ON THE FEASIBILITY OF MOUNTING BENDER ELEMENTS IN A

FLEXIBLE WALL PERMEAMETER

by

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Abstract

Zoned embankment dams comprise some of Canada’s largest and most important infrastructure. A phenomenon that has emerged in recent times as a matter of concern for dam safety risk management is seepage-induced internal erosion in embankment dams and their foundations. A candidate method of monitoring the progression of internal erosion in the field is that of crosshole shear wave velocity measurement. To inform the interpretation of shear wave velocity data, the relation between change in shear wave velocity and occurrence of internal erosion must be characterized.

This study examines the feasibility of equipping a flexible wall permeameter (FWP) with bender elements in order to measure shear wave velocity. Bender elements were designed and fabricated with a custom mounting system and a FWP was upgraded to accommodate the bender elements. The study was devised to determine if the changes made to the FWP device, including a 6% reduction in the cross-sectional area available for flow, affect the seepage regime through the test specimen or internal erosion of its finer fraction, from tests conducted on three different gradations of glass beads. Comparisons of tests performed with and without bender elements indicate no systematic change to the seepage regime or the internal erosional response of the specimens. Thus, the inclusion of bender elements in the flexible wall permeameter, for purposes of shear wave velocity measurements, appears feasible.
Lay Summary

Embankment dams comprise some of Canada’s largest and most important infrastructure. A phenomenon that has emerged in recent times as a matter of concern for dam safety risk management is internal erosion. Seismic testing has emerged as a potential method of monitoring the progression of this phenomenon in the field.

This study helps address the research need of further understanding the relation between field seismic testing results and changes to the condition of the soils in the dam caused by the phenomenon. A state-of-the art device to study the internal erosion phenomenon in a controlled laboratory environment was developed in past research at UBC. Of interest is inserting new equipment into the existing device to allow for a laboratory analog of the field seismic tests. This study found that it is feasible to insert the new equipment without compromising the ability to obtain past results using the device.
Preface

This thesis is original and unpublished and is the work of the author, Adam Thomas Morgan Silvester.
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**List of Symbols**

\( \rho \) – material density

\( \varphi \) – piezometric head

\( \gamma_w \) – unit weight of water

\( csae \) – cross-sectional area at the exit boundary of a flexible wall permeameter specimen

\( C_c \) – coefficient of curvature

\( C_u \) – coefficient of uniformity

\( d_0 \) – particle diameter at 0\% mass passing in a sieve analysis, smallest particle size of a gradation

\( d_{15} \) – particle diameter at 15\% mass passing in a sieve analysis

\( d_{50} \) – particle diameter at 50\% mass passing in a sieve analysis

\( d_{85} \) – particle diameter at 85\% mass passing in a sieve analysis

\( d_{100} \) – particle diameter at 100\% mass passing in a sieve analysis, largest particle size of a gradation

\( d'_{85} \) – particle diameter at 85\% mass passing for the finer fraction of a gradation

\( D'_{15} \) – particle diameter at 15\% mass passing for the coarser fraction of a gradation

\( D'_{50} \) – particle diameter at 50\% mass passing for the coarser fraction of a gradation

\( D'_{15}/d'_{85} \) – particle size ratio of the coarse and fine fractions of a gradation

