempton and Brogan, 1994; Wittmann, 1978) al- luded to the concept of a clast-supported micro-structure to explain seepage-induced internal instability. Crawford-Flett (2014), based on the work of Thevanayagam et al. (2002), examined the characteristics of three types of micro-structure in relation with experiments, and found that a clast-supported micro-structure is susceptible to suffusion. The influence of micro-structure on suffosion appears not to have been investigated. Hypothesis No. 3 is proposed to examine the influence of the micro-structure on suffosion, and advance the knowledge of the influence of the micro-structure on suffusion.

2.6.4 Hypothesis No. 4

Finally, the fourth research hypothesis was proposed as follows: Gap-graded gradations of rounded particles are more susceptible to seepage-induced internal instability than identical gap-graded gradations of sub-angular particles. Although the particle shape greatly affects the engineering response of granular soils, it appears to have received no attention in the investigation of seepage-induced internal instability. Hypothesis No. 4 seeks to address this knowledge gap.

2.7 Summary

A review of the literature established three distinct phenomena of soils subject to seepage flow:

- Migration of fine particles from a soil, termed suffusion, which is characterised as seepage-induced mass loss, without change in volume, accompanied by an increase of hydraulic conductivity; and,

- Collapse of the soil structure, termed suffosion, which is characterised as a seepage-induced mass loss, accompanied by a reduction in volume, and change in hydraulic conductivity; and,
- Reduction of effective stress to zero in internally stable soils, termed fluidisation, which is characterised as a seepage-induced volumetric expansion, accompanied by an increase in hydraulic conductivity, with no mass loss.

The micro-structure of a soil is defined as the arrangement of the particles, or the soil fabric, and its stability. The characteristics of the micro-structure of packings of equal-size spherical particles are presented first, prior to a discussion on the different micro-structures that have been identified in binary mixtures of discrete coarse and fine fractions. The concepts of three types of micro-structures have been invoked in relation to seepage-induced internal instability: a coarse-particle dominated clast supported micro-structure, a fine-particle dominated matrix supported micro-structure and a transitional micro-structure. The role of the particle shape on the stability of the arrangement of particles is briefly described.

Following a description of the seepage flow in granular materials, the characteristics of experimental investigations on seepage-induced internal instability are presented. Seepage-induced internal instability is commonly quantified by a change in particle size distribution, mass loss from the specimen, a change in hydraulic conductivity, axial deformation and radial deformation. The ability to control the effective stress has driven the recent development of flexible wall permeameters.

Several empirical tools exist to assess the susceptibility of a material to seepage-induced internal instability. The onset of suffusion initiates at a relatively small hydraulic gradient, independent of the effective stress. The occurrence of suffosion is temporally and spatially variable. The onset of failure in internally unstable materials, associated with large deformations, appears dependent on the hydraulic load and the effective stress. Finally, the knowledge gaps associated with the research hypotheses are discussed in light of the review of the literature.
## Table 2.1: Descriptions of seepage-induced internal instability phenomena (source: Fannin and Slangen (2014), with permission from ICE Publishing).

<table>
<thead>
<tr>
<th>Study</th>
<th>Phenomenon</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>USACE (1953)</td>
<td>Inherent stability</td>
<td>“Inherent stability was determined by the degree to which the gradation curves of the sections compared with those of the original material”</td>
</tr>
<tr>
<td>Wittmann (1978)</td>
<td>Suffosion</td>
<td>“[…] mixtures with a gravel skeleton […] permit transport of sand particles into, inside and out of the skeleton. These phenomena are known as suffosion (transport out of the skeleton) and colmatation or sluicing (transport into the skeleton). These processes influence the permeability of the mixture […] The skeleton remains stable.”</td>
</tr>
<tr>
<td></td>
<td>Erosion</td>
<td>“For pure sand or only small amounts of the gravel component this [deformation] phenomenon is known as piping by heave, whereas mixtures with a higher amount of coarser particles show the phenomenon of erosion piping. Erosion leads to collapse of the mixture, with the finer particles drawn away by the seeping water.”</td>
</tr>
<tr>
<td>Kezdi (1979)</td>
<td>Suffusion</td>
<td>“Suffusion is a phenomenon where water, while seeping through the pores, carries along the fine particles without destroying the soil structure.”</td>
</tr>
<tr>
<td></td>
<td>Erosion</td>
<td>“Erosion […] destroys the soil structure. Not only are single grains or fractions disrupted, but the whole soil structure is progressively destroyed and tubelike cavities are formed.”</td>
</tr>
</tbody>
</table>

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Table 2.1 – *Continued from previous page*

<table>
<thead>
<tr>
<th>Study</th>
<th>Phenomenon</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molenkamp et al. (1979)</td>
<td>Suffosion</td>
<td>“[..] migration of the finer material of the very filter layer [..]”</td>
</tr>
<tr>
<td></td>
<td>Internal instability</td>
<td>“The internal stability of the filter material could possibly be checked by comparing the grain size distributions of the top and bottom part of the column”</td>
</tr>
<tr>
<td>Sherard (1979)</td>
<td>Internal erosion stability</td>
<td>“[..] a concentrated leak developed through the core which caused a type of internal erosion in which the soil fines are eroded selectively and carried out of the core, leaving the coarse sand and gravel particles behind to act as a pervious drain. The volume of fine material eroded was larger than the volume of the void spaces between the coarser soil particles causing progressive collapse of the material above the initial leakage channel, which action finally reaches the dam surface as manifested by the sinkhole or crater.”</td>
</tr>
<tr>
<td>Jones (1981)</td>
<td>Suffosion</td>
<td>“To Pavlov (1898) and Savarensky (1940) [..] suffosion meant mechanical removal of loose particles [..] Both mechanical and chemical forms of suffosion process were described by Russian, Polish and French workers [..]”</td>
</tr>
<tr>
<td>Kovacs (1981)</td>
<td>Suffusion</td>
<td>“Redistribution of fine grains within the layer [..] when the solid volume of the layer is not changed only the local permeability is altered”</td>
</tr>
<tr>
<td></td>
<td>Internal suffusion</td>
<td>“[..] when the solid volume of the layer is not changed only the local permeability is altered”</td>
</tr>
<tr>
<td></td>
<td>External suffusion</td>
<td>“[..] when the volume of the solid matrix is reduced, accompanied by an increase in permeability”</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>Study</th>
<th>Phenomenon</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>D. Burenkova</td>
<td>Destruction of the skeleton</td>
<td>“Subsidence of the layer, when some of the coarse grains are removed from the solid matrix, and thus the load of overlying layers causes the total volume of the layer to decrease”</td>
</tr>
<tr>
<td>Kenney and Lau (1985)</td>
<td>Internal instability</td>
<td>“Because of its wide grain size distribution, the small grains can easily be washed out, through the skeleton of the large grains.”</td>
</tr>
<tr>
<td>Lafleur et al. (1989)</td>
<td>Internally unstable</td>
<td>“[…] substantial migration took place within the layers […] This trend was supported by the permeability curves […]”</td>
</tr>
<tr>
<td>Å. Berg (1993)</td>
<td>Grading instability</td>
<td>“[…] the material has loose grains, which are so small that they can pass through the constrictions between fixed grains […] loose grains should be considered potentially unstable”</td>
</tr>
<tr>
<td></td>
<td>Internal filter formation process or self-filtration</td>
<td>“[…] when this process proceeds in a […] upward direction […] shrinkage of the material during washout causes movement in the overlying material […] and thereby also make washout of fixed grains possible”</td>
</tr>
<tr>
<td>Burenkova (1993)</td>
<td>Inner suffosion</td>
<td>“Inner suffosion takes place, when fine particles are transported in the soil structure […] This process can lead to an increase of the permeability of the soil […]”</td>
</tr>
<tr>
<td></td>
<td>Outer suffosion</td>
<td>“Outer suffosion means transportation of fine fractions out of the soil […] This leads to an increase of the void ratio, the permeability and […] to instability of the whole structure.”</td>
</tr>
<tr>
<td></td>
<td>Internal instability</td>
<td>“The tests showed particle movements along the interface of the test apparatus and the soil specimen under seepage flow. The readings of the piezometers altered during the tests and particles eroded.”</td>
</tr>
<tr>
<td>Study</td>
<td>Phenomenon</td>
<td>Description</td>
</tr>
<tr>
<td>------------------------</td>
<td>-------------</td>
<td>--------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Skempton and Brogan</td>
<td>Internal instability</td>
<td>“[...] the sand can migrate within the interstices of a framework of primary fabric formed predominantly of the gravel particles and can be washed out [...]”</td>
</tr>
<tr>
<td></td>
<td>Segregation piping</td>
<td>“[...] failure took the form of piping of the fines whereas the gravel particles remained practically undisturbed [...] In the stable materials this occurred at approximately the critical gradient given by piping theory [...] but in the unstable materials migration and strong piping of fines took place at gradients of about one fifth to one third of the theoretical value [...]”</td>
</tr>
<tr>
<td></td>
<td>Onset of instability</td>
<td>“A further increase in gradient causes a disproportionate increase in flow, leading towards failure either by piping [...] or by the opening of a horizontal crack [...] which then works its way upwards until piping occurs throughout.”</td>
</tr>
<tr>
<td>Chapuis et al. (1996)</td>
<td>Suffossion</td>
<td>“[...] migration of fine particles of a soil within its own pore space.”</td>
</tr>
<tr>
<td></td>
<td>Internal instability</td>
<td>“If a 0-20 mm base has an internal instability problem [...] creation of small layers with high capillarity and low permeability [...] are likely to develop with time.”</td>
</tr>
<tr>
<td></td>
<td>Internal segregation</td>
<td>“The internal segregation of particles was evaluated by wet sieve analysis” and “ [...] changes [in permeability] appeared with [internally unstable] gradation 2.”</td>
</tr>
<tr>
<td>Chapuis and Aubertin</td>
<td>Suffusion</td>
<td>“[...] a permeating process, often a fluid movement towards a surface or over a surface; thus, using it for internal erosion would be incorrect [...]”</td>
</tr>
<tr>
<td></td>
<td>Suffosion</td>
<td>“[...] this word is not found in English and French dictionaries”</td>
</tr>
<tr>
<td></td>
<td>Suffossion</td>
<td>“[...] correctly represents the phenomenon of internal erosion. It is unfortunate that it has been forgotten after having been used a long time ago by military engineers as an undermining technique.”</td>
</tr>
<tr>
<td>Study</td>
<td>Phenomenon</td>
<td>Description</td>
</tr>
<tr>
<td>-----------------------</td>
<td>---------------</td>
<td>--------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Honjo et al. (1996)</td>
<td>Self-filtration</td>
<td>“As flow starts, the finer base particles pass through the filter but the coarser particles are caught at the base soil-filter interface quickly forming a thin dense layer [which] consists of the coarser particles. The rest of the base soil is then protected by this layer [..]”</td>
</tr>
<tr>
<td></td>
<td>Stable</td>
<td>“The loss of base soil is observed for a limited time and the development of [a] self-filtration layer is prominent as observed from the after test sieve analysis”</td>
</tr>
<tr>
<td></td>
<td>Unstable</td>
<td>“Loss of base soil is observed to be continuous and the whole sample is subject to disturbance”; “self-filtration layer is absent in this case”, also related to “progressive settlement”</td>
</tr>
<tr>
<td>Garner and Sobkowicz</td>
<td>Suffosion</td>
<td>“[..] the mass movement of the fine fraction within the skeleton of a dispersed, potentially unstable coarse fraction”, associated with an increase of permeability</td>
</tr>
<tr>
<td>(2002)</td>
<td>Suffusion</td>
<td>“[..] the redistribution of fine grains within a stable densely packed skeleton” and associated reduction in permeability, referring to the term “internal suffusion” used by Kovacs (1981)</td>
</tr>
<tr>
<td>Wan and Fell (2004)</td>
<td>Suffusion or internal instability</td>
<td>“[..] an internal erosion process which involves selective erosion of fine particles from the matrix of a soil made up of coarse particles”</td>
</tr>
<tr>
<td></td>
<td>Unstable</td>
<td>“[..] a change in the grain-size distribution of the test sample after the test”; “[..] signs of erosion [..] are observed as the hydraulic gradient across the test sample increases”; and “The colour of the effluent provided an indication of whether or not erosion was taking place [..]”</td>
</tr>
<tr>
<td>Study</td>
<td>Phenomenon</td>
<td>Description</td>
</tr>
<tr>
<td>------------------------------</td>
<td>--------------------------------</td>
<td>------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Richards and Reddy (2007)</td>
<td>Suffosion</td>
<td>“This process can result in a loose framework of granular material with relatively high seepage flows that leads to collapse of the soil skeleton (McCook, 2004). In non-cohesive materials suffosion leads to zones of high permeability (and water transmission), potential outbreaks of increased seepage, increased erosive forces and potential collapse of the skeletal soil structure.”</td>
</tr>
<tr>
<td>Suffusion</td>
<td></td>
<td>“Gradual loss of finer matrix materials in a soil supported by a coarser grained skeleton is termed suffusion, which may lead to a more general collapse and loss of soil structure, termed suffosion (Kezdi 1979; McCook 2004).”</td>
</tr>
<tr>
<td>Fell and Fry (2007)</td>
<td>Suffusion or internal instability</td>
<td>“[..] selective erosion of fine particles from the matrix of coarser particles [..] by seepage flow, leaving behind an intact soil skeleton formed by the coarser particles”</td>
</tr>
<tr>
<td>Li (2008)</td>
<td>Internal suffosion</td>
<td>“[..] refers to the redistribution of finer particles within layers that is accompanied by a change in local hydraulic conductivity”. “No displacement or mass loss was observed.”</td>
</tr>
<tr>
<td></td>
<td>External suffosion</td>
<td>“[..] refers to the scouring of finer particles that is associated with an overall increase in hydraulic conductivity”. “A contractive displacement and mass loss was observed”</td>
</tr>
<tr>
<td>Bendahmane et al. (2008)</td>
<td>Suffusion</td>
<td>“[..] the permeability [..] decreased by a factor of 10 during the tests where erosion was initiated [..] characterized by some diffuse mass losses”</td>
</tr>
</tbody>
</table>

Continued on next page
<table>
<thead>
<tr>
<th>Study</th>
<th>Phenomenon Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bonelli and Marot (2011)</td>
<td>“Suffusion (or suffosion)” “[..] an internal erosion process by which finer soil particles are detached from the solid matrix and transported through pore constrictions by seepage flow.”</td>
</tr>
<tr>
<td>Moffat et al. (2011)</td>
<td>Suffusion “[..] the finer fraction of an internally unstable soil moves within the coarser fraction without any loss of matrix integrity or change in total volume [..] The visual observations, and the companion spatial and temporal variations of local hydraulic gradient, reveal a transport of finer particles from the soil with each increment of hydraulic gradient that yields a relatively slow and small change in local permeability, but no change in volume.” Suffosion “[..] particle migration yields a reduction in total volume and a consequent potential for collapse of the soil matrix (Richards and Reddy, 2007).” “Visual observations and the companion spatial and temporal variations of local hydraulic gradient, reveal a particle loss that yields a relatively large and rapid change in local permeability and a companion change in specimen volume.”</td>
</tr>
</tbody>
</table>
Table 2.2: Overview of selected studies on seepage-induced internal instability using a flexible wall permeameter.

<table>
<thead>
<tr>
<th>Publication</th>
<th>Material</th>
<th>Specimen size (cm)²</th>
<th>Measurements</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molenkamp et al. (1979)</td>
<td>Sand and gravel</td>
<td>$D = 45$ $l = 100$</td>
<td>DF, no, no, no, no</td>
<td></td>
</tr>
<tr>
<td>Sanchez et al. (1983)</td>
<td>Silt and clay</td>
<td>$D = 7$ $l = 15.5$</td>
<td>DF, yes, no, no, no</td>
<td></td>
</tr>
<tr>
<td>Sun (1989)</td>
<td>Sand and clayey silt</td>
<td>$D = 7$ $l = 2.5$</td>
<td>DF, UF, yes, no, no</td>
<td></td>
</tr>
<tr>
<td>Bendahmane et al. (2008)</td>
<td>Clayey sand</td>
<td>$D = 5$ $l = 5$</td>
<td>DF, yes, no, no, yes</td>
<td></td>
</tr>
<tr>
<td>Chang and Zhang (2011)</td>
<td>Sand and gravel</td>
<td>$D = 10$ $l = 10$</td>
<td>UF, DF, yes, yes, yes</td>
<td>$\approx 0.85$</td>
</tr>
<tr>
<td>Luo et al. (2012)</td>
<td>Sandy gravel</td>
<td>$D = 10$ $l = 10$</td>
<td>DF, yes, yes, yes, yes</td>
<td></td>
</tr>
<tr>
<td>Xiao and Shwiyhat (2012)</td>
<td>Clayey sand</td>
<td>$D = 5.1$ $l = 10.2$</td>
<td>DF, yes, yes, yes</td>
<td>$&gt; 0.95$</td>
</tr>
<tr>
<td>Ke and Takahashi (2014)</td>
<td>Sand</td>
<td>$D = 7$ $l = 15$</td>
<td>DF, yes, yes, yes</td>
<td>$&gt; 0.95$</td>
</tr>
<tr>
<td>This study (2014)</td>
<td>Glass beads and soils</td>
<td>$D = 10$ $l = 10$</td>
<td>UF, no, yes, yes</td>
<td>$&gt; 0.95$</td>
</tr>
</tbody>
</table>

Notes:
1. All studies measured flow rate and hydraulic pressure difference across the specimen.
2. $D$, specimen diameter and $l$, specimen length.
3. UF = Upward flow, DF = Downward flow.
4. Using a photographic method.
5. Derived from strain gauges.
6. By means of monitoring the volume of the inflow and outflow.
7. Monitoring of volume change of cell fluid.
Figure 2.1: Non-destructive seepage-induced internal instability in a test conducted by Skempton and Brogan (1994) (source: Fannin and Slangen (2014), with permission from ICE Publishing).

Figure 2.2: Destructive seepage-induced internal instability in a test conducted by Li (2008) (source: Fannin and Slangen (2014), with permission from ICE Publishing).
Figure 2.3: Seepage-induced instability in a test conducted by Li (2008) (source: Fannin and Slangen (2014), with permission from ICE Publishing).
Figure 2.4: Schematic illustration of seepage-induced instability phenomena: (a) suffusion; (b) suffosion; and (c) fluidisation (source: Fannin and Slangen (2014), with permission from ICE Publishing).
Figure 2.5: Conceptual framework for seepage-induced instability phenomena (source: Fannin and Slangen (2014), with permission from ICE Publishing).

Figure 2.6: Inter-coarse and inter-fine void ratios (adapted from Thevanayagam, 1998, with permission from ASCE).
Figure 2.7: Micro-structure cases (source: Thevanayagam et al., 2002, with permission from ASCE).
Figure 2.8: Definitions of particle size and shape (source: Altufi et al., 2013, with permission from ASCE).

Figure 2.9: Plot of sphericity versus convexity for determination of particle shape (source: Altufi et al., 2013, with permission from ASCE).
Chapter 3

Apparatus, materials and testing program

This Chapter addresses the design of a new flexible wall permeameter (research objective No. 2), that was developed for this experimental investigation, the test procedure, the selection of the materials, and the test program. The test device, with its novel measurement of total volume change, is described in detail first (see Section 3.1), followed by a characterisation of the materials, comprising glass beads and soils, in Section 3.2. The test procedure is presented in Section 3.3, followed by the presentation of the test program in Section 3.4. A summary of this Chapter is provided in Section 3.5.

3.1 Flexible wall permeameter

A flexible wall permeameter was designed by the author and was custom-made at the Civil Engineering workshop at UBC. The general configuration of the flexible wall permeameter is illustrated in Fig. 3.1. The term “flexible wall permeameter” is selected in agreement with the terminology used by ASTM D5084-10 (ASTM, 2010). The device comprises a double-walled triaxial cell, which is assembled in a large water bath; a seepage control system, through which unidirectional upward multi-stage seepage flow can be imposed; and instrumentation.

3.1.1 Double-walled triaxial cell

The concept of a double-walled triaxial cell was originally introduced by Bishop and Donald (1961) to determine volume change during shear of an unsaturated specimen: the double-walled arrangement enables measurement of volume change of the cell fluid, from which the volume change of the specimen is deduced, independent of changes in cell pressure. The elegant design of the double-walled triaxial cell reported by Wheeler (1986), with its improved accuracy in the measurement of volume change, forms the basis for the triaxial cell developed for this investigation.
The use of an inner acrylic tube (see Fig. 3.2), with internal diameter of 206 mm and length of 440 mm, and an outer acrylic tube, with internal diameter of 236 mm and length of 440 mm, creates two chambers: an inner chamber, in which the specimen is located, and an outer chamber, between the two tubes. The use of acrylic tubes permits visual observations during testing, which proved to be very useful when interpreting the test results. The inner and outer chamber ports are connected to a common pressure source (see Fig. 3.3), through a parallel arrangement of two air/water interface measurement burettes. By means of pressurising both chambers to an equal cell pressure (see Fig. 3.4), the differential pressure across the inner acrylic tube is reduced to zero, thus eliminating any cell pressure dependent volume change of the inner chamber.

For this study, all specimens were reconstituted and subject to isotropic consolidation (see Section 3.3). The axial loading system consists of a rod through which loading is applied to compensate for the combined effect of buoyancy force from the cell pressure, and friction in the two sets of linear ball bearings mounted on the top plate. A U-cup provides a water tight seal between the inner chamber and the loading ram.

3.1.2 Membrane, base pedestal and top cap

The double-walled triaxial cell accommodates a cylindrical test specimen with diameter of 100 mm. The specimen is reconstituted to a height of approximately 100 mm, yielding a volume of approximately 780 cm$^3$, which appears a typical size compared to other flexible wall permeameters used in experimental investigations of seepage-induced internal instability (see Table 2.2). The specimen is enclosed by a rubber membrane with dimensions 10.2 cm x 0.03 cm x 30.5 cm, which is sealed to the base pedestal and top cap, respectively, using O-rings. Fig. 3.5 shows a dummy specimen in the cell.

In contrast to many other flexible wall permeameters (see Table 2.2), this device is configured for upward seepage flow in order to physically separate the basal support of the specimen from its outflow boundary, at the bottom and top of the specimen, respectively. The upward seepage flow configuration allows for selection of relatively fine wire meshes for the basal support of the specimen, which prevent mass loss during specimen reconstitution. The disadvantage that mass loss during multi-stage seepage flow cannot be measured in this configuration is mitigated by obtaining forensic observations of mass loss at the end of a test.

The conceptual design of the hollow base pedestal and the hollow top cap are similar to the designs of Sun (1989) and Chang and Zhang (2011): they are designed to allow unimpeded upward seepage flow. The cavity in the base pedestal is shaped as a inversed cone (see Fig.
3.6): the inner diameter increases from 10 mm at the bottom, where the opening connects to the inlet port in the base frame, to 90 mm at the top. A small port in the base pedestal connects to measurement port (MP) #1 in the base frame, to which the base pedestal is attached with an air-tight seal using bolts and O-rings. A narrow rim at the top of the base pedestal provides support for a perforated plate with 5 mm diameter holes, spaced 10 mm centre-to-centre. Two bottom wire meshes are placed on the perforated plate: the primary bottom wire mesh has a small opening size, which prevents particle loss during specimen reconstitution; a secondary, coarser and stiffer bottom wire mesh keeps the primary wire mesh in place. A gasket of PVC material seals the interface between the bottom wire meshes and the rim of the base pedestal. Two wire meshes are placed against a perforated plate mounted in the top cap, which sits on the top surface of the reconstituted specimen. The primary top wire mesh retains the coarse particles and the secondary, coarser wire mesh provides spacing for migration of washed-out particles between the primary top wire mesh and the perforated plate. A gasket of PVC material seals the interface between the top wire meshes and the top cap. The selection of the opening sizes of the wire meshes is dependent on the particle size distribution of the material (see Section 3.4).

The top cap with an outer diameter of 100 mm sits on the top surface of the reconstituted specimen. The top cap has a cylindrical cavity with inner diameter of 90 mm and height of 50 mm, which serves as a settling reservoir for any washed-out particles. Three ports (see Fig. 3.6) connect to different ports in the base frame using flexible nylon tubes: two ports connect to the outlet port, whereas the third port connects to MP #2 (see Fig. 3.3). A small perforated plate and a fine tertiary wire mesh, mounted in the top cap (see Fig. 3.6), prevent washed-out particles from entering the seepage control system.

3.1.3 Seepage control system

The seepage control system is a recirculation circuit based on the principle of multi-stage head control. The principle of head control is commonly applied in permeameter testing (e.g. Bendahmane et al., 2008; Chang and Zhang, 2011; Luo et al., 2012; Moffat and Fannin, 2006), and is conceptually different from the principle of flow control adopted by Ke and Takahashi (2014b). The total dynamic head (TDH) (see Fig. 3.1) between the free water surface in the inflow constant-head device (I-CHD), which connects to the inlet port in the base frame (see Fig. 3.3), and the free water surface in the outflow constant-head device (O-CHD), which connects to the outlet port in the base frame, yields upward seepage flow through the specimen. The elevation of the wall-mounted I-CHD is changed by a manually controlled winch. In contrast, the elevation of the O-CHD is fixed. The maximum total dynamic head, TDHmax that can be imposed in this manner is limited to 165 cm by the geometry of the apparatus and the height of the laboratory ceiling.
A supply of filtered, de-aired water is prepared from tap water in the manner described by Moffat and Fannin (2006): tap water is passed through a sand filter and a carbon filter (see Fig. 3.1), removing suspended solids larger than 10 µm and 3 µm, respectively. The filtered water is then dripped into a de-airing tank where it is stored under a vacuum of approximately -70 kPa for a minimum of 8 hours, which experience has shown yields a dissolved oxygen content less than 2.5 mg/L. At the beginning of a test, the storage reservoir (see Fig. 3.1) is filled with the filtered de-aired water. During multi-stage seepage flow, this water is recirculated to the I-CHD using a peristaltic pump.

3.1.4 Instrumentation

An overview of the instrumentation scheme is presented in Fig. 3.3. One transducer is used to control the cell pressure and five additional transducers are used to monitor the specimen response during consolidation and multi-stage seepage flow. The output voltages are automatically recorded at a frequency of 20 Hz and time-averaged over 1 s intervals for improved precision using a computer connected to a data acquisition system (DAQ) (see Fig. 3.1).

The accuracy, precision and resolution are discussed in detail in Appendix A. In summary, the accuracy, a measure for the error associated with a measured value, is defined as the standard deviation of the calibration data around the linear regression line; the precision, associated with repeatability, is defined as the standard deviation of the measured values around the mean of the measured values; and the resolution, or the smallest significant change that can be detected, is assumed as four times the precision. Importantly, the accuracy of the derived variables is a function of the value of the variable (see Table A.3).

3.1.4.1 Cell pressure

The cell pressure is measured using a total pressure transducer (TPT) #1, which connects to the inner chamber port (see IC-P on Fig. 3.3). TPT # 1 is a model PDCR 130/w/c manufactured by Druck, with a pressure range of 0 to 700 kPa, accuracy of +/- 0.2 kPa, precision of 0.02 kPa, and resolution of 0.08 kPa.

The air pressure to the air/water interface measurement burettes #2, #3 and #4 is regulated using two manual regulators, the second of which has a smaller working range. The regulators are connected in series to facilitate sensitive control of the cell pressure.
3.1.4.2 Pore water pressure and differential pore water pressure

The pore water pressure during consolidation of the specimen is measured using TPT #2, which connects to the base pedestal via measurement port MP #1. TPT #2 is a model 111 manufactured by GP:50, with a pressure range of 0 to 1050 kPa, accuracy of +/- 0.5 kPa, precision of 0.1 kPa, and resolution of 0.4 kPa.

The differential pore water pressure across the specimen, \( \Delta u \), is measured using a differential pressure transducer (DPT) #1: the low and high pressure ends are connected to the top cap (see Figs. 3.3 and 3.6), via MP #2, and to the base pedestal, via MP #1, respectively. DPT #1 is a model PDW/E972-05-01, manufactured by Sensotec, with a range of +/- 70 kPa, accuracy of +/- 0.1 kPa, precision of 0.003 kPa, and resolution of 0.012 kPa. A value of the mean effective stress, \( p' \), is derived from measurement of the cell pressure and mean pore water pressure in the specimen.

3.1.4.3 Flow rate

Flow rate through the specimen is measured manually by collecting the mass of the water that flows from the O-CHD (see Fig. 3.1) over an increment of time. The accuracy of the manual method is +/- 0.0004 cm\(^3\)/s, which is derived from the uncertainties of the measured quantities of mass of collected water and elapsed time (see Appendix A). For the precision and resolution of the flow rate measurement, conservative values equal to the accuracy are assumed. The specific discharge, \( v \), is derived from the flow rate measurement assuming a constant cross-sectional area of the specimen.

3.1.4.4 Axial displacement

The specimen height during reconstitution, and change of height during consolidation, is monitored using a dial gauge with an accuracy of +/- 0.01 mm. The axial deformation during multi-stage seepage flow, from which the axial strain \( \varepsilon_a \) is derived, is measured using a linear variable differential transformer (LVDT), mounted on the loading ram (see Fig. 3.2). The LVDT is a model TS 25, manufactured by Novotechnik, with a range of 0 to 25 mm, accuracy of +/- 0.01 mm, precision of 0.0008 mm, and resolution of 0.0032 mm.

3.1.4.5 Volume change

The volume change of the test specimen during consolidation is monitored in measurement burette #1. The measurement is corrected for membrane compliance using the single specimen method proposed by Vaid and Negussey (1984), see Appendix B.

A novel feature of the device is the measurement of the total volume change during multi-
stage seepage flow. The arrangement of the double-walled triaxial cell eliminates the pressure-
dependent volume change of the inner chamber. Thus, volume change of the inner chamber
is only caused by: 1) tiny pockets of air trapped underneath the top plate, which dissolve in
water over time; 2) absorption of water into the acrylic tube with time; 3) volume change of
the specimen; and 4) movement of the loading ram (Wheeler, 1986). The presence of air in
the inner chamber is significantly reduced by assembling the double-walled triaxial cell in a
large bath filled with de-aired water (see Fig. 3.1). Absorption of water into the acrylic tubes
is minimized by maintaining a high degree of saturation of the acrylic tubes by storing them in
water when they are not used for testing.

Calibration tests indicate that the rate of volume change attributed to the actions of dissolv-
ing air and absorption of water is very small and fairly repeatable: the rate of volume change
reduces to 0.036 +/- 0.025 cm$^3$/h after an elapsed time of approximately 16 h (see Fig. 3.7).
Therefore, upon completion of consolidation, the assembled apparatus is left standby for a min-
imum of 16 h prior to imposing the first stage of seepage flow. The volume change of the inner
chamber is derived from the measurement of the water level in measurement burette #2 (see
Fig. 3.3), using DPT #2, similar to the technique used by Tatsuoka (1981): the low-pressure
end of DPT #2 is connected to the air pressure supply, while the high-pressure end of DPT
#2 is connected to the bottom of measurement burette #2. The working range of measurement
 burette #2 is 20 cm$^3$ and it can be recharged from the larger measurement burette #3. DPT #2
is a model 316, manufactured by GP:50, with a range of 0-14 kPa, accuracy of +/-0.02 kPa,
precision of 0.004 kPa, and resolution of 0.012 kPa. The resolution of DPT #2 and the inner
surface area of measurement burette # 2 (0.47 cm$^2$), govern the resolution of the volume change
measurement, which is 0.06 cm$^3$ or approximately 0.01% volumetric strain.

The total volume change of the specimen is determined by monitoring the volume change
of the fluid in the inner chamber and correcting it for: the intrusion of the loading ram; mem-
brane penetration; and the calibrated, time-dependent volume change arising from the actions
dissolving air and absorption of water. The accuracy of the volume change measurement
system is derived from the uncertainties of the measured quantities (see Appendix A); the accu-
Bility is +/- 0.5 cm$^3$, or approximately +/- 0.07% volumetric strain, $\varepsilon_v$, for a multi-stage seepage
duration of less than 8 hours.

### 3.2 Materials

The materials tested in the laboratory investigation were selected to investigate the influence of
the particle size distribution and the particle shape on seepage-induced internal instability. Nine
gap-graded mixtures of glass beads and ten gap-graded gradations of angular soil particles with
varying finer fraction content, $S_f$, and $D'_{15}/d'_{85}$-ratios were produced from uniformly graded
component-fractions. The code used for the gap-graded gradations are generated as follows: the first two numbers are the particle size ratio of the coarse and the fine fractions, $D'_{15}/d'_{85}$, followed by two letters indicating the type of material (GB for glass beads or BT for soil particles); the last two numbers denote the percentage fine fraction. For example, gradation 4.8GB20 is a gap-graded gradation of glass beads with $D'_{15}/d'_{85} = 4.8$ and $S_f = 0.20$.

3.2.1 Glass beads

Glass beads (GB) were selected for the main program of testing, because of their shape and relatively easy handling. Spherical particles have the benefit that extensive experimental studies (e.g. McGeary, 1961; Scott, 1960; Scott and Kilgour, 1969) and DEM studies (e.g. Shire and O’Sullivan, 2013) have been conducted on packing arrangements of such particles.

The glass beads, manufactured by Potters Industries Inc., are specified as having a soda-lime silica glass composition, with density $\rho = 2.5 \text{ g/cm}^3$, coefficient of static friction $\mu = 0.9$ to 1.0 and roundness $R = 0.8$ to 0.9. The specific gravity of the glass beads $G_s = 2.49$ was determined following ASTM D854-14 (ASTM, 2014). The glass beads components used to prepare gap-graded mixtures are fine component GB-F and coarse components, GB-C1, GB-C2, GB-C3 and GB-C4 (in order of increasing particle size, see Fig. 3.8). The particle size distribution and characteristics of the particle shape of all components except GB-C1 (see Table 3.1 and Fig. 3.9), were quantified by the author using the QicPic apparatus (Sympatec, 2008) during a research visit to Imperial College London. All components were uniform, with $C_u$ ranging from 1.1 to 1.25, and $C_c$ ranging from 0.99 to 1.03. The particle shapes (see Section 2.2.2.1) of the three coarse components GB-C2, GB-C3 and GB-C4 were nearly identical with $AR = 0.95$ to 0.97, $Cx = 0.98$, and $S_{QP} = 0.94$. The particles of these components are almost perfectly spherical, which can be observed on the microscopic image of GB-C4 (see Fig. 3.10). The particle shape of the fine component GB-F is slightly less perfectly spherical (see Fig. 3.11), with $AR = 0.91$, $Cx = 0.94$, and $S_{QP} = 0.94$. Based on the indices of particle shape, all glass beads components would qualify as rounded (see Fig. 2.9). The minimum index void ratio $e_{\text{min}} = 0.57$ and maximum index void ratio $e_{\text{max}} = 0.67$ of component GB-C1 were determined using ASTM D4253-14 (ASTM, 2015b) and ASTM D4254-14 (ASTM, 2015a), respectively. These values are also assumed for the other coarse GB components, given the similar particle shape and uniformity of the particle size distribution. Nine gap-graded glass gradations were fabricated (see Table 3.2 and Figs. 3.12 to 3.15). Additionally, component GB-F was tested directly as gradation GB-F to commission the device, and the results serve as a benchmark for comparative analysis: it is uniformly graded with $d_0 = 0.12 \text{ mm}$, $d_{100} = 0.20 \text{ mm}$ and $d_{85} = 0.19 \text{ mm}$. 

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3.2.2 Soils

In order to investigate the influence of the particle shape, gradations of sub-angular soil particles were fabricated with particle size distributions that were nearly identical to some of the glass beads mixtures. The sub-angular soil particles (BT) originate from a filter in a zoned embankment dam. The bulk sample of filter material was separated into uniform components by means of mechanical sieving.

The specific gravity of the angular soil particles $G_s = 2.70$ was determined following ASTM D854-14 (ASTM, 2014). The BT components used to prepare the gap-graded mixtures are fine component BT-F and coarse components BT-C1, BT-C2, BT-C3, BT-C4 and BT-C5 (see Fig. 3.16). The particle size distribution and characteristics of the particle shape of the individual components, were quantified using the same QicPic apparatus at Imperial College London (see Table 3.1 and Fig. 3.17). All fine and coarse components were uniform, with $C_u$ ranging from 1.27 to 1.38, and $C_r$ ranging from 1.00 to 1.03. The indices of particle shape of the coarse components fall within a very narrow range with $AR = 0.73$ to 0.74, $Cx = 0.96$ to 0.97, and $S_{QP} = 0.87$ to 0.88. The particle shape of the fine component is very similar, with $AR = 0.76$, $Cx = 0.97$, and $S_{QP} = 0.88$. Microscopic images of BT-F and BT-C3 are presented in Figs. 3.18 and 3.19 respectively. Based on the measures of particle shape, all BT components qualify as sub-angular (see Fig. 2.9). The minimum index void ratio $e_{min} = 0.63$ and maximum index void ratio $e_{max} = 0.80$ of component BT-C1 were determined using ASTM D4253-14 (ASTM, 2015b) and ASTM D4254-14 (ASTM, 2015a), respectively. These values are assumed for the other coarse BT components, given the similar particle shape and uniformity of the particle size distribution. Ten gap-graded gradations of sub-angular soil particles were fabricated (see Table 3.2 and Figs. 3.20 to 3.24).

3.3 Test procedure

Following preparation of the specimen, it is consolidated and then subject to multi-stage seepage flow. Each step is described in detail herein.

3.3.1 Specimen preparation

The objective of the preparation method is to produce a saturated, homogeneous specimen. The method adopted for this study involves: 1) thoroughly mixing the coarse and fine components of glass beads or soil, and saturating the mixture by boiling it in de-aired water for a minimum of 30 min and, after cooling to room temperature, storing it in a vacuum desiccator for at least 12 hrs; 2) reconstituting the specimen in a forming mold that supports the triaxial membrane on the base pedestal; 3) placing the hollow top cap on the leveled top surface of the specimen; 4) sealing the membrane against the top cap with a rubber O-ring, and applying a vacuum pres-
sure of approximately -20 kPa to the specimen through the air/water interface in measurement burette #1 (see Fig. 3.3); 5) removing the forming mold and assembling the flexible wall permeameter; and 6) applying a cell pressure of approximately 20 kPa and subsequently releasing the vacuum pressure.

More specifically, on the matter of specimen reconstitution, the uniformly graded GB-F material is reconstituted using the water pluviation technique (Fannin et al., 1994; Vaid and Negussey, 1988). In contrast, the gap-graded glass beads and soils are reconstituted using the modified slurry deposition technique (Moffat and Fannin, 2006). The ability of the slurry deposition technique to produce saturated, homogeneous specimens of angular tailings sand has been demonstrated by Kuerbis and Vaid (1988). The free water surface in the I-CHD and in the O-CHD (see Section 3.1.3) does not permit the application of a back pressure during multi-stage seepage flow. Therefore, the B value was determined without application of additional back pressure following step six of the specimen preparation method. All gradations tested in this study exhibited B-values greater than 0.95 (see Tables 4.1 and 4.3), indicating fully saturated specimens (ASTM, 2011). The homogeneity of the slurry deposited gap-graded glass beads materials was evaluated by excavating, in five layers of equal thickness, trial specimens reconstituted solely for this purpose. The homogeneity of the materials 4.8GB20, 6.0GB35, 6.5GB25 and 6.5GB35 was achieved with a variation in the finer fraction content of $S_f = +/- 0.03$ (see Figs. 3.25, 3.26 and 3.27, respectively). The relatively large spatial variations of $S_f = +/- 0.08$ in two trial specimens of gradation 6.0GB20 (see Figs. 3.28 and 3.29) demonstrates that the homogeneity of this material, with its relatively low fines content and relatively large ratio of particle sizes, cannot be guaranteed. Accordingly, the findings suggest that the modified slurry deposition technique is capable of producing a homogeneous saturated specimen of gap-graded glass beads gradations with: $S_f = 0.25$ to 0.35 and $D'_{15}/d'_{85} \leq 6.5$; and $S_f = 0.20$ and $D'_{15}/d'_{85} \leq 4.8$. As the upper limit for a reasonably homogeneous specimen of glass beads with $S_f = 0.20$, $D'_{15}/d'_{85} = 6.0$ is considered appropriate.

3.3.2 Stage 1: Consolidation

Test specimens are consolidated isotropically at a cell pressure of 50, 100 or 150 kPa. The resulting excess pore water pressure dissipates under a condition of single drainage in the upward direction.

3.3.3 Stage 2: Multi-stage seepage flow

Hydraulic head is applied across the specimen by incrementally raising the elevation of the I-CHD (see Fig. 3.1) in a multi-stage test procedure, to impose upward seepage flow through the specimen. Energy losses occur in the fittings and tubes, which reduce the TDH to the differential head across the specimen ($\Delta u / \gamma_w$). Accordingly, the mode of operation of the flexible wall
permeameter is one of TDH-control, rather than control of the differential pore water pressure across the specimen $\Delta u$. Relatively small increments of $\Delta TDH = 1$ cm were imposed in the initial 4 to 5 stages of a test, in order to quantify the pre-critical response; a test is terminated at $TDH_{\text{max}} = 165$ cm, or when the range of the volume change measurement is exceeded. In the intermediate stages, $\Delta TDH = 5$ to 20 cm, depending on the hydraulic conductivity of the specimen. The duration of each stage $\Delta t$ is typically 10 to 60 min to permit at least two independent measurements of flow rate.

The variation of effective stress of the specimen, isotropically consolidated and subsequently subject to upward multi-stage seepage flow, is discussed in Appendix C. The effective stress of a specimen diminishes with subsequent stages of seepage flow.

### 3.4 Test program

An overview of the test program is presented in Fig. 3.30. The test codes are constructed as follows: “gradation” + “target cell pressure” + “(R)” (optional). The designation “(R)” is used when a test is repeated. For example, test code 4.8GB20-50(R) refers to the repeated test on gradation 4.8GB20 consolidated at a target cell pressure 50 kPa.

Commissioning tests were conducted on uniform gradation GB-F and gap-graded gradation 6.5GB25, isotropically consolidated at cell pressures of 100 kPa, respectively. The objectives of these commissioning tests were to:

- verify the reliability of the measurements in the flexible wall permeameter, especially the volume change measurement.
- determine the seepage regime, including hydraulic conductivity, of the fine component of the gap-graded glass beads mixtures.