\( e \) – void ratio

\( e_c \) – void ratio after consolidation

\( e_{\text{min}} \) – minimum void ratio of a gradation

\( e_{\text{max}} \) – maximum void ratio of a gradation

\( \varepsilon_a \) – axial strain of the specimen

\( \varepsilon_v \) – volumetric strain of the specimen

\( G_s \) – specific gravity
\( i \) – hydraulic gradient across the specimen

\( i_{so} \) – hydraulic gradient at the onset of suffosion

\( i_{su} \) – hydraulic gradient at the onset of suffusion

\( k \) – hydraulic conductivity of the specimen

\( k_{avg} \) – average hydraulic conductivity of a permeameter test

\( k_i \) – initial hydraulic conductivity of a permeameter test

\( k_f \) - final hydraulic conductivity of a permeameter test

\( k_{max} \) – maximum hydraulic conductivity of a permeameter test

\( k_{min} \) – minimum hydraulic conductivity of a permeameter test

\( l \) – length of specimen

\( L_s \) – Reynolds number length scale

\( n \) – porosity of specimen

\( p' \) – mean effective stress in the specimen

\( p'_{c} \) – mean effective stress at the end of consolidation

\( P \) – polarization

\( Q \) – flow discharge

\( R \) – particle roundness

\( R_e \) – Reynolds number

\( S_f \) – finer fraction content

\( t \) – test duration

\( \Delta t \) – stage duration

\( u \) – water pressure

\( v \) – fluid velocity or specific discharge
νₛ — seepage velocity

νₛ Re = 1 — theoretical seepage velocity at the upper limit of the Darcian flow regime
List of Abbreviations

ASTM – American Society for Testing and Materials

BC – British Columbia

BEM – bender element mount

CDA – Canadian Dam Association

CPT – cone penetration test

DAQ – data acquisition

DEM – discrete element method

DO – dissolved oxygen

DPT – differential pressure transducer

EEP – expert engineering panel

FWP – flexible wall permeameter

I-CHD – inflow constant-head device

ICOLD – International Commission on Large Dams

I-CP – inner chamber port

GB – glass beads

LVDT – linear variable differential transformer

MP – measurement port

NI – National Instruments

NPT – national pipe thread

NSERC – National Sciences and Engineering Research Council of Canada

NRCan – National Resources Canada

O-CHD – outflow constant-head device
O-CP – outer chamber port

PC – personal computer

PVC – polyvinyl chloride

PWP – pore water pressure

RTV – room temperature vulcanization

SO – suffusion

SU – suffusion

TDH – total dynamic head

TPT – total pressure transducer

UBC – University of British Columbia

USACE – United States Army Corps of Engineers

USBR – United States Bureau of Reclamation

VI – virtual instrument

W.A.C. Bennett – William Andrew Cecil Bennett
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Chapter 1: Introduction

Zoned embankment dams are some of the largest and most important infrastructure in Canada. These examples of high consequence engineering, predominantly constructed between 1960 and 1985, generate a combined 375 TWh/year of electricity and place Canada among the world’s largest producers of hydro power (NRCan, 2016). Like all other ageing infrastructure, these dams occasionally exhibit signs of deterioration. In 1996, a sinkhole incident occurred at the W.A.C. Bennett Dam, a 183 m high dam in northern British Columbia (Stewart and Watts, 2000). Although the structural integrity of the dam was ultimately assured, the event directed the attention of BC Hydro and the people of British Columbia to the risk posed by ageing dam infrastructure. During investigation of the event, a likely contributing phenomenon to the disturbed zone underlying the sinkhole was identified as internal erosion (Stewart and Garner, 2000).

Internal erosion is a matter of growing concern in the practice of dam safety risk management (ICOLD, 2013). Correspondingly, it has become a focus of several recent laboratory studies conducted on embankment dam materials at the University of British Columbia (e.g. Moffat, 2005; Li, 2008; Crawford-Flett, 2014; Roos, 2014; Slangen, 2015). The outcomes of these works have included an improved understanding of the mechanisms involved, as well as advances in laboratory permeameter testing and interpretation. Rigid-wall permeameters have allowed for study of scalped gradations of dam materials and their response to varying confining stresses and hydraulic gradients (e.g. Moffat, 2005; Crawford-Flett, 2014). More generally, the use of flexible wall permeameters has allowed for greater stress control and the measurement of volumetric deformations of a representative soil element (e.g. Luo et al., 2012; Ke and Takahashi, 2014; Slangen, 2015). Field monitoring techniques have similarly advanced, and shear wave tomography has emerged as a promising tool for dam owners in the characterization of the internal erosion risk.
(Gaffran et al., 2000; Garner and Fannin, 2010; Hoeg et al., 2012). The method involves cross-hole shear wave velocity determinations on multiple planes of interest. One constraint in its use remains a limited understanding of the relation between the occurrence of internal erosion and changes in shear wave velocity. Intuitively, a change in the void ratio of a soil matrix will affect its stiffness and thus, its shear wave velocity; however, there is need to characterize the relation. High-quality laboratory data can be used to inform numerical and continuum mechanics-based models and develop a basis for the interpretation of shear wave velocity measurements collected in the field. Options for laboratory measurement of shear wave velocity are limited. Bender elements are a widely-used technology with an established history of installation within soil laboratory devices (Styler, 2014; Lee et al., 2008; Campbell, 2006; Kuwano and Jardine, 2002; Thomann and Hryciw, 1990) and thus, are well-suited to this study.