In the main test program, all specimens were isotropically consolidated and then subject to upward multi-stage seepage flow. The objectives of the main test program were to:

- assess the repeatability of the test results.
- gather experimental data to investigate the influence of the effective stress, particle size distribution, and particle shape on suffusion and suffosion (see research hypotheses Nos. 1 to 4 in Section 1.1).

The 23 tests on glass beads mixtures comprise the majority of the test program. The tests on gradations 4.8GB20 were conducted to examine the influence of the effective stress on gradations with $S_f = 0.20$, which were anticipated to yield a clast-supported micro-structure. Test 4.8GB20-50(R) was conducted to examine the repeatability of the test results on gradations
with \( S_f = 0.20 \). Additionally, one test was conducted on 3.3GB20 in an attempt to establish, at 
\( S_f = 0.20 \), the limit of \( D'_{15}/d'_{85} \) at which internal instability could occur. The tests on gradations 
6.0GB25, 6.0GB30 and 6.0GB35 were conducted to investigate the influence of increasing \( S_f \) 
with constant \( D'_{15}/d'_{85} \). Test 6.0GB35-100(R) was conducted to examine the repeatability of 
the test results at the upper boundary of \( S_f = 0.35 \). Tests on gradations 4.8GB35 and 6.5GB35 
were conducted to investigate the influence of \( D'_{15}/d'_{85} \) at \( S_f = 0.35 \).

The 16 tests on BT mixtures were conducted to investigate the influence of particle shape. 
At the lower boundary of \( S_f = 0.20 \) three tests were conducted on 5.7BT20, isotropically con-
solidated at cell pressures of 50, 100 ad 150 kPa. Since the results indicated that the instability 
at the lower boundary was not governed by effective stress, gradations 5.1BT20 and 7.0BT20 
were only tested at cell pressures of 50 and 150 kPa. The test on 8.6BT20 was only conducted 
at 50 kPa. The tests 5.7BT35-100, 7.0BT35-50 and 8.6BT35-50 exhibited no internal insta-
bility. Therefore, these gradations were not tested at different pressures. Tests on 10.4BT35 
did exhibit an internally unstable response and hence this gradation was tested at different cell 
pressures. Test 10.4BT35-50(R) was conducted to examine the repeatability of the test results 
on BT gradations at \( S_f = 0.35 \). Tests 10.4BT25-50 and 10.4BT30-50 were conducted to gain 
an appreciation of the response of soils at intermediate finer fraction contents.

For all gradations tested in this study, the same bottom wire meshes were used: the opening 
size of the primary bottom wire mesh (see Fig. 3.6) is equal to 0.033 mm, in order to prevent 
particle loss during specimen reconstitution; the secondary bottom wire mesh, with opening 
size of 0.6 mm, serves to keep the fine wire mesh in place. The opening size of the primary top 
wire mesh is equal to \( D_0 \) for the gap-graded specimens and equal to 0.033 mm for gradation 
GB-F. The opening size of the secondary top wire mesh and tertiary top wire mesh are 2.8 mm 
and 0.033 mm, respectively, for all gradations.

3.5 Summary

A new flexible wall permeameter has been developed at the University of British Columbia to 
investigate seepage-induced internal instability in gap-graded materials. The device comprises 
a double-walled triaxial cell; a seepage control system, through which unidirectional multi-
stage seepage flow can be imposed; and instrumentation. A novel feature in seepage-induced 
internal instability testing is the measurement of total volume change. It is derived from mon-
itoring the volume change of the cell fluid in the inner chamber of the double-walled triaxial 
cell, that, with correction for the intrusion of the loading ram, membrane penetration, and small 
calibrated volume changes of dissolving air and absorption of water, yields an accurate mea-
urement of total volume change. In addition, the flow rate, differential pore water pressure 
across the specimen, the pore water pressure and the axial deformation are measured. The main
limitations of the apparatus relate to the control and working range of the total dynamic head and the working range of the volume change measurement.

Gap-graded mixtures of glass beads and soils are prepared by combining, in various ratios, the respective fine components with different coarse components. Assessment of trial specimens suggest that the modified slurry deposition technique is capable of producing saturated specimens of gap-graded glass bead mixtures with a small variation of $S_f = +/\sim 0.03$ with: $S_f = 0.25$ to $0.35$ and $D_{15}'/d_85' \leq 6.5$; and $S_f = 0.20$ and $D_{15}'/d_85' \leq 4.8$. The upper limit for a reasonably homogeneous specimen ($S_f = +/\sim 0.08$) of glass beads with $S_f = 0.20$, was found to occur at $D_{15}'/d_85' = 6.0$. The cylindrical specimens, with a diameter of 100 mm, are reconstituted to a height of approximately 100 mm, subsequently isotropically consolidated to a target cell pressure of 50, 100 or 150 kPa and then subject to multi-stage upward seepage flow.

The testing program has been developed to: commission the apparatus; assess the repeatability of the test results; and generate data to investigate the influence on seepage-induced internal instability in gap-graded materials of effective stress, particle size distribution and particle shape. The commissioning program comprised two tests conducted on glass beads mixtures. The main testing program comprises 23 tests on glass beads mixtures, of which two are repeatability tests, and 16 test on soil mixtures, of which one is a repeatability test.
Table 3.1: Characteristics of test materials.

<table>
<thead>
<tr>
<th>Component</th>
<th>$d_0$ (mm)</th>
<th>$d_{15}$ (mm)</th>
<th>$d_{85}$ (mm)</th>
<th>$d_{100}$ (mm)</th>
<th>$C_u$ (-)</th>
<th>$C_c$ (-)</th>
<th>$AR_{50}$ (-)</th>
<th>$Cx_{50}$ (-)</th>
<th>$S^{OP}_{50}$ (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GB-F</td>
<td>0.12</td>
<td>0.14</td>
<td>0.19</td>
<td>0.20</td>
<td>1.25</td>
<td>1.03</td>
<td>0.91</td>
<td>0.94</td>
<td>0.94</td>
</tr>
<tr>
<td>GB-C1</td>
<td>0.60</td>
<td>0.63</td>
<td>0.81</td>
<td>0.85</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>GB-C2</td>
<td>0.80</td>
<td>0.90</td>
<td>1.03</td>
<td>1.20</td>
<td>1.10</td>
<td>1.00</td>
<td>0.97</td>
<td>0.98</td>
<td>0.94</td>
</tr>
<tr>
<td>GB-C3</td>
<td>1.00</td>
<td>1.13</td>
<td>1.29</td>
<td>1.40</td>
<td>1.11</td>
<td>1.00</td>
<td>0.97</td>
<td>0.98</td>
<td>0.94</td>
</tr>
<tr>
<td>GB-C4</td>
<td>1.10</td>
<td>1.23</td>
<td>1.50</td>
<td>1.80</td>
<td>1.15</td>
<td>0.99</td>
<td>0.95</td>
<td>0.98</td>
<td>0.94</td>
</tr>
<tr>
<td>BT-F</td>
<td>0.09</td>
<td>0.12</td>
<td>0.17</td>
<td>0.21</td>
<td>1.38</td>
<td>1.03</td>
<td>0.76</td>
<td>0.92</td>
<td>0.91</td>
</tr>
<tr>
<td>BT-C1</td>
<td>0.70</td>
<td>0.89</td>
<td>1.19</td>
<td>1.5</td>
<td>1.27</td>
<td>1.01</td>
<td>0.73</td>
<td>0.96</td>
<td>0.88</td>
</tr>
<tr>
<td>BT-C2</td>
<td>0.80</td>
<td>0.98</td>
<td>1.46</td>
<td>2.0</td>
<td>1.33</td>
<td>1.00</td>
<td>0.73</td>
<td>0.96</td>
<td>0.87</td>
</tr>
<tr>
<td>BT-C3</td>
<td>0.90</td>
<td>1.21</td>
<td>1.76</td>
<td>2.2</td>
<td>1.34</td>
<td>1.00</td>
<td>0.73</td>
<td>0.97</td>
<td>0.88</td>
</tr>
<tr>
<td>BT-C4</td>
<td>1.10</td>
<td>1.50</td>
<td>2.14</td>
<td>2.6</td>
<td>1.32</td>
<td>1.00</td>
<td>0.74</td>
<td>0.97</td>
<td>0.88</td>
</tr>
<tr>
<td>BT-C5</td>
<td>1.40</td>
<td>1.79</td>
<td>2.49</td>
<td>3.0</td>
<td>1.30</td>
<td>1.01</td>
<td>0.74</td>
<td>0.97</td>
<td>0.88</td>
</tr>
</tbody>
</table>

Notes:
1. GB = Glass beads, BT = sub-angular soils, F = Fine component, C = Coarse component
2. Material GB-C1 was not tested in the QicPic device

Table 3.2: Gradations of the test specimens.

<table>
<thead>
<tr>
<th>$R^1$</th>
<th>Gradation</th>
<th>Fine fraction</th>
<th>Coarse fraction</th>
<th>$S_f$ (-)</th>
<th>$D'<em>{15}/d'</em>{85}$ (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>3.3GB20</td>
<td>GB-F</td>
<td>GB-C1</td>
<td>0.20</td>
<td>3.3</td>
</tr>
<tr>
<td>R</td>
<td>4.8GB20</td>
<td>GB-F</td>
<td>GB-C2</td>
<td>0.20</td>
<td>4.8</td>
</tr>
<tr>
<td>R</td>
<td>4.8GB35</td>
<td>GB-F</td>
<td>GB-C2</td>
<td>0.35</td>
<td>4.8</td>
</tr>
<tr>
<td>R</td>
<td>6.0GB20</td>
<td>GB-F</td>
<td>GB-C3</td>
<td>0.20</td>
<td>6.0</td>
</tr>
<tr>
<td>R</td>
<td>6.0GB25</td>
<td>GB-F</td>
<td>GB-C3</td>
<td>0.25</td>
<td>6.0</td>
</tr>
<tr>
<td>R</td>
<td>6.0GB30</td>
<td>GB-F</td>
<td>GB-C3</td>
<td>0.30</td>
<td>6.0</td>
</tr>
<tr>
<td>R</td>
<td>6.0GB35</td>
<td>GB-F</td>
<td>GB-C3</td>
<td>0.35</td>
<td>6.0</td>
</tr>
<tr>
<td>R</td>
<td>6.5GB25</td>
<td>GB-F</td>
<td>GB-C4</td>
<td>0.35</td>
<td>6.5</td>
</tr>
<tr>
<td>R</td>
<td>6.5GB35</td>
<td>GB-F</td>
<td>GB-C4</td>
<td>0.35</td>
<td>6.5</td>
</tr>
<tr>
<td>SA</td>
<td>5.1BT20</td>
<td>BT-F</td>
<td>BT-C1</td>
<td>0.20</td>
<td>5.1</td>
</tr>
<tr>
<td>SA</td>
<td>5.7BT20</td>
<td>BT-F</td>
<td>BT-C2</td>
<td>0.20</td>
<td>5.7</td>
</tr>
<tr>
<td>SA</td>
<td>5.7BT35</td>
<td>BT-F</td>
<td>BT-C2</td>
<td>0.35</td>
<td>5.7</td>
</tr>
<tr>
<td>SA</td>
<td>7.0BT20</td>
<td>BT-F</td>
<td>BT-C3</td>
<td>0.20</td>
<td>7.0</td>
</tr>
<tr>
<td>SA</td>
<td>7.0BT35</td>
<td>BT-F</td>
<td>BT-C3</td>
<td>0.35</td>
<td>7.0</td>
</tr>
<tr>
<td>SA</td>
<td>8.6BT20</td>
<td>BT-F</td>
<td>BT-C4</td>
<td>0.20</td>
<td>8.6</td>
</tr>
<tr>
<td>SA</td>
<td>8.6BT35</td>
<td>BT-F</td>
<td>BT-C4</td>
<td>0.35</td>
<td>8.6</td>
</tr>
<tr>
<td>SA</td>
<td>10.4BT25</td>
<td>BT-F</td>
<td>BT-C5</td>
<td>0.25</td>
<td>10.4</td>
</tr>
<tr>
<td>SA</td>
<td>10.4BT30</td>
<td>BT-F</td>
<td>BT-C5</td>
<td>0.30</td>
<td>10.4</td>
</tr>
<tr>
<td>SA</td>
<td>10.4BT35</td>
<td>BT-F</td>
<td>BT-C5</td>
<td>0.35</td>
<td>10.4</td>
</tr>
</tbody>
</table>

Note:
1. R = Rounded; SA = Sub-angular.
**Figure 3.1:** General configuration of flexible wall permeameter arrangement.

**Figure 3.2:** Double-walled triaxial cell.
**Figure 3.3:** Schematic plan view of double-walled triaxial cell, including volume change measurement systems.

**Figure 3.4:** Pressures in the double-walled triaxial cell.
**Figure 3.5:** Dummy specimen mounted between base pedestal and top cap in double-walled triaxial cell (without acrylic tubes).
Figure 3.6: Exploded view of connections between base frame, base pedestal, specimen, and top cap.
Figure 3.7: Relation between rate of volume change of inner chamber and cell pressure from calibration testing ($t$ from 16 to 22 h after application of cell pressure).

Figure 3.8: Particle size distribution of the glass bead components using QicPic $d_{F_{min}}$. 
Figure 3.9: Shape attributes of the glass bead particles.
Figure 3.10: Microscope image of component GB-C4 of glass beads.

Figure 3.11: Microscope image of component GB-F of glass beads.
Figure 3.12: Particle size distribution of the 3.3GB gradation.

Figure 3.13: Particle size distribution of the 4.8GB gradations.

Figure 3.14: Particle size distribution of the 6.0GB gradations.
**Figure 3.15:** Particle size distribution of the 6.5GB gradations.

**Figure 3.16:** Particle size distribution of the components of soil.
Figure 3.17: Shape attributes of the soil particles.
Figure 3.18: Microscope image of the component BT-F of soil.

Figure 3.19: Microscope image of the component BT-C3 of soil.
Figure 3.20: Particle size distribution of the 5.1BT gradation.

Figure 3.21: Particle size distribution of the 5.7BT gradations.

Figure 3.22: Particle size distribution of the 7.0BT gradations.
**Figure 3.23:** Particle size distribution of the 8.6BT gradations.

**Figure 3.24:** Particle size distribution of the 10.4BT gradations.

**Figure 3.25:** Variation of percentage finer fraction content per layer of a trial specimen of gradation 4.8GB20.
**Figure 3.26:** Variation of percentage finer fraction content per layer of a trial specimen of gradation 6.5GB25.

**Figure 3.27:** Variation of percentage finer fraction content per layer of a trial specimen of gradation 6.5GB35.

**Figure 3.28:** Variation of percentage finer fraction content per layer of a trial specimen of gradation 6.0GB20.
Figure 3.29: Variation of percentage finer fraction content per layer of a second trial specimen of gradation 6.0GB20.
<table>
<thead>
<tr>
<th>Fine component</th>
<th>Coarse components</th>
</tr>
</thead>
<tbody>
<tr>
<td>( d = 0.06-0.85 \text{ mm} )</td>
<td>( D = 0.8-1.2 \text{ mm} )</td>
</tr>
<tr>
<td>GB-F-100 (commissioning)</td>
<td>3.3GB20-50</td>
</tr>
<tr>
<td>GB-B-100 (commissioning)</td>
<td>4.8GB35-50</td>
</tr>
</tbody>
</table>

**Figure 3.30**: Test program.
Chapter 4

Results

Laboratory experiments were performed to commission the flexible wall permeameter, assess the repeatability of the test results (research objective No. 3) and generate experimental data. The results of these experiments are presented in this Chapter: the results and findings of the commissioning tests are described in Section 4.1 followed by descriptions of the results of tests on glass beads gradations in Section 4.2 and descriptions of the results of tests on soil gradations in Section 4.3. Upward multi-stage seepage flow, with head control, was imposed in all tests. The results are reported in terms of the response variables $\Delta u$, $v$, $\varepsilon_a$ and $\varepsilon_v$ (see Fig. 4.1); contractive strains are positive. In addition, visual observations and post-test particle size analyses are reported for select tests in Appendix D. The repeatability of the test results is examined in Section 4.4. A synthesis of the findings of the experiments, including a short description of typical responses, is provided in Section 4.5.

4.1 Commissioning tests

Two commissioning tests were performed on two glass beads gradations: one test was conducted on the uniform gradation GB-F and the other on the gap-graded gradation 6.5GB25.

4.1.1 Test GB-F-100

Gradation GB-F was reconstituted by water pluviation and isotropically consolidated to $p'_c = 102$ kPa, $l = 97$ mm and $e_c = 0.65$ (see Table 4.1). Twenty-one stages of seepage flow were applied; the test commenced with $\Delta H = 2$ cm for $\Delta t = 40$ min, yielding $\Delta u = 0.2$ kPa and $v = 0.002$ cm/s; it was terminated at $\Delta H_{\text{max}}$ after $t = 280$ min, yielding $\Delta u = 8.1$ kPa, and $v = 0.117$ cm/s (see Table 4.2).

$^1$The results are reported in terms of $\Delta u$, instead of hydraulic gradient, as the former is more suitable to quantify the seepage-induced change of effective stress (see Section 2.3). Considering the limited extent of axial deformation, typically $\varepsilon_a < 2\%$, and typical length of the specimen $l = 100$ mm, the value of hydraulic gradient is approximately equal to the value of $\Delta u$. 

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The specific discharge, \( v \), was directly proportional to the differential pore water pressure across the specimen, \( \Delta u \), throughout the test (see Fig. 4.2a). A very small axial strain of \( \varepsilon_a = 0.04 \% \) (see Fig. 4.2b), and a small volumetric strain of \( \varepsilon_v = 0.18 \% \) (see Fig. 4.2c), were recorded at the end of the test.

### 4.1.2 Test 6.5GB25-100

Gradation 6.5GB25 was reconstituted by slurry deposition and isotropically consolidated to \( p'_c = 102 \) kPa, \( l = 96 \) mm and \( e_c = 0.36 \) (see Table 4.1). Twelve stages of seepage flow were applied; the test commenced with TDH = 1 cm for \( \Delta t = 20 \) min, yielding \( \Delta u = 0.1 \) kPa and \( v = 0.004 \) cm/s; it was terminated at TDH = 35 cm after \( t = 270 \) min, when the volume change measurement device approached the limit of its working range, yielding \( \Delta u = 1.6 \) kPa and \( v = 0.077 \) cm/s (see Table 4.2).

The variation of \( v: \Delta u \) exhibited an overall curvilinear response in three sequences (see Fig. 4.3a): (i) it commenced with an approximately directly proportional relation to \( v = 0.039 \) cm/s and \( \Delta u = 1.1 \) kPa; (ii) it was followed by a marked increase to \( v = 0.048 \) cm/s at \( \Delta u = 1.1 \) kPa; (iii) it was then followed by an approximately proportional relation for the remainder of the test. The variation of \( \varepsilon_a: \Delta u \) exhibited an overall curvilinear response in two sequences (see Fig. 4.3b): (i) there was no axial strain to \( \Delta u = 1.1 \) kPa; (ii) the axial strain subsequently increased to a very small value \( \varepsilon_a = 0.08 \% \) at the end of the test. The variation of \( \varepsilon_v: \Delta u \) exhibited an overall curvilinear response in two sequences (see Fig. 4.3c): (i) the relation was directly proportional to a very small value of \( \varepsilon_v = 0.06 \% \) at \( \Delta u = 1.1 \) kPa; (ii) it was followed by a series of discrete increments of increasing volumetric strain to \( \varepsilon_v = 1.65 \% \) at the end of the test.

### 4.1.3 Findings of the commissioning tests

Two commissioning tests were performed with the primary objective of assessing the measurement techniques of the apparatus. In test GB-F-100, the small end-of-test values of axial and volumetric strains \( \varepsilon_a = 0.04 \% \) and \( \varepsilon_v = 0.18 \% \), respectively, and the directly proportional response of \( v: \Delta u \), indicate that no substantial change of the specimen fabric occurred. Accordingly, the variations of \( v: \Delta u \), \( \varepsilon_a: \Delta u \) and \( \varepsilon_v: \Delta u \) in test GB-F-100 are consistent, and indicate that no change transpired in the specimen during the test.

The second commissioning test, 6.5GB25-100, was conducted to assess the measurement techniques of the apparatus on a specimen where substantial change was anticipated. The nature of the \( v: \Delta u \) relation, and the absence of significant axial and volumetric deformations, indicate no change occurred to \( \Delta u = 1.1 \) kPa. The marked increase to \( v = 0.048 \) cm/s at \( \Delta u = 1.1 \) kPa indicates a change occurred in the fabric of the specimen, which is also apparent from the marked development of volumetric strain at this stage. Accordingly, the variations of \( v: \Delta u \) and
\( \varepsilon_v; \Delta u \) in test 6.5GB25-100 appear to be consistent and indicate that substantial change occurred during the test. The variation of \( \varepsilon_v; \Delta u \) does not indicate substantial change, which is attributed to the localised nature of the volume change. On the matter of accuracy, the end of the test \( \varepsilon_v = 1.65 \% \) is more than one order of magnitude greater than the accuracy of the total volume change measurement of \( \varepsilon_v = \pm /- 0.07\% \). On the matter of resolution, the first increment of volumetric strain at the onset of deformation \( \Delta \varepsilon_v = 0.5\% \), is more than one order of magnitude greater than the resolution of the volume change measurement of \( \pm /- 0.01\% \) volumetric strain. The resolution and accuracy of the volume change measurement technique are thus believed sufficient to quantify the onset and progression of deformation in specimens with volume of approximately 780 cm³.

### 4.2 Tests on glass beads

The initial and the end-of-test conditions of each test on glass beads are tabulated in Tables 4.1 and 4.2 respectively. The response to seepage flow measured in each test is described herein. A summary of typical responses in tests on glass beads gradations is provided in Section 4.5.

#### 4.2.1 Gradation 3.3GB20

One test was conducted on gradation 3.3GB20, which has the smallest gap-ratio of all gradations tested. The specimen was reconstituted by slurry deposition and isotropically consolidated to a target cell pressure of 50 kPa. The tests code is 3.3GB20-50.

##### 4.2.1.1 Test 3.3GB20-50

The specimen was isotropically consolidated to \( p'_c = 54 \text{ kPa}, \ l = 102 \text{ mm and } e_c = 0.53 \) (see Table 4.1). It was subject to 26 stages of seepage flow: the test commenced at TDH = 1 cm for \( \Delta t = 30 \text{ min}, \) yielding \( \Delta u = 0.1 \text{ kPa and } v = 0.003 \text{ cm/s}; \) it was terminated at TDH \( \text{max} \) after \( t = 280 \text{ min}, \) yielding \( \Delta u = 3.6 \text{ kPa and } v = 0.127 \text{ cm/s} \) (see Table 4.2). The variation of \( v; \Delta u \) exhibited a curvilinear response in two sequences (see Fig. 4.4a): (i) the relation was proportional during the first eleven stages of the test to \( \Delta u = 1.0 \text{ kPa and } v = 0.043 \text{ cm/s}, \) with an intercept of \( v = 0.005 \text{ cm/s at } \Delta u = 0 \text{ kPa}; \) (ii) it was followed by an approximately proportional response, at a slightly smaller rate, during the remaining stages. There was no axial deformation during the test (see Fig. 4.4b). A very small end-of-test value \( \varepsilon_v = 0.05 \% \) was measured (see Fig. 4.4c). A post-test particle size analysis of the specimen showed that the finer fraction content was equal to \( S_f = 0.20 \) in all five layers (see Fig. D.23).

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4.2.2 Gradation 4.8GB20

Four tests were conducted on gradation 4.8GB20. The specimens were reconstituted by slurry deposition and isotropically consolidated to target cell pressures of 50 kPa (in two sequential tests), 100 kPa and 150 kPa, respectively. The corresponding test codes are 4.8GB20-50, 4.8GB20-50(R), 4.8GB20-100, and 4.8GB20-150.

4.2.2.1 Test 4.8GB20-50

The specimen was isotropically consolidated to $p'_c = 54$ kPa, $l = 103$ mm and $e_c = 0.48$ (see Table 4.1). It was subject to 20 stages of seepage flow: the test commenced at TDH = 1 cm for \( \Delta t = 40 \) min, yielding $\Delta u = 0.1$ kPa and $v = 0.002$ cm/s; it was terminated at TDH$_{\text{max}}$ after $t = 310$ min, yielding $\Delta u = 5.3$ kPa and $v = 0.148$ cm/s (see Table 4.2).

The variation of $v: \Delta u$ exhibited a curvilinear response in three sequences (see Fig. 4.5a): (i) the relation was directly proportional during the first two stages of the test to $\Delta u = 0.2$ kPa and $v = 0.004$ cm/s; (ii) it was followed by an increasing specific discharge at an initially increasing rate and subsequently decreasing rate, to $\Delta u = 2.9$ kPa and $v = 0.090$ cm/s; (iii) it was then followed by an approximately proportional relation during the remaining stages. There was no axial deformation (see Fig. 4.5b). A small end-of-test value $\varepsilon_v = 0.12 \%$ (see Fig. 4.5c) was recorded.

4.2.2.2 Test 4.8GB20-50(R)

The specimen was isotropically consolidated to $p'_c = 53$ kPa, $l = 102$ mm and $e_c = 0.45$ (see Table 4.1). It was subject to 23 stages of seepage flow: the test commenced at TDH = 1 cm for \( \Delta t = 40 \) min, yielding $\Delta u = 0.1$ kPa and $v = 0.002$ cm/s; it was terminated at TDH$_{\text{max}}$ after $t = 370$ min, yielding $\Delta u = 6.7$ kPa and $v = 0.138$ cm/s (see Table 4.2).

The variation of $v: \Delta u$ also exhibited a curvilinear response comprising three sequences (see Fig. 4.5a): (i) the relation was directly proportional during the first two stages of the test to $\Delta u = 0.2$ kPa and $v = 0.005$ cm/s; (ii) it was followed by an increasing specific discharge at an initially increasing rate and subsequently decreasing rate to $\Delta u = 2.3$ kPa and $v = 0.055$ cm/s; (iii) it was then followed by an approximately proportional relation during the remaining stages. The negligible end-of-test values $\varepsilon_v = -0.01 \%$ and $\varepsilon_v = 0.03 \%$ indicate that there was no axial and volumetric deformation (see Figs. 4.5b and 4.5c).

4.2.2.3 Test 4.8GB20-100

The specimen was isotropically consolidated to $p'_c = 104$ kPa, $l = 102$ mm and $e_c = 0.47$ (see Table 4.1). It was subject to 21 stages of seepage flow: the test commenced at TDH = 1 cm for
$\Delta t = 70$ min, yielding $\Delta u = 0.1$ kPa and $v = 0.001$ cm/s; it was terminated at TDH$_{\text{max}}$ after $t = 310$ min, yielding $\Delta u = 6.0$ kPa and $v = 0.142$ cm/s (see Table 4.2).

The variation of $v$:$\Delta u$ exhibited a curvilinear response comprising three sequences (see Fig. 4.5a): (i) the relation was directly proportional during the first two stages of the test to $\Delta u = 0.2$ kPa and $v = 0.004$ cm/s; (ii) it was followed by an increasing specific discharge, at an initially slightly increasing rate and subsequently slightly decreasing rate, to $\Delta u = 2.1$ kPa and $v = 0.050$ cm/s in stage 11; (iii) it was then followed by an approximately proportional relation during the remaining stages. A very small end-of-test value $\varepsilon_a = 0.02$ % (see Fig. 4.5b) was recorded. The variation of $\varepsilon_v$:$\Delta u$ exhibited a curvilinear response in three sequences (see Fig. 4.5c): (i) it commenced with an increasing volumetric strain to a very small value $\varepsilon_v = 0.05$ % during stages one to nine; (ii) it was followed by an isolated increase to $\varepsilon_v = 0.50$ % at $\Delta u = 1.8$ kPa in stage ten; (iii) it was then followed by a sequence of constant volumetric strain through the remainder of the test.

4.2.2.4 Test 4.8GB20-150

The specimen was isotropically consolidated to $p'_c = 153$ kPa, $l = 101$ mm and $e_c = 0.44$ (see Table 4.1). It was subject to 21 stages of seepage flow: the test commenced at TDH = 1 cm for $\Delta t = 70$ min, yielding $\Delta u = 0.1$ kPa and $v = 0.038$ cm/s; it was terminated at TDH$_{\text{max}}$ after $T = 410$ min, yielding $\Delta u = 6.0$ kPa and $v = 0.142$ cm/s (see Table 4.2).

The variation of $v$:$\Delta u$ exhibited a curvilinear response comprising three sequences (see Fig. 4.5a): (i) it commenced with a directly proportional relation during the first three stages of the test to $\Delta u = 0.2$ kPa and $v = 0.003$ cm/s; (ii) it was followed by an increasing $v$ at an increasing rate to $\Delta u = 1.5$ kPa and $v = 0.021$ cm/s; (iii) it was then followed by an approximately proportional relation to the end of the test. A very small end-of-test value $\varepsilon_a = 0.04$ % (see Fig. 4.5b) indicates that there was no substantial axial deformation. The variation of $\varepsilon_v$:$\Delta u$ exhibited a curvilinear response in three sequences (see Fig. 4.5c): (i) it commenced with an increasing volumetric strain to a very small value $\varepsilon_v = 0.05$ % during stages one and two; (ii) it was followed by an isolated increase to $\varepsilon_v = 0.44$ % at $\Delta u = 0.25$ kPa in stage three; (iii) it was then followed by a very small increase to $\varepsilon_v = 0.48$ % at the end of the test. A post-test particle size analysis of the specimen showed that the finer fraction content of $S_f = 0.15$ in the top layer was markedly lower than the finer fraction content of $S_f = 0.24$ to 0.28 in the other four layers (see Fig. D.24).

4.2.3 Gradation 4.8GB35

Three tests were conducted on gradation 4.8GB35. The specimens were reconstituted by slurry deposition and isotropically consolidated to target cell pressures of 50 kPa, 100 kPa and 150
kPa, respectively. The corresponding test codes are 4.8GB35-50, 4.8GB35-100, and 4.8GB35-150.

4.2.3.1 Test 4.8GB35-50

The specimen was isotropically consolidated to $p'_c = 57$ kPa, $l = 103$ mm and $e_c = 0.36$ (see Table 4.1). It was subject to 28 stages of seepage flow: the test commenced at TDH = 1 cm for $\Delta t = 40$ min, yielding $\Delta u = 0.1$ kPa and $v = 0.001$ cm/s; it was terminated at TDH$_{\text{max}}$ after $t = 360$ min, yielding $\Delta u = 8.7$ kPa and $v = 0.114$ cm/s (see Table 4.2).

The variation of $v:\Delta u$ exhibited a curvilinear response in two sequences (see Fig. 4.6a): (i) it commenced with a directly proportional relation to $\Delta u = 2.1$ kPa and $v = 0.003$ cm/s; (ii) it was followed by an increasing specific discharge, at initially slightly decreasing and subsequently slightly increasing rate, to the end of the test. The variation of $\varepsilon_a:\Delta u$ exhibited a curvilinear response in three sequences (see Fig. 4.6b): (i) it commenced with a very small value $\varepsilon_a = 0.04$ % at $\Delta u = 2.7$ kPa; (ii) it was followed by a series of discrete increments of increasing axial strain to $\varepsilon_a = 1.15$ % at the end of the test. The variation of $\varepsilon_v:\Delta u$ also exhibited a curvilinear response in three sequences (see Fig. 4.6c): (i) it commenced with an increasing volumetric strain to a very small value $\varepsilon_v = 0.07$ % at $\Delta u = 1.5$ kPa; (ii) it was followed by a series of discrete increments of increasing volumetric strain to $\varepsilon_v = 1.60$ % at the end of the test. Visual observations (see Fig. D.1) suggest that the volumetric deformation was restricted to the top half of the specimen.

4.2.3.2 Test 4.8GB35-100

The specimen was isotropically consolidated to $p'_c = 103$ kPa, $l = 102$ mm and $e_c = 0.37$ (see Table 4.1). It was subject to 29 stages of seepage flow: the test commenced at TDH = 1 cm for $\Delta t = 30$ min, yielding $\Delta u = 0.1$ kPa and $v = 0.001$ cm/s; it was terminated at TDH$_{\text{max}}$ after $t = 360$ min, yielding $\Delta u = 7.3$ kPa and $v = 0.128$ cm/s (see Table 4.2).

The specific discharge $v$ was approximately directly proportional to $\Delta u$ throughout the test (see Fig. 4.6a). The variation of $\varepsilon_a:\Delta u$ exhibited a curvilinear response in three sequences (see Fig. 4.6b): (i) it commenced with a very small value $\varepsilon_a = 0.02$ % to $\Delta u = 1.6$ kPa; (ii) it was followed by a series of discrete increments of increasing axial strain to $\varepsilon_a = 0.79$% at $\Delta u = 4.3$ kPa; (iii) it was then followed by a constant axial strain to the end of the test. The variation of $\varepsilon_v:\Delta u$ exhibited a curvilinear response in three sequences (see Fig. 4.6c): (i) it commenced with an increasing volumetric strain to a very small value $\varepsilon_v = 0.07$ % at $\Delta u = 1.6$ kPa; (ii) it was followed by a series of discrete increments of increasing volumetric strain to $\varepsilon_v = 1.13$% at $\Delta u = 4.3$ kPa; (iii) it was then followed by a slightly increasing volumetric strain to $\varepsilon_v = 1.20$ % at the end of the test. A post-test particle size analysis of the specimen showed that the finer
fraction content $S_f = 0.37$ was identical in all five layers (see Fig. D.25).

4.2.3.3 Test 4.8GB35-150

The specimen was isotropically consolidated to $p'_c = 152$ kPa, $l = 103$ mm and $e_c = 0.37$ (see Table 4.1). It was subject to 29 stages of seepage flow: the test commenced at TDH = 1 cm for $\Delta t = 30$ min, yielding $\Delta u = 0.1$ kPa and $v = 0.002$ cm/s; it was terminated at TDH$_{max}$ after $t = 390$ min, yielding $\Delta u = 8.6$ kPa and $v = 0.114$ cm/s (see Table 4.2).

The variation of $v: \Delta u$ exhibited a curvilinear response in two sequences (see Fig. 4.6a): (i) it commenced with a directly proportional increase during the first twelve stages to $\Delta u = 2.8$ kPa and $v = 0.045$ cm/s; (ii) it was followed by an increasing $v$ at initially decreasing and subsequently slightly varying rate to the end of the test. A very small end-of-test value $\varepsilon_u = 0.05$ % (see Fig. 4.6b) was recorded. In contrast, the variation of $\varepsilon_v: \Delta u$ exhibited a curvilinear response in two sequences (see Fig. 4.6b): (i) it commenced with an increasing volumetric strain to a very small value $\varepsilon_v = 0.08$ kPa at $\Delta u = 2.8$ kPa; (ii) it was followed by a series of discrete increments of increasing volumetric strain to $\varepsilon_v = 0.78$ % at the end of the test. A post-test particle size analysis of the specimen showed that the finer fraction content varied from $S_f = 0.36$ to 0.39 throughout the specimen (see Fig. D.26).

4.2.4 Gradation 6.0GB20

Three tests were conducted on gradation 6.0GB20, which proved challenging to reconstitute in a homogeneous manner (see Figs. 3.28 to 3.29), owing to the combination of the spherical particles, the relatively low fines content and the relatively large value of $D'_{15}/d'_{65}$. The specimens were reconstituted by slurry deposition and isotropically consolidated to target cell pressures of 50 kPa, 100 kPa and 150 kPa, respectively. The corresponding test codes are 6.0GB20-50, 6.0GB20-100 and 6.0GB20-150.

4.2.4.1 Test 6.0GB20-50

The specimen was isotropically consolidated to $p'_c = 54$ kPa, $l = 103$ mm and $e_c = 0.45$ (see Table 4.1). It was subject to 14 stages of seepage flow: the test commenced at TDH = 1 cm for $\Delta t = 50$ min, yielding $\Delta u = 0.1$ kPa and $v = 0.004$ cm/s; it was terminated at TDH = 70 cm after $t = 260$ min, yielding $\Delta u = 3.9$ kPa and $v = 0.098$ cm/s (see Table 4.2).

The variation of $v: \Delta u$ exhibited a curvilinear response in three sequences (see Fig. 4.7a): (i) it commenced with a constant specific discharge during the first stage; (ii) it was followed by a greater, but subsequently decreasing specific discharge during the second stage from $v = 0.011$ cm/s to $v = 0.010$ cm/s at $\Delta u = 0.2$ kPa; (iii) it was then followed by a sequence of increasing
specific discharge at initially increasing and subsequently decreasing rate to the end of the test. There was no axial deformation and the volumetric strain increased to a very small end-of-test value \( \varepsilon_v = 0.09 \% \) (see Fig. 4.7c). A post-test particle size analysis of the specimen showed that the finer fraction content of \( S_f = 0.14 \) in the top layer was markedly lower than the finer fraction content of \( S_f = 0.21 \) to 0.28 in the other four layers (see Fig. D.27).

### 4.2.4.2 Test 6.0GB20-100

The specimen was isotropically consolidated to \( p'_c = 102 \) kPa, \( l = 102 \) mm and \( e_c = 0.41 \) (see Table 4.1). It was subject to 27 stages of seepage flow: the test commenced at TDH = 1 cm for \( \Delta t = 30 \) min, yielding \( \Delta u = 0.1 \) kPa and \( v = 0.004 \) cm/s; it was terminated at TDH\(_{\text{max}}\) after \( t = 370 \) min, yielding \( \Delta u = 6.9 \) kPa and \( v = 0.133 \) cm/s (see Table 4.2).

The variation of \( v: \Delta u \) exhibited a curvilinear response comprising three sequences (see Fig. 4.7a): (i) the relation was directly proportional to \( \Delta u = 0.3 \) kPa and \( v = 0.011 \) cm/s during the first four stages; (ii) it was followed by an increase of \( v \) at an initially smaller rate (during the fifth stage); (iii) it was then followed by an increase of \( v \) at an initially constant and subsequently decreasing rate, to the end of the test. The variation of \( \varepsilon_a: \Delta u \) exhibited a curvilinear response comprising three sequences (see Fig. 4.7b): (i) there was no axial deformation during the first stage; (ii) it was followed by an increase of axial strain, which initiated at \( \Delta u = 0.2 \) kPa to \( \varepsilon_a = 0.28 \% \) at \( \Delta u = 0.4 \) kPa; (iii) it was then followed by a very small increase to \( \varepsilon_a = 0.30 \% \) at the end of the test. The variation of \( \varepsilon_v: \Delta u \) exhibited a curvilinear response in three sequences (see Fig. 4.7c): (i) there was no volumetric deformation during the first stage; (ii) it was followed by an increasing volumetric strain in two increments to \( \varepsilon_v = 0.76 \% \), which initiated at \( \Delta u = 0.2 \) kPa; (iii) it was then followed by a very small increase of volumetric strain to \( \varepsilon_v = 0.82 \% \) at the end of the test. A post-test particle size analysis of the specimen showed that the finer fraction content of \( S_f = 0.13 \) in the top layer was markedly lower than the finer fraction content of \( S_f = 0.23 \) to 0.27 in the other four layers (see Fig. D.28).

### 4.2.4.3 Test 6.0GB20-150

The specimen was isotropically consolidated to \( p'_c = 151 \) kPa, \( l = 101 \) mm and \( e_c = 0.40 \) (see Table 4.1). It was subject to twelve stages of seepage flow: the test commenced at TDH = 5 cm for \( \Delta t = 60 \) min, yielding \( \Delta u = 0.4 \) kPa and \( v = 0.004 \) cm/s; it was terminated at TDH = 70 cm after \( t = 240 \) min, yielding \( \Delta u = 3.9 \) kPa and \( v = 0.067 \) cm/s (see Table 4.2).

The variation of \( v: \Delta u \) exhibited a curvilinear response in three sequences (see Fig. 4.7a): (i) it commenced with a decreasing specific discharge, from \( v = 0.0042 \) cm/s to \( v = 0.0038 \) cm/s during the first stage; (ii) it was followed by a greater, but decreasing specific discharge, from \( v = 0.007 \) cm/s to \( v = 0.006 \) cm/s, at \( \Delta u = 0.7 \) kPa in the second stage; (iii) it was then followed
by an increasing specific discharge, at an initially increasing and subsequently decreasing rate, to the end of the test. An insignificant axial strain $\varepsilon_a = 0.01\%$ and a very small volumetric strain $\varepsilon_v = 0.09\%$ were measured at the end of the test (see Figs. 4.7b and 4.7c, respectively). A post-test particle size analysis of the specimen showed that the finer fraction content of $S_f = 0.05$ in the top layer was markedly lower than the finer fraction content of $S_f = 0.19$ to 0.29 in the other four layers (see Fig. D.29).

4.2.5 Gradation 6.0GB25

Three tests were conducted on gradation 6.0GB25, which experience showed could be reconstituted with a much smaller spatial variation of the finer fraction content than gradation 6.0GB20 (see Section 3.3.1). The specimens were reconstituted by slurry deposition and were isotropically consolidated to target cell pressures of 50 kPa, 100 kPa and 150 kPa, respectively. The test codes are 6.0GB25-50, 6.0GB25-100 and 6.0GB25-150.

4.2.5.1 Test 6.0GB25-50

The specimen was isotropically consolidated to $p'_c = 53$ kPa, $l = 100$ mm and $e_c = 0.38$ (see Table 4.1). It was subject to 21 stages of seepage flow: the test commenced at TDH = 1 cm for $\Delta t = 60$ min, yielding $\Delta u = 0.1$ kPa and $v = 0.003$ cm/s; it was terminated at TDH$_{\text{max}}$ after $t = 380$ min, yielding $\Delta u = 6.2$ kPa and $v = 0.138$ cm/s (see Table 4.2).

The variation of $v: \Delta u$ exhibited a curvilinear response in two sequences (see Fig. 4.8a): (i) the relation was directly proportional to $\Delta u = 0.7$ kPa and $v = 0.016$ cm/s; (ii) it was followed by a sequence of increasing specific discharge at varying rates. The variation of $\varepsilon_a : \Delta u$ exhibited a curvilinear response in three sequences (see Fig. 4.8b): (i) there was no axial strain to $\Delta u = 0.7$ kPa; (ii) it was followed by a small increase to $\varepsilon_a = 0.12\%$ at $\Delta u = 2.1$ kPa; (iii) it was then followed by a series of discrete increments of increasing axial strain to an end-of-test value $\varepsilon_a = 0.68\%$. The variation of $\varepsilon_v : \Delta u$ exhibited a curvilinear response in two sequences (see Fig. 4.8c): (i) the relation was directly proportional to a very small value $\varepsilon_v = 0.05\%$ at $\Delta u = 0.7$ kPa; (ii) it was followed by a series of discrete increments of increasing volumetric strain to an end-of-test value $\varepsilon_v = 1.61\%$. Visual observations (see Fig. D.2) established that the volumetric deformation did not develop uniformly across the specimen, but was rather restricted to one side of the specimen.

4.2.5.2 Test 6.0GB25-100

The specimen was isotropically consolidated to $p'_c = 103$ kPa, $l = 100$ mm and $e_c = 0.37$ (see Table 4.1). It was subject to eleven stages of seepage flow: the test commenced at TDH = 1 cm for $\Delta t = 20$ min, yielding $\Delta u = 0.1$ kPa and $v = 0.004$ cm/s; it was terminated at TDH = 60 cm.
after $t = 140$ min, yielding $\Delta u = 2.5$ kPa and $v = 0.057$ cm/s (see Table 4.2).

The variation of $v: \Delta u$ exhibited a curvilinear response in two sequences (see Fig. 4.8b): (i) it commenced with an increasing specific discharge at slightly decreasing rate to $v = 0.016$ cm/s at $\Delta u = 0.7$ kPa; (ii) it was followed by a proportional relation to the end of the test. There was no significant axial strain or volumetric strain during the test (see Figs. 4.8b and 4.8c).

4.2.5.3 Test 6.0GB25-150

The specimen was isotropically consolidated to $p'_c = 151$ kPa, $l = 101$ mm and $e_c = 0.36$ (see Table 4.1). It was subject to 23 stages of seepage flow: the test commenced at TDH = 4 cm for $\Delta t = 50$ min, yielding $\Delta u = 0.3$ kPa and $v = 0.008$ cm/s; it was terminated at TDH$_{\text{max}}$ after $t = 320$ min, yielding $\Delta u = 8.0$ kPa and $v = 0.120$ cm/s (see Table 4.2).

The variation of $v: \Delta u$ exhibited a curvilinear response in three sequences (see Fig. 4.8a): (i) the relation was directly proportional to $\Delta u = 1.4$ kPa and $v = 0.034$ cm/s; (ii) it was followed by a constant specific discharge to $\Delta u = 1.9$ kPa and $v = 0.034$ cm/s, and subsequently proportional increase to $\Delta u = 4.8$ kPa and $v = 0.082$ cm/s; (iii) it was then followed by a initially constant specific discharge to $\Delta u = 5.9$ kPa and $v = 0.082$ cm/s, and a subsequently proportional increase to the end of the test. A very small axial strain $\varepsilon_a = 0.05 \%$ (see Fig. 4.8b) was measured at the end of the test. The variation of $\varepsilon_v: \Delta u$ exhibited a curvilinear response in two sequences (see Fig. 4.8c): (i) it commenced with an increasing volumetric strain to a very small value $\varepsilon_v = 0.05 \%$ at $\Delta u = 1.4$ kPa; (ii) it was followed by a series of discrete increments of increasing volumetric strain to an end-of-test value $\varepsilon_v = 1.58 \%$. A post-test particle size analysis of the specimen showed that the finer fraction content of $S_f = 0.18$ in the top layer was substantially lower than the finer fraction content of $S_f = 0.25$ to 0.30 in the other four layers (see Fig. D.30).

4.2.6 Gradation 6.0GB30

Three tests were conducted on gradation 6.0GB30. The specimens were reconstituted by slurry deposition and isotropically consolidated to target cell pressures of 50 kPa, 100 kPa and 150 kPa, respectively. The corresponding test codes are 6.0GB25-50, 6.0GB25-100 and 6.0GB25-150.

4.2.6.1 Test 6.0GB30-50

The specimen was isotropically consolidated to $p'_c = 53$ kPa, $l = 100$ mm and $e_c = 0.36$ (see Table 4.1). It was subject to 21 stages of seepage flow: the test commenced at TDH = 2 cm for $\Delta t = 70$ min, yielding $\Delta u = 0.2$ kPa and $v = 0.001$ cm/s; it was terminated at TDH = 120 cm, when the volume change measurement device approached the limit of its working range, after
The variation of $v: \Delta u$ exhibited a curvilinear response in three sequences (see Fig. 4.9a): (i) the relation was directly proportional to $v = 0.005$ cm/s at $\Delta u = 0.6$ kPa; (ii) it was followed by an increasing specific discharge, at an initially increasing rate and subsequently constant rate, to $v = 0.047$ cm/s at $\Delta u = 3.7$ kPa; (iii) it was then followed by a decreasing specific discharge to $v = 0.043$ cm/s at $\Delta u = 3.9$ kPa and a subsequently increasing specific discharge at varying rates to the end of the test. The variation of $\varepsilon_a: \Delta u$ exhibited a curvilinear response in two sequences (see Fig. 4.9b): (i) there was no axial deformation to $\Delta u = 3.4$ kPa; (ii) it was followed by a series of discrete increments of increasing axial strain to an end-of-test value $\varepsilon_a = 0.44\%$. The variation of $\varepsilon_v: \Delta u$ also exhibited a curvilinear response in two sequences (see Fig. 4.9c): (i) it commenced with an increasing volumetric strain to a small value $\varepsilon_v = 0.13\%$ at $\Delta u = 3.4$ kPa; (ii) it was followed by a series of discrete increments of increasing volumetric strain to an end-of-test value of $\varepsilon_v = 1.90\%$. Visual observations showed signs of local distress, which were restricted to one side of the specimen and more pronounced near the top than near the bottom (see Fig. D.3).

4.2.6.2 Test 6.0GB30-100

The specimen was isotropically consolidated to $p_c' = 102$ kPa, $l = 98$ mm and $e_c = 0.34$ (see Table 4.1). It was subject to 22 stages of seepage flow: the test commenced at TDH = 1 cm for $\Delta t = 50$ min, yielding $\Delta u = 0.1$ kPa and $v = 0.003$ cm/s; it was terminated at TDH = 140 cm, when the volume change measurement device approached the limit of its working range, after $t = 350$ min, yielding $\Delta u = 7.5$ kPa and $v = 0.065$ cm/s (see Table 4.2).

The variation of $v: \Delta u$ exhibited a curvilinear response in three sequences (see Fig. 4.9a): (i) it commenced with an increasing specific discharge at diminishing rate to $v = 0.046$ cm/s at $\Delta u = 3.7$ kPa; (ii) it was followed by a decreasing specific discharge at increasing rate to a local minimum of $v = 0.034$ cm/s at $\Delta u = 4.9$ kPa; (iii) it was then followed by a typically increasing specific discharge, at varying rates, to the end of the test (noteworthy during the sequence is a small decrease from $v = 0.044$ cm/s at $\Delta u = 5.4$ kPa, to $v = 0.042$ cm/s at $\Delta u = 5.9$ kPa). The variation of $\varepsilon_a: \Delta u$ exhibited a curvilinear response in two sequences (see Fig. 4.9b): (i) there was no axial deformation to $\Delta u = 3.7$ kPa; (ii) it was followed by a series of discrete increments of increasing axial strain to a small end-of-test value of $\varepsilon_a = 0.21\%$. The variation of $\varepsilon_v: \Delta u$ exhibited a curvilinear response in two sequences (see Fig. 4.9c): (i) it commenced with an increasing volumetric strain to a small value $\varepsilon_v = 0.11\%$ at $\Delta u = 3.7$ kPa; (ii) it was followed by a series of discrete increments of increasing volumetric strain to an end-of-test value of $\varepsilon_v = 1.78\%$. 

$t = 360$ min, yielding $\Delta u = 5.9$ kPa and $v = 0.073$ cm/s (see Table 4.2).
4.2.6.3 Test 6.0GB30-150

The specimen was isotropically consolidated to $p'_c = 151$ kPa, $l = 102$ mm and $e_c = 0.34$ (see Table 4.1). It was subject to 18 stages of seepage flow: the test commenced at TDH = 5 cm for $\Delta t = 50$ min, yielding $\Delta u = 0.4$ kPa and $v = 0.004$ cm/s; it was terminated at TDH = 140 cm, when the volume change measurement device approached the limit of its working range, after $t = 350$ min, yielding $\Delta u = 7.4$ kPa and $v = 0.053$ cm/s (see Table 4.2).

The variation of $v:\Delta u$ exhibited a curvilinear response in three sequences (see Fig. 4.9a): (i) it commenced with an increasing specific discharge at slightly decreasing rate to $v = 0.034$ cm/s at $\Delta u = 4.5$ kPa; (ii) it was followed by a diminishing specific discharge to a local minimum $v = 0.026$ cm/s at $\Delta u = 5.3$ kPa; (iii) it was then followed by an increasing specific discharge, at varying rates, to the end of the test. A very small axial strain $\varepsilon_a = 0.04\%$ (see Fig. 4.9b) was recorded at the end of the test. The variation of $\varepsilon_v:\Delta u$ exhibited a curvilinear response in two sequences (see Fig. 4.9c): (i) it commenced with an increasing volumetric strain to a very small value $\varepsilon_v = 0.07\%$ at $\Delta u = 4.5$ kPa; (ii) it was followed by an an approximately proportional increase to an end-of-test value $\varepsilon_v = 1.87\%$. Visual observations indicated that the volumetric deformation occurred predominantly across the top half of the specimen (see Fig. D.4). An abundance of fine particles was observed at the top of the specimen, after dis-assembly of the cell (see Fig. D.5). The post-test particle size analysis yields a relatively high finer fraction content of $S_f = 0.44$ compared to $S_f = 0.28$ to 0.34 in the centre and bottom of the specimen (see Fig. D.31).

4.2.7 Gradation 6.0GB35

Four tests were conducted on gradation 6.0GB35. The specimens were reconstituted by slurry deposition and isotropically consolidated to target cell pressures of 50 kPa, 100 kPa (in two sequential tests) and 150 kPa, respectively. The corresponding test codes are 6.0GB35-50, 6.0GB35-100, 6.0GB35-100(R), and 6.0GB35-150.

4.2.7.1 Test 6.0GB35-50

The specimen was isotropically consolidated to $p'_c = 54$ kPa, $l = 98$ mm and $e_c = 0.33$ (see Table 4.1). It was subject to 17 stages of seepage flow: the test commenced at TDH = 2 cm for $\Delta t = 60$ min, yielding $\Delta u = 0.2$ kPa and $v = 0.002$ cm/s; it was terminated at TDH = 105 cm after $t = 370$ min, when the range of the volume change measurement device approached its limit, yielding $\Delta u = 6.6$ kPa and $v = 0.039$ cm/s (see Table 4.2).

The variation of $v:\Delta u$ exhibited a curvilinear response in two sequences (see Fig. 4.10a): (i) the relation was directly proportional to $\Delta u = 2.1$ kPa and $v = 0.018$ cm/s; (ii) it was followed
by a decreasing specific discharge to a local minimum of \( v = 0.016 \text{ cm/s} \) at \( \Delta u = 2.7 \text{ kPa} \); (iii) it was then followed by an increasing specific discharge at varying rates to the end of the test. The variation of \( \varepsilon_a: \Delta u \) exhibited a curvilinear response in two sequences (see Fig. 4.10b): (i) there was no axial deformation to \( \Delta u = 2.1 \text{ kPa} \); (ii) it was followed by an increasing axial strain to a small end-of-test value \( \varepsilon_a = 0.21 \% \). The variation of \( \varepsilon_v: \Delta u \) exhibited a curvilinear response in two sequences (see Fig. 4.10c): (i) it commenced with an increasing volumetric strain to a very small value of \( \varepsilon_v = 0.07 \% \) at \( \Delta u = 1.7 \text{ kpa} \); (ii) it was followed by an increasing volumetric strain, at an approximately constant rate, to an end-of-test value of \( \varepsilon_v = 2.19 \% \). Visual observations (see Fig. D.6) established that the volumetric deformation developed predominantly in the top half of the specimen. An abundance of fine particles at the top of the specimen was observed after dis-assembly of the cell (see Fig. D.7).

4.2.7.2 Test 6.0GB35-100

The specimen was isotropically consolidated to \( p_c' = 102 \text{ kPa}, l = 100 \text{ mm} \) and \( e_c = 0.37 \) (see Table 4.1). It was subject to twelve stages of seepage flow: the test commenced at TDH = 1 cm for \( \Delta t = 20 \text{ min} \), yielding \( \Delta u = 0.1 \text{ kPa} \) and \( v = 0.003 \text{ cm/s} \); it was terminated at TDH = 60 cm after \( t = 150 \text{ min} \), when the volume change measurement device approached the limit of its working range, yielding \( \Delta u = 4.7 \text{ kPa} \) and \( v = 0.028 \text{ cm/s} \) (see Table 4.2).

The variation of \( v: \Delta u \) exhibited a curvilinear response in two sequences (see Fig. 4.10a): (i) the relation was directly proportional to \( \Delta u = 1.2 \text{ kPa} \) and \( v = 0.016 \text{ cm/s} \); (ii) it was followed by an increasing specific discharge, at a varying rate to the end of the test. The variation of \( \varepsilon_a: \Delta u \) exhibited a curvilinear response in two sequences (see Fig. 4.10b): (i) the relation was directly proportional response to a very small value of \( \varepsilon_a = 0.02 \% \) at \( \Delta u = 1.2 \text{ kPa} \); (ii) it was followed by a series of discrete increments of increasing axial strain to an end-of-test value of \( \varepsilon_a = 0.62 \% \). The variation of \( \varepsilon_v: \Delta u \) also exhibited a curvilinear response in two sequences (see Fig. 4.10c): (i) it was negligible to \( \Delta u = 1.2 \text{ kPa} \); (ii) it was followed by an increasing volumetric strain to an end-of-test value of \( \varepsilon_v = 1.54 \% \). Visual observations (see Fig. D.8) established that the volumetric deformation occurred mainly at one side of the specimen, at the top half. A large amount of fine particles was detected at the top of the specimen, after dis-assembly of the cell (see Fig. D.9).

4.2.7.3 Test 6.0GB35-100(R)

The specimen was isotropically consolidated to \( p_c' = 102 \text{ kPa}, l = 102 \text{ mm} \) and \( e_c = 0.37 \) (see Table 4.1). It was subject to 23 stages of seepage flow: the test commenced with TDH = 1 cm for \( \Delta t = 30 \text{ min} \), yielding \( \Delta u = 0.1 \text{ kPa} \) and \( v = 0.001 \text{ cm/s} \); it was terminated at TDH = 80 cm after \( t = 270 \text{ min} \), when the volume change measurement device approached the limit of its working range, yielding \( \Delta u = 5.9 \text{ kPa} \) and \( v = 0.035 \text{ cm/s} \) (see Table 4.2).
The variation of \( v: \Delta u \) exhibited a curvilinear response comprising two sequences (see Fig. 4.10a): (i) the relation was directly proportional to \( \Delta u = 1.8 \) kPa and \( v = 0.025 \) cm/s in stage 4; (ii) it was followed by an initially decreasing specific discharge in stage five, and an increasing specific discharge at varying rates to the end of the test. The variation of \( \varepsilon_a: \Delta u \) exhibited a curvilinear response comprising two sequences (see Fig. 4.10b): (i) the axial strain increased to a very small value of \( \varepsilon_a = 0.04 \% \) at \( \Delta u = 1.8 \) kPa; (ii) it was followed by a series of discrete increments of increasing axial strain to an end-of-test value \( \varepsilon_a = 0.70 \% \). The variation of \( \varepsilon_v: \Delta u \) also exhibited a curvilinear response comprising two sequences (see Fig. 4.10c): (i) the volumetric strain increased to a small value \( \varepsilon_v = 0.16 \% \) at \( \Delta u = 1.8 \) kPa; (ii) it was followed by an increasing volumetric strain, at an approximately constant rate, to an end-of-test value of \( \varepsilon_v = 2.19 \% \). Post-test particle size analysis indicated a slightly greater finer fraction content of \( S_f = 0.39 \) in the top layer of the specimen than the finer fraction content of \( S_f = 0.33 \) to 0.36 in the other four layers of the specimen (see Fig. D.32).

4.2.7.4 Test 6.0GB35-150

The specimen was isotropically consolidated to \( p'_c = 152 \) kPa, \( l = 102 \) mm and \( e_c = 0.34 \) (see Table 4.1). It was subject to 19 stages of seepage flow: the test commenced with TDH = 1 cm for \( \Delta t = 50 \) min, yielding \( \Delta u = 0.1 \) kPa and \( v = 0.002 \) cm/s; it was terminated at TDH = 115 cm after \( t = 320 \) min, when the volume change measurement device approached the limit of its working range, yielding \( \Delta u = 6.9 \) kPa and \( v = 0.047 \) cm/s (see Table 4.2).

The variation of \( v: \Delta u \) exhibited a curvilinear response in three sequences (see Fig. 4.10a): (i) the relation was directly proportional to \( v = 0.027 \) cm/s at \( \Delta u = 2.7 \) kPa; (ii) it was followed by an initial small increase at a smaller rate to \( v = 0.028 \) cm/s at \( \Delta u = 3.1 \) kPa and a subsequent decrease to a local minimum of \( v = 0.023 \) cm/s at \( \Delta u = 3.4 \) kPa; (ii) it was then followed by an increasing specific discharge at varying rates to the end of the test. A very small \( \varepsilon_a = 0.02 \% \) was measured at the end of the test (see Fig. 4.10b). The variation of \( \varepsilon_v: \Delta u \) exhibited a curvilinear response in two sequences (see Fig. 4.10c): (i) it commenced with an increasing volumetric strain to a small value of \( \varepsilon_v = 0.14 \% \) at \( \Delta u = 2.7 \) kPa; (ii) it was followed by an increasing volumetric strain, at a slightly increasing rate, to an end-of-test value of \( \varepsilon_v = 2.46 \% \). Post-test particle size analysis did not indicate a substantial variation of fine fraction content of \( S_f = 0.32 \) to 0.38, between five layers of the specimen (see Fig. D.33).

4.2.8 Gradation 6.5GB35

Two tests were conducted on gradation 6.5GB35. The specimens were reconstituted by slurry deposition and isotropically consolidated to target cell pressures of 50 kPa and 100 kPa, respectively. The corresponding test codes are 6.5GB35-50 and 6.5GB35-100.
4.2.8.1 Test 6.5GB35-50

The specimen was isotropically consolidated to $p'_c = 54$ kPa, $l = 95$ mm and $e_c = 0.30$ (see Table 4.1). It was subject to seven stages of seepage flow: the test commenced with TDH = 1 cm for $\Delta t = 10$ min, yielding $\Delta u = 0.1$ kPa and $v = 0.003$ cm/s; it was terminated at TDH = 35 cm after $t = 90$ min, when sudden continuing deformations occurred, yielding $\Delta u = 1.3$ kPa and $v = 0.037$ cm/s (see Table 4.2).

The variation of $v: \Delta u$ exhibited a curvilinear response in two sequences (see Fig. 4.11a): (i) there was a directly proportional relation during the first four stages to $\Delta u = 1.2$ kPa and $v = 0.018$ cm/s; (ii) it was followed by a decrease of specific discharge from stage four to five and then a marked increase in specific discharge during the final two stages. A small axial strain $\varepsilon_a = 0.14$ % was recorded at the end of the test (see Fig. 4.11b). The variation of $\varepsilon_v: \Delta u$ exhibited a curvilinear response in two sequences (see Fig. 4.11c): (i) there was negligible volumetric strain to $\Delta u = 1.2$ kPa; (ii) it was followed by a marked increase in volumetric strain during the final three stages to an end-of-test value of $\varepsilon_v = 1.89$ %, accompanied by a decrease from $\Delta u = 1.4$ to 1.3 kPa. A post-test particle size analysis of the specimen showed that the finer fraction content of $S_f = 0.48$ in the top layer was greater than the finer fraction content of $S_f = 0.30$ to 0.33 in the other three layers (see Fig. D.34).

4.2.8.2 Tests 6.5GB35-100

The specimen was isotropically consolidated to $p'_c = 101$ kPa, $l = 96$ mm and $e_c = 0.31$ (see Table 4.1). It was subject to six stages of seepage flow: the test commenced with TDH = 1 cm for $\Delta t = 10$ min, yielding $\Delta u = 0.1$ kPa and $v = 0.003$ cm/s; it was terminated at TDH = 30 cm after $t = 60$ min, when sudden, continuing deformations occurred, yielding $\Delta u = 1.6$ kPa and $v = 0.033$ cm/s (see Table 4.2).

The variation of $v: \Delta u$ exhibited a curvilinear response in two sequences (see Fig. 4.11a): (i) the relation was directly proportional to $v = 0.023$ cm/s at $\Delta u = 1.4$ kPa; (ii) it was followed by a marked increase in specific discharge to the end of the test. A very small end-of-test value $\varepsilon_u = 0.04$ % was measured (see Fig. 4.11b). The variation of $\varepsilon_v: \Delta u$ exhibited a curvilinear response in two sequences (see Fig. 4.11c): (i) there was an initial increase to a very small value $\varepsilon_v = 0.04$ % at $\Delta u = 0.8$ kPa; (ii) it was followed by a marked increase at a much greater rate during the final three stages to an end-of-test value of $\varepsilon_v = 1.68$ %. Visual observations (see Fig. D.10) indicated that the volumetric deformation was restricted to one side of specimen. A large amount of fine particles was observed at the top of the specimen, after dis-assembly of the cell (see Fig. D.11), which was in agreement with the relatively high finer fraction content of $S_f = 0.42$ in the top layer, compared to the finer fraction content of $S_f = 0.33$ to 0.35 in the other three layers (see Fig. D.35).
4.3 Tests on soils

The BT test series comprises all tests conducted on soils of sub-angular particles. The initial and the end-of-test conditions of all tests on soils are tabulated in Tables 4.3 and 4.4, respectively. A summary of typical responses in tests on soil gradations is provided in Section 4.5.

4.3.1 Gradation 5.1BT20

Two tests were conducted on gradation 5.1BT20, which has a very similar particle size distribution as glass beads gradation 4.8GB20. The specimens were reconstituted by slurry deposition and isotropically consolidated at target cell pressures of 50 kPa and 150 kPa, respectively. The corresponding test codes are 5.1BT20-50 and 5.1BT20-150.

4.3.1.1 Test 5.1BT20-50

The specimen was isotropically consolidated to $p'_c = 53$ kPa, $l = 101$ mm and $e_c = 0.63$ (see Table 4.3). It was subject to 26 stages of seepage flow: the test commenced at TDH = 2 cm for $\Delta t = 30$ min, yielding $\Delta u = 0.2$ kPa and $v = 0.003$ cm/s; it was terminated at TDH$_{\text{max}}$ after $t = 400$ min, yielding $\Delta u = 8.7$ kPa and $v = 0.114$ cm/s (see Table 4.4).

The variation of $v:\Delta u$ exhibited a curvilinear response in three sequences (see Fig. 4.12a): (i) the relation was directly proportional to $\Delta u = 0.3$ kPa and $v = 0.005$ cm/s; (ii) it was followed by an increase at an initially increasing rate and subsequently diminishing rate to $\Delta u = 5.4$ kPa and $v = 0.081$ cm/s; (iii) it was then followed by an increasing specific discharge at increasing rate to the end of the test. A negligible axial strain (see Fig. 4.12b) and a small end-of-test value $\varepsilon_v = 0.10$ % (see Fig. 4.12c) were recorded. A post-test particle size analysis showed that the fine fraction content varied from $S_f = 0.19$ in the top layer to $S_f = 0.25$ in the bottom layer (see Fig. D.36).

4.3.1.2 Test 5.1BT20-150

The specimen was isotropically consolidated to $p'_c = 152$ kPa, $l = 102$ mm and $e_c = 0.65$ (see Table 4.3). It was subject to 25 stages of seepage flow: the test commenced at TDH = 1 cm for $\Delta t = 20$ min, yielding $\Delta u = 0.1$ kPa and $v = 0.003$ cm/s; it was terminated at TDH$_{\text{max}}$ after $t = 280$ min, yielding $\Delta u = 6.0$ kPa and $v = 0.141$ cm/s (see Table 4.4).

The variation of $v:\Delta u$ exhibited a curvilinear response in two sequences (see Fig. 4.12a): (i) the relation was directly proportional to $\Delta u = 0.3$ kPa and $v = 0.014$ cm/s; (ii) it was followed by an increase, at an initially increasing rate and subsequently diminishing rate, to the end of the test. There was no axial strain during the test (see Fig. 4.12b). The volumetric strain increased to a small end-of-test value $\varepsilon_v = 0.14$ % (see Fig. 4.12c). A post-test particle size analysis
established that the fine fraction content $S_f = 0.13$ in the top layer was smaller than the finer fraction content of $S_f = 0.19$ to 0.22 in the four other layers (see Fig. D.37).

### 4.3.2 Gradation 5.7BT20

Three tests were conducted on gradation 5.7BT20. The specimens were reconstituted by slurry deposition and isotropically consolidated to target cell pressures of 50 kPa, 100 kPa and 150 kPa, respectively. The corresponding test codes are 5.7BT20-50, 5.7BT20-100 and 5.7BT20-150.

#### 4.3.2.1 Test 5.7BT20-50

The specimen was isotropically consolidated to $p'_c = 54$ kPa, $l = 101$ mm and $e_c = 0.59$ (see Table 4.3). It was subject to 21 stages of seepage flow: the test commenced at TDH = 1 cm for $\Delta t = 50$ min, yielding $\Delta u = 0.1$ kPa and $v = 0.003$ cm/s; it was terminated at TDH$_{\max}$ after $t = 310$ min, yielding $\Delta u = 5.4$ kPa and $v = 0.147$ cm/s (see Table 4.4).

The variation of $v:\Delta u$ exhibited a curvilinear response in two sequences (see Fig. 4.13a): (i) the relation was directly proportional to $\Delta u = 0.3$ kPa and $v = 0.013$ cm/s; (ii) it was followed by an increasing specific discharge, at an initially increasing rate and subsequently diminishing rate, to the end of the test. A negligible axial strain (see Fig. 4.13b) and small volumetric strain $\varepsilon_v = 0.10\%$ (see Fig. 4.13c) were recorded at the end of the test. A post-test particle size analysis established that the fine fraction content $S_f = 0.17$ in the top layer was smaller than the finer fraction content of $S_f = 0.20$ to 0.23 in the other layers (see Fig. D.38).

#### 4.3.2.2 Test 5.7BT20-100

The specimen was isotropically consolidated to $p'_c = 102$ kPa, $l = 101$ mm and $e_c = 0.56$ (see Table 4.3). It was subject to 18 stages of seepage flow: the test commenced at TDH = 1 cm for $\Delta t = 40$ min, yielding $\Delta u = 0.1$ kPa and $v = 0.002$ cm/s; it was terminated at TDH$_{\max}$ after $t = 280$ min, yielding $\Delta u = 5.3$ kPa and $v = 0.146$ cm/s (see Table 4.4).

The variation of $v:\Delta u$ exhibited a curvilinear response in two sequences (see Fig. 4.13a): (i) the relation was directly proportional to $v = 0.011$ cm/s at $\Delta u = 0.2$ kPa; (ii) it was followed by an increasing specific discharge, at an initially increasing rate and subsequently diminishing rate, to the end of the test. There was no axial strain during the test (see Fig. 4.13b) and only a very small volumetric strain, with an end-of-test value $\varepsilon_v = 0.06\%$ (see Fig. 4.13c). A post-test particle size analysis indicated that the fine fraction content $S_f = 0.13$ in the top layer was smaller than the finer fraction content of $S_f = 0.21$ to 0.26 in the other layers (see Fig. D.39).
4.3.2.3 Test 5.7BT20-150

The specimen was isotropically consolidated to \( p'_c = 154 \) kPa, \( l = 102 \) mm and \( e_c = 0.57 \) (see Table 4.3). It was subject to 23 stages of seepage flow: the test commenced at TDH = 1 cm for \( \Delta t = 30 \) min, yielding \( \Delta u = 0.1 \) kPa and \( v = 0.002 \) cm/s; it was terminated at TDH\(_{max}\) after \( t = 300 \) min, yielding \( \Delta u = 5.8 \) kPa and \( v = 0.141 \) cm/s (see Table 4.4).

The variation of \( v: \Delta u \) exhibited a curvilinear response in two sequences (see Fig. 4.13a): (i) the relation was directly proportional to \( v = 0.008 \) cm/s at \( \Delta u = 0.2 \) kPa; (ii) it was followed by an increasing specific discharge, at an initially increasing rate and subsequently diminishing rate, to the end of the test. There was no axial strain during the test (see Fig. 4.13b) and the volumetric strain increased to a small end-of-test value \( \varepsilon_v = 0.17 \% \) (see Fig. 4.13c). A post-test particle size analysis indicated that the fine fraction content of \( S_f = 0.18 \) to 0.19 in the top two layers was somewhat lower than the finer fraction content of \( S_f = 0.20 \) to 0.23 in the bottom three layers (see Fig. D.40).

4.3.3 Gradation 5.7BT35

One test was conducted on gradation 5.7BT35, which has a nearly identical particle size distribution as glass beads gradation 6.0GB35. The specimen was reconstituted by slurry deposition and isotropically consolidated to a target cell pressure of 100 kPa. The test code is 5.7BT35-100.

4.3.3.1 Test 5.7BT35-100

The specimen was isotropically consolidated to \( p'_c = 102 \) kPa, \( l = 102 \) mm and \( e_c = 0.46 \) (see Table 4.3). It was subject to 24 stages of seepage flow: the test commenced at TDH = 5 cm for \( \Delta t = 50 \) min, yielding \( \Delta u = 0.3 \) kPa and \( v = 0.006 \) cm/s; it was terminated at TDH\(_{max}\) after \( t = 360 \) min, yielding \( \Delta u = 8.6 \) kPa and \( v = 0.114 \) cm/s (see Table 4.4).

The variation of \( v: \Delta u \) exhibited a directly proportional response throughout the test (see Fig. 4.14a). A negligible axial strain (see Fig. 4.14b) and a small volumetric strain \( \varepsilon_v = 0.22 \% \) (see Fig. 4.14c) were recorded at the end of the test. A post-test particle size analysis showed that the finer fraction content varied from \( S_f = 0.32 \) to 0.38 in the specimen (see Fig. D.41).

4.3.4 Gradation 7.0BT20

Two tests were conducted on gradation 7.0BT20. The specimens were reconstituted by slurry deposition and isotropically consolidated to target cell pressures of 50 kPa and 150 kPa, respectively. The corresponding test codes are 7.0BT20-50 and 7.0BT20-150.
4.3.4.1 Test 7.0BT20-50

The specimen was isotropically consolidated to $p'_c = 56$ kPa, $l = 99$ mm and $e_c = 0.55$ (see Table 4.3). It was subject to 23 stages of seepage flow: the test commenced at TDH = 1 cm for $\Delta t = 30$ min, yielding $\Delta u = 0.1$ kPa and $v = 0.003$ cm/s; it was terminated at TDH$_{\text{max}}$ after $t = 320$ min, yielding $\Delta u = 3.3$ kPa and $v = 0.167$ cm/s (see Table 4.4).

The variation of $v: \Delta u$ exhibited a curvilinear response in two sequences (see Fig. 4.15a): (i) the relation was directly proportional to $\Delta u = 0.2$ kPa and $v = 0.020$ cm/s; (ii) it was followed by an increasing specific discharge, at an initially slightly increasing rate and subsequently diminishing rate to the end of the test. There was no axial strain during the test (see Fig. 4.15b). A very small volumetric strain $\varepsilon_v = 0.07$ % (see Fig. 4.15c) was measured at the end of the test. A post-test particle size analysis indicated that the fine fraction content of $S_f = 0.18$ to 0.19 in the top two layers was lower than the finer fraction content of $S_f = 0.19$ to 0.22 in the bottom three layers (see Fig. D.42).

4.3.4.2 Test 7.0BT20-150

The specimen was isotropically consolidated to $p'_c = 153$ kPa, $l = 100$ mm and $e_c = 0.53$ (see Table 4.3). It was subject to 20 stages of seepage flow: the test commenced at TDH = 1 cm for $\Delta t = 50$ min, yielding $\Delta u = 0.1$ kPa and $v = 0.003$ cm/s; it was terminated at TDH$_{\text{max}}$ after $t = 320$ min, yielding $\Delta u = 4.0$ kPa and $v = 0.158$ cm/s (see Table 4.4).

The variation of $v: \Delta u$ exhibited a curvilinear response in two sequences (see Fig. 4.15a): (i) the relation was directly proportional to $\Delta u = 0.3$ kPa and $v = 0.014$ cm/s; (ii) it was followed by an increasing specific discharge, at an initially increasing rate and subsequently diminishing rate, to the end of the test. There was no axial strain during the test (see Fig. 4.15b). The volumetric strain increased to a small end-of-test value of $\varepsilon_v = 0.12$ % (see Fig. 4.15c). A post-test particle size analysis showed a substantially lower finer fraction content of $S_f = 0.14$ in the top layer than the finer fraction content of $S_f = 0.19$ to 0.26 in the other layers (see Fig. D.43).

4.3.5 Gradation 7.0BT35

One test was conducted on gradation 7.0BT35. Tests on similar gradation of glass beads (6.5GB35, see Section 4.2.8) exhibited substantial contractive volume changes. The specimen of gradation 7.0BT35 was reconstituted by slurry deposition and isotropically consolidated to a target cell pressure of 50 kPa. The tests code is 7.0BT35-50.
4.3.5.1 Test 7.0BT35-50

The specimen was isotropically consolidated to $p'_c = 54$ kPa, $l = 102$ mm and $e_c = 0.42$ (see Table 4.3). It was subject to twenty-eight stages of seepage flow: the test commenced at TDH = 1 cm for $\Delta t = 50$ min, yielding $\Delta u = 0.1$ kPa and $v = 0.006$ cm/s; it was terminated at TDH$_{\text{max}}$ after $t = 380$ min, yielding $\Delta u = 9.5$ kPa and $v = 0.104$ cm/s (see Table 4.4).

The variation of $v$:$\Delta u$ exhibited a response in two sequences (see Fig. 4.16a): (i) the relation was directly proportional to $\Delta u = 7.3$ kPa and $v = 0.084$ cm/s; (ii) it was followed by an increasing specific discharge, at an initially decreasing and subsequently constant rate, to the end of the test. A very small axial strain $\varepsilon_a = 0.02$ % (see Fig. 4.16b) and a small volumetric strain $\varepsilon_v = 0.16$ % (see Fig. 4.16c) were recorded at the end of the test.

4.3.6 Gradation 8.6BT20

One test was conducted on gradation 8.6BT20. The specimen was reconstituted by slurry deposition and isotropically consolidated to a target cell pressures of 50 kPa. The test code is 8.6BT20-50.

4.3.6.1 Test 8.6BT20-50

The specimen was isotropically consolidated to $p'_c = 53$ kPa, $l = 98$ mm and $e_c = 0.51$ (see Table 4.3). It was subject to twenty-six stages of seepage flow: the test commenced at TDH = 1 cm for $\Delta t = 30$ min, yielding $\Delta u = 0.1$ kPa and $v = 0.002$ cm/s; it was terminated at TDH$_{\text{max}}$ after $t = 360$ min, yielding $\Delta u = 7.5$ kPa and $v = 0.126$ cm/s (see Table 4.4).

The variation of $v$:$\Delta u$ exhibited a curvilinear response in two sequences (see Fig. 4.17a): (i) the relation was directly proportional to $v = 0.010$ cm/s at $\Delta u = 0.4$ kPa; (ii) it was followed by an increasing specific discharge, at an initially increasing rate and subsequently diminishing rate, to the end of the test. No axial strain (see Fig. 4.17b) and a very small volumetric strain $\varepsilon_v = 0.06$ % (see Fig. 4.17c) were measured at the end of the test. A post-test particle size analysis indicated that the fine fraction content of $S_f = 0.14$ in the top layer was substantially lower than the finer fraction content of $S_f = 0.20$ to 0.25 in the other layers (see Fig. D.44).

4.3.7 Gradation 8.6BT35

One test was conducted on gradation 8.6BT35. The specimen was reconstituted by slurry deposition and isotropically consolidated to a target cell pressure of 50 kPa. The test code is 8.6BT35-50.
4.3.7.1 Test 8.6BT35-50

The specimen was isotropically consolidated to \( p'_c = 55 \text{ kPa}, \ l = 97 \text{ mm and } e_c = 0.46 \) (see Table 4.3). It was subject to 25 stages of seepage flow: the test commenced at TDH = 1 cm for \( \Delta t = 40 \text{ min}, \) yielding \( \Delta u = 0.1 \text{ kPa and } v = 0.001 \text{ cm/s}; \) it was terminated at TDH\(_{\max}\) after \( t = 370 \text{ min}, \) yielding \( \Delta u = 9.5 \text{ kPa and } v = 0.089 \text{ cm/s} \) (see Table 4.4).

The variation of \( v: \Delta u \) exhibited a response in two sequences (see Fig. 4.18a): (i) the relation was directly proportional to \( \Delta u = 5.3 \text{ kPa and } v = 0.042 \text{ cm/s}; \) (ii) it was followed by an increasing specific discharge, at a slightly increasing rate, to the end of the test. The axial strain was negligible throughout the test (see Fig. 4.18b) and the volumetric strain increased to a small end-of-test value of \( \varepsilon_v = 0.15 \% \) (see Fig. 4.18c).

4.3.8 Gradation 10.4BT25

One test was conducted on gradation 10.4BT25. The specimen was reconstituted by slurry deposition and isotropically consolidated to a target cell pressure of 50 kPa. The test code is 10.4BT25-50.

4.3.8.1 Test 10.4BT25-50

The specimen was isotropically consolidated to \( p'_c = 53 \text{ kPa}, \ l = 98 \text{ mm and } e_c = 0.44 \) (see Table 4.3). It was subject to 24 stages of seepage flow: the test commenced at TDH = 1 cm for \( \Delta t = 30 \text{ min}, \) yielding \( \Delta u = 0.1 \text{ kPa and } v = 0.002 \text{ cm/s}; \) it was terminated at TDH\(_{\max}\) after \( t = 280 \text{ min}, \) yielding \( \Delta u = 8.6 \text{ kPa and } v = 0.117 \text{ cm/s} \) (see Table 4.4).

The variation of \( v: \Delta u \) exhibited a response in three sequences (see Fig. 4.19a): (i) the relation was directly proportional to \( \Delta u = 0.3 \text{ kPa and } v = 0.008 \text{ cm/s at } \Delta u = 0.3 \text{ kPa}; \) (ii) it was followed by an increasing specific discharge, at an initially increasing and subsequently diminishing rate, to a local maximum of \( v = 0.081 \text{ cm/s at } \Delta u = 3.1 \text{ kPa}; \) (iii) it was then followed by a decreasing specific discharge to a local minimum of \( v = 0.069 \text{ cm/s at } \Delta u = 5.0 \text{ kPa and a subsequently increasing specific discharge at an approximately constant rate to the end of the test. There was no axial strain during the test (see Fig. 4.19b). The variation of } \varepsilon_v: \Delta u \text{ exhibited a curvilinear response in two sequences: (i) it commenced with an increasing volumetric strain to a small value } \varepsilon_v = 0.17 \% \text{ at } \Delta u = 2.5 \text{ kPa; (ii) it was followed by an isolated event of increasing volumetric strain to } \varepsilon_v = 0.72 \%, \text{ after which it remained constant to the end of the test (see Fig. 4.19c). Visual observations (see Figs. D.12) show more coarse particles protruding from the top half of the specimen than from the bottom half. A relatively large portion of fine particles was observed on top of the specimen after dis-assembly of the cell (see Fig. D.13). A post-test particle size analysis showed that spatial variation in the specimen of finer fraction content of} \)
$S_f = 0.25$ to $0.28$ was small (see Fig. D.45).

### 4.3.9 Gradation 10.4BT30

One test was conducted on gradation 10.4BT30. The specimen was reconstituted by slurry deposition and isotropically consolidated to a target cell pressure of 50 kPa. The test code is 10.4BT30-50.

#### 4.3.9.1 Test 10.4BT30-50

The specimen was isotropically consolidated to $p'_c = 53$ kPa, $l = 98$ mm and $e_c = 0.41$ (see Table 4.3). It was subject to 23 stages of seepage flow: the test commenced at TDH = 1 cm for $\Delta t = 30$ min, yielding $\Delta u = 0.1$ kPa and $v = 0.001$ cm/s; it was terminated at TDH$_{\text{max}}$ after $t = 410$ min, yielding $\Delta u = 7.4$ kPa and $v = 0.130$ cm/s (see Table 4.4).

The variation of $v: \Delta u$ exhibited a response in two sequences (see Fig. 4.20a): (i) the relation was directly proportional to $\Delta u = 2.0$ kPa and $v = 0.003$ cm/s; (ii) it was followed by an increasing specific discharge at a varying rate to the end of the test. A very small axial strain $\varepsilon_v = 0.02$ % (see Fig. 4.20b) and a small volumetric strain $\varepsilon_v = 0.20$ % (see Fig. 4.20c) were recorded at the end of the test. Visual observations (see Fig. D.14) showed signs of local distress near the top of the specimen and established that fine particles had migrated out of the specimen (see Fig. D.15). A post-test particle size analysis indicated that the finer fraction content in the specimen increased from $S_f = 0.27$ in the top layer to $S_f = 0.32$ in the bottom layer (see Fig. D.46).

### 4.3.10 Gradation 10.4BT35

Three tests were conducted on gradation 10.4BT35. The specimens were reconstituted by slurry deposition and isotropically consolidated to target cell pressures of 50 kPa (in two sequential tests) and 100 kPa. The respective test codes are 10.4BT35-50, 10.4BT35-50(R) and 10.4BT35-100.

#### 4.3.10.1 Test 10.4BT35-50

The specimen was isotropically consolidated to $p'_c = 55$ kPa, $l = 103$ mm and $e_c = 0.36$ (see Table 4.3). It was subject to 31 stages of seepage flow: the test commenced at TDH = 1 cm for $\Delta t = 40$ min, yielding $\Delta u = 0.1$ kPa and $v = 0.001$ cm/s; it was terminated at TDH$_{\text{max}}$ after $t = 430$ min, yielding $\Delta u = 8.8$ kPa and $v = 0.113$ cm/s (see Table 4.4).