1.1 Scope and objectives of the thesis research

The work in this thesis represents a pilot study of the relation between the occurrence of internal erosion and resultant change, if any, in shear wave velocity. The primary goal of this laboratory study is to examine the feasibility of equipping the UBC flexible wall permeameter with bender elements, necessary for shear wave velocity measurement. Three research objectives arise from this goal: (1) modify the flexible wall permeameter to add the capacity for shear wave velocity measurement; (2) demonstrate the repeatability of results obtained using the modified flexible wall permeameter; and, (3) determine if the modifications made affect the ability to reproduce past results using the device.

1.2 Definitions

Definitions from ASTM E177 (2008) of key terms pertaining to inter- and intra-study comparisons of test results are as follows:
• **Precision**: the closeness of agreement between test results obtained from a measurement process.

• **Repeatability**: precision determined when the test method is conducted by a single operator using one set of equipment in a short period of time during which neither the environment nor the equipment changes appreciably. Sources of variability are limited to either small changes in conducting the test operations and variation of the measured property among test specimens.

• **Reproducibility**: precision determined when the test method is conducted by multiple operators, in different laboratories, and with different apparatuses.

• **Intermediate precision**: precision determined under conditions in-between repeatability and reproducibility conditions.

These are standardized terms adopted by ASTM with prescribed conditions. Comparisons to FWP test results from previous studies conducted at UBC, according to the ASTM definitions, are an examination of intermediate precision. The term *intra-laboratory reproducibility* is invoked herein to represent the reproduction of past results with a different operator, on a modified apparatus, in the same laboratory.

1.3 **Organization of the thesis**

The research is presented in seven chapters:

• Chapter one introduces the subject of internal erosion, laboratory testing of the phenomenon, and the knowledge gap in interpreting field monitoring data. The scope of this study, in context of the research needs and definitions of key terms, is described.
• Chapter two summarizes the elements of literature that pertain to this study, including the current conceptual framework of internal erosion, shear wave velocity testing at the W.A.C. Bennett Dam, and permeameter studies on seepage-induced internal instability.

• Chapter three describes the flexible wall permeameter used in this study, the modifications made to the device, and the revised test procedure (research objective No. 1). After introduction of the test device, the hypothesis of the study is stated.

• Chapter four describes the materials used in the laboratory investigation and introduces the testing program designed to test the hypothesis and meet the study objectives.

• Chapter five presents the results of the laboratory investigation, including repeated tests, and the associated analysis (research objective No. 2).

• Chapter six compares the results of the laboratory study to previous studies and reflects on the investigated hypothesis (research objective No. 3). Limitations of the investigation are also discussed.

• Chapter seven summarizes the findings of the study and discusses implications for future research.

Figures and tables are included at the end of the chapters in which they are referenced.
Chapter 2: Literature review

This chapter summarizes information pertinent to the study, obtained from a review of related literature. The phenomenon of internal erosion, along with the mechanisms and concepts involved, are introduced with reference to current terminology for the subject in Section 2.1. Then, details and implications of the W.A.C. Bennett Dam sinkhole incident are outlined in Section 2.2. Next, types of laboratory permeameters used to study internal erosion are introduced in Section 2.3. Finally, a brief synthesis is provided at the end of the chapter, in Section 2.4.