The variation of $v: \Delta u$ exhibited a response in two sequences (see Fig. 4.21a): (i) the relation was directly proportional to $\Delta u = 1.9$ kPa and $v = 0.044$ cm/s; (ii) it was followed by a varying
specific discharge to the end of the test. The axial strain increased to a small end-of-test value $\varepsilon_a = 0.13\%$ (see Fig. 4.21b). The variation of $\varepsilon_v:\Delta u$ exhibited a response in two sequences (see Fig. 4.21c): (i) it commenced with an increasing volumetric strain to a small value $\varepsilon_v = 0.13\%$ and $\Delta u = 1.8\, \text{kPa}$; (ii) it was followed by a series of discrete increments of increasing volumetric strain to an end-of-test value $\varepsilon_v = 1.74\%$. Visual observations (see Fig. D.16) showed signs of local distress near the top of the specimen and established that fine particles had migrated out of the specimen (see Fig. D.17).

4.3.10.2 Test 10.4BT35-50(R)

The specimen was isotropically consolidated to $p'_c = 57\, \text{kPa}$, $l = 101\, \text{mm}$ and $e_c = 0.37$ (see Table 4.3). It was subject to 25 stages of seepage flow: the test commenced at TDH = 1 cm for $\Delta t = 30\, \text{min}$, yielding $\Delta u = 0.1\, \text{kPa}$ and $v = 0.001\, \text{cm/s}$; it was terminated at TDH$_\text{max}$ after $t = 320\, \text{min}$, yielding $\Delta u = 6.3\, \text{kPa}$ and $v = 0.139\, \text{cm/s}$ (see Table 4.4).

The variation of $v:\Delta u$ also exhibited a response comprising two sequences (see Fig. 4.21a): (i) the relation was directly proportional to $\Delta u = 0.5\, \text{kPa}$ and $v = 0.007\, \text{cm/s}$; (ii) it was followed by a varying specific discharge to the end of the test. The axial strain was negligible throughout the test (see Fig. 4.21b). The variation of $\varepsilon_v:\Delta u$ exhibited a response comprising two sequences (see Fig. 4.21c): (i) it commenced with an increasing volumetric strain to a very small value $\varepsilon_v = 0.06\%$ at $\Delta u = 0.8\, \text{kPa}$; (ii) it was followed by a series of discrete increments of increasing volumetric strain to an end-of-test value $\varepsilon_v = 1.08\%$. Visual observations (see Figs. D.19, D.18) showed signs of local distress on one side of the specimen and established that fine particles had migrated out of the specimen (see Fig. D.20). A post-test particle size analysis established that the finer fraction content of $S_f = 0.35$ in top of the specimen, was somewhat greater than the finer fraction content of $S_f = 0.30$ to 0.32 in the rest of the specimen (see Fig. D.47).

4.3.10.3 Test 10.4BT35-100

The specimen was isotropically consolidated to $p'_c = 102\, \text{kPa}$, $l = 100\, \text{mm}$ and $e_c = 0.38$ (see Table 4.3). It was subject to 29 stages of seepage flow: the test commenced at TDH = 1 cm for $\Delta t = 30\, \text{min}$, yielding $\Delta u = 0.1\, \text{kPa}$ and $v = 0.001\, \text{cm/s}$; it was terminated at TDH$_\text{max}$ after $t = 370\, \text{min}$, yielding $\Delta u = 8.3\, \text{kPa}$ and $v = 0.118\, \text{cm/s}$ (see Table 4.4).

The variation of $v:\Delta u$ exhibited a response in two sequences (see Fig. 4.21a): (i) the relation was directly proportional to $\Delta u = 0.8\, \text{kPa}$ and $v = 0.013\, \text{cm/s}$; (ii) it was followed by a varying specific discharge to the end of the test. There was no axial strain to $\Delta u = 1.1\, \text{kPa}$. The axial subsequently decreased to a small end-of-test value $\varepsilon_a = -0.18\%$ (see Fig. 4.21b). The variation of $\varepsilon_v:\Delta u$ exhibited a response in two sequences (see Fig. 4.21c): (i) it commenced with an increasing volumetric strain to a very small value $\varepsilon_v = 0.06\%$ and $\Delta u = 1.1\, \text{kPa}$; (ii) it
was followed by a series of discrete increments of increasing volumetric strain to an end-of-test value \( \varepsilon_v = 2.04\% \). Visual observations (see Figs. D.21 and D.22) showed signs of local distress, which were restricted to one side of the specimen. A post-test particle size analysis showed that the finer fraction content of \( S_f = 0.44 \) in top layer of the specimen was substantially greater than the finer fraction content of \( S_f = 0.29 \) to 0.34 in the other layers of the specimen (see Fig. D.48).

### 4.4 Repeatability of the test results

Three tests, on two glass beads gradations with finer fraction contents of \( S_f = 0.20 \) and 0.35, respectively, and on one soil gradation with \( S_f = 0.35 \), were performed to assess the repeatability of the test results. On the matter of specimen reconstitution and consolidation, the void ratio at the end of consolidation of \( e_c = 0.48 \) of test specimen 4.8GB20-50 was somewhat greater than the void ratio of \( e_c = 0.45 \) of the companion test specimen 4.8GB20-50(R). No substantial differences between void ratios at the end of consolidation were observed in the ensuing reproducibility tests of 6.0GB35-100 and 6.0GB35-100(R); and 10.4BT35-50 and 10.4BT35-50(R). On the matter of multi-stage seepage flow, the response in tests 4.8GB20-50 and 4.8GB20-50(R) was characterised by a similar variation of specific discharge with differential pore water pressure across the specimen: a sequence of direct proportionality to \( \Delta u = 0.2 \) kPa was followed by a sequence of increasing specific discharge, at an increasing and subsequently diminishing rate, in the absence of substantial axial or volumetric deformation. The response to seepage flow in test 6.0GB35-100 was characterised by two sequences: (i) a directly proportional relation of \( v \) with \( \Delta u \) to \( \Delta u = 1.2 \) kPa, in absence of substantial axial and volumetric strains; (ii) it was followed by an increasing specific discharge at a varying rate, accompanied by a series of discrete increments of increasing axial and volumetric strains. The response in the companion test 6.0GB35-100(R) was characterised in a similar manner with the second sequence commencing at \( \Delta u = 1.8 \) kPa. Likewise, the response to seepage flow in tests 10.4BT35-50 and 10.4BT35-50(R) was similar and characterised by two sequences: (i) a directly proportional relation of \( v \) with \( \Delta u \), in the absence of substantial axial and volumetric strains; (ii) it was followed by a varying specific discharge, accompanied by a series of discrete increments of increasing volumetric strain, in the absence of the development of substantial axial strain. Accordingly, these comparisons indicate that the test procedure, which comprises specimen preparation, consolidation and multi-stage seepage flow, yields repeatable results in test specimens of glass beads and soils, with finer fraction contents of \( S_f = 0.20 \) and \( S_f = 0.35 \).

### 4.5 Synthesis

Two commissioning tests on glass beads gradations, subject to upward seepage flow in the flexible wall permeameter, yielded consistent variations of the response variables. In particular, the
resolution and accuracy of the volume change measurement technique are believed sufficient to quantify the onset and progression of deformation, in specimens with volume of approximately 780 cm$^3$.

The main test program consisted of 23 tests on eight glass beads gradations and 16 tests on ten soil gradations. The responses can be broadly clustered into five groups:

- The variation of $v: \Delta u$ exhibited a response in two or three sequences: (i) the relation was initially directly proportional; (ii) it was followed by an increasing specific discharge at an initially increasing rate and subsequently decreasing rate; (iii) in some tests, it was followed by a proportional relation to the end of the test. Negligible to small axial and volumetric strains are measured. The forensic observation at the end of the test indicates that the top layer is depleted of fine particles. Glass beads test 6.0GB20-150 and soil test 8.6BT20-50 are typical examples of this response.

- The variation of $v: \Delta u$ exhibited a response in two or three sequences, similar to the previous response: (i) the relation was initially directly proportional; (ii) it was followed by an increasing specific discharge at an initially increasing rate and subsequently decreasing rate; (iii) in some tests, it was followed by a proportional relation to the end of the test. The variation of $\epsilon_v: \Delta u$ exhibited a response in three sequences: (i) it commenced with a very small strain; (ii) it was followed by a marked, isolated increase of volumetric strain; (iii) it was then followed by a sequence of approximately constant strain through the remainder of the test. Glass beads test 4.8GB20-100 and soil test 10.4BT25-50 are typical examples of this response.

- The variation of $v: \Delta u$ exhibited a response in two sequences: (i) the relation was initially directly proportional; (ii) it was followed by a varying specific discharge to the end of the test. The variation of $\epsilon_v: \Delta u$ exhibited a response in two sequences: (i) it commenced with a sequence of very small volumetric strain; (ii) it was followed by an increasing volumetric strain. The axial strain varied from negligible to substantial. Visual observations established that the volumetric deformation did not occur uniformly across the specimen. Glass beads test 6.0GB35-100 and soil test 10.4BT35-100 are typical examples of this response.

- The variation of $v: \Delta u$ exhibited a response in two sequences: (i) the relation was initially directly proportional; (ii) it was followed by a marked increase in specific discharge during the final stages. There was no axial strain. The variation of $\epsilon_v: \Delta u$ exhibited a response in two sequences: (i) it commenced with a sequence of very small volumetric strain; (ii) it was followed by a marked increase in volumetric strain after which the test was terminated. Forensic observations established a relatively high finer fraction content.
in the top layer at the end of the test, compared to the other layers of the specimen. This response only occurred in glass beads tests 6.5GB35-50 and 6.5GB35-100.

- The variation of $v:\Delta u$ exhibited a directly proportional relation in absence of any substantial axial or volumetric strain. Glass beads test 3.3GB20-50 and soil test 7.0BT35-50 are typical examples of this response.

Finally, the repeatability of the test results is examined. The comparisons of three sets of companion tests indicate that the test procedure yields reproducible results in test specimens of glass beads and soils, with finer fraction contents of $S_f = 0.20$ and $S_f = 0.35$. 
Table 4.1: Initial test conditions: glass beads gradations.

<table>
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<tr>
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<th>$l$ (mm)</th>
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<th>$p_c'$ (kPa)</th>
<th>B-value (-)</th>
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Table 4.2: End-of-test conditions: glass beads gradations.

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<th>$\nu$ (cm/s)</th>
<th>$\varepsilon_u$ (-)</th>
<th>$\varepsilon_v$ (-)</th>
<th>$t$ (min)</th>
<th>Notes</th>
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<tr>
<td>6.0GB20-100</td>
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<td>0.30</td>
<td>0.82</td>
<td>370</td>
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<td>6.0GB20-150</td>
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<td>0.067</td>
<td>0.01</td>
<td>0.09</td>
<td>240</td>
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<tr>
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<td>1.61</td>
<td>380</td>
<td>See Fig. D.2</td>
</tr>
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<td>6.0GB25-100</td>
<td>2.5</td>
<td>0.057</td>
<td>0.00</td>
<td>0.01</td>
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</tr>
<tr>
<td>6.0GB25-150</td>
<td>8.0</td>
<td>0.120</td>
<td>0.05</td>
<td>1.58</td>
<td>320</td>
<td>See Fig. D.20</td>
</tr>
<tr>
<td>6.0GB30-50</td>
<td>5.9</td>
<td>0.073</td>
<td>0.44</td>
<td>1.90</td>
<td>360</td>
<td>See Fig. D.3</td>
</tr>
<tr>
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<td>0.065</td>
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<td>1.78</td>
<td>350</td>
<td></td>
</tr>
<tr>
<td>6.0GB30-150</td>
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<td>0.04</td>
<td>1.87</td>
<td>350</td>
<td>See Figs. D.30</td>
</tr>
<tr>
<td>6.0GB35-50</td>
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<td>0.039</td>
<td>0.21</td>
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<td>370</td>
<td>See Figs. D.6 and D.7</td>
</tr>
<tr>
<td>6.0GB35-100</td>
<td>4.7</td>
<td>0.028</td>
<td>0.62</td>
<td>1.54</td>
<td>150</td>
<td>See Figs. D.8 and D.9</td>
</tr>
<tr>
<td>6.0GB35-100(R)</td>
<td>5.9</td>
<td>0.035</td>
<td>0.70</td>
<td>2.19</td>
<td>270</td>
<td>See Fig. D.32</td>
</tr>
<tr>
<td>6.0GB35-150</td>
<td>6.9</td>
<td>0.047</td>
<td>0.02</td>
<td>2.46</td>
<td>320</td>
<td>See Fig. D.33</td>
</tr>
<tr>
<td>6.5GB25-100</td>
<td>1.6</td>
<td>0.077</td>
<td>0.08</td>
<td>1.65</td>
<td>270</td>
<td></td>
</tr>
<tr>
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<td>90</td>
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<td>0.033</td>
<td>0.04</td>
<td>1.68</td>
<td>60</td>
<td>See Figs. D.10, D.11 and D.35</td>
</tr>
</tbody>
</table>
Table 4.3: Initial test conditions: soil gradations.

<table>
<thead>
<tr>
<th>Test code</th>
<th>l (mm)</th>
<th>$e_c$ (-)</th>
<th>$p'_c$ (kPa)</th>
<th>B-value (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1BT20-50</td>
<td>101</td>
<td>0.63</td>
<td>53</td>
<td>0.96</td>
</tr>
<tr>
<td>5.1BT20-150</td>
<td>102</td>
<td>0.65</td>
<td>152</td>
<td>0.95</td>
</tr>
<tr>
<td>5.7BT20-50</td>
<td>101</td>
<td>0.59</td>
<td>54</td>
<td>0.96</td>
</tr>
<tr>
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<td>101</td>
<td>0.56</td>
<td>102</td>
<td>0.98</td>
</tr>
<tr>
<td>5.7BT20-150</td>
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<td>0.57</td>
<td>154</td>
<td>0.97</td>
</tr>
<tr>
<td>5.7BT35-100</td>
<td>102</td>
<td>0.46</td>
<td>102</td>
<td>0.98</td>
</tr>
<tr>
<td>7.0BT20-50</td>
<td>99</td>
<td>0.55</td>
<td>56</td>
<td>0.97</td>
</tr>
<tr>
<td>7.0BT20-150</td>
<td>100</td>
<td>0.53</td>
<td>153</td>
<td>0.96</td>
</tr>
<tr>
<td>7.0BT35-50</td>
<td>102</td>
<td>0.42</td>
<td>54</td>
<td>0.97</td>
</tr>
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<td>8.6BT20-50</td>
<td>98</td>
<td>0.51</td>
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<td>0.98</td>
</tr>
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<td>8.6BT35-50</td>
<td>97</td>
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<td>0.44</td>
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<td>0.98</td>
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<td>10.4BT30-50</td>
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<td>10.4BT35-50</td>
<td>103</td>
<td>0.36</td>
<td>55</td>
<td>0.97</td>
</tr>
<tr>
<td>10.4BT35-50(R)</td>
<td>101</td>
<td>0.37</td>
<td>57</td>
<td>0.91</td>
</tr>
<tr>
<td>10.4BT35-100</td>
<td>100</td>
<td>0.38</td>
<td>102</td>
<td>0.96</td>
</tr>
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</table>
Table 4.4: End-of-test conditions: soil gradations.

<table>
<thead>
<tr>
<th>Test code</th>
<th>$\Delta u$ (kPa)</th>
<th>$\nu$ (cm/s)</th>
<th>$\varepsilon_a$ (-)</th>
<th>$\varepsilon_v$ (-)</th>
<th>$t$ (min)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1BT20-50</td>
<td>8.7</td>
<td>0.224</td>
<td>0.01</td>
<td>0.10</td>
<td>400</td>
<td>See Fig. D.36</td>
</tr>
<tr>
<td>5.1BT20-150</td>
<td>6.0</td>
<td>0.141</td>
<td>0.00</td>
<td>0.14</td>
<td>280</td>
<td>See Fig. D.37</td>
</tr>
<tr>
<td>5.7BT20-50</td>
<td>5.4</td>
<td>0.147</td>
<td>0.01</td>
<td>0.10</td>
<td>310</td>
<td>See Fig. D.38</td>
</tr>
<tr>
<td>5.7BT20-100</td>
<td>5.3</td>
<td>0.146</td>
<td>0.00</td>
<td>0.06</td>
<td>280</td>
<td>See Fig. D.39</td>
</tr>
<tr>
<td>5.7BT20-150</td>
<td>5.8</td>
<td>0.141</td>
<td>0.00</td>
<td>0.17</td>
<td>300</td>
<td>See Fig. D.40</td>
</tr>
<tr>
<td>5.7BT35-100</td>
<td>8.6</td>
<td>0.114</td>
<td>0.00</td>
<td>0.22</td>
<td>360</td>
<td>See Fig. D.41</td>
</tr>
<tr>
<td>7.0BT20-50</td>
<td>3.3</td>
<td>0.167</td>
<td>0.00</td>
<td>0.07</td>
<td>320</td>
<td>See Fig. D.42</td>
</tr>
<tr>
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<td>4.0</td>
<td>0.158</td>
<td>0.00</td>
<td>0.12</td>
<td>320</td>
<td>See Fig. D.43</td>
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<tr>
<td>7.0BT35-50</td>
<td>9.5</td>
<td>0.104</td>
<td>0.02</td>
<td>0.16</td>
<td>380</td>
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</tr>
<tr>
<td>8.6BT20-50</td>
<td>7.5</td>
<td>0.126</td>
<td>0.00</td>
<td>0.06</td>
<td>360</td>
<td>See Fig. D.44</td>
</tr>
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<td>8.6BT35-50</td>
<td>9.5</td>
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<td>0.01</td>
<td>0.15</td>
<td>370</td>
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</tr>
<tr>
<td>10.4BT25-50</td>
<td>8.6</td>
<td>0.117</td>
<td>0.00</td>
<td>0.72</td>
<td>280</td>
<td>See Figs. D.12, D.13 and D.45</td>
</tr>
<tr>
<td>10.4BT30-50</td>
<td>7.4</td>
<td>0.130</td>
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<td>0.20</td>
<td>410</td>
<td>See Figs. D.14, D.15 and D.46</td>
</tr>
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<td>0.13</td>
<td>1.74</td>
<td>430</td>
<td>See Figs. D.16 and D.17</td>
</tr>
<tr>
<td>10.4BT35-50(R)</td>
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<td>0.139</td>
<td>0.00</td>
<td>1.08</td>
<td>320</td>
<td>See Figs. D.18, D.19, D.20 and D.47</td>
</tr>
<tr>
<td>10.4BT35-100</td>
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<td>-0.18</td>
<td>2.04</td>
<td>370</td>
<td>See Figs. D.21, D.22 and D.48</td>
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</table>
Figure 4.1: Response variables.
Figure 4.2: GB-F-100 test results.
Figure 4.3: 6.5GB25-100 test results.
Figure 4.4: 3.3GB20 test results.
Figure 4.5: 4.8GB20 test results.
Figure 4.6: 4.8GB35 test results.
Figure 4.7: 6.0GB20 test results.
Figure 4.8: 6.0GB25 test results.
Figure 4.9: 6.0GB30 test results.
Figure 4.10: 6.0GB35 test results.
Figure 4.11: 6.5GB35 test results.
**Figure 4.12:** 5.1BT20 test results.
Figure 4.13: 5.7BT20 test results.
Figure 4.14: 5.7BT35 test results.
Figure 4.15: 7.0BT20 test results.
Figure 4.16: 7.0BT35 test results.
Figure 4.17: 8.6BT20 test results.
Figure 4.18: 8.6BT35 test results.
Figure 4.19: 10.4BT25 test results.
Figure 4.20: 10.4BT30 test results.
Figure 4.21: 10.4BT35 test results.
Chapter 5

Analysis of the test results

In this Chapter, the results of the commissioning tests and of the tests constituting the main test program are analysed to establish the phenomenological responses of each test (research objective No. 4). The distinct seepage-induced instability responses of suffusion, suffosion and fluidisation were identified in the literature (see Section 2.1). The responses, which are characterised by mass loss, volume change and change in hydraulic conductivity, are used to inform the analysis of each test presented herein. Accordingly, the following evidence is considered to establish the phenomenological response of the test specimens to seepage flow: 1) the potential for particle migration and particle rearrangement is determined by evaluating the characteristics of the micro-structure of the gradation; 2) the variation of the hydraulic conductivity is quantified based on the variation of the specific discharge and the differential pore water across the specimen; 3) the change of the element volume is quantified by the variation of the volumetric strain; 4) any mass loss is inferred from the variation of hydraulic conductivity in conjunction with the variation of element volume; and, for some but not all tests, 5) forensic evidence of mass loss or particle migration, presented in Appendix D.

The calculation of the variation of the hydraulic conductivity, and the inference of any mass loss from the variation of hydraulic conductivity volume change, are common to all gradations and are therefore discussed first (see Section 5.1). The procedure for determining the microstructure is presented in Section 5.2; the identification of the phenomenological response of gradations of glass beads (GB test series), and gradations of soils (BT test series) to seepage flow, is presented in Sections 5.3 and 5.4, respectively. A synthesis of the analysis, including a summary of quintessential responses identified in glass beads and soil tests, is presented in Section 5.5.
5.1 Analysis of the seepage regime

Analysis of seepage flow in instability tests has been commonly undertaken to investigate certain aspects of the phenomena (e.g. Chang and Zhang, 2013; Chapuis et al., 1996; Garner and Sobkowicz, 2002; Ke and Takahashi, 2012; Lafleur et al., 1989, Li, 2008; Moffat et al., 2011; Skempton and Brogan, 1994; Wan and Fell, 2004). In this study, the seepage flow is analysed by calculating the hydraulic conductivity $k$ using Eq. 2.11, with $\Delta \phi = \Delta u / \gamma_w$, and subsequently evaluating the causes for changes in the seepage flow. Importantly, in the absence of any change to the porous medium itself, the seepage flow is controlled by the flow regime. The transition from the Darcy flow regime to a laminar inertial flow regime (see Section 2.3) can occur at relatively low specific discharge, at Reynolds numbers $Re = 1$ to 10 (Bear, 1972). It is associated with a non-linear relation between $v$ and $\Delta u$. As an approximation to the upper limit of the Darcy flow regime, the specific discharge $v$ at $Re = 1$, $v_{Re=1}$, is determined for each test, using Eq. 2.12 with $L_s = D'_{50}$.

Additionally, the hydraulic conductivity is very sensitive to changes of the fabric of the porous medium. Inspection of the Kozeny-Carman Equation, Eq. 2.14, establishes that:

- Particle migration from an element, in the absence of volume change, results in a greater void ratio, and hence, a greater hydraulic conductivity.

- Contractive volume change of an element, in the absence of particle migration, results in a lower void ratio, and hence, a smaller hydraulic conductivity. Gradual, and generally small, contractive volume changes are associated with consolidation of a specimen subject to an increasing mean effective stress. Alternatively, contractive deformations are associated with the rearrangement of particles, or even collapse of an open, low-density fabric (Mitchell and Soga, 2005).

- Expansive volume change of an element, in the absence of particle migration, results in a greater void ratio, and hence, a greater hydraulic conductivity. Small, elastic expansive deformations occur as a result of the seepage-induced reduction of mean effective stress. Large, expansive volume changes associated with fluidisation (see Section 2.1.1) occur when the effective stress in the specimen reduces to zero (Terzaghi and Peck, 1948).

An increase of hydraulic conductivity can thus only be attributed to particle migration or expansive volume change. Two phenomena can yield a less than proportional increase of $v$ with $\Delta u$: (i) a transition from the Darcy flow regime to a laminar inertial flow regime at $Re = 1$ to 10; or, (ii) a contractive volume change as a result of particle rearrangement. A decrease of hydraulic conductivity, observed as a decreasing $v$ with increasing $\Delta u$, can only be caused by

1Shear-induced volume changes are not considered here, as the shear stress on the element remains constant during multi-stage seepage flow.
contractive volume change as a result of particle rearrangement.

For each test, the seepage regime is determined, based on the comparison of the variation of the specific discharge and $v_{R_e} = 1$, and the hydraulic conductivity is calculated. Analysis of the variation of hydraulic conductivity and volume change, may or may not yield conclusive evidence on the occurrence of mass loss during the test.

5.2 Analysis of micro-structure

Kovacs (1981) noted that the stability of the packing of coarse particles in “loose elasic sediments” can be determined by comparing the inter-coarse void ratio to the maximum index void ratio of the coarse fraction: a stable packing of coarse particles exists if $e_s < e_{s,max}$. This implies that the fine particles do not contribute to the stability of the packing arrangement, in contrast to a micro-structure with $e_s > e_{s,max}$, where the fine grains must, of necessity, be load bearing. Clast-supported micro-structures are commonly held susceptible to seepage-induced internal instability (e.g. Kenney and Lau, 1985; Kezdi, 1979; Kovacs, 1981; Skempton and Brogan, 1994; Wittmann, 1978) and the theoretical fine fraction content at which a clast-supported micro-structure exists can be determined assuming a credible range for the void ratios of the coarse and fine fractions (see Section 2.2.1). Recently, Crawford-Flett (2014) introduced the concepts of Thevanayagam et al. (2002) on the micro-structures of gap-graded mixtures, which yielded further insights into the potential for suffusion. For glass beads, Crawford-Flett (2014) assumed theoretical values of $e_{max} = 0.91$ and $e_{min} = 0.35$ and distinguished between three types of micro-structure. Considering the work of McGeary (1961) and Scott and Kilgour (1969) on packings of spherical particles, an opportunity exists to relieve the micro-structure identification of gap-graded gradations of glass beads from its assumptions and found it on experimental observations instead. The concepts of Thevanayagam et al. (2002) will be respected and, where necessary, refined in order to attain a quantitative framework to distinguish between five types of micro-structures, in contrast to the distinction of only three micro-structures by Crawford-Flett (2014).

5.2.1 Micro-structures of glass beads gradations

5.2.1.1 Construction of micro-structure identification diagram

The construction of the micro-structure identification diagram for the glass beads gradations is based on the following assumptions:

- The void ratio and micro-structure is uniform throughout the specimen.
- The specimens are reconstituted using the modified slurry deposition method.
• The coarse and fine glass beads have the same shape and specific gravity and, hence, equal packing characteristics.

• Glass beads have minimum and maximum index densities of $e_{\text{min}} = 0.57$ and $e_{\text{max}} = 0.67$, as determined experimentally and reported by McGeary (1961); Scott (1960); Scott and Kilgour (1969) and the author (see Section 3.2).

• The theoretical simple cubic fabric of glass beads, associated with a theoretical void ratio of $e_{\text{cub}} = 0.91$, is the loosest possible arrangement of spherical particles that can exist where the particles are still in contact with each other. It can only exist if proper lateral support is provided (McGeary, 1961), for example in the case of a single column of spheres with diameter $d$ in a tube of equal diameter.

The limits of stable arrangements of coarse spherical particles alone ($S_f = 0$) are thus well defined with $e_{s,\text{min}} = 0.57$ and $e_{s,\text{max}} = 0.67$, marked as reference points A (see Table 5.1) and B, respectively, in Fig. 5.1. In addition, consideration is given to the theoretical simple cubic particle arrangement as it is the loosest possible arrangement where spherical particles are in contact with each other. The theoretical simple cubic particle arrangement, with $e_{\text{cub}} = 0.91$, is marked as reference point C in Fig. 5.1. Similarly, the reference points for packings of fine spherical particles alone ($S_f = 1$) are: $e_{f,\text{min}} = 0.57$, $e_{f,\text{max}} = 0.67$, and $e_{\text{cub}} = 0.91$, denoted as reference points D, E, and F, respectively, in Fig. 5.1.

The lower bound of the void ratio of binary mixtures is established by determining the minimum void ratio at each finer fraction content $S_f$. McGeary (1961) showed that the theoretical lower bound can be attained experimentally if $D'/d' > 10$. Considering the varying ratios of $3.3 \leq D'/d' \leq 6.5$ of the glass beads gradations in this study, the theoretical lower bound is preferred herein to simplify the conceptual construction of micro-structure identification diagram. The minimum void ratio is obtained when both the coarse component and the fine component are in their respective densest states; it is calculated by combining Eqs. 2.2 and 2.3 with $e_s = e_{s,\text{min}} = 0.57$ and $e_f = e_{f,\text{min}} = 0.57$ and solving for $e$, which yields $e = 0.15$ at $S_f = 0.27$. This state is denoted as reference point G in Fig. 5.1. The minimum void ratio at different finer fraction contents is then defined by the line connecting reference points A, G and D.

Conceptually, any packing arrangement on the line connecting A and G, where $e_s = e_{s,\text{min}}$, can be characterised as a true clast-supported micro-structure: the coarse particle packing is inherently stable and does not require the support of the fine particles. The fine particles are thus presumed non-load bearing. The true clast-supported micro-structure is very similar to case i of Thevanayagam et al. (2002). A true clast-supported micro-structure can also exist for packing arrangements of coarse particles at a looser states than the maximum density packing, with $e_{s,\text{min}} \leq e_s \leq e_{s,\text{max}}$. This notion leads to the upper boundary B-H of true clast-supported...
micro-structures where \( e_s = e_{s, \text{max}} \). The fine particles are also presumed non-load bearing. The void ratio and finer fraction content of reference point \( H \), with \( e_s = e_{s, \text{max}} = 0.67 \) and \( e_f = e_{s, \text{min}} = 0.57 \), can be calculated by combining Equations 2.2 and 2.3, yielding \( e = 0.17 \) at \( S_f = 0.30 \). Reference point \( H \) is identical to the theoretical critical finer fraction content of Skempton and Brogan (1994) (see Eq. 2.1), with \( e_s = e_{s, \text{max}} = 0.67 \) and \( e_f = e_{s, \text{min}} = 0.57 \).

Now consider the case where the coarse particle arrangement of a true clast-supported micro-structure becomes looser, i.e. \( e_{s, \text{max}} < e_s < e_{cub} \). Such a packing arrangement in which the coarse particles are still in contact with each other can only exist with lateral support, which is postulated to be provided by the fine particles filling the inter-coarse voids. A portion of the fine particles is thus presumed to be load-bearing. The upper limit of a transitional (referring to the support of the fine particles) clast-supported micro-structure is the simple cubic packing arrangement of coarse particles, which is defined by the line connecting reference points \( C \) and \( I \) in Fig. 5.1 where \( I \) corresponds to the case where \( e_s = e_{cub} \) and \( e_f = e_{f, \text{min}} \), yielding \( e = 0.21 \) and \( S_f = 0.37 \). The transitional clast-supported micro-structure is very similar to case ii of Thevanayagam et al. (2002), but the boundaries of this case are now explicitly defined.

Introducing a small percentage of coarse particles to a ‘mixture’ of only fine particles at reference point \( D \), would yield fully dispersed coarse particles in a matrix of fine particles. The domain of a micro-structure of fine particles with fully dispersed coarse particles characterises a true matrix-supported micro-structure. This micro-structure, with its stable fine particle packing, can only exist with \( e_{f, \text{min}} \leq e_f \leq e_{f, \text{max}} \). The true matrix-supported micro-structure is very similar to case iv-1 of Thevanayagam et al. (2002). According to Thevanayagam et al. (2002), the coarse particles contribute to the stability of the micro-structure if spaced less than ten particle diameters apart. The measurements of McGeary (1961), who found that the influence of two boundaries negates when they are spaced more than ten particle diameters apart, justify the use of this value. The limiting finer fraction content, \( S_{f, \text{L}} \), above which the distance between the coarse particles in a matrix-supported micro-structure is at least ten times the diameter, can be then calculated using Eq. 2.5 with \( a = 10 \). For the glass beads gradations, typical values are \( D' = 1.0 \text{ mm} \) and \( d' = 0.15 \text{ mm} \), which yields \( R_d = 6.7 \) as a first approximation. The limiting finer fraction contents and corresponding void ratio at \( e_s = e_{s, \text{min}} \) are then \( S_{f, \text{L}} = 0.94 \) and \( e = 0.54 \), which is denoted as reference point \( J \) in Fig. 5.1. Similarly, for \( e_s = e_{s, \text{max}}, S_{f, \text{L}} = 0.95 \) and \( e = 0.63 \), which is denoted as reference point \( K \) in Fig. 5.1. The domain between the matrix-supported micro-structures and the transitional clast-supported micro-structures is considered to represent a transitional matrix-supported micro-structure. The transitional matrix-supported micro-structure is very similar to case iv-2 of Thevanayagam et al. (2002). The limit for a transitional matrix-supported micro-structure is determined by considering a packing arrangement where coarse particles are just separated from each other by infinitesimally small fine particles;
i.e. the coarse particle packing is just slightly looser than the theoretical simple cubic packing arrangement. The distance between the coarse particles is thus occupied by a singular fine particle, which in the limit also yields a simple cubic packing arrangement of fine particles. This case, with $e_s = e_f = e_{\text{cub}}$, yields $e = 0.29$ at $S_f = 0.32$, which is denoted by $L$ on Fig. 5.1.

Finally, the domain of micro-structures at states looser than the limits of the transitional clast-supported and transitional matrix-supported micro-structures, is referred to as transitional. The fine particles are presumed to separate the coarse grains in these micro-structures, resulting in relatively open particle arrangements, typically with $e_s > e_{\text{cub}}$ and $e_f > e_{\text{cub}}$. The transitional micro-structure is very similar to case iii of Thevanayagam et al. (2002).

5.2.1.2 Micro-structure types

Accordingly, the distinct micro-structures, and their potential for the presence of non-load bearing fine particles, and potential for rearrangement of coarse particles are:

1. Clast-supported micro-structure, Type C (see Fig. 5.2a): only the coarse particles are load-bearing. The inter-coarse void ratio is smaller than the maximum void ratio of the coarse particles: $e_{s,\text{min}} < e_s < e_{s,\text{max}}$, which indicates no potential for the rearrangement of coarse particles and a large portion of non-load bearing fine particles.

2. Transitional clast-supported micro-structure, Type C-T (see Fig. 5.2b): the micro-structure is dominated by the inter-coarse particle contacts, with $e_{s,\text{max}} < e_s < e_{\text{cub}}$, but at least a portion of the fine particle fraction provides support to the coarse particle packing arrangement. Therefore, a portion of the fine particles in this micro-structure is non-load bearing, while the relatively high inter-coarse void ratio indicates a potential for coarse-particle rearrangement.

3. Transitional micro-structure, Type T (see Fig. 5.2c): this relatively open micro-structure comprises coarse and fine particles, which exist at states that are typically looser than the equivalent cubic packing arrangement; $e_f > e_{\text{cub}}$ and $e_s > e_{\text{cub}}$. The relatively high inter-coarse and inter-fine void ratios further suggest a potential for contractive particle rearrangement or even collapse of the micro-structure, towards states of $e_{s,\text{max}}$ and $e_{f,\text{max}}$, respectively. Non load-bearing fine and coarse particles may or may not exist in a very open micro-structure.

4. Transitional matrix-supported micro-structure, Type M-T (see Fig. 5.2d): the micro-structure is dominated by the inter-fine particle contacts with $e_{f,\text{min}} < e_f < e_{\text{cub}}$ and supported by partially dispersed coarse particles at $e_s > e_{\text{cub}}$ and $S_f < S_{f,L}$. Therefore, a very large portion of the fine particles is expected to be load-bearing, while there is potential for the rearrangement of particles to $e_{s,\text{max}}$ and $e_{f,\text{max}}$, which would yield contractive
volumetric deformation.

5. Matrix-supported micro-structure, **Type M** (see Fig. 5.2d): the stability of the micro-structure is governed by the fine particles alone, $e_{f,\text{min}} < e_f < e_{f,\text{max}}$, as the coarse particles are fully embedded in the fine particle packing arrangement at a finer fraction content $S_f > S_{f,L}$. Therefore, all fine particles are deemed load-bearing and there appears no potential for rearrangement of particles.

The micro-structure identification diagram constructed for glass beads gradations in this study, distinguishes between five types of micro-structure, as originally proposed by Thanavanayagam et al. (2002). Considering that the influence of the specimen reconstitution technique on the structure, defined by particle arrangement, composition and inter-particle forces, is not characterised by the type micro-structure (see Section 2.2.1), the following comments are limited to specimens reconstituted by slurry deposition. In general, the re-introduction (in comparison to the micro-structure identification diagram for glass beads gradations of Crawford-Flett 2014), of transitional clast-supported type C-T and transitional matrix-supported type M-T micro-structures, illustrates that both fine and coarse particles are load-bearing in a large domain of admissible packing states of binary mixtures. It is noteworthy that the boundaries between type C and type C-T micro-structures and between type M and type M-T micro-structures, respectively, are based on measurements of the minimum and maximum index void ratios of the fine and coarse fractions. The true clast-supported type C and matrix-supported type M micro-structures are thus restricted to well defined domains at relatively low and high fine fraction contents, respectively. Accordingly, caution is warranted in interpreting the response of type C-T and type M-T micro-structures, based on type C and type M micro-structures, respectively, as it may lead to misconceptions regarding the contribution of the coarse and fine particles to the stability of the particle fabric. The ability to distinguish between type C and type C-T micro-structures, and between type M and type M-T micro-structures, respectively, therefore yields a key improvement of the micro-structure identification diagram. The boundary between the type C-T and type T micro-structures is based on the theoretical reference point where the coarse particles, on average, are just in contact with each other. The boundary between the type M-T and type T micro-structures is not as well defined, as the fine and coarse particles are load-bearing in both domains. The distinction between the domains is intended to illustrate the relatively open nature of the type T micro-structure, in comparison to the type M-T micro-structure.

For each test, the initial micro-structure of the specimen is determined by projecting the finer fraction content $S_f$ (see Table 5.2) and the void ratio at the end of consolidation $e_c$ on to the micro-structure classification diagram for glass beads (see Fig. 5.3). The micro-structure at the end of the test cannot be determined, because the seepage-induced mass loss is not measured.
(see Section 3.1.2), which yields an unknown end-of-test void ratio.

5.2.2 Micro-structures of soil gradations

A micro-structure identification diagram for sub-angular particles is constructed in a similar manner, based on the measurement of $e_{\text{min}} = 0.63$ and $e_{\text{max}} = 0.80$ of the coarse fraction, respectively. The equivalent void ratio of a cubic packing of sub-angular particles $e_{\text{cub}} = 1.09$, is approximated by assuming that the relative increase of the void space $V_v$ in a sub-angular particle packing is identical to the relative increase of 19 % in $V_v$ from $e_{\text{max}} = 0.67$ to $e_{\text{cub}} = 0.91$ in a packing of spherical particles. The micro-structure identification diagram for the sub-angular particles is presented in Fig. 5.4, with the reference points A to L reported in Table 5.1. The different types of micro-structure of soil gradations are bounded by similar reference points as the micro-structure of glass beads gradations. With reference to Fig. 5.4, Type C is bounded by reference points A-B-G-H; Type C-T is bounded by reference points B-C-H-I; Type M-T is bounded by reference points I-J-K-L; Type M is bounded by reference points D-E-J-K; and Type T is bounded by reference points C-E-L. For each test, the micro-structure of the specimen is determined by projecting the finer fraction content $S_f$ (see Table 5.5) and the void ratio at the end of consolidation $e_c$ on to the micro-structure classification diagram for soils of sub-angular particles (see Fig. 5.5).

5.3 Analysis of tests on glass beads

The 25 tests on ten gradations of glass beads are analysed with respect to the assigned micro-structure type, the seepage flow and any deformation of the test specimen. Glass beads tests that exhibited a quintessential response to seepage flow are accentuated herein, and summarised in Section 5.5.

5.3.1 Gradation GB-F

The test on gradation GB-F serves as a benchmark for comparative analysis of the hydraulic conductivity of the fine component of the gap-graded glass beads gradations. The void ratio of the specimen $e_c = 0.65$ (see Table 5.2) is very close to the loosest state $e_{\text{max}} = 0.67$ of a packing of equal sized spheres. The seepage flow yields a constant hydraulic conductivity $k = 0.014$ cm/s and no substantial axial or volumetric deformation. Very similar hydraulic conductivities of $k = 0.015$ cm/s (Moffat and Fannin 2006) and $k = 0.019$ cm/s (Crawford-Flett 2014) were obtained for similarly loose specimens, tested in a rigid wall permeameter. The specific discharge at the last stage of seepage flow $v = 0.117$ cm/s (see Table 5.3) is smaller than the calculated upper limit of specific discharge in the Darcy flow regime, $v_{R_{c=1}} = 0.257$ cm/s, which suggests the Darcy flow regime existed throughout the test. The constant hydraulic conductivity and the absence of any substantial volume change or change in length, (see Fig.
suggest no particle rearrangement or mass loss within the specimen. Accordingly, the test is deemed to have been terminated at a “pre-critical” condition (see Table 5.4).

5.3.2 Gradation 3.3GB20

The micro-structure of this specimen is identified as type C-T (see Table 5.2 and Fig. 5.3), based on the finer fraction content $S_f = 0.20$ and the void ratio at the end of consolidation $e_c = 0.53$. The specific discharge at the last stage of seepage flow of $v = 0.127$ cm/s is greater than the calculated specific discharge $v_{R_e=1} = 0.034$ cm/s at which the transition from the Darcy flow regime to an inertial regime is anticipated. The sequence (see Fig. 4.4) of a constant initial hydraulic conductivity $k_i = k_{max} = 0.037$ cm/s (see Table 5.3), and the absence of any substantial volume change or change in length, suggest no particle rearrangement or mass loss within the specimen. The subsequent sequence of a slight decrease to the hydraulic conductivity at the last stage of seepage flow $k_l = k_{min} = 0.034$ cm/s, in the absence of volume change, is attributed to the transition to the inertial flow regime. It also suggests no particle rearrangement or mass loss occurred within the specimen. Accordingly, this quintessential test is deemed to have been terminated at a “pre-critical” condition (see Table 5.4).

5.3.3 Gradation 4.8GB20

The micro-structure of the specimens of tests 4.8GB20-50, 4.8GB20-50(R), 4.8GB20-100 and 4.8GB20-150 is type C-T, which exhibits non-load bearing fine particles and a potential for the rearrangement of coarse particles, (see Table 5.2 and Fig. 5.3), based on $S_f = 0.20$ and $e_c = 0.44$ to 0.48.

The seepage flow in test 4.8GB20-50 exhibits an initial sequence of constant hydraulic conductivity $k_i = k_{min} = 0.022$ cm/s (see Table 5.3), in the absence of any axial or volumetric deformation (see Fig. 4.5), which suggests the fabric of the specimen did not change. It is followed by a sequence of increasing hydraulic conductivity to $k_{max} = 0.032$ cm/s, also in absence of any substantial axial and volumetric deformation (see Table 5.4), which is attributed to migration of fine particles out of a stable, coarse-particle dominated micro-structure. The subsequent sequence of decreasing hydraulic conductivity to $k_l = 0.028$ cm/s (see Table 5.3), again in the absence of any substantial deformation, commences approximately at the calculated value of $v_{R_e=1} = 0.031$ cm/s, at which the transition from the Darcy flow regime to the inertial flow regime is anticipated. Accordingly, the response of the specimen to seepage flow is characterised by an initial sequence where the fabric remains unchanged and a subsequent sequence of migration of fine particles out of a stable, coarse-particle dominated micro-structure: this response is termed suffusion. The differential pore water pressure at the onset of suffusion $\Delta u_{su} = 0.2$ kPa, is by definition the greatest differential pore water pressure at which a constant hydraulic conductivity is maintained, prior to an increase in hydraulic conductivity. The corre-
sponding mean effective stress at the onset of suffusion is \( p'_{su} = 54 \) kPa.

The seepage flow in test 4.8GB20-50(R) yields an initially constant hydraulic conductivity \( k_i = 0.025 \) cm/s (see Table 5.3), followed by an increase to \( k_{max} = 0.028 \) cm/s and subsequent decrease to \( k_f = k_{min} = 0.020 \) cm/s, which is attributed to the transition to the inertial flow regime. The variation of hydraulic conductivity, in the absence of volume change (see Fig. 4.5 and Table 5.4), is similarly termed suffusion with \( \Delta u_{su} = 0.2 \) kPa and \( p'_{su} = 53 \) kPa.

The seepage flow in test 4.8GB20-100 yields an initially constant hydraulic conductivity \( k_i = k_{min} = 0.017 \) cm/s (see Table 5.3), followed by an increase to a hydraulic conductivity at the last stage of seepage flow \( k_f = k_{max} = 0.025 \) cm/s. The increase in hydraulic conductivity is accompanied by an isolated event of contractive volume change, in the absence of axial deformation (see Fig. 4.5). Although the occurrence of some contractive deformation is indicative of limited particle rearrangement, this isolated event does not appear to progress with increasing hydraulic load. The predominant response of increasing hydraulic conductivity, in the absence of progressive development of volumetric deformation, is attributed to the migration of fine particles out of a largely stable, coarse-particle dominated micro-structure. Considering the predominant phenomenon, the quintessential response to seepage flow is termed suffusion (see Table 5.4) with \( \Delta u_{su} = 0.2 \) kPa and \( p'_{su} = 104 \) kPa. Comparison (see Table 5.3) of the specific discharge at the last stage of seepage flow \( v = 0.142 \) cm/s and \( v_{Re=1} = 0.031 \) cm/s, indicates a transition to the inertial flow regime occurred. It is postulated that the anticipated decrease of hydraulic conductivity associated with the transition to the inertial flow regime, which was not measured, was offset by the effects of suffusion.

The seepage flow in test 4.8GB20-150 yields an initially constant hydraulic conductivity \( k_i = k_{min} = 0.018 \) cm/s (see Table 5.3), and a subsequent increase to \( k_f = k_{max} = 0.024 \) cm/s. The increase in hydraulic conductivity is accompanied by an isolated event of contractive volume change, in the absence of axial deformation (see Fig. 4.5). The predominant phenomenon of increasing hydraulic conductivity, in the absence of progressive development of volumetric deformation, is similarly attributed to the migration of fine particles out of a largely stable, coarse-particle dominated micro-structure. The migration of fine particles is confirmed by the reduced percentage finer fraction in the top layer of the specimen at the end of the test. The response to seepage flow is also termed suffusion (see Table 5.4), with \( \Delta u_{su} = 0.2 \) kPa and \( p'_{su} = 153 \) kPa. It is postulated that the anticipated decrease of hydraulic conductivity, associated with the transition to the inertial flow regime, was offset by the effects of suffusion.
5.3.4 Gradation 4.8GB35

The micro-structure of the specimens of tests 4.8GB35-50, 4.8GB35-100 and 4.8GB35-150 is type T, which exhibits a potential for particle rearrangement, (see Table 5.2 and Fig. 5.3), based on $S_f = 0.35$ and $e_c = 0.36$ to 0.37.

The response of 4.8GB35-50 exhibits an initial sequence of constant hydraulic conductivity $k_i = k_{max} = 0.015$ cm/s (see Table 5.3), in the absence of any axial and volumetric strain (see Fig. 4.6), which suggests the fabric of the specimen did not change. The subsequent sequence of a reduced and slightly varying hydraulic conductivity to $k_l = k_{min} = 0.013$ cm/s, is accompanied by the incremental development of non-uniform contractive volumetric and axial deformations, which is attributed to particle rearrangement. Accordingly, the response of the specimen to seepage flow is characterised by an initial sequence where the fabric remains unchanged and a subsequent sequence of particle rearrangement: this response is termed suffosion. Comparison (see Table 5.3) of the specific discharge at the last stage of seepage flow $v = 0.114$ cm/s and $v_{R_e} = 0.027$ cm/s, indicates a transition to the inertial flow regime occurred. However, it is believed that the effects of suffosion have masked the anticipated decrease in hydraulic conductivity associated with the transition to the inertial flow regime. The differential pore water pressure at the onset of suffosion $\Delta u_{so} = 1.5$ kPa, is defined as the greatest differential pore water pressure at which the original specimen volume was maintained. The corresponding mean effective stress at the onset of suffosion is $p'_{so} = 56$ kPa (see Table 5.4).

The seepage flow in test 4.8GB35-100 yields an initially constant hydraulic conductivity $k_i = k_{max} = 0.018$ cm/s, followed by an approximately constant hydraulic conductivity $k_l = k_{min} = 0.017$ cm/s (see Table 5.3). Although the end-of-test specimen appears not depleted of a large portion of fines (see Fig. D.25), the seepage-induced incremental development of non-uniform volumetric deformations, accompanied by the incremental development of axial and volumetric deformations (see Fig. 4.6 and Table 5.4) is indicative of suffosion, with $\Delta u_{so} = 1.6$ kPa and $p'_{so} = 102$ kPa. It is postulated that the effects of suffosion have obscured the anticipated decrease in hydraulic conductivity, associated with the transition to the inertial flow regime (see Table 5.3).

The seepage flow in test 4.8GB35-150 yields an initially constant hydraulic conductivity $k_i = k_{max} = 0.017$ cm/s (see Table 5.3), followed by a decreasing hydraulic conductivity to $k_l = k_{min} = 0.013$ cm/s. It is postulated that the decrease in hydraulic conductivity was caused by the combined effects of contractive volume change (see Fig. 4.6) and a transition to the inertial flow regime (see Table 5.3). The small variation in finer fraction content in the post-test specimen, indicates that the extent of migration of fine particles was limited. The seepage-induced incremental development of non-uniform contractive volumetric deformation, although
in absence of substantial axial deformation (see Table 5.4), is termed suffosion, with $\Delta u_{so} = 2.8$ kPa and $p'_{so} = 150$ kPa.

### 5.3.5 Gradation 6.0GB20

The micro-structure of the specimens of tests 6.0GB20-50, 6.0GB20-100 and 6.0GB20-150 is type C-T, which exhibits non-load bearing fine particles and a potential for the rearrangement of coarse particles, (see Table 5.2 and Fig. 5.3), based on $S_f = 0.20$ and $e_c = 0.40$ to 0.45.

The seepage flow in test 6.0GB20-50 yields an initially constant hydraulic conductivity $k_i = k_{min} = 0.024$ cm/s (see Fig. 4.7, see Table 5.3), followed by an increase to $k_{max} = 0.027$ cm/s and subsequent decrease to $k_l = 0.025$ cm/s, which is attributed to the transition to the inertial flow regime at $v_{R_e=1} = 0.024$ cm/s. The increase in hydraulic conductivity and the absence of any substantial axial or volumetric deformation (see Table 5.4), are attributed to the migration of fine particles out of a stable, coarse-particle dominated micro-structure. The migration of fine particles is confirmed by the relatively low finer fraction content in the top layer of the specimen at the end of the test. The response to seepage flow is termed suffusion, with $\Delta u_{su} = 0.2$ kPa and $p'_{su} = 54$ kPa.

The seepage flow in test 6.0GB20-100 yields an initially constant hydraulic conductivity $k_i = k_{max} = 0.037$ cm/s (see Fig. 4.7 and Table 5.3), and a subsequently decreasing hydraulic conductivity to $k_l = k_{min} = 0.019$ cm/s, which is attributed to the transition to the inertial flow regime at $v_{R_e=1} = 0.024$ cm/s. The reduced finer fraction content in the top layer (see Fig. D.28), and the absence of progressive volumetric deformations (see Table 5.4), suggests a seepage-induced migration of fine particles out of a largely stable, coarse-particle dominated micro-structure. The effect of the isolated event of contractive volume change is speculated to have negated the effect of the migration of particles on the hydraulic conductivity. The response to seepage flow is termed suffusion. The conditions at the onset of particle migration are associated with the onset of contractive volume change at $\Delta u_{su} = 0.3$ kPa and $p'_{su} = 102$ kPa.

The seepage flow in test 6.0GB20-150 yields an initially slightly decreasing hydraulic conductivity from $k_i = 0.010$ cm/s to $k_{min} = 0.009$ cm/s (see Fig. 4.7 and Table 5.3), followed by a subsequently increasing hydraulic conductivity to $k_{max} = k_l = 0.017$ cm/s. Comparison of the specific discharge at the last stage of seepage flow $v = 0.067$ cm/s and $v_{R_e=1} = 0.024$ cm/s, indicates a transition to the inertial flow regime occurred. The increase in hydraulic conductivity and the absence of any substantial axial or volumetric deformation (see Table 5.4), suggest migration of fine particles out of a stable, coarse-particle dominated micro-structure. The migration of fine particles is confirmed by the reduced finer fraction content $S_f = 0.05$ in the top layer of the specimen at the end of the test (see Fig. D.29). The quintessential response
to seepage flow is suffusion. It is postulated that the anticipated decrease in hydraulic conductivity, associated with the transition to the inertial flow regime, was compensated by the effect of suffusion. The changes in hydraulic conductivity during the first stage of seepage flow, for which $\Delta u = 0.4$ kPa, suggest that particle migration occurred during this stage. Accordingly, this stage is considered an upper limit for the onset of suffusion, with $\Delta u_{su} = 0.4$ kPa and $p'_{su} = 151$ kPa.

5.3.6 Gradation 6.0GB25

The micro-structure of the specimens of tests 6.0GB25-50, 6.0GB25-100 and 6.0GB25-150 is type C-T, which exhibits non-load bearing fine particles and a potential for the rearrangement of coarse particles, (see Table 5.2 and Fig. 5.3), based on $S_f = 0.25$ and $e_c = 0.36$ to 0.38.

The seepage flow in test 6.0GB25-50 yields an initially constant hydraulic conductivity $k_i = 0.021$ cm/s (see Table 5.3), followed by a varying hydraulic conductivity between $k_{min} = 0.017$ cm/s and $k_i = k_{max} = 0.022$ cm/s. Comparison of the specific discharge at the last stage of seepage flow $v = 0.138$ cm/s and $v_{R_e=1} = 0.22$ cm/s, indicates a transition to the inertial flow regime occurred. The incremental development of non-uniform contractive volumetric deformation (see Fig. 4.8 and Table 5.4), accompanied by a contractive axial deformation, is attributed to the rearrangement of the particle packing of fine and coarse particles. The volumetric deformation is believed to have masked the transition to the inertial flow regime. The response to seepage flow is suffosion and the conditions at the onset of suffosion are $\Delta u_{so} = 0.7$ kPa and $p'_{so} = 53$ kPa.

The seepage flow in test 6.0GB25-100 yields an initial hydraulic conductivity $k_i = k_{max} = 0.026$ cm/s (see Fig. 4.8 and Table 5.3), which decreases to $k_{min} = k_i = 0.022$ cm/s. The small reduction in constant hydraulic conductivity is attributed to a transition from the Darcy flow regime to the inertial flow regime. The absence of any substantial volumetric or axial deformation (see Table 5.4), suggest no particle migration or rearrangement of the coarse-particle dominated micro-structure. The test was terminated at “pre-critical” condition.

The seepage flow in test 6.0GB25-150 yields an initially constant hydraulic conductivity $k_i = k_{max} = 0.032$ cm/s (see Table 5.3) and a subsequently smaller and varying hydraulic conductivity with $k_{min} = 0.014$ cm/s and $k_i = 0.015$ cm/s. During the sequence of varying hydraulic conductivity, the specific discharge exceeded $v_{R_e=1} = 0.22$ cm/s, which indicates a transition from the Darcy flow regime to the inertial flow regime. The incremental development of non-uniform contractive volumetric deformation, in absence of any axial deformation (see Fig. 4.8 and Table 5.4), is attributed to the rearrangement of the particle packing of fine and coarse particles, which is believed to have masked the transition to the inertial flow regime. Accordingly,
the response to seepage flow is suffosion, with $\Delta u_{so} = 1.4 \text{ kPa}$, and $p'_{so} = 150 \text{ kPa}$. Forensic evidence indicates that the coarse-particle rearrangement was accompanied by a migration of fine particles from the top half of the specimen (see Fig. D.30).

5.3.7 Gradation 6.0GB30

The micro-structure of the specimens of tests 6.0GB30-50, 6.0GB30-100 and 6.0GB30-150 is type T, which exhibits a potential for particle rearrangement, (see Table 5.2 and Fig. 5.3), based on $S_f = 0.30$ and $e_c = 0.34$ to 0.36.

The seepage flow in test 6.0GB30-50 yields an initially constant hydraulic conductivity $k_i = k_{min} = 0.008 \text{ cm/s}$ (see Table 5.3), and a subsequently varying hydraulic conductivity between $k_{max} = 0.013 \text{ cm/s}$ and $k_l = 0.012 \text{ cm/s}$. During the sequence of varying hydraulic conductivity, the specific discharge exceeded $v_{R_e=1} = 0.021 \text{ cm/s}$, which indicates a transition from the Darcy flow regime to the inertial flow regime. The development of non-uniform contractive volumetric and axial deformations (see Fig. 4.9 and Table 5.4) is attributed to the seepage-induced rearrangement of the particle packing. The substantial contractive deformations are believed to have masked the transition to the inertial flow regime. Accordingly, the response to seepage flow is suffosion with $\Delta u_{so} = 3.4 \text{ kPa}$ and $p'_{so} = 51 \text{ kPa}$.

The seepage flow in test 6.0GB30-100 yields an initial hydraulic conductivity $k_i = k_{max} = 0.017 \text{ cm/s}$ (see Table 5.3), which decreases sharply to $k_{min} = 0.006 \text{ cm/s}$, and subsequently varies to $k_l = 0.008 \text{ cm/s}$. The development of contractive volumetric and axial deformation (see Fig. 4.9 and Table 5.4) is attributed to the rearrangement of the particle packing of fine and coarse particles, and is held to have obscured the transition to the inertial flow regime (see Table 5.3). The response to seepage flow is suffosion, with $\Delta u_{so} = 3.7 \text{ kPa}$ and $p'_{so} = 100 \text{ kPa}$.

The response to seepage flow in test 6.0GB30-150 is very similar with $k_i = k_{max} = 0.009 \text{ cm/s}$, $k_{min} = 0.005 \text{ cm/s}$ and $k_l = 0.008 \text{ cm/s}$ (see Table 5.3). The presence of an abundance of fine particles on top of the specimen (see Fig. D.5) suggests the non-uniform contractive volumetric deformation (see Fig. 4.9 and Table 5.4), which is believed to have masked the transition to the internal flow regime (see Table 5.3), was accompanied by an upward migration of fine particles. The response to seepage flow is identified as suffosion with $\Delta u_{so} = 4.5 \text{ kPa}$ and $p'_{so} = 149 \text{ kPa}$.

5.3.8 Gradation 6.0GB35

The micro-structure of the specimens of tests 6.0GB35-50, 6.0GB35-100, 6.0GB35-100(R) and 6.0GB35-150 is type T, which exhibits a potential for particle rearrangement, (see Table 5.2 and Fig. 5.3), based on $S_f = 0.35$ and $e_c = 0.33$ to 0.37.
The seepage flow in test 6.0GB35-50 yields an initially constant hydraulic conductivity $k_i = k_{\text{max}} = 0.009 \text{ cm/s}$ (see Table 5.3), which subsequently decreases to $k_{\text{min}} = 0.005 \text{ cm/s}$, and increases to $k_l = 0.006 \text{ cm/s}$. During the sequence of varying hydraulic conductivity, the specific discharge exceeded $v_{R_c=1} = 0.021 \text{ cm/s}$, which indicates a transition from the Darcy flow regime to the inertial flow regime. The development of substantial non-uniform contractive volumetric deformation, accompanied by much smaller axial deformation (see Fig. 4.10 and Table 5.4), is attributed to a seepage-induced rearrangement of the particle packing, and is believed to have obscured the transition to the internal flow regime. The presence of an abundance of fine particles in the top of the specimen suggests that the rearrangement of the particle packing was accompanied by an upward migration of fine particles. The response to seepage flow is suffosion, with $\Delta u_{so} = 1.7 \text{ kPa}$ and $p'_{so} = 53 \text{ kPa}$.

The seepage flow in test 6.0GB35-100 yields an initially constant hydraulic conductivity $k_i = k_{\text{max}} = 0.014 \text{ cm/s}$ (see Table 5.3), which subsequently decreases to $k_{\text{min}} = k_l = 0.006 \text{ cm/s}$. The presence of an abundance of fines in the top of the specimen suggests that the development of non-uniform contractive volumetric and axial deformations (see Fig. 4.10 and Table 5.4), was accompanied by an upward migration of fine particles, and is held to have masked the anticipated transition from the Darcy to the inertial flow regime (see Table 5.3). Accordingly, the quintessential response to seepage flow is suffosion, with $\Delta u_{so} = 1.2 \text{ kPa}$ and $p'_{so} = 101 \text{ kPa}$.

The suffosive response in test 6.0GB35-100(2) is very similar to the response in test 6.0GB35-100 with $k_i = k_{\text{max}} = 0.016 \text{ cm/s}$ and $k_l = k_{\text{min}} = 0.006 \text{ cm/s}$ (see Table 5.3), accompanied by contractive volumetric and axial deformations (see Fig. 4.10 and Table 5.4), which are believed to have obscured the transition to the inertial flow regime. The conditions at the onset of suffosion are $\Delta u_{so} = 1.8 \text{ kPa}$ and $p'_{so} = 101 \text{ kPa}$. Forensic evidence indicates that the extent of the migration of fine particles was limited (see Fig. D.32).

The seepage flow in test 6.0GB35-150 yields an initially constant hydraulic conductivity $k_i = k_{\text{max}} = 0.010 \text{ cm/s}$ (see Table 5.3), which decreases to $k_{\text{min}} = 0.005 \text{ cm/s}$, and subsequently varies to $k_l = 0.007 \text{ cm/s}$. Comparison of the specific discharge at the last stage of seepage flow $v = 0.047 \text{ cm/s}$ and $v_{R_c=1} = 0.021 \text{ cm/s}$, indicates a transition to the inertial flow regime occurred. The development of non-uniform contractive volumetric deformation, in absence of axial deformations (see Fig. 4.10 and Table 5.4), which is believed to have masked the anticipated transition to the inertial flow regime (see Table 5.3), is attributed to the rearrangement of the particle packing. Accordingly, the response to seepage flow is identified as suffosion, with $\Delta u_{so} = 2.7 \text{ kPa}$ and $p'_{so} = 150 \text{ kPa}$. Forensic evidence indicates that the extent of the migration of fine particles was limited (see Fig. D.33).
5.3.9 Gradation 6.5GB25

The micro-structure of the specimens of test 6.5GB25-100 is type C-T, which exhibits non-load bearing fine particles and a potential for the rearrangement of coarse particles, (see Table 5.2 and Fig. 5.3), based on $S_f = 0.25$ and $e_c = 0.36$.

The seepage flow yields an initially slightly decreasing hydraulic conductivity from $k_i = 0.032$ cm/s to $k_{min} = 0.028$ cm/s (see Table 5.3). It is followed by a marked increase to $k_{max} = 0.045$ cm/s after which it decreases slightly to $k_l = 0.044$ cm/s. During the test, the specific discharge exceeded $v_{R_e=1} = 0.019$ cm/s (see Table 5.3), which indicates a transition from the Darcy flow regime to the inertial flow regime occurred. The development of non-uniform contractive volumetric deformation, in the absence of substantial axial deformations (see Fig. 4.3 and Table 5.4), is attributed to the rearrangement of the particle packing of fine and coarse particles, and is believed to have masked the transition to the inertial flow regime. Accordingly, the response to seepage flow is suffosion with $\Delta u_{so} = 1.1$ kPa and $p'_{so} = 101$ kPa.

5.3.10 Gradation 6.5GB35

The micro-structure of the specimens of tests 6.5GB35-50 and 6.5GB25-100 is type M-T, which exhibits a potential for particle rearrangement, (see Table 5.2 and Fig. 5.3), based on $S_f = 0.35$, $e_c = 0.30$ to 0.31 and $S_{f,LL} = 0.89$ to 0.90.

The seepage flow in test 6.5GB35-50 yields an initially constant hydraulic conductivity $k_i = 0.015$ cm/s (see Table 5.3), followed by a decrease to $k_{min} = 0.010$ cm/s and a marked increase to $k_{max} = k_l = 0.027$ cm/s at the end of the test. Comparison of the specific discharge at the last stage of seepage flow $v = 0.037$ cm/s and $v_{R_e=1} = 0.017$ cm/s, indicates a transition from the Darcy flow regime to the inertial flow regime occurred. The development of contractive volumetric deformation (see Fig. 4.11 and Table 5.4), accompanied by small axial deformations, is attributed to the rearrangement of the particle packing, and is believed to have masked the transition to the inertial flow regime. The presence of an abundance of fine particles in the top of the specimen (see Fig. D.34), suggests the rearrangement of the particle packing was accompanied by an upward migration of fine particles. Accordingly, the response to seepage flow is suffosion with the conditions at the onset of suffosion $\Delta u_{so} = 1.2$ kPa and $p'_{so} = 54$ kPa. The continuing deformations in the last stage are interpreted as an overall instability of the soil structure, associated with failure. More specifically, failure is defined as continuing deformation at a constant differential pore water pressure $\Delta u_f$. The differential pore water pressure and the mean effective stress at the onset of failure are $\Delta u_f = 1.4$ kPa and $p'_{f} = 53$ kPa, respectively.
The seepage flow in test 6.5GB35-100 yields an initial hydraulic conductivity $k_i = 0.016$ cm/s (see Table 5.3) which decreased slightly to $k_{\text{min}} = 0.014$ cm/s. It is followed by a marked increase to $k_{\text{max}} = k_t = 0.020$ cm/s. The development of non-uniform contractive volumetric deformation (see Fig. 4.11 and Table 5.4), in absence of substantial axial deformations, is attributed to the rearrangement of the particle packing, which is believed to have masked the anticipated transition (see Table 5.3) to the inertial flow regime. The presence of an abundance of fine particles in the top of the specimen (see Fig. D.35), suggests the rearrangement of the particle packing was accompanied by an upward migration of fine particles. Accordingly, the response to seepage flow is suffosion with $\Delta u_{so} = 0.8$ kPa and $p_{so}' = 100$ kPa. Failure was reached in the last stage multi-stage seepage flow, at $\Delta u_f = 1.6$ kPa and $p_f' = 97$ kPa.

5.4 Analysis of tests on soils

The 16 tests on ten gradations of soils are analysed with respect to the assigned micro-structure type, the seepage flow, and any deformation of the test specimen. Soil tests that exhibited a quintessential response to seepage flow are accentuated herein, and summarised in Section 5.5.

5.4.1 Gradation 5.1BT20

The micro-structure of the specimens in tests 5.1BT20-50 and 5.1BT20-150 is type C-T, which exhibits non-load bearing fine particles and a potential for the rearrangement of coarse particles, (see Table 5.5 and Fig. 5.5), based on $S_f = 0.20$ and $e_c = 0.63$ to 0.65.

The seepage flow in test 5.1BT20-50 yields an initially constant hydraulic conductivity $k_i = 0.016$ cm/s (see Table 5.6), followed by an increase in hydraulic conductivity to $k_{\text{max}} = 0.025$ cm/s. The subsequent decrease to $k_t = k_{\text{min}} = 0.013$ cm/s is attributed to the transition to the inertial flow regime at $v_{Re-1} = 0.038$ cm/s. The increase in hydraulic conductivity and absence of any substantial axial or volumetric deformation (see Fig. 4.12 and Table 5.7), is attributed to migration of fine particles out of a stable, coarse-particle dominated micro-structure. The variation of $S_f = 0.19$ to 0.25 across the end-of-test specimen (see Fig. D.36) indicates that the extent of particle migration was relatively small. The response to seepage flow is indicative of a suffusive response. The conditions at the onset of suffusion are $\Delta u_{su} = 0.3$ kPa and $p_{su}' = 53$ kPa.

The response to seepage flow in test 5.1BT20-150 was very similar with $k_i = 0.036$ cm/s (see Table 5.6), $k_{\text{max}} = 0.040$ cm/s and $k_t = k_{\text{min}} = 0.023$ cm/s, in the absence of any substantial axial or volumetric deformations (see Fig. 4.12 and Table 5.7). Forensic observations yielded a top layer of the end-of-test specimen that was depleted of fine particles (see Fig. D.37), which confirms the migration of fine particles. The response is also termed suffusion, with $\Delta u_{su} = 0.3$ kPa and $p_{su}' = 152$ kPa.
5.4.2 Gradation 5.7BT20

The micro-structure of the specimens in tests 5.7BT20-50, 5.7BT20-100 and 5.1BT20-150 is type C-T, which exhibits non-load bearing fine particles and a potential for the rearrangement of coarse particles, (see Table 5.5 and Fig. 5.5), based on $S_f = 0.20$ and $e_c = 0.56$ to 0.59.

The seepage flow in test 5.7BT20-50 yields an initially constant hydraulic conductivity $k_i = 0.030$ cm/s (see Table 5.6), followed by an increase to $k_{max} = 0.042$ cm/s. The subsequent decrease to $k_l = k_{min} = 0.027$ cm/s is attributed to the transition to the inertial flow regime at $v_{R_i=1} = 0.030$ cm/s. The increase in hydraulic conductivity, and the absence of any substantial axial or volumetric deformation (see Fig. 4.13 and Table 5.7), is attributed to the migration of fine particles out of a stable, coarse-particle dominated micro-structure. Forensic observations (see Fig. D.38) confirm the migration of fine particles from the top layer of the specimen. Accordingly, the response to seepage flow is suffusion, with $\Delta u_{su} = 0.3$ kPa and $p'_{su} = 54$ kPa.

The responses to seepage flow in tests 5.7BT20-100 and 5.7BT20-150 are very similar with $k_i = 0.027$ cm/s, $k_{max} = 0.035$ cm/s, $k_l = k_{min} = 0.027$ cm/s in tests 5.7BT20-100 (see Fig. 4.12 and Table 5.6) and $k_i = 0.025$ cm/s, $k_{max} = 0.030$ cm/s, $k_l = k_{min} = 0.024$ cm/s in test 5.7BT20-150. In both tests, the migration of fine particles is inferred from the sequence of an increasing hydraulic conductivity, in the absence of any substantial axial or volumetric deformation. A forensic observation (see Fig. D.39) confirmed the migration of a substantial portion of fine particles from the top of the specimen in test 5.7BT20-100. The variation of finer fraction content $S_f = 0.18$ to 0.23 in the end-of-test specimen 5.7BT20-150, indicates that the extend of the migration of fine particles was limited in this test (see Fig. D.39). In both tests, the response is suffusion. The conditions at the onset of suffusion were $\Delta u_{su} = 0.2$ kPa and $p'_{su} = 102$ kPa in tests 5.7BT20-100, and $\Delta u_{su} = 0.2$ kPa and $p'_{su} = 154$ kPa in test tests 5.7BT20-150 (see Table 5.7).

5.4.3 Gradation 5.7BT35

The micro-structure of the specimen in test 5.7BT35-100 is type T, which exhibits a potential for particle rearrangement, (see Table 5.5 and Fig. 5.5), based on $S_f = 0.35$ and $e_c = 0.46$.

The seepage flow yields a constant hydraulic conductivity $k_i = k_l = 0.013$ cm/s (see Fig. 4.14 and Table 5.6), in the absence of substantial axial or volumetric deformation (see Table 5.7). Comparison of the specific discharge at the last stage of seepage flow $v = 0.114$ cm/s and $v_{R_i=1} = 0.026$ cm/s, suggests a transition from the Darcy flow regime to the inertial flow regime occurred. However, in contrast to several other tests, the anticipated decreasing hydraulic conductivity associated with a transition to the inertial flow regime (see Table 5.6), is not detected in the response to seepage flow. A speculative explanation is that a limited suffusive response
occurred, but that the effect on the hydraulic conductivity was compensated by the transition to the inertial flow regime. Considering that the variation at the end of the test of \( S_f = 0.32 \) to \( S_f = 0.38 \) in the specimen (see Fig. D.41) falls with the range of \( S_f = 0.35 \pm 0.03 \) with which a specimen can be reconstituted (see Section 3.3.1), no conclusive evidence is available to firmly establish the migration of fine particles. The constant hydraulic conductivity and absence of any progressive substantial volume change or change in length, suggest no significant particle rearrangement or, as previously noted, no substantial mass loss within the specimen. The test is deemed to have been terminated at a “pre-critical” condition.

5.4.4 Gradation 7.0BT20

The micro-structure of the specimens in tests 7.0BT20-50 and 7.0BT20-150 is type C-T, which exhibits non-load bearing fine particles and a potential for the rearrangement of coarse particles, (see Table 5.5 and Fig. 5.5), based on \( S_f = 0.20 \) and \( e_c = 0.53 \) to 0.55.

The seepage flow in test 7.0BT20-50 yields an initially constant hydraulic conductivity \( k_i = 0.065 \text{ cm/s} \) (see Fig. 4.15 and Table 5.6), followed by an increase in hydraulic conductivity to \( k_{max} = 0.073 \text{ cm/s} \). The subsequent decrease to \( k_i = k_{min} = 0.049 \text{ cm/s} \) is attributed to the transition to the inertial flow regime at \( v_{R_e=1} = 0.024 \text{ cm/s} \). The increase in hydraulic conductivity, and the absence of any substantial axial or volumetric deformation (see Table 5.7), is attributed to migration of fine particles out of a stable, coarse-particle dominated micro-structure. The variation of finer fraction content \( S_f = 0.18 \) to 0.22 in the end-of-test specimen, indicates that the extend of the migration of fine particles was limited (see Fig. D.42). The response to seepage flow is suffusion, with \( \Delta u_{su} = 0.2 \text{ kPa} \) and \( p'_{su} = 56 \text{ kPa} \).

The response to seepage flow in test 7.0BT20-150 was qualitatively very similar (see Fig. 4.15) with \( k_i = k_{min} = 0.037 \text{ cm/s} \), \( k_{max} = 0.044 \text{ cm/s} \), \( k_{l} = 0.038 \text{ cm/s} \) (see Table 5.6), in the absence of any substantial volume change. A forensic observation (see Fig. D.43) confirmed the migration of a substantial portion of fine particles from the top of the specimen. The response is suffusion, with \( \Delta u_{su} = 0.3 \text{ kPa} \) and \( p'_{su} = 153 \text{ kPa} \) (see Table 5.7).

5.4.5 Gradation 7.0BT35

The micro-structure of the specimen in test 7.0BT35-50 is type T, which exhibits a potential for particle rearrangement, (see Table 5.5 and Fig. 5.5), based on \( S_f = 0.35 \) and \( e_c = 0.42 \).

The initially constant hydraulic conductivity \( k_i = k_{max} = 0.012 \text{ cm/s} \) (see Fig. 4.16 and Table 5.6), and subsequent slight decrease to \( k_{min} = 0.011 \text{ cm/s} \), which is attributed to the transition from a Darcy to the inertial flow regime at \( v_{R_e=1} = 0.021 \text{ cm/s} \), and the absence of any substantial axial or volumetric deformation (see Table 5.7), suggest no particle rearrangement.
or mass loss within the specimen. This quintessential test is deemed to have been terminated at a “pre-critical” condition.

5.4.6 Gradation 8.6BT20

The micro-structure of the specimen in test 8.6BT20-50 is type C-T, which exhibits non-load bearing fine particles and a potential for the rearrangement of coarse particles, (see Table 5.5 and Fig. 5.5), based on $S_f = 0.20$ and $e_c = 0.51$.

The seepage flow yields an initially constant hydraulic conductivity $k_i = 0.017$ cm/s (see Fig. 4.17 and Table 5.6), followed by an increase in hydraulic conductivity to $k_{max} = 0.024$ cm/s. The subsequent decrease to $k_l = k_{min} = 0.016$ cm/s is attributed to the transition to the inertial flow regime at $v_{R_e} = 0.019$ cm/s. The increase in hydraulic conductivity, and the absence of any substantial axial or volumetric deformation (see Table 5.7), is attributed to migration of fine particles out of a stable, coarse-particle dominated micro-structure. A forensic observation (see Fig. D.44) confirmed the migration of a substantial portion of fine particles from the top of the specimen. The quintessential response to seepage flow is suffusion, with $\Delta u_{su} = 0.4$ kPa and $p'_{su} = 53$ kPa.

5.4.7 Gradation 8.6BT35

The micro-structure of the specimen in test 8.6BT35-50 is type T, which exhibits a potential for particle rearrangement, (see Table 5.5 and Fig. 5.5), based on $S_f = 0.35$ and $e_c = 0.46$.

The seepage flow in test 8.6BT35-50 yields an initially constant hydraulic conductivity $k_i = 0.008$ cm/s (see Fig. 4.18 and Table 5.6), followed by an increase in hydraulic conductivity to $k_l = k_{max} = 0.009$ cm/s. The increase in hydraulic conductivity and the absence of any substantial axial or volumetric deformation (see Table 5.7), is attributed to migration of fine particles out of a stable, coarse-particle dominated micro-structure. Accordingly, the response to seepage flow is suffusion, with $\Delta u_{su} = 5.3$ kPa and $p'_{su} = 52$ kPa. It is postulated that the anticipated decreasing hydraulic conductivity, associated with the transition to the inertial flow regime (see Table 5.6), was masked by the effects of suffusion.

5.4.8 Gradation 10.4BT25

The micro-structure of the specimen in test 10.4BT25-50 is type C-T, which exhibits non-load bearing fine particles and a potential for the rearrangement of coarse particles, (see Table 5.5 and Fig. 5.5), based on $S_f = 0.25$ and $e_c = 0.44$.

The seepage flow in test 10.4BT25-50 yields an initially constant hydraulic conductivity $k_i$
= 0.019 cm/s (see Table 5.6), followed by an increase in hydraulic conductivity to $k_{\text{max}} = 0.034$ cm/s and a marked decrease, which was then followed by a varying hydraulic conductivity to $k_l = k_{\text{min}} = 0.013$. The initial increase in hydraulic conductivity at a small differential pore water pressure and the absence of any substantial axial or volumetric deformation (see Fig. 4.19) is attributed to migration of fine particles out of a stable, coarse-particle dominated micro-structure. The subsequent decrease of hydraulic conductivity is accompanied by an isolated event of contractive volumetric deformation (Table 5.7), which is attributed to a small rearrangement of a largely stable coarse particle dominated micro-structure, similar to the isolated event of volumetric strain development in tests 4.8GB20-100 and 4.8GB20-150. It is postulated that the anticipated decreasing hydraulic conductivity, associated with the transition to the inertial flow regime (see Table 5.6), was masked by the effects of the isolated contractive volume change. Forensic observations indicated that a limited portion of fine particles had migrated from the top half of the specimen (see Figs. D.12, D.13, and D.45). The quintessential response to seepage flow is suffusion, with $\Delta u_{\text{su}} = 0.4$ kPa and $p'_{\text{su}} = 53$ kPa.

5.4.9 Gradation 10.4BT30

The micro-structure of the specimen in test 10.4BT30-50 is type C-T, which exhibits non-load bearing fine particles and a potential for the rearrangement of coarse particles, (see Table 5.5 and Fig. 5.5), based on $S_f = 0.30$ and $e_c = 0.41$.

The seepage flow in test 10.4BT30-50 yields an initially constant hydraulic conductivity $k_i = k_{\text{min}} = 0.012$ cm/s (see Fig. 4.20 and Table 5.6), followed by an increase in hydraulic conductivity to $k_{\text{max}} = 0.021$ cm/s, and a subsequent decrease to $k_l = 0.017$ cm/s, which is attributed to a transition to the inertial flow regime. The increase in hydraulic conductivity, and the absence of any progressive axial or volumetric deformation (see Table 5.7), is attributed to migration of fine particles out of a stable, coarse-particle dominated micro-structure. The variation of finer fraction content $S_f = 0.27$ to 0.32 in the end-of-test specimen 5.7BT20-150 indicates that the extend of the migration of fine particles was limited (see Fig. D.46). The response to seepage flow is suffusion, with $\Delta u_{\text{su}} = 2.0$ kPa and $p'_{\text{su}} = 52$ kPa.

5.4.10 Gradation 10.4BT35

The micro-structure of the specimens in tests 10.4BT35-50, 10.4BT35-50(R) and 10.4BT35-100 is type M-T, which exhibits a potential for particle rearrangement, (see Table 5.5 and Fig. 5.5), based on $S_f = 0.35$ and $e_c = 0.36$ to 0.38 and $S_{f,L} = 0.82$.

The seepage flow in test 10.4BT35-50 yields an initially constant hydraulic conductivity $k_i = 0.011$ cm/s (see Table 5.6), followed by a varying hydraulic conductivity, between $k_{\text{min}} = 0.009$ cm/s and $k_{\text{max}} = 0.023$ cm/s, to $k_l = 0.013$ cm/s. The specific discharge exceeds $v_{R_e} = 1$.
during the test, which indicates a transition from the Darcy flow regime to the inertial flow regime occurred. The seepage-induced incremental development of non-uniform contractive volumetric deformation (see Fig. 4.21 and Table 5.4), in the absence of substantial axial deformation is attributed to the rearrangement of the particle packing and is believed to have masked the transition to the inertial flow regime. Visual observations established that the rearrangement of the particle packing was accompanied by migration of fine particles out of the specimen (see Fig. D.17). Accordingly, the response to seepage flow is suffosion with $\Delta u_{so} = 1.8$ kPa and $p'_{so} = 54$ kPa.

The response to seepage flow (see Table 5.6) in tests 10.4BT35-50(R) and 10.4BT35-100 is very similar with $k_i = 0.013$ cm/s, $k_{\text{max}} = 0.051$ cm/s, $k_{\text{min}} = 0.013$ cm/s, $k_l = 0.022$ cm/s in test 10.4BT35-50(R), and $k_i = 0.013$ cm/s, $k_{\text{max}} = 0.035$ cm/s, $k_{\text{min}} = 0.009$ cm/s, $k_l = 0.014$ cm/s in test 10.4BT35-100. The seepage-induced incremental development of non-uniform contractive volumetric deformation (see Fig. 4.21 and Table 5.4), in the absence of substantial axial deformation is attributed to the rearrangement of the particle packing. Forensic observations in both tests established that the particle rearrangement was accompanied by a migration of fine particles from the bottom to the top of the specimen (see Figs. D.47 and D.48). The response is suffosion. The conditions at the onset of suffosion are $\Delta u_{so} = 0.8$ kPa and $p'_{so} = 57$ kPa in test 10.4BT35-50(R), and $\Delta u_{so} = 1.1$ kPa and $p'_{so} = 102$ kPa, in the quintessential soil test 10.4BT35-100, respectively.

### 5.5 Synthesis

The results of 25 tests on ten glass beads gradations, including the commissioning tests, and 16 tests on ten soil gradations have been analysed. The analysis of the test results considered evidence on: 1) the potential for particle migration and particle rearrangement, based on a well defined micro-structure identification diagram; 2) the variation of the hydraulic conductivity; 3) axial and volumetric strains; 4) any mass loss inferred from the variation of hydraulic conductivity, in conjunction with the variation of element volume; and, for some but not all tests, 5) forensic observations and measurements of mass loss.

A micro-structure identification diagram (Thevanayagam et al., 2002), with explicit definitions of all boundaries, has been constructed for gap-graded gradations of glass beads and soils, based on considerations of the experimental limits of stable particle packing arrangements of the fine fraction and coarse fraction. Gap-graded materials can exhibit one of five different types of micro-structure: clast-supported type C; transitional clast-supported type C-T; transitional type T; transitional matrix-supported type M-T, and matrix supported type M. The ability to distinguish between type C and type C-T micro-structures, and between type M and type M-T micro-structures yields a key improvement of the micro-structure identification diagram,
because of the distinction between micro-structures that exhibit potential for particle rearrange-
ment and micro-structures that do not exhibit this potential. The potential for seepage-induced
internal instability is examined for each micro-structure type: it is inferred that type C and C-T
micro-structures exhibit a substantial portion of non-load bearing fine particles, whereas a po-
tential for particle rearrangement was established in type C-T, M-T and T micro-structures, but
not type C or M micro-structures.

Analysis of the test result leads to one of two evidence-based phenomenological responses.
A suffusive response was characterised by an initially constant hydraulic conductivity, in ab-
sence of axial and volumetric deformation, and a subsequent increases in hydraulic conductivity
at differential pore water pressures greater than a threshold value $\Delta u_{su}$, which is either accom-
panied by negligible or very small axial and volumetric strains, or else it is accompanied by
a non-progressive development of small axial or volumetric strains. A suffusive response as-
associated with negligible or very small strains, which is in agreement with the strict definition
established from a review of the literature (see Section 2.1.3), was established in four tests on
two glass beads gradations and in ten tests on six soil gradations: glass beads test 6.0GB20-150
and soil test 8.6BT20-50 are typical examples of this response. The somewhat broader defini-
tion of suffusion associated with the non-progressive development of small axial or volumetric
strains, was invoked to characterise the response in three tests on two glass beads gradations
and in one test on a soil gradation: glass beads test 4.8GB20-100 and soil test 10.4BT25-50 are
typical examples of this response. The need to extend the definition of suffuision will be
discussed in Section 6.2.1. A type C-T micro-structure was identified in 17 of 18 soil and glass
beads specimens that exhibited a suffusive response; a type T micro-structure was identified in
one soil specimen.

A suffosive response was characterised by a sequence of an initially constant hydraulic con-
ductivity, in absence of axial and volumetric deformation, and a subsequent varying hydraulic
conductivity at differential pore water pressures greater than a threshold value $\Delta u_{su}$, accom-
panied by the progressive development of non-uniform contractive volumetric deformation.
Forensic evidence in a four glass beads tests and three soil tests, suggests that the rearrange-
ment of the coarse particle packing was accompanied by a downstream migration of fine parti-
cles. A suffosive response was established in 15 tests on six gradations of glass beads and three
tests on one gradation of soils, which yielded type C-T, type T or type M-T micro-structures.
Glass beads test 6.0GB35-100 and soil test 10.4BT35-100 are typical examples of a suffosive
response. In two tests that exhibited a suffosive response, on gradation 6.5GB35 with a type
M-T micro-structure, failure, defined as continuing deformations at a constant differential pore
water pressure $\Delta u_f$, was reached.
In addition, a “pre-critical” condition, characterised by a constant hydraulic conductivity in the absence of axial and volumetric deformation, was established in three tests on three gradations of glass beads and in two tests on two gradations of soils. Glass beads test 3.3GB20-50 and soil test 7.0BT35-50 are typical examples of a test terminated at a “pre-critical” condition. It is postulated that a “pre-critical” condition is a precursor to suffusion, suffosion or fluidisation.
Table 5.1: Reference points in the micro-structure identification diagram for glass beads and soil gradations.

<table>
<thead>
<tr>
<th>Reference point</th>
<th>Glass beads</th>
<th>Soils</th>
</tr>
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<tbody>
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<td>$S_f$</td>
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<tr>
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</tr>
<tr>
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<td>0.27</td>
</tr>
<tr>
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*Note:*  
\(^1\) For gradations with $D'd' = 6.7$, for a gradation specific value of $S_{f,L}$, use Eq. 2.5.
Table 5.2: Micro-structure: glass beads test specimens.

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<th>$e_f^4$</th>
<th>$S_{LL}^5$</th>
<th>Micro-structure$^6$</th>
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Notes:
1. From Table 3.2.
2. From Table 4.1.
3. Using Eq. 2.2
4. Using Eq. 2.3
5. Determined only to distinguish between type M and type M-T, using Eq. 2.5
6. See also Fig. 5.3
**Table 5.3:** Seepage regime: tests on glass beads gradations.

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<th>Test code</th>
<th>$k_i^1$ (cm/s)</th>
<th>$k_{min}$ (cm/s)</th>
<th>$k_{max}$ (cm/s)</th>
<th>$k_l^2$ (cm/s)</th>
<th>$v^3$ (cm/s)</th>
<th>$v_{R_e=1}$ (cm/s)</th>
<th>Seepage regime$^5$</th>
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**Notes:**

1. Initial hydraulic conductivity $k_i$.
2. Hydraulic conductivity at the last stage of seepage flow $k_l$.
3. Specific discharge at the last stage of seepage flow, from Table 4.2.
4. Using Eq. 2.12 with $L_s = D_{50}$.
5. I = Darcy flow regime; II = Inertial flow regime.
Table 5.4: Responses: tests on glass beads gradations.

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Notes:
1 Calculated using Table 5.3;
2 End-of-test axial strain, from Table 4.2;
3 End-of-test volumetric strain, from Table 4.2;
4 Mass loss inferred from analysis of seepage regime and deformations y = yes, n = no, o = inconclusive;
5 Mass loss established through forensic observations;
6 PC = Pre-critical condition; SU = Suffusion; SO = Suffosion; SO-F = Suffusion and Failure.
Table 5.5: Micro-structure: soil test specimens.

<table>
<thead>
<tr>
<th>Test code</th>
<th>$S_f$</th>
<th>$e_c^2$</th>
<th>$e_s^3$</th>
<th>$e_f^4$</th>
<th>$S_{fL}^5$</th>
<th>Micro-structure</th>
<th>Type$^6$</th>
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<td>1.06</td>
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<td>C-T</td>
<td></td>
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</tr>
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</tr>
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<td>C-T</td>
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<td>-</td>
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<td>0.46</td>
<td>1.25</td>
<td>1.31</td>
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<td>C-T</td>
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</tr>
<tr>
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<td>0.82</td>
<td>M-T</td>
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</tr>
</tbody>
</table>

Notes:
1 From Table 3.2
2 From Table 4.3
3 Using Eq. 2.2
4 Using Eq. 2.3
5 Determined only to distinguish between type M and type M-T, using Eq. 2.5
6 See also Fig. 5.5
Table 5.6: Seepage regime: tests on soil gradations.

<table>
<thead>
<tr>
<th>Test code</th>
<th>$k_i$ 1 (cm/s)</th>
<th>$k_{min}$ (cm/s)</th>
<th>$k_{max}$ (cm/s)</th>
<th>$k_i$ 2 (cm/s)</th>
<th>$v^3$ (cm/s)</th>
<th>$v_{R_e=1}$ 4 regime 5</th>
<th>Seepage</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.013</td>
<td>0.025</td>
<td>0.013</td>
<td>0.224</td>
<td>0.038</td>
<td>I-II</td>
</tr>
<tr>
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<td>0.036</td>
<td>0.023</td>
<td>0.040</td>
<td>0.023</td>
<td>0.141</td>
<td>0.038</td>
<td>I-II</td>
</tr>
<tr>
<td>5.7BT20-50</td>
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<td>0.027</td>
<td>0.042</td>
<td>0.027</td>
<td>0.147</td>
<td>0.030</td>
<td>I-II</td>
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<tr>
<td>5.7BT20-100</td>
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<td>0.027</td>
<td>0.035</td>
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<td>0.030</td>
<td>0.024</td>
<td>0.141</td>
<td>0.030</td>
<td>I-II</td>
</tr>
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<td>0.038</td>
<td>0.158</td>
<td>0.024</td>
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</tr>
<tr>
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<td>0.011</td>
<td>0.012</td>
<td>0.011</td>
<td>0.104</td>
<td>0.021</td>
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<td>0.016</td>
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<td>0.008</td>
<td>0.009</td>
<td>0.009</td>
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<td>0.013</td>
<td>0.051</td>
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<td>0.014</td>
<td>0.118</td>
<td>0.013</td>
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</tr>
</tbody>
</table>

Notes:
1 Initial hydraulic conductivity $k_i$.
2 Hydraulic conductivity at the last stage of seepage flow $k_l$.
3 Specific discharge at the last stage of seepage flow, from Table 4.4.
4 Using Eq. 2.12 with $L_x = D'_{50}$.
5 I = Darcy flow regime; II = Inertial flow regime.
Table 5.7: Responses: tests on soil gradations.

<table>
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<th>Test code</th>
<th>$k_{\text{min}} / k_{i}^1$ (-)</th>
<th>$k_{\text{max}} / k_{i}^1$ (-)</th>
<th>$\varepsilon_a^2$ (%)</th>
<th>$\varepsilon_v^3$ (%)</th>
<th>$\Delta m_{\text{inf}}$ $^4$</th>
<th>$\Delta m_{\text{obs}}$ $^5$</th>
<th>Phenomenon $^6$</th>
<th>$\Delta t_{\text{su}}$ (kPa)</th>
<th>$\Delta t_{\text{so}}$ (kPa)</th>
<th>$p_{\text{su}}^\prime$ (kPa)</th>
<th>$p_{\text{so}}^\prime$ (kPa)</th>
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<td>0.10</td>
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<td>o</td>
<td>SU</td>
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<td>-</td>
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<td>-</td>
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<td>y</td>
<td>SU</td>
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<td>y</td>
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Notes:

1 Calculated using Table 5.6; 2 End-of-test axial strain, from Table 4.4; 3 End-of-test volumetric strain, from Table 4.4; 4 Mass loss inferred from analysis of seepage regime and deformations $y = \text{yes}, n = \text{no}, o = \text{inconclusive};$ 5 Mass loss established through forensic observations; 6 PC = Pre-critical condition; SU = Suffusion; SO = Suffosion; SO-F = Suffusion and Failure.
Figure 5.1: Micro-structure identification diagram for glass beads.

![Diagram showing micro-structures](image)

Figure 5.2: Micro-structure types.
Figure 5.3: Identification of initial micro-structure of glass beads test specimens: a) overview; b) detail.

Figure 5.4: Micro-structure identification diagram for soils.
Figure 5.5: Identification of initial micro-structure of soil test specimens: a) overview; b) detail.
Chapter 6

Factors governing suffusion and suffosion

In the previous Chapter suffusion was identified in seven tests on two glass beads gradations and in eleven tests on seven soil gradations, whereas suffosion was identified in 15 tests on six glass beads gradations and in three tests on one soil gradation. In addition, a “pre-critical” end-of-test condition, which is postulated to be a precursor to suffusion, suffosion or fluidisation, was reached in three tests on three glass beads gradations and in two tests on two soil gradations.

In this Chapter, the factors governing suffusion and suffosion are examined by means of comparison of select sets of tests from this study, which exhibit variation in only one of the independent variables of finer fraction content, gap ratio, particle shape, mean effective stress, and differential pore water pressure across the specimen. A reader guide to this Chapter is presented in Fig. 6.1 The findings are compared to a limited body of evidence found in the literature, for which an experimental database is compiled in Section 6.1 The discussion of the factors governing suffusion and suffosion is guided by the four research hypotheses introduced in Section 1.1. Hypotheses Nos. 1 to 3 are first examined based on the tests on glass beads of this study that exhibited suffusion or suffosion, which includes one commissioning test, supplemented by select tests found in the literature. Hypothesis No. 1, which seeks to establish the suitability of the volume change to distinguish between suffusion and suffosion, is then tested in Section 6.2 Section 6.3 addresses the dependence of the onset of suffosion on effective stress (hypothesis No. 2). Hypothesis No. 3, which was proposed to investigate the relation between the soil micro-structure and seepage-induced internal instability, is tested in Section 6.4. The influence of the particle shape on seepage-induced internal instability (hypothesis No. 4) is examined in Section 6.5 by the explicit comparison of select tests on glass beads and soils, for which the particle shape is the only independent variable. The factors governing suffusion and suffosion, identified in the evaluation of hypotheses Nos. 1 to 3 based on tests on glass
beads, are then further examined in Section 6.6 based on the tests on soils of this study and supplemented by select tests on soils found in the literature. Finally, a unified approach for the characterisation of suffosion, and a summary of the factors governing suffusion and suffosion are presented in Sections 6.7, and 6.8, respectively.

6.1 Compilation of experimental database on suffusion and suffosion

In addition to the glass beads and soil tests of this study, a database of gap-graded materials, reported in the literature, that exhibited a suffusive or suffosive response to seepage flow is compiled (see Table 6.1), based on the following criteria:

- The gap-graded media are of sand and gravel size (either glass beads or soil).
- The test results that are reported include values of effective stress, hydraulic conductivity, volume change and, preferably, include information on mass loss.

Herein, important features of the test method, the materials and the response to seepage flow are presented for each study. Details of the tests are presented in the discussion, if necessary. Select tests of the studies of Moffat (2005), Li (2008), Sail et al. (2011), and Crawford-Flett (2014), who all prepared specimens using the modified slurry deposition technique, and select tests of studies of Skempton and Brogan (1994) and Chang and Zhang (2013), who used a moist tamping technique, are included in the database (see Fig. 6.2).

Crawford-Flett (2014) identified the phenomenological response to upward seepage flow of four tests on a glass beads gradation 6.6GB22, tested in a rigid wall permeameter, as suffusion. Using the same rigid wall permeameter, Li (2008) reported the response of five tests on a glass beads gradation FR7, subject to upward or downward flow, and four tests on a glass beads gradation FR8, subject to downward flow. All tests exhibited suffosion. Sail et al. (2011) subjected a glass beads gradation G4-C to downward seepage flow in a rigid wall permeameter. The response was identified as suffosion. Skempton and Brogan (1994) reported a suffusive response on their soil gradation A, tested in a rigid wall permeameter. Chang and Zhang (2013), using a flexible wall permeameter, reported a suffusive response for four downward flow seepage tests on a soil gradation GS, isotropically consolidated to varying values of mean effective stress; the results of 18 seepage tests on the same soil gradation GS, anisotropically consolidated to varying values of mean effective stress and deviatoric stress, exhibited suffosion. Moffat (2005), using a rigid wall permeameter, conducted three tests on a soil gradation T-0 subject to upward seepage flow, and five tests on a soil gradation T-5 subject to upward or downward seepage flow; all tests on gradations T-0 and T-5 exhibited a suffusive response.

1The studies of the author, Moffat (2005), Li (2008) and Crawford-Flett (2014) have all been conducted at the University of British Columbia.
6.2 Test of hypothesis No. 1

The first hypothesis was proposed as follows: *Volume change is a characteristic variable of seepage-induced internal instability and serves to distinguish between suffusion and suffosion.*

The hypothesis is first examined based on the glass beads tests of this study in Section 6.2.1. The findings are subsequently compared to select tests reported in the literature in Section 6.2.2.

6.2.1 Glass beads tests of this study

In this study, the response to seepage flow in seven tests on two gradations of glass beads was identified as suffusion (see Table 5.4). In Section 5.3, a suffusive response was characterised by an initial sequence of no volumetric strain and a constant hydraulic conductivity, and a subsequent sequence of an increasing hydraulic conductivity accompanied by either: (i) a negligible or very small volume change; or, (ii) an isolated event of a small volumetric deformation to end-of-test values of $\varepsilon_v = 0.48$ to $0.82$ % (see Table 5.4), which did not progress in subsequent stages of seepage flow. The former is in agreement with the definition of suffusion established from a review of the literature (see Section 2.1.3). Considering the latter, it is speculated that, given the variation of finer fraction content of $S_f = +/- 0.03$ and $+/ - 0.08$ across five layers of the trial specimens 4.8GB20 (see Fig. 3.25) and 6.0GB20 (see Figs. 3.28 and 3.29), respectively, in a few zones, locally unstable particle packings are formed during reconstitution of specimens with $S_f = 0.20$. These small zones of unstable particle packings may, with the slightest disturbance, of for example, a small hydraulic load, rearrange to a stable packing. The absence of progressive volume change is then explained by the predominant presence of a stable particle packing throughout the specimen and the limited spatial extend of zones of locally unstable packings. The predominant response in such specimens is one of local migration of fine particles, largely in the absence of volume change. In light of this discussion on the practical limitations of the reconstitution of homogeneous specimens of glass beads, it seems prudent to broaden the strict definition of suffusion, as established from the literature review, to “suffusion is characterised as seepage-induced mass loss, without change in volume, or with a small non-progressive change in volume, accompanied by an increase of hydraulic conductivity.”

In addition to suffusion, a suffosive response was identified in 15 tests on six different gradations of glass beads. A suffosive response was characterised by an initial sequence of no volumetric strain, and a subsequent sequence of a progressive development of substantial volumetric strain (see for example test 6.0GB35-100 in Fig. 4.10c), to end-of-test values ranging from $\varepsilon_v = 0.78$ to $2.46$ % (see Table 5.4). This characterisation is in agreement with the definition of suffosion established from a review of the literature (see Section 2.1.3). Visual observations established that the progressive, seepage-induced contractive volume change associated with suffosion did not occur equally throughout the specimen (see Appendix D.1), but was rather of a local nature. It is speculated that the entire specimen yields a potential for
particle rearrangement, but that small spatial variations in the particle packing cause the spatial variation in the volumetric deformation with the most susceptible zones to rearrange first. The use of end-of-test values of $\varepsilon_v$ is limited for the purpose of comparison between tests, as the values depend, amongst other factors, on the differential pore water pressure at the end of the test, which varies between tests. Notwithstanding this caveat, the end-of-test values of $\varepsilon_v$ in a suffusive specimen are typically small, whereas the end-of-test values of $\varepsilon_v$ in a suffosive specimen are substantial, and in all but one test, equal to or greater than 1.20%. Inspection of the variation of the volumetric strain with the differential pore water pressure across the specimen in tests on glass beads that exhibited a suffosive response (Figs. 4.8c to 4.11c), suggests that progression of volumetric deformation occurs at an approximately constant rate in each test. The rate of deformation appears to be very similar for a given gradation, and is independent of effective stress. To quantify the progression of volumetric deformation, the average unit rate of volumetric deformation $E_v$ is defined as the increase of volume strain, $\Delta \varepsilon_v$, per unit increase in differential pore water pressure:

$$E_v = \frac{\Delta \varepsilon_v}{\Delta u_l - \Delta u_{sto}} \quad (6.1)$$

where $\Delta u_l$ is the differential pore water pressure at the last stage of seepage flow.

The increase in contractive strain is calculated from the onset of suffosion (see Fig. 6.3) to the end of the test, if continuing deformations associated with failure did not occur, else if continuing deformations did occur during the last stage of seepage flow (in tests on gradation 6.5GB35, see Fig. 4.11c), then to the last stage prior to failure. Determination of the average unit rate of deformation for every test that exhibited a suffosive response (see Table 6.2), yields a relatively narrow range of values for each gradation: 4.8GB35 yields $E_v = 0.12$ to 0.21 %/kPa; gradation 6.0GB25 yields $E_v = 0.23$ to 0.28 %/kPa; gradation 6.0GB30 yields $E_v = 0.44$ to 0.71 %/kPa; gradation 6.0GB35 yields $E_v = 0.43$ to 0.55 %/kPa; gradation 6.5GB35 yields $E_v = 0.75$ to 0.89 %/kPa. A relatively large unit rate of volumetric deformation of $E_v = 3.18$ %/kPa is obtained for the test on gradation 6.5GB25. The unit rate of deformation increases with increasing gap ratio for gradations 6.0GB25 and 6.5GB25, and for gradations 4.8GB35, 6.0GB35 and 6.5GB35, respectively (see Fig. 6.4). The variation of $E_v$ with $D'_{15}/d'_{85}$ demonstrates a strong dependence between the variables. The physical explanation is sought in the increasing particle size of the coarse component with increasing $D'_{15}/d'_{85}$: rearrangement of larger coarse particles apparently yields larger volumetric deformations than the rearrangement of smaller coarse particles. The average unit rate of volumetric deformation can thus be considered a gradation specific variable, which, in contrast to the end-of-test volumetric strain, is not dependent on the conditions at which the test was terminated. The relatively narrow range of the average unit rate of volumetric deformation, for any gradation, suggests it is a useful variable to quantify the volumetric deformations associated with suffosion.
Considering that, in a flexible wall permeameter, the measurement of axial deformation is simpler and less expensive than the measurement of the total volumetric deformation, the necessity of the measurement of volumetric deformation to quantify seepage-induced internal instability will be discussed herein. In all tests on gradations of glass beads that exhibited a suffosive response, comparison of the end-of-test values of axial and volumetric strains, yields greater volumetric strains than axial strains (see Table 6.2). More specifically, nine of 15 tests (4.8GB35-150, 6.0GB25-150, 6.0GB30-100, 6.0GB30-150, 6.0GB35-60 6.0GB35-150, 6.5GB25-100, 6.5GB35-50 and 6.5GB35-100) exhibited substantial volumetric deformations in the absence of substantial axial deformations (see Figs. 6.5 to 6.10). A tentative explanation for the absence of substantial axial deformation is that a partial, local collapse of the micro-structure does not significantly affect the overall stability of the specimen. These findings demonstrate that volumetric deformation is an essential variable to characterise seepage-induced deformations. Furthermore, it should be noted that the response to seepage flow in four tests on gradation 4.8GB20 (see Table 5.4), and in two tests on gradation 6.5GB35, is qualitatively very similar in the domain of axial deformations and hydraulic conductivity. The suffosive response of the tests on gradation 6.5GB35 can only be appreciated and distinguished from the suffusive response of the tests on gradation 4.8GB20 in terms of the progressive increase of volumetric deformation during multi-stage seepage flow (compare Figs. 4.11c and 4.5c respectively). Considering the localised nature of the contractive volumetric deformation associated with suffusion, which can occur in the absence of axial deformation, measurement of total volume change proves necessary to avoid any mis-interpretation of the phenomenological response to seepage flow.

6.2.2 Glass beads tests of other studies

In the experimental database compiled from the literature, the results of seepage tests on four other gap-graded gradations of glass beads are reported. Crawford-Flett (2014) reports a suffusive response to seepage flow in tests on gradation 6.6GB22 (see Table 6.1), which is fairly similar to gradation 6.0GB20 of this study. Isolated events of contractive axial deformation, which did not progress with subsequent stages of seepage flow, were observed in all tests on gradation 6.2GB20, which yielded end-of-test values ranging from $\varepsilon_a = 0.1$ to 0.6 % (see Table 6.2). It thus appears that Crawford-Flett (2014) also, at least implicitly, adopted a notion of a small, non-progressive volume change to characterise suffusion. These findings thus support the broader definition of suffusion adopted in the previous Section. Using a rigid wall permeameter, Li (2008) reported a suffosive response in a total of nine tests on glass beads gradations FR7 and FR8 (see Table 6.1), yielding end-of-test values ranging from $\varepsilon_a = 0.1$ to 4.7 %. Sail et al. (2011) also report substantial end-of-test axial strain of $\varepsilon_a = 4.9\%$ in the suffosive response of one test on glass beads gradation G4-C, using a rigid wall permeameter.
The range of axial strains measured in the tests of Li (2008) and Sail et al. (2011), on glass beads gradations using a rigid wall permeameter, imply that equivalent substantial volumetric strains occurred in these tests. Moreover, Li (2008) appears to have relied on visual observations to identify the phenomenological response. Visual observations of particle rearrangement were necessary to identify suffosion in test FR7-50-D, which only exhibited a very small value of $\varepsilon_a = 0.1\%$. In two other tests, FR8-100-D and FR7-100-D, visual observations of particle rearrangement are reported as a “disturbance to the specimen” during multi-stage seepage flow, which are not captured by the axial strain measurement. It is speculated that such a disturbance, visible through the side wall of the permeameter, would have been captured if the total volume change could have been measured. Considering the need to use visual observations, in addition to measurements of axial strain, to identify the phenomenological response, the findings of Li (2008) and Sail et al. (2011) lend further evidence to the limitation of the axial strain alone to quantify suffosion. The findings from the literature thus confirm the belief that volume change is a necessary variable to characterise, and to distinguish between, suffusion and suffosion.

6.3 Test of hypothesis No. 2

Hypothesis No. 2 seeks to establish the conditions at which the onset of suffosion initiates, especially in relation to the role of effective stress: The onset of suffosion is dependent on effective stress. The hypothesis is first tested based on the glass beads tests of this study in Section 6.3.1. The findings are subsequently compared to select tests reported in the literature in Section 6.3.2.

6.3.1 Glass beads tests of this study

The parametric study, with the mean effective stress as one of the test variables, permits a direct comparison between specimen response, where the effective stress is the only variable that changes: any difference in the response can be attributed to the influence of the effective stress. The influence of the effective stress on the onset of suffosion can thus be assessed by comparing the suffosive response in 15 tests on six gradations (4.8GB35, 6.0GB25, 6.0GB30, 6.0GB35, 6.5GB25 and 6.5GB35, see Table 6.2), which have been isotropically consolidated to a range of mean effective stress $p'_c = 53$ to $152$ kPa (see Table 4.1). For each test that exhibited a suffosive response, a plot is generated of the hydro-mechanical path, which is defined by the progression of the mean effective stress $p'_e$ of the element and the differential pore water pressure across the element $\Delta u$. Consider for example gradation 4.8GB35, which is the gradation with the smallest gap ratio that exhibited suffosion. The hydro-mechanical path of tests 4.8GB35-50, 4.8GB35-100 and 4.8GB35-150 is plotted in Fig. 6.11, the onset of suffosion is marked. Following an initial response of no volume change in the tests (see also Fig. 4.6c), the onset of suffosion is associated with the beginning of contractive volume change. The volume change progressed
in a localised manner with increasing differential pore water pressure across the specimen, but overall instability of the soil structure did not occur. The onset of suffosion in test 4.8GB35-50 at $\Delta u_{so} = 1.5$ kPa and $p'_{so} = 53$ kPa (see Table 5.4) initiates at a slightly smaller differential pore water pressure and substantially smaller mean effective stress than the onset of suffosion in test 4.8GB35-100 at $\Delta u_{so} = 1.6$ kPa and $p'_{so} = 103$ kPa. The onset of suffosion in test 4.8GB35-150 initiates at $\Delta u_{so} = 2.8$ kPa and $p'_{so} = 150$ kPa. These data suggest that the differential pore water pressure at the onset of suffosion increases with increasing mean effective stress. The relation is approximately proportional with a gentle slope that may or may not pass through the origin. The hydro-mechanical paths of the other glass beads tests that exhibited suffosion are plotted in Figs. 6.12 to 6.16. In particular, the tests on gradations 6.0GB25 (see Fig. 6.12), 6.0GB30 (see Fig. 6.13), 6.0GB35 (see Fig. 6.14), and 6.5GB35 (see Fig. 6.16), exhibit a trend of increasing $\Delta u_{so}$ with increasing $p'_{so}$ at a gentle slope. Theoretically, in the limit of zero mean effective stress, any differential pore water pressure across an element yields fluidisation of the element. It is therefore speculated that the relation between mean effective stress and differential pore water pressure at the onset of suffosion, must pass through the origin. Presenting the conditions at the onset of volume change of all glass beads tests in one plot, (see Fig. 6.17) indicates a moderate positive correlation between the mean effective stress and the differential pore water pressure at the onset of volume change, which demonstrates that the differential pore water pressure at the onset of suffosion is dependent on the mean effective stress. However, comparison of the tests on gradation 6.0GB30, with $S_f = 0.30$, gradations 6.0GB25 and 6.5GB25, with $S_f = 0.25$, and tests on gradations 4.8GB35, 6.0GB35 and 6.5GB35, with $S_f = 0.35$ (see Fig. 6.17), reveals a greater variation in values for $\Delta u_{so}$ with $S_f$ than with $p'_{so}$. The influence of the finer fraction content is addressed in Section 6.4.

### 6.3.2 Glass beads tests of other studies

From the literature, only Li (2008) has reported a suffosive response in tests on specimens of glass beads subject to varying values of effective stress. Li (2008), however, was primarily interested in the seepage-induced failure of internally unstable gradations, and did not explicitly report the conditions at the onset of suffosion. The response to seepage flow of five tests on gradation FR7 and four test on gradation FR8 is re-interpreted by examining the variation of axial deformation, and reproduced in terms of $\Delta u$ and $p'$, by assuming $K_0 = 0.4$ (after Moffat 2005). Recall that volumetric deformation has been identified to be a more correct measure for suffosion than axial deformation, and it is apparent that the onset of suffosion based on measurements of axial deformation should be considered an upper limit for the conditions at the onset of suffosion. Re-interpretation of the tests on FR7 and FR8 (see Fig. 6.18) indicates that the onset of suffosion occurred at differential pore water pressures ranging from $\Delta u_{so} = 0.0$ to 3.0 kPa in all but test FR7-100-D, which exhibited $\Delta u_{so} = 6.8$ kPa. These values fall in a similar range as the values of $\Delta u_{so} = 0.7$ kPa to 4.5 kPa reported for tests on glass beads.
in this study (compare Figs. 6.17 and 6.18), but the re-interpreted data do not yield a clear dependence of $\Delta u_{so}$ on $p'_{so}$. Further, in four of five tests on FR7 and in one of four tests on FR8 (see Fig. 6.18), the onset of suffosion appears to have initiated at lower differential pore water pressures than the onset of failure, yielding a similar overall response of suffosion prior to failure as in the two tests on gradation 6.5GB35 of this study (see Fig. 6.16). Hence, the apparent range of values of $\Delta u_{so}$, and the observed progression from suffosion to failure in tests on the glass bead gradations FR7 and FR8 reported by Li (2008), are generally similar to the response to seepage flow on the gradations of glass beads tested in this study. The findings from the literature are however inconclusive regarding the influence of the mean effective stress on the onset of suffosion.

6.4 Test of hypothesis No. 3

The third hypothesis was defined with the purpose of establishing a causative relation between the micro-structure of a particle arrangement and its potential for seepage-induced internal instability: The micro-structure of internally unstable materials controls the phenomenological response to seepage flow. The hypothesis is first tested based on the glass beads tests of this study in Section 6.4.1. The findings are subsequently compared to select glass beads tests reported in the literature in Section 6.4.2.

6.4.1 Glass beads tests of this study

Inspection of the responses on gradations of glass beads tested in this study with varying $S_f$ and varying $D_{15}'/d_{85}'$ (see Fig. 6.19) demonstrates that glass beads gradations with $S_f = 0.20$ and $D_{15}'/d_{85}' > 4$ exhibited suffusion, whereas a suffosive response was only identified in gradations with $0.25 \leq S_f \leq 0.35$ and $D_{15}'/d_{85}' > 4$. In the following detailed investigation of the influence of the micro-structure, a distinction is made between micro-structures that exhibited a suffusive response (see Section 6.4.1.1), and micro-structures that exhibited a suffosive response (see Section 6.4.1.2).

6.4.1.1 Micro-structures that exhibited a suffusive response

The micro-structure of specimens of two glass beads gradations that exhibited a suffusive response are both type C-T, with, as noted previously, $S_f = 0.20$ (see Fig. 6.20). From the analysis of the micro-structures of gap-graded materials (see Section 5.2), it was postulated that a portion of the fine particles in the C-T type micro-structure is load bearing, based on the relatively loose state of the coarse fraction $e_s > e_{s,max}$. This postulate can be examined by assessing the micro-structures of the gap-graded gradations of perfectly spherical particles simulated by Shire and O’Sullivan (2013) using DEM. It is unknown to what extent the method to configure the particle arrangement, and hence its micro-structure, adapted by Shire and O’Sullivan (2013)
approximates the physical specimen preparation by slurry deposition. The micro-structure of the gradations simulated by Shire and O’Sullivan (2013), which are included herein for the purpose of comparison, can be assessed using the micro-structure identification diagram that has been developed for the glass beads (see Fig. 6.20 and Table 6.3): gradations G1-10 and G1-20 exhibit a type C micro-structure, gradations G1-30 and G2-20 exhibit a type C-T micro-structure, and gradation G1-40 exhibits a type M-T micro-structure. For these gradations, Shire and O’Sullivan (2013) reported the portion of load bearing fine particles $b$ (see Table 6.3). In the type C micro-structure of gradations G1-10 and G1-20, the portion of load bearing fine particles is $b = 0.01$ and 0.02, respectively, whereas in type C-T micro-structure of gradations G1-30 and G2-20, it is 0.24 and 0.12, respectively. In the type M-T micro-structure of gradation G1-40, 0.61 of the fine particles are non-load bearing. The very small values of $b = 0.01$ to 0.02 in gradations with a type C micro-structure, confirm the postulate that the fine particles do not contribute significantly to the stability of this type of micro-structure. In contrast, the findings of DEM simulations indicate that a substantial portion of the fine particles of $b \geq 0.12$ is indeed load bearing in type C-T micro-structures. The findings further suggest that nearly half of the fine particles may be non-load bearing in type M-T.

Given this insight from DEM simulations, a novel procedure is proposed to determine the portion of load-bearing fine particles in micro-structures of gap-graded gradations: it is based on the concept of an equivalent inter-coarse void ratio $e_{se}$ (see Eq. 2.7). Thevanayagam et al. (2002) hypothesised that the shear response of a specimen with a type C micro-structure with a value $e_s$, was similar to the shear response of an equivalent specimen with a type C-T microstructure with an equal value of $e_{se}$. It is postulated that a type C-T micro-structure can only be stable if the volume of all load-bearing coarse and fine spherical particles is equal to the volume of all coarse particles in a particle packing without fine particles, in the loosest stable state; that is $e_{se} = e_{s,max}$. The portion of load bearing fine particles $b$ then follows from Eq. 2.7, if $e_{se} = e_{s,max}$:

$$b = 1 - \frac{1}{S_f} \frac{e_{s,max} - e}{e_{s,max} + 1}$$  \hspace{1cm} (6.2)

with $0 \leq b \leq 1$.

Values for $b$ of the four gradations of spherical particles with type C or type C-T microstructures simulated by Shire and O’Sullivan (2013), are calculated using Eq. 6.2 with $e_{s,max} = 0.67$ (see Table 6.3). The calculated value of the portion of load bearing fine particles of $b = 0$ in type C micro-structures of gradations C1-10 and C1-20, respectively, are in very good agreement with the findings of the DEM simulations of $(1-b) = 0.01$ and $(1-b) = 0.02$, respectively. Of the two gradations that classify as micro-structure type C-T, namely G1-30 and G2-20, the
calculated portion of load bearing fine particles using Eq. 6.2 yield nearly identical values, \( b = 0.21 \) and 0.09, respectively, as the values of \( b = 0.21 \) and 0.12 determined using DEM simulations. Although Eq. 6.2 was developed based on the concept of a type C-T micro-structure, the calculated value of \( b = 0.48 \) for the G1-40 specimen with micro-structure type M-T is comparable to that of \( b = 0.61 \) determined by DEM (see Table 6.3). Accordingly, Eq. 6.2 appears to provide a very good estimate of the portion of load bearing fine particles in type C and type C-T micro-structures, and a reasonable estimate of the portion of load bearing fine particles in type M-T micro-structures.

In absence of DEM simulations of the gradations tested in this study, the portion of non-load bearing fine particles \((1-b)\) in the specimens of glass beads is calculated using Eq. 6.2 (see Table 6.2): the portion of non-load bearing fine particles in specimens that exhibited suffusion, which were all of a type C-T micro-structure, varies from \((1-b) = 0.56 - 0.81\). The potential for non-load bearing fine particles is thus fulfilled in C-T micro-structures that exhibited suffusion in this study. Inspection of the variation of the relative increase in hydraulic conductivity, \(k_{\text{max}}/k_i\), with the portion of non-load bearing fine particles \((1-b)\) (see Fig. 6.21), in four tests on gradation 4.8GB20 and three tests on gradation 6.0GB20, suggests that an increasing portion of non-load bearing fine particles is associated with a greater relative increase of hydraulic conductivity. The portion of non-load bearing fine particles then appears a useful parameter to quantify the potential for particle migration in gap-graded gradations of glass beads.

The potential for suffusion is not only determined by the presence of non-load bearing fine particles, but also by the constrictions of the micro-structure, which need to be sufficiently large to permit passage of the fine particles. Crawford-Flett (2014) demonstrated that the controlling constriction size in transitional clast-supported micro-structures is controlled by the smallest coarse particles. Accordingly, \(D'_{15}\) appears a suitable index for the controlling constriction size, which renders the gap ratio \(D'_{15}/d'_{85}\) a suitable index for the transportation potential of fine particles from a type C or type C-T supported micro-structure. A gap-ratio of \(D'_{15}/d'_{85} = 4\) (Kezdi, 1979), or \(D'_{15}/d'_{85} = 4\) to 5 (Sherard, 1979) has traditionally been used as a transportation criterion of fine particles through the pores of a coarse particle arrangement. The suffusive response of tests on gradations 4.8GB20 and 6.0GB20 with \(D'_{15}/d'_{85} = 4.8\) and \(D'_{15}/d'_{85} = 6.0\), respectively, broadly confirm the validity of \(D'_{15}/d'_{85} = 4\) to 5 as a transportation criterion of fine particles through the pores of a coarse particle arrangement.

### 6.4.1.2 Micro-structures that exhibited a suffusive response

Gradations that exhibited a suffusive response in this study yield type C-T (gradations 6.0GB25 and 6.5GB25), type T (6.0GB30, 4.8GB35 and 6.0GB35) or type M-T (6.5GB35) micro-structures (see Table 6.2). The potential for particle rearrangement of a micro-structure was
qualitatively assessed as $e_s > e_{s,max}$, or $e_f > e_{f,max}$ in Section 5.2. In order to investigate the influence of the micro-structure on the onset of suffosion, two quantitative indices are proposed to characterise the potential for particle rearrangement. The modified inter-coarse state parameter $\Psi_s$, as a variation to the inter-coarse state parameter proposed by Thevanayagam and Mohan (2000), is defined as the difference between the inter-coarse void ratio $e_s$ and the maximum index void ratio corresponding to a stable packing of the coarse particle component $e_{s,max}$:

$$\Psi_s = e_s - e_{s,max}$$

Similarly, the inter-fine state parameter $\Psi_f$, is defined as the difference between the inter-fine void ratio $e_f$ and the maximum index void ratio corresponding to a stable packing of the fine particle component $e_{f,max}$:

$$\Psi_f = e_f - e_{f,max}$$

The modified inter-coarse state parameter $\Psi_s$ is selected as a measure of the potential for particle rearrangement in the type C-T micro-structure (gradations 6.0GB25 and 6.5GB25) as $\Psi_s$ relates to the dominant particle type in the micro-structure. Similarly, for the fine particle dominated micro-structure type M-T (gradation 6.5GB35) the inter-fine state parameter $\Psi_f$ is selected as a measure for the potential for particle rearrangement. Now consider the matter of assigning a state parameter to the transitional type T micro-structure. The inter-coarse void ratio of the type T micro-structure is greater than the theoretical cubic packing arrangement, $e_s > e_{cub}$, as is the case in type M-T micro-structures, which indicates that the coarse particles are not in contact with each other. A comparison of the modified state parameters for all gradations of glass beads that exhibited a suffosive response (see Fig. 6.22), indicates that the values of $\Psi_s$ and $\Psi_f$ for gradations with type T micro-structure (6.0GB30, 4.8GB35 and 6.0GB35) are similar to the values of $\Psi_s$ and $\Psi_f$ of the gradations with an M-T micro-structure (6.5GB35). The inter-fine state parameter is therefore selected as a measure for the potential for particle rearrangement in transitional type T micro-structures.

Following is an examination of the influence of the proposed state parameters on suffosion. On the matter of the spatial variation of the volumetric deformation in tests that exhibited a suffosive response, positive values of $\Psi_s$ or $\Psi_f$, indicate an average potential for particle rearrangement of coarse or fine particles, respectively, throughout the specimen. It is speculated that small spatial variations in the micro-structure cause the spatial variation in the volumetric deformation, with the most susceptible zones rearranging first. On the matter of the influence of the proposed state parameters on the conditions at the onset of suffosion, the three tests on gradations 6.0GB25 and 6.5GB25 with a type C-T micro-structure yield $\Psi_s = 0.14$ to 0.17 (see Table 6.2) and differential pore water pressures at the onset of suffosion $\Delta u_{so} = 0.7$ to
1.4 kPa (see Table 5.4). The twelve tests on gradations with type M-T and T micro-structures gave \( \Psi_f = 0.19 \) to 0.53 and \( \Delta u_{so} = 0.8 \) to 4.5 kPa. The variation of the differential pore water pressure at the onset of suffosion with the \( \Psi_f \) in type T and type M-T micro-structures (see Fig. 6.23) yields a strong linear strong correlation, with correlation coefficient \( r_c = 0.75 \). Interestingly, the variation of \( \Psi_f \) in type T and type M-T micro-structures, together with \( \Psi_s \) in type C-T micro-structures, yields a stronger linear correlation \( (r_c = 0.78) \) with the differential pore water pressure at the onset of suffosion. Considering the relative plotting positions of the conditions at the onset of suffosion in glass beads gradations (see Fig. 6.17), it appears that the gradation 6.0GB30, which yields a type T micro-structure and exhibited the largest values of \( \Delta u_{so} \), corresponds to the largest value of the characteristic state parameter. Furthermore, gradations 6.0GB25 and 6.5GB25, which yield a type C-T micro-structure and exhibited the lowest values of \( \Delta u_{so} \), correspond to the smallest value of the characteristic state parameter. It is speculated that, in a type C-T micro-structure, local rearrangement of coarse particles can only occur if a small portion of load-bearing fine particles becomes detached, which occurs at a relatively low differential pore water pressure proportional to \( \Psi_s \). In contrast, in type T, and also in type M-T micro-structure, an increasing \( \Psi_f \) is speculated to yield stronger force chains through fewer fine particles, which requires relatively large differential pore water pressures to initiate suffosion. These findings suggests that the proposed state parameters are predictors of the relative susceptibility to suffosion: \( \Psi_f \) is a characteristic state parameter of type T and type M-T micro-structures, and \( \Psi_s \) is a characteristic state parameter of a type C-T micro-structure.

### 6.4.2 Glass beads tests of other studies

From the literature, the suffusive response in four tests on glass beads gradation 6.6GB22 reported by Crawford-Flett (2014) (see Table 6.1), for which \( D'_{15}/d'_{85} = 6.6 \) and \( S_f = 0.22 \), suggests a refinement of the upper boundary of finer fraction content for which suffusion is the predominant phenomenological response to \( S_f < 0.25 \) (see Fig. 6.19). Additionally, one test on glass beads gradation G4-C of Sail et al. (2011), with \( D'_{15}/d'_{85} = 7.4 \) and \( S_f = 0.40 \), exhibited suffosion, as did five tests on glass beads gradation FR-7, with \( D'_{15}/d'_{85} = 7.1 \) and \( S_f = 0.30 \), and four tests on glass beads gradation FR-8, with \( D'_{15}/d'_{85} = 7.9 \) and \( S_f = 0.30 \), reported by Li (2008), respectively. The findings of Li (2008) and of Sail et al. (2011) thus appear in broad agreement with the findings of this study; hence it can be reasonably claimed that a suffosive response occurs for glass beads gradations with \( 0.25 \leq S_f \leq 0.40 \) and \( D'_{15}/d'_{85} > 4 \).

On the matter of factors controlling the potential for suffusion, Crawford-Flett (2014) found that a glass beads gradation 5.2GB22 with \( S_f = 0.22 \) and \( D'_{15}/d'_{85} = 5.2 \), which is very similar to gradation 4.8GB20 of this study, exhibited fluidisation when subject to upward seepage flow. Considering the previous discussion on the potential for suffusion, it would appear that a value of \( D'_{15}/d'_{85} > 5 \), instead of \( D'_{15}/d'_{85} > 4 \), is an appropriate index for the transportation criterion
of fine particles being able to pass through the pores of a coarse particle arrangement, especially considering the uncertainty associated with values for $d'_{85}$ and $D'_{15}$. Secondly, the response of the four tests on gradation 6.6GB22 (Crawford-Flett, 2014), which exhibited a type C-T micro-structure, can be compared to the suffusive response on gradations of glass beads tested in this study. The portion of non-load bearing fine particles is calculated for each specimen (see Table 6.2), yielding a range of $(1-b) = 0.65$ to $0.68$. Comparison of the portion of non-load bearing fine particles, and the relative increase in hydraulic conductivity of $k_{max}/k_i = 1.7$ to $1.9$ (see Fig. 6.21), appears to confirm the previous finding that the portion of non-lead bearing fine particles is a useful parameter to quantify the potential for particle migration in gap-graded gradations of glass beads.

On the matter of factors controlling the potential for suffosion, it appears that the tests on gradations FR7 and FR8, of Li (2008), yielded a micro-structure on the boundary between type C-T and type T (see Fig. 6.20). Similarly, gradation G4-C of Sail et al. (2011) is identified to exhibit a type T micro-structure. The response in tests on gradations FR7, FR8, and G4-C is thus in agreement with the previous finding that a suffosive can occur in type C-T, type T, or type M-T micro-structures. Further, the values of the inter-coarse and inter-fine state parameters of gradations FR7 and FR8 are very similar to gradation 6.0B30 (see Fig. 6.22), which exhibits the same finer fraction content $S_f = 0.30$. The values of the proposed state parameters of gradation G4-C follow the trend of increasing values of $\Psi_s$ and decreasing values of $\Psi_f$ with increasing finer fraction content. The range of values of $\Delta u_{so} = 0.0$ to $6.8$ kPa inferred for five tests on gradation FR7 and four tests on gradation FR8, shows considerable overlap with the range of values of $\Delta u_{so} = 3.4$ to $4.5$ kPa of the tests on gradation 6.0GB30. Although the values of the state parameters, and the conditions at the onset of suffusion, of the glass beads tests reported in the literature are similar, the limited data from the literature is deemed to yield inconclusive evidence on the belief that the state parameters are predictors of the relative susceptibility to suffosion.

6.5 Test of hypothesis No. 4

The fourth hypothesis seeks to establish a causative relation between particle shape and the stability of the soil structure subject to seepage flow: *Gap-graded gradations of rounded particles are more susceptible to seepage-induced internal instability than identical gap-graded gradations of sub-angular particles.*

6.5.1 Glass beads and soil tests

A parametric study, with particle shape as one of the control variables, permits a direct comparison between tests where the particle shape is the only variable that changes. Any difference

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in the response to seepage flow can then be attributed to the particle shape. Tests with particle shape as the single control variable were made on gradations at the lower end of the percentage finer fraction, with $S_f = 0.20$, and on gradations at the upper end, with $S_f = 0.35$, respectively. No two seepage tests were found in the literature on internally unstable gradations that only differ in particle shape. Accordingly, hypothesis No. 4 is examined solely based on tests conducted in this study.

### 6.5.1.1 Influence of particle shape on gradations with $S_f = 0.20$

Consideration is first given to the two tests on the soil gradation 5.1BT20 and the two tests on the glass beads gradation 4.8GB20, which had been isotropically consolidated to 55 kPa and 155 kPa, and 54 kPa and 153 kPa, respectively (see Table 6.4). Tests 5.1BT20-50 and 5.1BT20-150 only differ from tests 4.8GB20-50 and 4.8GB20-150, respectively, in the particle shape of the sub-angular grains of the BT soil and the spherical grains of the GB glass beads. All gradations were reconstituted using the modified slurry deposition technique without any attempt to densify the specimen, which yielded a type C-T micro-structure (see Table 6.4). The initial condition of the soils yielded a much larger void ratio of $e_c = 0.63$ and 0.65 for tests 5.1BT20-50 and 5.1BT20-150, respectively, compared to that of $e_c = 0.48$ and 0.44, for tests 4.8GB20-50 and 4.8GB20-150, respectively. The difference in initial void ratio is attributed solely to the particle shape, in agreement with the findings of Youd (1973) (see Section 2.2.2.2). The phenomenological response in the 4.8GB20 glass beads tests, and the 5.1BT20 soil tests, is identified as suffusion. Suffusion initiated at $\Delta u_{su} = 0.2$ to 0.3 kPa in all four tests, independent of particle shape (see Table 6.4). The increase in hydraulic conductivity of $k_{max}/k_i = 1.1$ to 1.6 (see Table 5.6) in the soils tests is similar to the range of $k_{max}/k_i = 1.3$ to 1.5 in the glass beads tests (see Table 5.3). The finding indicates that the particle shape did not significantly affect the response of specimens with a type C-T soil structure at $S_f = 0.20$. Now consider the three tests on the soil gradation 5.7BT20 and three tests on the glass beads gradation 6.0GB20 (see Table 6.4). Again, the void ratios $e_c = 0.56$ to 0.59 of the soil gradation were substantially greater than the void ratios of $e_c = 0.40$ to 0.45 of the glass beads gradation. The phenomenological response in the 6.0GB20 glass beads tests and the 5.7BT20 soil tests is identified as suffusion, with $\Delta u_{su} = 0.1$ to 0.4 kPa (see Table 6.4) and $k_{max}/k_i = 1.0$ to 1.7 (compare Tables 5.3 and 5.6), independent of particle shape. This comparison further supports the finding that the particle shape does not significantly affect the response of the materials with a type C-T micro-structure at $S_f = 0.20$.

An explanation for the nearly identical response to seepage flow of soils and glass beads with $S_f = 0.20$ is sought by further examining the factors controlling suffusion (Crawford-Flett, 2014): (i) the presence of non-load bearing fine particles; (ii) the hydraulic load; and (iii) the controlling constriction size of the material. The postulate of a presence of non-load bearing
fine particles in a type C-T micro-structure was confirmed for the glass beads specimens in Section 6.4.1.1 and it can be reasonably extended to soil specimens. On the matter of the hydraulic load, Crawford-Flett (2014) convincingly argued that, under conditions of upward seepage flow, movement of a non-load bearing particle initiates when the seepage-induced drag force exceeds the buoyant weight of the particle. The fine particles of glass beads with \( d'_{85} = 0.19 \text{ mm} \) and soils with \( d'_{85} = 0.17 \text{ mm} \) (see Table 3.1) are nearly identical in size which, in addition to the very similar values of specific gravity of the solids of \( G_s = 2.49 \) and 2.70, respectively, implies that the buoyant weight of individual glass beads and sub-angular particles is approximately the same. Although the drag force depends on particle shape, the difference in drag coefficient of the glass beads (with sphericity \( S_{QP} = 0.94 \)) and the sub-angular soil particles (with \( S_{QP} = 0.88 \)) is negligible for flow regimes of this study with \( R_e < 10 \), taking into account the observations of Haider and Levenspiel (1989). The hydraulic threshold for migration of the finer fraction of glass beads and the finer fraction of sub-angular soil particles can thus be reasonably anticipated to be of similar value, which is in agreement with the experimental results of this study. Given the comparable response to seepage flow of the glass bead and soil test specimens at \( S_f = 0.20 \), it is postulated that the constrictions of the glass beads and soils are of a similar size in these specimens, which exhibit a type C-T micro-structure.

### 6.5.1.2 Influence of particle shape on gradations with \( S_f = 0.35 \)

The effect of the particle shape at \( S_f = 0.35 \) can be appreciated by comparing the response to seepage flow in tests on glass beads gradations 6.0GB35 and 6.5GB35, with tests on soil gradations 5.7BT35 and 7.0BT35, respectively. All gradations were reconstituted using the modified slurry deposition technique, without any attempt to densify the specimen. The void ratio \( e_c = 0.46 \) of gradation 5.7BT35 (see Table 6.4) was substantially greater than the void ratio of \( e_c = 0.37 \) of gradation 6.0GB35. The response to seepage flow is identified as suffosion in the glass beads test 6.0GB35-100 (see Table 6.4), whereas soil test 5.7BT35-100 reached a “pre-critical” condition, despite a much greater differential pore water pressure across the specimen of \( \Delta u = 8.6 \text{ kPa} \) at the end of test 5.7BT35-100, compared to \( \Delta u = 4.7 \text{ kPa} \) at the end of test 6.0GB35-100. Both specimens exhibited a type T micro-structure (see Table 6.4). The comparison of tests 6.5GB35-50, which exhibited a type M-T micro-structure, and 7.0BT35-50, which exhibited a type T micro-structure, appears to indicate a similar influence of the particle shape. Again, the void ratio \( e_c = 0.42 \) of gradation 7.0BT35 (see Table 6.4) was substantially greater than the void ratio of \( e_c = 0.30 \) of gradation 6.5GB35. The glass beads test exhibited a suffosive response, which eventually resulted in failure at \( \Delta u_f = 1.4 \text{ kPa} \), whereas the soil test reached a “pre-critical” conditions even at an end-of-test value of \( \Delta u = 9.5 \text{ kPa} \). Inspection of the response to seepage flow of other soil specimens with \( S_f = 0.35 \) (see Table 6.4) indicates that the gap ratio needs to be increased to \( D'_{15}/d'_{85} = 8.6 \) for a suffusive response to occur (test 8.6BT35-50), and to \( D'_{15}/d'_{85} = 10.4 \) for a suffusive response to occur (tests 10.4BT35-
50, 10.4BT35-50(R) and 10.4BT35-100). It can thus reasonably be concluded that specimens of sub-angular particles with $S_f = 0.35$ yield stronger type T or M-T micro-structures than specimens with a nearly identical gradation of spherical particles. In these micro-structures, both the fine and coarse particles exist at relatively loose states and hence, large portions of the fine and coarse particles are presumed load-bearing and contributing to the stability of the micro-structure. Collapse of a type T or M-T micro-structure implies rearrangement of particles and hence the greater resistance against particle rotation, and especially contact slipping, of sub-angular particles (Holtz et al., 2011; see also Section 2.2.2.2) is postulated to yield a stronger transitional micro-structure of sub-angular particles than of spherical particles.

### 6.6 Factors governing suffusion and suffosion

The influence of several factors governing suffusion and suffosion has been established in the preceding using glass beads tests of this study, and supplemented by limited evidence found in the literature of glass beads tests. What follows is a general discussion on the factors governing suffusion and suffosion. The findings from the glass beads tests are compared to the soil tests from this study and the literature, and where necessary expanded upon.

#### 6.6.1 Volume change

In this study, the response to seepage flow in seven tests on two glass beads gradations (see Table 5.4), and in eleven tests on seven soil gradations was identified as suffusion (see Table 5.7). The volumetric deformation was negligible to small in ten soil tests, ranging from end-of-test values of $\varepsilon_v = 0.06$ to 0.12 % (see Table 5.4). In one test, 10.4BT25-50, volumetric deformation occurred as an isolated, non-progressive event, yielding an end-of-test value $\varepsilon_v = 0.72 \%$, but the predominant response was one of local migration of fine particles, largely in the absence of volume change. Accordingly, the broader definition of suffusion as seepage-induced mass loss without change in volume, or else a small non-progressive change in volume, accompanied by an increase of hydraulic conductivity, appears a useful, and necessary extension of the definition of suffusion established from the review of the literature (see Section 2.1.3).

In addition to suffusion, a suffosive response was identified in 15 tests on six different glass beads gradations (see Table 5.4), and in three tests on one soil gradation (see Table 5.7). Suffosion was characterised by an initial sequence of no volumetric strain and a subsequent sequence of a progressive development of substantial volumetric strain, in both the glass beads and soil tests. The end-of-test values $\varepsilon_v = 0.78$ to 2.46 % in the glass beads tests (see Table 5.4) and $\varepsilon_v = 1.10$ to 2.00 % in the soil tests (see Table 5.7) yield comparable values. The average unit rate of deformation in the suffosive response in tests on gradation 10.4BT35 varied within a relatively narrow range of $E_v = 0.19$ to 0.27 %/kPa (see Table 6.4), which broadly confirms the
prior finding that the average unit rate of deformation is a useful variable to quantify volumetric deformation associated with suffosion, independent of particle shape. The three tests on gradation 10.4BT35 exhibited substantial volumetric deformations in the absence of substantial axial deformations (see Figs. 6.24), which enhances the finding that measurement of total volume change is necessary to avoid any mis-interpretation of the phenomenological response to seepage flow.

From the literature, Chang and Zhang (2013), found that axial and radial strains enable a useful distinction between an “initiation phase”, which is believed equivalent to suffusion in this study, and a “development phase”, which is believed equivalent to suffosion in this study. Secondly, Moffat et al. (2011), testing soil T-0 in a rigid wall permeameter, observed that “[s]mall movements occurred […] prior to the development of a relatively large displacement during the final stage […]”. Hence, it appears that the rearrangement of the particle packing of the soil was not recorded in the measurement of axial strain, an issue which Li (2008), as noted in Section 6.2.2, also alluded to in the tests on glass beads. These observations from the literature further confirm the need to measure volume change in order to correctly characterise suffosion.

### 6.6.2 Effective stress

The independence of the effective stress on the onset of suffusion in gap-graded glass beads was conclusively established by Crawford-Flett (2014). The prior comparison between tests on glass beads gradations and soil gradations with $S_f = 0.20$ (see Section 6.5.1.1), established that the particle shape does not have a significant effect on the response of these gradations, which exhibit a type C-T micro-structure. Inspection of the variation (see Fig. 6.25) of the mean effective stress $p'_su$ and the differential pore water across the specimen at the onset of suffusion $\Delta u_{su}$, in tests on glass beads and soils, reveals that in all but two soil tests, a small value $\Delta u_{su} = 0.1$ to 0.4 kPa is independent of $p'_su$. The gradations which exhibit suffusion at these small values of $\Delta u_{su}$, namely 4.8GB20, 6.0GB20, 5.1BT20, 5.7BT20, 7.0BT20, 8.6BT20 and 10.4BT25, exhibit a type C-T micro-structure (see Tables 5.2 and 5.5). This observations thus confirms the finding of Crawford-Flett (2014) that the onset suffusion is not dependent on effective stress. However, one test on gradation 8.6BT35 (see Table 6.4), with a type T micro-structure, and one test on gradation 10.4BT30, with a type C-T micro-structure, exhibited a suffusive response that initiated at relatively large values of $\Delta u_{su} = 5.3$ and 2.0 kPa, respectively. From the literature, Chang and Zhang (2013) also appear to have reported a suffusive response on a similar gradation GS, with $S_f = 0.35$, which exhibited relatively large values of $\Delta u_{su} = 0.8$ to 2.5 kPa. These limited data indicate that suffusion can be dependent on effective stress in gradations with $S_f > 0.25$, which is tentatively attributed to the characteristics of the micro-structure for this range of finer fraction contents. Notwithstanding this caveat, the findings of the suffusive
response in tests on glass beads and soils, support the conclusion of Crawford-Flett (2014) that the onset of suffusion is not dependent on effective stress, and extend it to the domain of the soils. However, it is noteworthy that this holds only true in specimens that exhibit a type C-T micro-structures with $S_f \leq 0.25$.

The examination of the conditions at the onset of suffusion in 15 tests on six glass beads gradations indicated a trend of increasing $\Delta u_{so}$ with increasing $p'_{so}$ at a gentle slope. In comparison, the onset of suffusion in soil tests 10.4BT35-50, 10.4BT35-50(R) and 10.4BT35-100 (see Fig. 6.26) initiates at values of $\Delta u_{so} = 0.8$ to $1.8$ kPa and $p'_{so} = 54$ to $102$ kPa. The data of these soils test are deemed insufficient to further examine the influence of the effective stress on the onset of suffusion.

From the literature, Moffat (2005) identified a suffosive response in three tests on soil gradation T-0 and in five tests on soil gradation T-5. Re-interpretation of the response, based on the variation of the axial strain, of the tests on gradation T-0 (see Fig. 6.27) indicates that suffosion initiated prior to failure in all three tests, where failure is defined as continuing deformations at a constant hydraulic gradient. In the tests, the hydraulic gradients at the onset of axial deformation are relatively small, and yield an apparent increase in hydraulic gradient with increasing effective stress with a gentle slope. Similarly, in two of five tests on gradation T-5 (see Fig. 6.28), suffosion was identified to initiate at relatively small hydraulic gradients, prior to failure of the specimen. Chang and Zhang (2013) reported a suffosive response in 18 tests on a soil gradation GS, which was anisotropically consolidated to varying states of effective stress. The reported values of $\Delta u_{so} = 0.9$ to $3.8$ kPa in these tests (see Fig. 6.29) plot in a similar range as the values of $\Delta u_{so}$ in the glass beads and soil tests (see Figs. 6.17 and 6.26). More importantly, the data exhibit a trend of increasing $\Delta u_{so}$ with increasing $p'_{so}$ with a gentle non-linear slope: the trend line can reasonably be extrapolated through the origin. The tests of Moffat (2005), and in particular Chang and Zhang (2013), thus appear consistent with the finding of this study that the onset of suffosion is governed by effective stress: the variation of differential pore water pressure at the onset of suffosion with the mean effective stress, exhibits a gentle positive slope.

### 6.6.3 Micro-structure

A suffusive response has been identified in tests on glass beads gradations with $D'_{15}/d'_{85} > 5$ and $S_f < 0.25$, whereas a suffosive response was identified in tests on glass beads gradations with similar gap-ratios $D'_{15}/d'_{85} > 5$, but greater finer fraction contents $0.25 \leq S_f \leq 0.40$ (see Fig. 6.19). For the soils tested in this study, a suffusive response was identified in tests on seven gradations with $0.20 \leq S_f \leq 0.35$ and $D'_{15}/d'_{85} > 5$, whereas a suffosive response was identified in tests on one gradation with $S_f = 10.4$ and $S_f = 0.35$. Inclusion of the suffusive response on a gradation A of Skempton and Brogan (1994), the suffusive or suffosive response
on a gradation GS of Chang and Zhang (2013), and the suffosive response on gradations T-0 and T-5 of Moffat (2005), allows for the limits for seepage-induced internal instability in soils to be refined (see Fig. 6.30) as follows: a suffusive response in soil gradations with $0.15 \leq S_f \leq 0.35$ and $D'_{15}/d'_{85} > 5$; and, a suffusive response in soil gradations with $0.30 \leq S_f \leq 0.40$ and $D'_{15}/d'_{85} > 8$. Accordingly, gradations with $D'_{15}/d'_{85} > 5$ and with a relatively small finer fraction content $S_f \leq 0.25$, are susceptible to suffusion, independent of particle shape. In contrast, the particle shape has a profound influence on the susceptibility of gradations with $0.30 \leq S_f \leq 0.40$: glass beads gradations are susceptible to suffosion if $D'_{15}/d'_{85} > 5$, whereas soil gradations are susceptible to suffusion if $D'_{15}/d'_{85} > 8$.

### 6.6.3.1 Influence of micro-structure on suffusion

From the glass beads tests, the portion of non-load bearing fine particles was found a useful parameter to quantify the potential for migration of fine particles in type C-T micro-structures. Given that the response for gradations with $S_f = 0.20$, which yielded a type C-T micro-structure, is not affected by the particle shape, it is reasonable to claim that the proposed procedure to determine the portion of non-load bearing fine particles (i.e. Eq. 6.2) is also valid for soil gradations with a type C-T micro-structure. Six of seven soil gradations that exhibited a suffusive response yield a type C-T micro-structure (gradations 5.1BT20, 5.7BT20, 7.0BT20, 8.6BT20, 10.4BT25 and 10.4BT30, see Table 6.4). The range of the calculated values of $(1-b) = 0.42$ to 0.81 (see Table 6.4) for the soil gradations, together with the range of increasing hydraulic conductivity $k_{max}/k_i = 1.0$ to 1.8 (see Table 5.6), are similar to the glass beads specimens (see Fig. 6.31). This observation confirms the previous finding that the portion of non-lead bearing fine particles is a useful parameter to quantify the potential for migration of fine particles for type C-T micro-structures, independent of particle shape.

On the matter of suffusion in gradations 8.6BT35 and 10.4BT30, which exhibited type T and C-T micro-structures, respectively, it seems reasonable to claim that a substantial portion of the fine particles is non-load bearing in these micro-structures in soils, considering it was established for glass beads gradations in Section 6.4.1.1. Considering the substantial potential for particle rearrangement in a type T micro-structure, it is further speculated that gradation 8.6BT35 may exhibit suffusion when subject to more adverse hydraulic loads. The findings of Chang and Zhang (2013) established that certain soils can exhibit either suffusion or suffosion, depending on the stress condition. In contrast, considering the suffusive response in soils with $S_f \leq 0.25$ and $D'_{15}/d'_{85} > 5$, which exhibit a C-T micro-structure, and the limited potential for particle rearrangement in this micro-structure (see Section 6.4.1.1), it is postulated that these gradations are only susceptible to suffusion.
6.6.3.2 Influence of micro-structure on suffosion

The proposed state parameters appear to be predictors of the relative susceptibility to suffosion: $\Psi_f$ is a characteristic state parameter of type T and type M-T micro-structures and $\Psi_s$ is a characteristic state parameter of a type C-T micro-structure. Calculation of the modified interfine state parameter of the soil specimens of gradation 10.4BT35, using Eq. 6.4 with $e_{s,max} = 0.80$, yields very similar values of $\Psi_f = 0.23$ to 0.29 (see Table 6.4), compared to $\Psi_f = 0.20$ to 0.40 (see Table 6.2) of the glass beads specimens with $S_f = 0.35$ (see also Fig. 6.32). The tests on gradation 10.4BT35 yielded a suffosive response with $\Delta u_{so} = 0.8$ to 1.8 kPa (see Table 5.7 and Fig. 6.26), which is of very similar range to the values of $\Delta u_{so} = 0.8$ to 2.8 kPa obtained from the tests on glass beads gradations 4.8GB35, 6.0GB35 and 6.5GB35 (see Table 5.7), despite the difference in particle shape and gap ratio. The similar values of the differential pore water pressures required to initiate suffosion, implies that the glass beads specimens, and soil specimens, exhibit similar micro-structures with similar force chains. The combination of values of $\Psi_f$ and $\Delta u_{so}$ for the soil gradation plot in the same range of glass beads gradations (see Fig. 6.33), which tentatively confirms that the proposed state parameters are predictors of the relative susceptibility to suffosion, independent of particle shape.

6.7 A unified approach for suffosion

A suffosive response was characterised in this study (see Section 5.5) by the sequence of an initially constant hydraulic conductivity in the absence of volumetric deformation, and a subsequent varying hydraulic conductivity at differential pore water pressures across the specimen greater than a threshold value, accompanied by the progressive development of non-uniform contractive volumetric deformations. In some tests, the onset of suffosion was followed by continuing deformations in the last stage associated with failure. The prior discussion has established that volume change is a necessary variable to correctly quantify suffosion and that the onset of suffosion occurs at a critical combination of mean effective stress $p'$ and differential pore water pressure across the specimen $\Delta u$. Considering the variables necessary to quantify a suffosive response have been identified, an opportunity exists to develop a unified approach to characterise suffosion (see Fig. 6.34). An element is consolidated to $p'_{c}$ and subsequently subject to an increasing differential pore water pressure across the specimen $\Delta u$, yielding upward seepage flow. In Fig. 6.34 a typical hydro-mechanical path is depicted for a specimen subject to upward seepage flow in a flexible wall permeameter, with a decreasing value $p'$ for increasing values of $\Delta u$. No volume change occurs if the hydro-mechanical path remains below the suffosion boundary. Suffosion initiates if the hydro-mechanical path reaches the suffosion boundary at point ($p'_{so}$, $\Delta u_{so}$). Suffosion progresses with increasing $\Delta u$, at an approximately constant unit rate of deformation $E_v$. Failure, defined as continuing volumetric deformations at a constant differential pore water pressure across the specimen, occurs if the hydro-mechanical
path reaches the failure boundary at point \((p_f', \Delta u_f')\).

The proposed state parameters appear good predictors of the conditions at the onset of suffosion (see Fig. 6.33): the modified inter-coarse state parameter \(\Psi_s\) is characteristic for type C-T micro-structure, whereas the inter-fine state parameter \(\Psi_f\) is characteristic for type T and type M-T micro-structures. The average unit rate of deformation \(E_v\) appears mainly dependent on the particle shape and \(D_{15}'/d_{85}'\): \(E_v\) was found to increase with increasing values of \(D_{15}'/d_{85}'\) for glass beads gradations (see Fig. 6.4).

### 6.8 Summary

Factors controlling suffusion and suffosion have been discussed in this Chapter, guided by the examination of four research hypotheses using the tests of this study and select tests reported in the literature (see Fig. 6.1). Based on seven tests on two glass beads gradations and eleven tests on seven soil gradation of this study, and supplemented by experimental observations in the literature, it is proposed to broaden the definition of suffusion to “a seepage-induced mass loss without change in volume, or a with small, non-progressive contractive volume change, accompanied by an increase in hydraulic conductivity”. The suitability of volume change as a variable to characterise seepage-induced internal instability was tested in the discussion of hypothesis No. 1. The average unit rate of deformation \(E_v\) was introduced as a characteristic variable of the progression of suffosion and it was deemed useful to quantify seepage-induced volumetric deformation in 15 tests on six glass beads gradations and in three tests on one soil gradation. Considering the localised nature of the progressive contractive volumetric deformation associated with suffosion, which can occur in absence of axial deformation, measurement of total volume change proved necessary to avoid any mis-interpretation of the phenomenological response to seepage flow.

The influence of effective stress on suffosion was tested in the discussion of hypothesis No. 2. The differential pore water pressure at the onset of suffosion was found to increase with increasing mean effective stress in 15 tests on six glass beads gradations that exhibited suffosion in this study, and in 18 tests on one soil gradation reported in the literature. It was confirmed for glass beads and soil gradations, that the onset of suffusion is not dependent on effective stress in specimens with \(S_f \leq 0.25\), which exhibit a transitional clast-supported micro-structure.

In the discussion of hypothesis No. 3, the dependence of the micro-structure on suffusion and suffosion was investigated. Based on the results of tests reported in this study and tests reported in the literature, a suffusive response was identified in tests on glass beads gradations with \(D_{15}'/d_{85}' > 5\) and \(S_f < 0.25\), whereas it was identified in tests on soil gradations with \(0.15 \leq S_f \leq 0.35\) and \(D_{15}'/d_{85}' > 5\). The micro-structures of seven glass beads specimens and of ten
soil specimens of this study that exhibited a suffusive response are transitional clast-supported; one soil specimen yielded a transitional micro-structure. Similarly, a suffusive response was identified in tests on glass beads gradations with $D'_{15}/d'_{85} > 5$ and $0.25 \leq S_f \leq 0.40$. The particle shape has a profound influence on the susceptibility to suffosion: suffosion was identified in soil gradations with $0.30 \leq S_f \leq 0.40$ and $D'_{15}/d'_{85} > 8$. Micro-structures of gradations that exhibited a suffusive response are transitional clast-supported, transitional, or transitional matrix supported. It appears that specimens with a transitional micro-structure may exhibit suffusion, prior to suffosion. A novel procedure to determine the portion of load-bearing fine particles in clast-supported and transitional clast-supported micro-structures was validated with DEM simulations. The findings inferred from seven tests on two glass beads gradations and from ten tests on six soil gradations that exhibited a suffusive response and a transitional clast-supported micro-structure in this study, supported by evidence found in the literature, indicate that the portion of non-load bearing fine particles is a useful parameter to quantify the potential for particle migration, independent of particle shape. The novel concepts of the modified inter-coarse state parameter $\Psi_s$ and the inter-fine state parameter $\Psi_f$ have been introduced. The findings inferred from 15 tests on six glass beads gradations and from three tests on soil gradations suggests that the proposed state parameters are predictors of the relative susceptibility to suffosion, independent of particle shape: $\Psi_f$ is a characteristic state parameter of transitional and transitional matrix-supported micro-structures and $\Psi_s$ is a characteristic state parameter of a transitional clast-supported micro-structure.

Discussion of hypothesis No. 4 examined the influence of the particle shape on seepage-induced internal instability. The comparison between five glass beads tests and five soils tests established that the particle shape does not significantly affect the response of gap-graded gradations with $S_f = 0.20$. It was postulated that the constrictions of the glass beads and soils are of a similar size in these specimens. The comparison between two glass beads tests and two soils tests demonstrated that sub-angular particles result in transitional micro-structure at $S_f = 0.35$ that is more resistant to collapse than a similar micro-structure of spherical particles, which is attributed to the greater resistance against particle rotation and contact slipping, of the sub-angular particles.

Finally, a unified approach is presented to characterise suffosion in the domain of mean effective stress, differential pore water pressure across the specimen, and volumetric deformation. The approach unifies the notion of a hydro-mechanical boundary at the onset of suffosion, and a hydro-mechanical boundary where seepage-induced failure of internally unstable gradations initiates. Failure is is defined as continuing deformations at a constant differential pore water pressure across the specimen.
Table 6.1: Experimental database on suffusion and suffosion compiled from the literature.

<table>
<thead>
<tr>
<th>Study</th>
<th>Apparatus</th>
<th>Flow(^2) direction</th>
<th>No. of tests</th>
<th>Material(^2)</th>
<th>Gradation type</th>
<th>(S_f) ((-))</th>
<th>(D'<em>{15}/d'</em>{85}) ((-))</th>
<th>(R^4) ((-))</th>
<th>Phenomenon(^5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crawford- (2014)</td>
<td>RWP</td>
<td>U</td>
<td>4</td>
<td>GB</td>
<td>6.6GB22</td>
<td>0.22</td>
<td>6.0</td>
<td>R</td>
<td>SU</td>
</tr>
<tr>
<td>Li (2008)</td>
<td>RWP</td>
<td>U/D</td>
<td>5</td>
<td>GB</td>
<td>FR7</td>
<td>0.30</td>
<td>7.1</td>
<td>R</td>
<td>SO</td>
</tr>
<tr>
<td>Li (2008)</td>
<td>RWP</td>
<td>D</td>
<td>4</td>
<td>GB</td>
<td>FR8</td>
<td>0.30</td>
<td>7.9</td>
<td>R</td>
<td>SO</td>
</tr>
<tr>
<td>Sail et. al (2011)</td>
<td>RWP</td>
<td>D</td>
<td>1</td>
<td>GB</td>
<td>G4-C</td>
<td>0.40</td>
<td>7.4</td>
<td>R</td>
<td>SO</td>
</tr>
<tr>
<td>Skempton and Brogan (1994)</td>
<td>RWP</td>
<td>U</td>
<td>1</td>
<td>Soil</td>
<td>A</td>
<td>0.15</td>
<td>11</td>
<td>SA</td>
<td>SU</td>
</tr>
<tr>
<td>Chang and Zhang (2013)</td>
<td>FWP</td>
<td>D</td>
<td>22</td>
<td>Soil</td>
<td>GS</td>
<td>0.35</td>
<td>7.9</td>
<td>SA(^6)</td>
<td>SU/SO</td>
</tr>
<tr>
<td>Moffat (2005)</td>
<td>RWP</td>
<td>U/D</td>
<td>3</td>
<td>Soil</td>
<td>T-0</td>
<td>0.40</td>
<td>13.7</td>
<td>SA</td>
<td>SO</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5</td>
<td>Soil</td>
<td>T-5</td>
<td>0.40</td>
<td>14.3</td>
<td>SA</td>
<td>SO</td>
</tr>
</tbody>
</table>

Notes:
1. RWP = Rigid Wall Permeameter, FWP = Flexible Wall Permeameter
2. U = Upward seepage flow, D = Downward seepage flow
3. Soil or Glass Beads (GB)
4. roundness, \(R\); R = Rounded, SA = sub-angular
5. SU = Suffusion; SO = Suffosion
6. The particle shape of the coarse component was identified by the author, based on Fig. 3-4.(a) of Chang (2012)
### Table 6.2: Seepage-induced internal instability in tests on glass beads.

<table>
<thead>
<tr>
<th>Study</th>
<th>Test code</th>
<th>$\varepsilon_a$ (%)</th>
<th>$\varepsilon_v$ (%)</th>
<th>Phenomenon²</th>
<th>Phenomenon² (%)/kPa</th>
<th>Micro-structure⁴</th>
<th>$(1-b)^{5}$</th>
<th>$\Psi_{s}$, $\Psi_{f}$⁶</th>
</tr>
</thead>
<tbody>
<tr>
<td>This study</td>
<td>4.8GB20-50</td>
<td>0.00</td>
<td>0.12</td>
<td>SU</td>
<td>-</td>
<td>C-T</td>
<td>0.56</td>
<td>0.19</td>
</tr>
<tr>
<td></td>
<td>4.8GB20-50(2)</td>
<td>-0.01</td>
<td>0.03</td>
<td>SU</td>
<td>-</td>
<td>C-T</td>
<td>0.67</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>4.8GB20-100</td>
<td>0.02</td>
<td>0.50</td>
<td>SU</td>
<td>-</td>
<td>C-T</td>
<td>0.60</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>4.8GB20-150</td>
<td>0.04</td>
<td>0.48</td>
<td>SU</td>
<td>-</td>
<td>C-T</td>
<td>0.69</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td>6.0GB20-50</td>
<td>0.00</td>
<td>0.09</td>
<td>SU</td>
<td>-</td>
<td>C-T</td>
<td>0.66</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>6.0GB20-100</td>
<td>0.30</td>
<td>0.82</td>
<td>SU</td>
<td>-</td>
<td>C-T</td>
<td>0.78</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td>6.0GB20-150</td>
<td>0.01</td>
<td>0.09</td>
<td>SU</td>
<td>-</td>
<td>C-T</td>
<td>0.81</td>
<td>0.00</td>
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<td>6.0GB25-50</td>
<td>0.68</td>
<td>1.61</td>
<td>SO</td>
<td>0.28</td>
<td>C-T</td>
<td>0.69</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>6.0GB25-100</td>
<td>0.05</td>
<td>1.58</td>
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<td>C-T</td>
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<tr>
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<td>0.08</td>
<td>1.65</td>
<td>SO</td>
<td>3.18</td>
<td>C-T</td>
<td>0.75</td>
<td>0.14</td>
</tr>
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<td>4.8GB35-50</td>
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<td>1.60</td>
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<td>T</td>
<td>-</td>
<td>0.36</td>
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<td>4.8GB35-100</td>
<td>0.79</td>
<td>1.20</td>
<td>SO</td>
<td>0.20</td>
<td>T</td>
<td>-</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>4.8GB35-150</td>
<td>0.05</td>
<td>0.78</td>
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<td></td>
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<td>0.44</td>
<td>1.90</td>
<td>SO</td>
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<td>1.78</td>
<td>SO</td>
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<td>T</td>
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<td>0.46</td>
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<td>6.0GB30-150</td>
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<td>1.87</td>
<td>SO</td>
<td>0.62</td>
<td>T</td>
<td>-</td>
<td>0.48</td>
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<td>6.0GB35-50</td>
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<td>SO</td>
<td>0.43</td>
<td>T</td>
<td>-</td>
<td>0.27</td>
</tr>
<tr>
<td></td>
<td>6.0GB35-100</td>
<td>0.62</td>
<td>1.54</td>
<td>SO</td>
<td>0.43</td>
<td>T</td>
<td>-</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>6.0GB35-100(2)</td>
<td>0.70</td>
<td>2.19</td>
<td>SO</td>
<td>0.50</td>
<td>T</td>
<td>-</td>
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</tr>
<tr>
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<td>SO</td>
<td>0.55</td>
<td>T</td>
<td>-</td>
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</tr>
<tr>
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<td>SO</td>
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<td>M-T</td>
<td>-</td>
<td>0.20</td>
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<td>1.68</td>
<td>SO</td>
<td>0.89</td>
<td>M-T</td>
<td>-</td>
<td>0.20</td>
</tr>
<tr>
<td>Crawford-Flett (2014)</td>
<td>6.6GB22-25</td>
<td>0.3</td>
<td>-</td>
<td>SU</td>
<td>-</td>
<td>C-T</td>
<td>0.65</td>
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<tr>
<td></td>
<td>6.6GB22-50</td>
<td>0.1</td>
<td>-</td>
<td>SU</td>
<td>-</td>
<td>C-T</td>
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<td>0.15</td>
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<td></td>
<td>6.6GB22-100</td>
<td>0.2</td>
<td>-</td>
<td>SU</td>
<td>-</td>
<td>C-T</td>
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<td>0.15</td>
</tr>
<tr>
<td></td>
<td>6.6GB22-150</td>
<td>0.6</td>
<td>-</td>
<td>SU</td>
<td>-</td>
<td>C-T</td>
<td>0.68</td>
<td>0.15</td>
</tr>
<tr>
<td>Li (2008)</td>
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<td>3.4</td>
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<td>SO</td>
<td>-</td>
<td>T⁷</td>
<td>-</td>
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<td>FR7-50-D</td>
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<td>-</td>
<td>SO</td>
<td>-</td>
<td>T⁷</td>
<td>-</td>
<td>0.43</td>
</tr>
<tr>
<td></td>
<td>FR7-100-D</td>
<td>1.6</td>
<td>-</td>
<td>SO</td>
<td>-</td>
<td>T⁷</td>
<td>-</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>FR7-150-D</td>
<td>0.6</td>
<td>-</td>
<td>SO</td>
<td>-</td>
<td>T⁷</td>
<td>-</td>
<td>0.40</td>
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<tr>
<td></td>
<td>FR7-150-U</td>
<td>3.0</td>
<td>-</td>
<td>SO</td>
<td>-</td>
<td>T⁷</td>
<td>-</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>FR8-25-D2</td>
<td>1.6</td>
<td>-</td>
<td>SO</td>
<td>-</td>
<td>T</td>
<td>-</td>
<td>0.56</td>
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<tr>
<td></td>
<td>FR8-50-D</td>
<td>0.7</td>
<td>-</td>
<td>SO</td>
<td>-</td>
<td>T</td>
<td>-</td>
<td>0.56</td>
</tr>
<tr>
<td></td>
<td>FR8-100-D</td>
<td>4.7</td>
<td>-</td>
<td>SO</td>
<td>-</td>
<td>T</td>
<td>-</td>
<td>0.53</td>
</tr>
<tr>
<td></td>
<td>FR8-200-D</td>
<td>3.9</td>
<td>-</td>
<td>SO</td>
<td>-</td>
<td>T</td>
<td>-</td>
<td>0.43</td>
</tr>
<tr>
<td>Sail et al. (2011)</td>
<td>G4-C</td>
<td>4.9</td>
<td>-</td>
<td>SO</td>
<td>-</td>
<td>T</td>
<td>-</td>
<td>0.23</td>
</tr>
</tbody>
</table>

**Note:**

1. At the end of test, from Table 5.4 or from literature.
2. SU = Suffusion; SO = Suffosion, from Table 5.4, or from literature.
3. For suffusive responses, using Eq. 6.1.
4. See Table 5.2 and Fig. 6.20.
5. Using Eq. 6.2.
6. Characteristic state parameter $\Psi_{s}$, using Eq. 6.3, for type C-T micro-structure and $\Psi_{f}$, using Eq. 6.4, for type T and M-T micro-structures.
7. See Fig. 6.20: specimens of gradation FR7 plot on the boundary between types C-T and T.
Table 6.3: Evaluation of portion of non-load bearing particles in gap-graded gradations.

<table>
<thead>
<tr>
<th>Gradation</th>
<th>$S_f$</th>
<th>$e$</th>
<th>$e_s$</th>
<th>$e_f$</th>
<th>$S_{fL}$</th>
<th>Microstructure</th>
<th>$b^1$</th>
<th>$b^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1-10</td>
<td>0.11</td>
<td>0.45</td>
<td>0.63</td>
<td>4.11</td>
<td>-</td>
<td>C</td>
<td>0.01</td>
<td>0</td>
</tr>
<tr>
<td>G1-20</td>
<td>0.21</td>
<td>0.32</td>
<td>0.67</td>
<td>1.54</td>
<td>-</td>
<td>C</td>
<td>0.02</td>
<td>0</td>
</tr>
<tr>
<td>G1-30</td>
<td>0.30</td>
<td>0.29</td>
<td>0.85</td>
<td>0.96</td>
<td>-</td>
<td>C-T</td>
<td>0.24</td>
<td>0.24</td>
</tr>
<tr>
<td>G1-40</td>
<td>0.40</td>
<td>0.32</td>
<td>1.21</td>
<td>0.79</td>
<td>0.95</td>
<td>M-T</td>
<td>0.61</td>
<td>0.48</td>
</tr>
<tr>
<td>G2-20</td>
<td>0.21</td>
<td>0.35</td>
<td>0.71</td>
<td>1.67</td>
<td>-</td>
<td>C-T</td>
<td>0.12</td>
<td>0.09</td>
</tr>
</tbody>
</table>

Note:
1 From Shire and O'Sullivan (2013).
2 Using Eq. 6.2
### Table 6.4: Comparison of select tests on glass beads and soils.

<table>
<thead>
<tr>
<th>Test code</th>
<th>$D'<em>{15}/d'</em>{85}$</th>
<th>$S_f^2$</th>
<th>$p'_c^3$</th>
<th>Microstructure</th>
<th>$\Delta u_{su}$</th>
<th>$\Delta u_{so}$</th>
<th>$\Delta u_f$</th>
<th>$p'_{su}$</th>
<th>$p'_{so}$</th>
<th>$p'_f$</th>
<th>$1-b^6$</th>
<th>Phenomenon</th>
</tr>
</thead>
<tbody>
<tr>
<td>R 4.8GB-50</td>
<td>4.8 0.20 54 0.48 C-T 0.2 - - 54 - - 0.56 SU</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>R 4.8GB-150</td>
<td>4.8 0.20 153 0.44 C-T 0.2 - - 153 - - 0.69 SU</td>
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<td></td>
</tr>
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Notes:
1 R = Rounded; SA = Sub-angular, from Table 3.2. 2 from Table 3.2. 3 from Tables 4.1 (GB tests) and 4.3 (BT tests). 4 from Tables 5.2 (GB tests) and 5.5 (BT tests). 5 from Tables 5.4 (GB tests) and 5.7 (BT tests). 6 using Eq. 6.2. 7 SU = Suffusion; SO = Suffosion, from Tables 5.4 (GB tests) and 5.7 (BT tests).
Figure 6.1: Reader guide for discussion on factors controlling suffusion and suffosion.
Figure 6.2: Experimental database compiled from literature.

Figure 6.3: Suffosion: definition of average unit rate of deformation $E_v$.

Figure 6.4: Suffosion: variation of $E_v$ and $D_{15}/d_{55}$ in suffosive responses of glass beads.
Figure 6.5: Suffosion: variation of volumetric and axial strain in tests on gradation 4.8GB35.

Figure 6.6: Suffosion: variation of volumetric and axial strain in tests on gradation 6.0GB25.

Figure 6.7: Suffosion: variation of volumetric and axial strain in tests on gradation 6.0GB30.
**Figure 6.8:** Suffosion: variation of volumetric and axial strain in tests on gradation 6.0GB35.

**Figure 6.9:** Suffosion: variation of volumetric and axial strain in test on gradation 6.5GB25.

**Figure 6.10:** Suffosion: variation of volumetric and axial strain in tests on gradation 6.5GB35.
Figure 6.11: Onset of suffosion in tests on gradation 4.8GB35.

Figure 6.12: Onset of suffosion in tests on gradation 6.0GB25.

Figure 6.13: Onset of suffosion in tests on gradation 6.0GB30.
**Figure 6.14:** Onset of suffosion in tests on gradation 6.0GB35.

**Figure 6.15:** Onset of suffosion in test on gradation 6.5GB25.

**Figure 6.16:** Onset of suffosion and condition at failure in tests on gradation 6.5GB35.
Figure 6.17: Onset of suffosion: variation between mean effective stress and differential pore water pressure across the specimen in tests on glass beads gradations.

Figure 6.18: Suffosion: upper limit for onset of suffosion and failure in tests on glass beads gradations FR7 and FR8 (of Li, 2008).

Figure 6.19: Seepage-induced internal instability phenomena in tests on glass beads gradations.
Figure 6.20: Variation of micro-structure of glass beads gradations with seepage-induced internal instability phenomena.

Figure 6.21: Suffusion: variation of relative increase in hydraulic conductivity and portion of non-load bearing fine particles in C-T micro-structures of glass beads.

Figure 6.22: Variation of inter-coarse and inter-fine state parameters in glass beads test specimens.
Figure 6.23: Onset of suffosion: variation of differential pore water pressure with characteristic state parameter in tests on glass beads gradations.

Figure 6.24: Suffosion: variation of volumetric and axial strains in tests on gradation 10.4BT35.

Figure 6.25: Onset of suffusion in tests on glass beads and soils.
Figure 6.26: Onset of suffosion in tests on gradation 10.4BT35.

Figure 6.27: Upper limit for onset of suffosion and failure in tests on soil gradation T-0 (adapted from Moffat et al., 2011, reproduced with permission from Canadian Science Publishing).
**Figure 6.28:** Upper limit for onset of suffosion and failure in tests on soil gradation T-5 (adapted from Moffat et al., 2011, reproduced with permission from Canadian Science Publishing).

**Figure 6.29:** Variation between $p'_{so}$ and $\Delta u_{so}$ in soil gradation GS (data extracted from Chang and Zhang, 2013).
Figure 6.30: Seepage-induced internal instability phenomena in soils.

Figure 6.31: Suffusion: variation of relative increase in hydraulic conductivity and portion of non-load bearing fine particles in C-T micro-structures of glass beads and soils.
Figure 6.32: Variation of inter-coarse and inter-fine state parameters in glass beads and soil test specimens.

Figure 6.33: Onset of suffosion: variation of differential pore water pressure across the specimen with characteristic state parameter in tests on glass beads and soil gradations.
Figure 6.34: Unified approach for characterisation of suffosion.
Chapter 7

Conclusions, recommendations and implications for practice

The aim of this study is to establish causative relations between factors governing suffusion and suffosion. Following a literature review of the state-of-art on seepage-induced internal instability, a new flexible wall permeameter was designed with control of effective stress and hydraulic load, and with the novel feature of measurement of total volume change. This laboratory investigation comprises a parametric sensitivity study where the dependent variable is the response of a gap-graded material, subject to isotropic consolidation to a mean effective stress ranging from 50 to 150 kPa and subsequently, multi-stage upward seepage flow, with head control. The control variables are the finer fraction content of the material $S_f$, the ratio of the particle sizes of the coarse and fine fractions of the material $D'_{15}/d'_{65}$, the particle shape of the material $R$, the mean effective stress of the specimen $p'$, and differential pore water pressure across the specimen $\Delta u$. Two commissioning tests, together with a main test program of 23 tests on eight glass beads gradations and 16 tests on ten soil gradations were conducted. The findings of this investigations are summarised in Section 7.1. The novel contributions are accentuated in Section 7.2 and recommendations for future research are presented in Section 7.3. Finally, implications for practice are discussed in Section 7.4.

7.1 Conclusions

7.1.1 Conclusions derived from the literature review

A conceptual framework is developed such that a distinction can be reasonably made between phenomenological responses based on mass loss and volume change, which can be measured directly, and change in hydraulic conductivity, which can be deduced from measurement of hydraulic gradient and flow rate. A review of the literature established three distinct phenomena of soils subject to seepage flow:
• Migration of fine particles from a soil, termed suffusion, which is characterised as seepage-induced mass loss without change in volume, accompanied by an increase of hydraulic conductivity; and,

• Collapse of the soil structure, termed suffosion, which is characterised as a seepage-induced mass loss, accompanied by a volumetric contraction and change in hydraulic conductivity; and,

• Reduction of effective stress to zero in internally stable soils, termed fluidisation, which is characterised as a seepage-induced volumetric expansion, accompanied by an increase in hydraulic conductivity, with no mass loss.

### 7.1.2 Conclusions concerning the test method

A flexible wall permeameter comprising a double-walled triaxial cell, a seepage control system, through which unidirectional multi-stage seepage flow can be imposed, and instrumentation, has been designed and built. The following conclusions are drawn:

• A novel feature in seepage-induced instability testing is the measurement of the total volume change, using a technique adopted from Wheeler (1986). It is derived from monitoring the volume change of the cell fluid in the inner chamber of a double-walled triaxial cell, that, with correction for the intrusion of the loading ram, membrane penetration and small calibrated volume changes of dissolving air and absorption of water, yields an accurate measure of total volume change in the test specimen.

• For test specimens with a typical volume of approximately 780 cm$^3$, the resolution of the volume change measurement of +/- 0.1 cm$^3$ is equivalent to $\varepsilon_v \approx 0.01\%$ and the accuracy of +/- 0.5 cm$^3$ is equivalent to $\varepsilon_v \approx 0.07\%$.

The commissioning of the apparatus and assessment of the repeatability of the test results yield the following conclusions:

• The resolution and accuracy of the volume change measurement technique are believed sufficient to quantify the onset and progression of deformation in specimens with a volume of approximately 780 cm$^3$.

• The comparisons of three sets of companion tests indicate that the test procedure yields repeatable results in test specimens of glass beads and soils with finer fraction contents of $S_f = 0.20$ and $S_f = 0.35$.

Additionally, the following conclusion is drawn on the method of specimen preparation:

• The reconstitution of homogeneous, saturated specimens of gap-graded spherical glass beads using the modified slurry deposition method yields test results that are reproducible.
7.1.3 Conclusions derived from the analysis of test results

The analysis of the results of the commissioning tests, and of the tests constituting the main test program, established the following:

- A micro-structure identification diagram (Thevanayagam et al., 2002), with explicit definitions of all boundaries, has been constructed for gap-graded gradations of glass beads and soils, based on considerations of the experimental limits of stable particle packing arrangements of the fine fraction and coarse fraction. Analysis of the micro-structure of gap-graded materials has yielded five different types of micro-structure, in compliance with the original work of Thevanayagam et al. (2002): clast-supported; transitional clast-supported; transitional; transitional matrix-supported; and matrix supported. The ability to explicitly distinguish between clast-supported and transitional clast-supported micro-structures, and between matrix-supported and transitional matrix-supported micro-structures yields a key improvement of the micro-structure identification diagram, because of the distinction between micro-structures that exhibit potential for particle rearrangement and micro-structures that do no exhibit this potential.

- The potential for seepage-induced internal instability is qualitatively examined for each micro-structure type: it is inferred that clast-supported and transitional clast-supported micro-structures exhibit a substantial portion of non-load bearing fine particles, whereas a potential for particle rearrangement was established in clast-supported, transitional and transitional matrix-supported micro-structures, but not in clast-supported or matrix-supported micro-structures.

- Analysis of the test results has yielded conclusive evidence for the establishment of the phenomenological response in 36 of 41 tests. The following evidence was considered: the potential for particle migration and particle rearrangement, the variation of the hydraulic conductivity, axial and volumetric strains, any mass loss inferred from the variation of hydraulic conductivity in conjunction with volume change, and forensic observations of mass loss.

- A suffusive response, characterised by negligible or very small strains, which is in agreement with the strict definition established from a review of the literature, was established in four tests on two glass beads gradations and in ten tests on six soil gradations. A broader definition of suffusion, associated with the non-progressive development of small axial or volumetric strains, was invoked to characterise the response in three tests on two glass beads gradations and in one test on a soil gradation.

- A suffosive response, associated with the progressive development of spatially variable contractive volumetric deformations was established in 15 tests on glass beads gradations
and three tests on soil gradations, which exhibited a transitional clast-supported, transitional or transitional matrix-supported micro-structure. Failure, defined as continuing contractive volumetric deformations at a constant differential pore water pressure across the specimen, was identified in two glass beads tests that exhibited suffosion.

- A “pre-critical” condition was reached in three tests on three glass beads gradations and in two tests on two soil gradations; it was characterised by a constant hydraulic conductivity in the absence of axial and volumetric deformation.

### 7.1.4 Factors governing suffusion and suffosion

Factors governing suffusion and suffosion are discussed based on the evidence of glass beads and soil tests from this study, supplemented by a limited body of evidence from six studies reported in the literature. The discussion of volume change as a characteristic variable of seepage-induced internal instability yields the following conclusions:

- The predominant response in specimens that exhibit a suffusive response associated with a small, non-progressive volume change, is one of local migration of fine particles, largely in the absence of volume change. Based on glass beads and soil tests in this study, and supplemented by the findings of Crawford-Flett (2014), it is proposed to broaden the definition of suffusion to “a seepage-induced mass loss without change in volume, or a small non-progressive change in volume, accompanied by an increase of hydraulic conductivity”.

- Visual observations established that the progressive, seepage-induced contractive volume change associated with suffosion did not occur equally throughout the specimen, but was rather of a local nature.

- The average unit rate of volumetric deformation $E_v$ was introduced and found a useful, gradation-specific variable to quantify the volumetric deformation associated with suffosion. The average unit rate of volumetric deformation increases with increasing particle size of the coarse component.

- Nine glass beads tests and three soil tests that exhibited a suffosive response, experienced substantial volumetric deformations in the absence of substantial axial deformations. Accordingly, measurement of total volume change is deemed necessary to avoid any mis-interpretation of the phenomenological response to seepage flow.

Discussion of the influence of effective stress on the onset of suffusion and suffosion established the following:

- The differential pore water pressure at the onset of suffosion increases with increasing mean effective stress. The findings of Chang and Zhang (2013), and a re-interpretation of tests of Moffat (2005), support this conclusion.
The onset of suffusion is not dependent on effective stress in glass beads or soil specimens that exhibit a transitional clast-supported micro-structure with $S_f \leq 0.25$.

Discussion of the influence of the micro-structure on suffusion and suffosion yielded the following conclusions:

- A suffusive response was identified in glass beads gradations with $D'_1/d'_{85} > 5$, and $S_f < 0.25$, whereas a suffusive response was identified in glass beads gradations with $D'_1/d'_{85} > 5$ and $0.25 \leq S_f \leq 0.40$.

- A suffusive response was identified in soil gradations with $0.15 \leq S_f \leq 0.35$ and $D'_1/d'_{85} > 5$, similar to the glass beads gradations. The particle shape has a profound influence on the susceptibility to suffosion: a suffusive response was identified in soil gradations with $0.30 \leq S_f \leq 0.40$, and $D'_1/d'_{85} > 8$.

- A novel procedure is proposed to determine the portion of load-bearing fine particles in micro-structures of gap-graded gradations. The procedure was validated using the DEM simulations of Shire and O’Sullivan (2013), and it yielded a very good estimate of the portion of non-load bearing fine particles in clast-supported and transitional clast-supported micro-structures, and a reasonable estimate of the portion of non-load bearing fine particles in transitional matrix-supported micro-structures.

- The findings indicate that: nearly all finer fraction is non-load bearing in a clast-supported micro-structure; a substantial portion of the finer fraction is load-bearing in a transitional clast-supported micro-structure; and that a substantial portion of the finer fraction in a transitional matrix-supported micro-structure is non-load bearing.

- The portion of non-load bearing fine particles, determined using the novel procedure, appears a useful parameter to quantify the potential for particle migration in gap-graded gradations: a greater portion of non-load bearing fine particles is associated with a greater increase of hydraulic conductivity at the end-of-test.

- The novel concepts of a modified inter-coarse state parameter $\Psi_s$ and a inter-fine state parameter $\Psi_f$ are introduced. The comparison of soil and glass beads tests indicates that the proposed state parameters are predictors of the relative susceptibility to suffosion, independent of particle shape: $\Psi_f$ is a characteristic state parameter of transitional and transitional matrix-supported micro-structures, and $\Psi_s$ is a characteristic state parameter of a transitional clast-supported micro-structure.

Discussion on the influence of particle shape yields the following conclusions:

- The comparison between tests on glass beads and soil gradations with $S_f = 0.20$, established that the particle shape does not significantly affect the response of the materials.
with transitional clast-supported micro-structure. It is postulated that the constrictions of the glass beads and soils are of a similar size in these transitional clast-supported micro-structures.

- The comparison between tests on glass beads and soil gradations with $S_f = 0.35$ demonstrates that sub-angular particles result in a transitional micro-structure that is more resistant to collapse than a similar micro-structure of glass beads. The greater resistance of micro-structures of sub-angular particles, is attributed to the greater resistance against particle rotation, and contact slipping, of sub-angular particles.

Finally, a unified approach is presented to characterise suffosion in the domain of mean effective stress, differential pore water pressure across the specimen, and volumetric deformation. The approach unifies the notion of a hydro-mechanical boundary at the onset of suffosion, and a hydro-mechanical boundary at seepage-induced failure of internally unstable gradations.

7.2 Novel contributions

The most important contributions of this investigation comprise a conceptual framework, measurement of total volume change in a flexible wall permeameter, and insights into the factors governing suffusion and suffosion:

- A conceptual framework, based on an extensive literature review, is developed such that a distinction can be reasonably made between suffusion and suffosion. Suffusion is defined as “a seepage-induced mass loss without change in volume, or a with small non-progressive change in volume, accompanied by an increase of hydraulic conductivity”. Suffosion is defined as “a seepage-induced mass loss accompanied by a reduction in volume and change in hydraulic conductivity”.

- A flexible wall permeameter comprising a double-walled triaxial cell, a seepage control system; and instrumentation has been designed, built and commissioned. A novel feature of the flexible wall permeameter, is the measurement of total volume change, using a technique adopted from Wheeler (1986). Measurement of total volume change is necessary to avoid any mis-interpretation of the phenomenological response to seepage flow. The average unit rate of volumetric deformation $E_v$ is introduced as a variable to characterise suffosion.

- The differential pore water pressure across the specimen at the onset of suffosion increases with increasing mean effective stress, which confirms the previous finding of Chang and Zhang (2013). The differential pore water pressure across the specimen at the onset of suffusion is independent of effective stress for gradations with $S_f \leq 0.25$, which expands the finding of Crawford-Flett (2014) into the domain of the soils.
• In a further advance of the concepts of Thevanayagam et al. (2002), a novel procedure is proposed to determine the portion of load-bearing fine particles in micro-structures of gap-graded gradations. It was established that: nearly all fine particles are non-load bearing in clast-supported micro-structures; a substantial portion of the fine particles is load-bearing in transitional clast-supported micro-structures; and a substantial portion of the fine particles in transitional matrix-supported micro-structures is non-load bearing.

• The novel concepts of the modified inter-coarse state parameter $\Psi_s$ and the inter-fine state parameter $\Psi_f$ are introduced, as another advance of the concepts of Thevanayagam et al. (2002). The state parameters are good indicators of the relative susceptibility to suffosion.

• The particle shape does not significantly affect the response of specimens with a transitional clast-supported type micro-structure at $S_f = 0.20$. However, sub-angular particles of gradations with $S_f = 0.35$ result in a transitional micro-structure that is more resistant to collapse that a similar particle arrangement of glass beads.

• A unified approach to characterise suffosion is provided.

### 7.3 Recommendations

The following recommendations are made to improve the flexible wall permeameter as an investigative tool:

• It is recommended to increase the maximum head than can be imposed, so that inherently stable specimens can be taken to fluidisation. It is further recommended to improve control of the hydro-mechanical loading path, by incorporating feedback systems in the seepage control system, the axial loading system and the cell pressure system, which would allow strength testing of the soil, post-seepage flow.

• The range of the volume change measurement device in this study, was limited to attain a high accuracy and resolution, necessary to detect the onset of suffosion. It is recommended to extend the range of the volume change measurement device, whilst maintaining sufficient accuracy and resolution, so that the extent of failure can be investigated.

The following recommendations are made concerning future studies on factors governing suffusion and suffosion:

• Given the influence of effective stress on the onset of suffosion, it is believed prudent to study the influence of the hydro-mechanical loading path, including anisotropic consolidation, on the onset of suffosion.
• This study was limited to gap-graded gradations. It is recommended to expand the investigation on the factors governing suffusion and suffosion to broadly graded soils.

• It is recommended to verify that the findings of this study are also valid for particle packings prepared using different reconstitution techniques, such as moist tamping or compaction.

7.4 Implications for practice

The findings of this investigation yield several implications for advanced laboratory testing, discrete element modelling, and dam safety management. Considering the localised nature of the volume change associated with suffosion, which can exhibit in the absence of axial deformation, measurement of the total volume change is necessary to avoid any mis-interpretation of the phenomenological response to seepage flow. Accordingly, caution is warranted when deriving seepage-induced volumetric deformations from measurements of radial strains or photographic measurements. Flexible wall permeameters, which permit independent control of effective stress, and hydraulic load, and measurement of total volume change, are thus recommended for future investigations of seepage-induced internal instability.

Studies using Discrete Element Models have examined aspects of the fabric of internally unstable materials, using spherical particles. The findings of this investigation demonstrate that the particle shape has a profound influence on the stability of the micro-structures of certain gap-graded materials, which appears to govern the seepage-induced internal instability phenomenon. Simulations using Discrete Element Modelling should account for the effect of particle shape.

Finally, concerning dam safety management, the distinction between the phenomena of suffusion and suffosion should be acknowledged in the failure mode analysis of embankment dams and the foundation. Suffusion, which is migration of fine particles from a soil by seepage flow, in the absence of volume change, is independent of effective stress and may initiate at small hydraulic loads. Suffosion, which is seepage-induced collapse of the soil structure, is of concern in broadly graded soils, especially if the possibility of segregation exists. Suffosion initiates at small hydraulic loads that are dependent on effective stress. Given the insights into the micro-structures of specimens that exhibit suffusion or suffosion, it is believed prudent to re-evaluate the premise of empirical tools used to assess the susceptibility to suffusion and suffosion.


Sympatec (2008). “Windox operating instructions release 5.4.1.0.” → pages 13, 44


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USACE (1953). “Filter experiments and design criteria.” *Report No. AEWES-TM-3-360*, Army Engineer Waterways Experiment Station, Vicksburg, Mississippi. → pages[17 18 19 24]


Appendix A

Measurement uncertainty

ASTM E2655 (ASTM 2008) describes uncertainty as “an indication of the magnitude of error associated with a value that takes into account both systematic errors and random errors associated with the measurement or test process.” Accuracy is a commonly referenced when seeking to quantify the uncertainty of measured parameters. In this study, accuracy is defined as the standard deviation of the calibration data around the linear regression line. Precision characterises the statistical variability of a measured value; it is defined as the standard deviation of the measured value around the mean measured value and thus not related to the calibration of a measurement technique. Resolution quantifies the smallest significant change of a measured value that can be detected, for which no standard mathematical expression appears to exist (Polvino, 2011). Consider two identically shaped normal distributions with standard deviation $s$: one distribution with mean value $\bar{x}$ and a second distribution with mean value $\bar{x} + 4s$. Only the tail ends of 2.5% of the values of each distribution would overlap and the values can be satisfactorily distinguished within the 95% confidence intervals. Accordingly, the resolution is defined as four times the precision. The remainder of this Appendix describes how the accuracy of the measured values is determined, and how these measured uncertainties propagate into the uncertainties of derived quantities.

A.1 Uncertainty in measured quantities

A linear regression is derived from the calibration data, including an unbiased estimate of the uncertainty, as a standard deviation, $s_i$, of the calibration data around the linear regression line:

$$ (s_i)^2 = \frac{1}{n-1} \sum_{i=1}^{n} (z_i - \bar{z_i})^2 \quad (A.1) $$

with base variable $z_i$ and $\bar{z}_i$ = predicted value of variable $z_i$.

The uncertainties in the measured quantities, determined using Eq. [A.1] or assumed values, are presented in Tables A.1 and A.2.
A.2 Propagation of uncertainty

For this study, the method of propagation of uncertainties suggested by ASTM E2655 (ASTM, 2008) is followed. The parameters reported in this study, for example $p', q, e, v, i, k, e_a, e_v$, are typically derived from combinations of measured quantities. Determination of the uncertainty in the derived parameters is then a purely mathematical exercise, which can be simplified by assuming that: 1) errors in measurements of different variables are uncorrelated; and 2) errors are relatively small compared to measured or mean values (Ku, 1966). Based on these assumptions, the propagation of uncertainty in derived parameters can be approximated using the following equation:

$$
(s_x)^2 = \sum_{i=1}^{n} \left( \frac{\delta f}{\delta z_i} \right)^2 (s_i)^2
$$

(A.2)

where $s_x$ = standard deviation of derived variable $z_x$ which is defined by function; and $s_i$ = standard deviation of base variable $z_i$. The uncertainty of the derived variable is evaluated at the mean values of $z_i$. The uncertainty in the derived quantities is presented in Table A.3.
<table>
<thead>
<tr>
<th>Measured quantity</th>
<th>Unit</th>
<th>Typical value</th>
<th>Standard deviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specimen length</td>
<td>mm</td>
<td>100</td>
<td>2</td>
<td>Uncertainty in determining specimen length between top and bottom wire meshes</td>
</tr>
<tr>
<td>Specimen diameter</td>
<td>mm</td>
<td>100</td>
<td>0.2</td>
<td>Uncertainty in determining internal diameter of split mold using a vernier caliper</td>
</tr>
<tr>
<td>Axial deformation</td>
<td>mm</td>
<td>0 to 15</td>
<td>0.01</td>
<td>Calibration uncertainty of LVDT</td>
</tr>
<tr>
<td>Water level in measurement burette</td>
<td>mm</td>
<td>NA</td>
<td>1</td>
<td>Measurement uncertainty of manual reading of water level in measurement burette</td>
</tr>
<tr>
<td>Specimen mass</td>
<td>g</td>
<td>1200 to 1500</td>
<td>0.5</td>
<td>Sum of balance resolution and potential for mass loss during specimen transfer</td>
</tr>
<tr>
<td>Mass of collected water in manual discharge measurement</td>
<td>g</td>
<td>200 to 2000</td>
<td>1</td>
<td>Sum of balance resolution and potential for moisture remaining in container between measurements</td>
</tr>
<tr>
<td>Mass of top cap</td>
<td>g</td>
<td>1234</td>
<td>1</td>
<td>Measurement uncertainty of mass of top cap</td>
</tr>
<tr>
<td>Test duration</td>
<td>h</td>
<td>2 to 8</td>
<td>1/3600</td>
<td>Measurement uncertainty of manual time measurement</td>
</tr>
<tr>
<td>Elapsed time in manual discharge measurement</td>
<td>s</td>
<td>120 to 600</td>
<td>1</td>
<td>Measurement uncertainty of manual time measurement</td>
</tr>
</tbody>
</table>
Table A.2: Uncertainty in measured quantities (Part 2 of 2).

<table>
<thead>
<tr>
<th>Measured quantity</th>
<th>Unit</th>
<th>Typical value</th>
<th>Standard deviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross sectional area of measurement burette #1</td>
<td>cm²</td>
<td>1.27</td>
<td>0.02</td>
<td>Measurement uncertainty based on five measurements</td>
</tr>
<tr>
<td>Cross sectional area of measurement burette #2</td>
<td>cm²</td>
<td>0.472</td>
<td>0.003</td>
<td>Measurement uncertainty based on five measurements</td>
</tr>
<tr>
<td>Cell pressure in TPT #1</td>
<td>kPa</td>
<td>0-150</td>
<td>0.2</td>
<td>Calibration uncertainty of TPT #1</td>
</tr>
<tr>
<td>Pore water pressure in TPT #2</td>
<td>kPa</td>
<td>0-150</td>
<td>0.5</td>
<td>Calibration uncertainty of TPT #2</td>
</tr>
<tr>
<td>Differential pressure in DPT #1</td>
<td>cmH₂O</td>
<td>0-160</td>
<td>0.1</td>
<td>Calibration uncertainty of DPT #1</td>
</tr>
<tr>
<td>Differential pressure in DPT #2</td>
<td>cmH₂O</td>
<td>0-40</td>
<td>0.016</td>
<td>Calibration uncertainty of DPT #2</td>
</tr>
<tr>
<td>Calibration factor of time-dependent volume change of inner chamber</td>
<td>cm³/h</td>
<td>0.036</td>
<td>0.025</td>
<td>Determined based on ten calibration measurements</td>
</tr>
<tr>
<td>Constant for proportionality of membrane penetration per unit area</td>
<td>kg/cm²</td>
<td>0.016</td>
<td>0.004</td>
<td>Determined from six measurements of membrane penetration</td>
</tr>
<tr>
<td>Density of solids</td>
<td>g/cm³</td>
<td>2.5 and 2.7</td>
<td>0.01</td>
<td>Measurement variation based on three tests for GB and BT materials, respectively.</td>
</tr>
<tr>
<td>Derived quantity</td>
<td>Unit</td>
<td>Typical value</td>
<td>Standard deviation</td>
<td></td>
</tr>
<tr>
<td>-------------------------------------------------------</td>
<td>------</td>
<td>---------------</td>
<td>--------------------</td>
<td></td>
</tr>
<tr>
<td>mean effective stress, $p'$</td>
<td>kPa</td>
<td>50</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>150</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>deviatoric stress, $q$</td>
<td>kPa</td>
<td>0</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>void ratio at the end of consolidation, $e$</td>
<td>-</td>
<td>0.50</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>axial strain, $\varepsilon_a$</td>
<td>%</td>
<td>0.00</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.5</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>volume change, $\Delta V$</td>
<td>cm$^3$</td>
<td>0.0</td>
<td>0.18</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>24.0</td>
<td>0.24</td>
<td></td>
</tr>
<tr>
<td>volumetric strain, $\varepsilon_v$</td>
<td>%</td>
<td>0.00</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.00</td>
<td>0.07</td>
<td></td>
</tr>
<tr>
<td>hydraulic gradient, $i$</td>
<td>-</td>
<td>0.00</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10.00</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>specific discharge, $v$</td>
<td>cm/s</td>
<td>0.0040</td>
<td>0.0004</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.20</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>hydraulic conductivity, $k$</td>
<td>cm/s</td>
<td>0.020</td>
<td>0.002</td>
<td></td>
</tr>
</tbody>
</table>
Appendix B

Membrane compliance

B.1 Measurement of membrane compliance

In the experimental procedure, volume change is measured using two different techniques (see Fig. 3.3): during consolidation of the specimen, volume change is measured in a measurement burette, whereas volume change of the specimen during multi-stage seepage flow is deduced from measurement of volume change of the cell fluid. The effective stress in the specimen changes during both stages, which necessitates the volume change as a consequence of membrane compliance be accounted for:

\[ \Delta V_t = \Delta V_m + \Delta V \]  

where \( \Delta V_t \) = total measured volume change, including membrane compliance, \( \Delta V_m \) = volume change resulting from membrane compliance, and \( \Delta V \) = volume change of the specimen.

Frydman et al. (1973) measured the volumetric deformations of three uniform glass beads materials in both a triaxial apparatus and hollow cylinder apparatus and deduced the membrane compliance from the difference in volume change measured in both devices. The results indicated that for a given particle size, the membrane penetration per unit area, \( \Delta v_m \) in [cm\(^3\)/cm\(^2\)], is directly proportional to the logarithm of the cell pressure. The constant of proportionality was defined as slope \( S_m \) (see Fig. B.1).

The membrane penetration per unit area, \( \Delta v_m \) is defined as:

\[ \Delta v_m = \frac{\Delta V_m}{A_m} \]  

where \( A_m \) = soil surface covered by the membrane.
Vaid and Negussey (1984) proposed two methods to determine the membrane compliance in a triaxial apparatus. The first method, Method 1, requires data from tests on at least two specimens of different diameter. Method 2, which was validated using the results of Method 1, can be included during the consolidation stage of a test: assuming isotropy of the specimen during unloading, the membrane penetration per unit area can be determined as the difference between the measured volume change, \( \Delta V_t \) and an ‘expected’ volume change during unloading, which is calculated assuming:

\[
\varepsilon_{v,u} = 3 \varepsilon_{a,u} \quad \text{(B.3)}
\]

where \( \varepsilon_{a,u} \) = axial strain during isotropic unloading and \( \varepsilon_{v,u} \) = volumetric strain during isotropic unloading.

The constant for proportionality of membrane penetration per unit area, \( S_m \) can then be determined by:

\[
S_m = \frac{(\Delta V_t - \varepsilon_{a,u} V) / A_m}{\log_{10} (\sigma_{c,f} / \sigma_{c,i})} \quad \text{(B.4)}
\]

where \( \sigma_{c,f} \) = final cell pressure, \( \sigma_{c,i} \) = initial cell pressure, and \( V \) = specimen volume.

The constant for proportionality of membrane penetration per unit area has been determined for three tests on GB material and BT material, respectively, see Table B.1 and Fig. B.1 with particle size \( d = D'_50 \) of the coarse fraction. The variability of the membrane compliance is attributed to the binary nature of the particle size distributions. The values determined for \( S_m \) of binary mixtures with \( S_f \leq 35 \% \) appear in reasonable agreement with the findings of Frydman et al. (1973) if \( d'_50 \) of the fine fraction is taken as the governing particle size.

### B.2 Effect of membrane compliance in this study

Analysis of the parameter space of typical values of the test variables in this research, yield insights into the relative contribution of membrane compliance to the volume changes during consolidation and during multi-stage seepage flow. Consider the following materials, which represent the limits of the materials tested: 1) material A has a relatively high (for this study) void ratio, not corrected for membrane compliance, \( e = 0.51 \) and \( d'_50 = 0.15 \) mm; and 2) material B has a relatively low void ratio, not corrected for membrane compliance, \( e = 0.25 \) and \( d'_50 = 0.15 \) mm. The typical specimen dimension is \( V \approx 785 \text{ cm}^3 \). The specimen consolidates under the increase of the cell pressure from \( \sigma_c \approx 20 \text{ kPa} \) to 150 kPa. Using Eqs. B.1, B.2 and B.4, and selecting \( S_m \) according to Fig. B.1 the effect of the membrane penetration on the void ratio of both materials can be calculated: \( e = 0.511 \), assuming \( S_m = 0.002 \), and \( e = 0.250 \), assuming \( S_m = 0.002 \text{ kg/cm}^2 \), for materials A and B, respectively. Hence, the void
Table B.1: Measurement of membrane compliance.

<table>
<thead>
<tr>
<th>Test</th>
<th>$S_m$ (kg/cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.8GB20-100</td>
<td>0.0031</td>
</tr>
<tr>
<td>4.8GB20-150</td>
<td>0.0055</td>
</tr>
<tr>
<td>4.8GB35-150</td>
<td>0.0046</td>
</tr>
<tr>
<td>5.1BT20-150</td>
<td>0.0012</td>
</tr>
<tr>
<td>7.0BT20-100</td>
<td>0.0062</td>
</tr>
<tr>
<td>7.0BT20-150</td>
<td>0.0061</td>
</tr>
</tbody>
</table>

Figure B.1: Membrane compliance: variation between particle size and constant of proportionality of membrane penetration per unit area (source: Frydman et al., 1973. Reprinted, with permission, from the Journal Testing and Evaluation 1(1) (1973), copyright ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19428).

The ratio would be estimated as 0.1% and 0.3% too low for materials A and B respectively, if the membrane compliance was ignored. The change of the principle effective stress during multi-stage seepage flow is less than 10 kPa. For materials A and B, if isotropically consolidated to 50 kPa, the volume change associated with membrane compliance resulting from $\Delta p' = 10$ kPa is approximately $0.03 \text{ cm}^3$, equivalent to $\varepsilon_v = 0.004 \%.$
Appendix C

Variation of effective stress during multi-stage seepage flow

The test procedure adopted in this investigation commences with specimen preparation, followed by consolidation in stage 1 and multi-stage upward seepage flow in stage 2. In stage 1, the specimen is isotropically consolidated to a mean effective stress $p'_{c}$. In stage 2, the specimen is subject to an in discrete increments increasing pore water pressure at the bottom of the specimen as a result of the inflow constant-head device (see Fig. 3.1) being raised. The elevation of the outflow constant-head device remains constant, which yields a constant pore water pressure at the top of the specimen: the difference in pore water pressure between the top and bottom of the specimen is $\Delta u$. Accordingly, the mean effective stress at the top of the specimen remains constant throughout the test, while the mean effective stress at the bottom of the specimen decreases with each subsequent stage of seepage flow. The mean effective stress at the centre of the specimen $p'$ is reported in the test results, which thus decreases with subsequent stages of seepage flow according to:

$$p' = p'_{c} - \frac{\Delta u}{2}$$

(C.1)

C.1 On the scale effect of hydraulic gradient

Li and Fannin (2012) inferred the existence of a ‘scale effect’ in reporting the results of seepage-induced internal instability tests on specimens of different lengths. Consider two elements of different length (see Fig. C.1). A small element, with length $\Delta z$ is isotropically consolidated to $p'_{c}$. When subject to upward seepage flow, ultimately fluidisation of the element would occur if the mean effective stress at the bottom of the element reduces to zero, which yields the differential pressure at the onset of fluidisation $\Delta u_{f} = p'_{c}$. The corresponding hydraulic gradient $i_{f}$ and mean principle effective stress $p'_{f}$ at the onset of fluidisation of the element with length
\( \Delta z \) are:

\[
i_f(\Delta z) = \frac{\Delta u_f}{\Delta z \gamma_w}
\]  \hspace{1cm} (C.2)

\[
p'_f = p'_c - \frac{1}{2} \Delta u_f = \frac{1}{2} p'_c
\]  \hspace{1cm} (C.3)

Now consider a larger element with length \((n \Delta z)\) isotropically consolidated to the same value of \(p'_c\). Fluidisation would still occur at the same values of \(\Delta u_f = p'_c\) and \(p'_f = 1/2\ p'_c\) as identified prior for the element with length \(\Delta z\). However, the corresponding hydraulic gradient across the element with length \((n \Delta z)\) would be:

\[
i_f(n\Delta z) = \frac{\Delta u_f}{n \Delta z \gamma_w} = \frac{i_f(\Delta z)}{n}
\]  \hspace{1cm} (C.4)

Hence, when reporting the conditions at the onset of fluidisation in terms of hydraulic gradient, for elements of different length, a scale effect may be observed. Li (2008) actually reported this effect when comparing the conditions at failure, obtained from tests in a large and a small rigid wall permeameter, respectively. The apparent scale effect can thus be attributed to the selection of the hydraulic gradient, which is a measure of the drag force per unit volume (see Section 2.3), instead of the use of the differential pore water pressure across the specimen, which is a measure of the seepage-induced change of effective stress.
Fluidisation if:
\[ \Delta u_i = p'_c \]

equivalent to

\[ i_i(\Delta z) = \Delta u_i / (\Delta z \gamma_w) \]

at

\[ p'_f = p'_c - \Delta u_i / 2 \]

Fluidisation if:
\[ \Delta u_i = p'_c \]

equivalent to

\[ i_i(n \Delta z) = \Delta u / (n \Delta z \gamma_w) = i_i(\Delta z) / n \]

at

\[ p'_f = p'_c - \Delta u_i / 2 \]

Figure C.1: Scale effect of hydraulic gradient.
Appendix D

Forensic observations

The forensic evidence compiled in this Appendix comprises visual observations (Section D.1) and post-test particle size analyses (Section D.2).

D.1 Visual observations

Visual observations were recorded to examine the nature of the volumetric deformations, through the walls of the water bath and the acrylic tubes, at the end of the tests as a “front view” and a “side view”, using a digital camera. The quintessential observations presented in Figs. D.8 and D.10 have been annotated to aid in the identification of the nature of the deformations. In addition, photographs were taken of the top surface of the post-test specimen during the forensic analysis. A selection of these images is presented in this Appendix as supporting evidence for the analysis of the test results reported in Chapter 5.
Figure D.1: 4.8GB35-50: end-of-test side view shows small sign of local distress, near the top cap.
Figure D.2: 6.0GB25-50: end-of-test front view shows signs of local distress at the top half of the specimen.
**Figure D.3:** 6.0GB30-50: end-of-test front view shows clear signs of local distress on the right side.
Figure D.4: 6.0GB30-150: end-of-test side view shows clear signs of local distress.

Figure D.5: 6.0GB30-150: top view, after dis-assembly of the device.
Figure D.6: 6.0GB35-50: end-of-test side view shows clear signs of distress.

Figure D.7: 6.0GB35-50: top view, after dis-assembly of the device, shows an abundance of fine particles.
**Figure D.8:** 6.0GB35-100: end-of-test side view shows clear signs of local distress.

**Figure D.9:** 6.0GB35-100: top view, after dis-assembly of the device, shows an abundance of fine particles.
Seepage-induced deformation

Top cap

Specimen

Base pedestal

Figure D.10: 6.5GB35-100: end-of-test side view.

Figure D.11: 6.5GB35-100: top view, after dis-assembly of the device, shows an abundance of fine particles.
**Figure D.12:** 10.4BT25-50: end-of-test side view shows coarse particles at the top half of the specimen protruding under the membrane.

**Figure D.13:** 10.4BT25-50: top view, after dis-assembly of the device, shows an abundance of fine particles.
Figure D.14: 10.4BT30-50: end-of-test front view shows coarse particles at the top half of the specimen protruding under the membrane.
**Figure D.15**: 10.4BT30-50: top view, after dis-assembly of the device, shows an abundance of fine particles.
Figure D.16: 10.4BT35-50: end-of-test side view, shows signs of local distress near the top cap.
Figure D.17: 10.4BT35-50: top view, after dis-assembly of the device, shows an abundance of fine particles.
Figure D.18: 10.4BT35-50(R): end-of-test side view, shows signs of local distress at the top half of the specimen.
Figure D.19: 10.4BT35-50(R): end-of-test front view shows signs of local distress at the right side of the specimen.
Figure D.20: 10.4BT35-50(R): top view, after dis-assembly of the device, shows an abundance of fine particles.
Figure D.21: 10.4BT35-100: end-of-test side view, shows signs of local distress on the left side of the specimen.
Figure D.22: 10.4BT35-100: end-of-test front view, shows signs of local distress at the right side of the specimen.
D.2 Post-test particle size analyses

For nearly all tests, a forensic particle size analysis was performed on the specimens at the end of a test. The procedure was as follows: (i) following the end of the test, the cell pressure was gradually reduced to $\sigma_c \approx 20$ kPa; (ii) all valves were closed, yielding an undrained specimen and a vacuum pressure of $u \approx -20$ kPa was applied through measurement burette #1 and the cell pressure reduced to atmospheric pressure; (iii) the triaxial cell was carefully disassembled and the water level in the water bath lowered to below the bottom of the specimen; (iv) the forming mold was then placed around the specimen and the vacuum on the specimen was subsequently released; (v) the top cap was removed and the specimen was dessicated in three to five layers using a siphoning device; (vi) the materials from the dessicated layers were oven-dried, manually sieved, after which the mass of the components was recorded. Occasionally, the mold could not be placed around the specimen, which is attributed to the seepage-induced deformations or deformations that occurred during dis-assembly of the triaxial cell. In these cases, no post-test particle size analyses were conducted.
Figure D.23: 3.3GB20-50: post-test particle size analyses.

Figure D.24: 4.8GB20-150: post-test particle size analyses.

Figure D.25: 4.8GB35-100: post-test particle size analyses.
Figure D.26: 4.8GB35-150: post-test particle size analyses.

Figure D.27: 6.0GB20-50: post-test particle size analyses.

Figure D.28: 6.0GB20-100: post-test particle size analyses.
Figure D.29: 6.0GB20-150: post-test particle size analyses.

Figure D.30: 6.0GB25-150: post-test particle size analyses.

Figure D.31: 6.0GB30-150: post-test particle size analyses.
Figure D.32: 6.0GB35-100(R): post-test particle size analyses.

Figure D.33: 6.0GB35-150: post-test particle size analyses.

Figure D.34: 6.5GB35-50: post-test particle size analyses.
Figure D.35: 6.5GB35-100: post-test particle size analyses.

Figure D.36: 5.1BT20-50: post-test particle size analyses.

Figure D.37: 5.1BT20-150: post-test particle size analyses.
Figure D.38: 5.7BT20-50: post-test particle size analyses.

Figure D.39: 5.7BT20-100: post-test particle size analyses.

Figure D.40: 5.7BT20-150: post-test particle size analyses.
Figure D.41: 5.7BT35-100: post-test particle size analyses.

Figure D.42: 7.0BT20-50: post-test particle size analyses.

Figure D.43: 7.0BT20-150: post-test particle size analyses.
**Figure D.44**: 8.6BT20-50: post-test particle size analyses.

**Figure D.45**: 10.4BT25-50: post-test particle size analyses.

**Figure D.46**: 10.4BT30-50: post-test particle size analyses.
**Figure D.47:** 10.4BT35-50(R): post-test particle size analyses.

**Figure D.48:** 10.4BT35-100: post-test particle size analyses.