2.1 The phenomenon of internal erosion

Internal erosion is the migration of the finer fraction within a soil structure, or its foundation, as a consequence of ground water seepage flow. It is a phenomenon that varies both spatially and temporally, and is recognized as one of the leading causes of embankment dam failures (Foster et al, 2000). For new dams, the potential for internal erosion can be addressed through proper design and construction. However, many existing dams were built without an appreciation of the phenomenon and before the inception of now-accepted empirical design criteria (e.g. Kenney and Lau, 1985; Foster and Fell, 2001). The occurrence of internal erosion in these older structures is relatively greater and the risk is likely increasing with time. Under the auspices of a European working group within ICOLD, dam owners, engineering consultants, and research institutions around the world have compiled knowledge and concepts into a guide of practice for assessment of the risks presented by internal erosion to dam safety (ICOLD, 2015). The recognized mechanisms of internal erosion are outlined in Section 2.1.1. Internal instability is explained in greater detail in Section 2.1.2.
2.1.1 **Internal erosion mechanisms in embankment dams**

Internal erosion in embankment dams occurs when the hydraulic forces exerted by water seeping through the soil are sufficient to cause detachment and transport of particles out of the dam (ICOLD, 2015). It is a spatial and temporal phenomenon typically localized along flaws in embankment structures—such as cracks, holes, and material inconsistencies—where zones of relatively high seepage velocity can develop. The process of internal erosion in embankment dams has four general phases of progression (ICOLD, 2015): (i) initiation, (ii) continuation, (iii) piping/surface sloughing, and (iv) dam breaching. From a dam risk management perspective, characterization of the initiation of internal erosion is most critical to develop proactive screening tools and mitigation techniques for existing dams. The four primary mechanisms of initiation, adapted from ICOLD (2015) and USBR-USACE (2015), are:

i. **Concentrated leaks**: erosion, via leaking water, of the walls of openings that form in plastic soils due to differential settlement, desiccation, frost action, or poor construction.

ii. **Backward erosion**: retrogressive erosion commencing at a seepage exit point and eroding upstream, decreasing the flow path and increasing the hydraulic gradient. Depending on the material type, the flow may remain concentrated in eroded “pipes” or result in the collapse of overlying material.

iii. **Contact erosion**: erosion occurring at the boundary of two or more soils with incompatible gradations, i.e. a gravel in contact with a silt. Dams with poor filter and transition designs are subject to contact erosion.

iv. **Internal instability**: the transport of fine particles via seepage flow through the pores of coarse particles within a soil. Internally unstable materials are typically widely graded or gap-graded non-plastic soils.
The mechanisms of initiation do not act independently; dam failures from internal erosion typically involve a combination of two or more of the processes. For example, contact erosion between two soil units may result in higher hydraulic gradients which may trigger internal instability in one of the soils.

Internal instability is a unique internal erosion mechanism that may occur within a single zoned material without the influence of deficiencies in the dam structure or poor construction practices: some fluvial soils used in construction or present in dam foundations are naturally gap-graded (see Figure 2.1) and prone to the phenomenon (Pettijohn, 1949; Morgan and Harris, 1967).

2.1.2 A conceptual framework for internal instability

The terminology for internal instability is still evolving and there remains inconsistency in its use in practice. The terminology used herein, and suggested by the author for continued use, is that adopted by Fannin and Slangen (2014), and USBR-USACE (2015). Internal instability manifests itself in two distinct phenomenological responses (see Figure 2.2):

- **Suffusion**: the transport of fine particles in an internally unstable soil by seepage flow, not resulting in a change to the soil structure. The response is observed as an increase in hydraulic conductivity, accompanied by mass loss, in the absence of substantial volumetric change (Fannin and Slangen, 2014).

- **Suffosion**: the transport of fines particles in an internally unstable soil resulting in a collapse of the soil structure. The response is observed by a change in hydraulic conductivity, accompanied by mass loss and substantial volumetric contraction (Fannin and Slangen, 2014).
Thus, the two phenomenological responses occurring in internally unstable soils can be distinguished by volume change, which can be measured directly, and change in hydraulic conductivity, which can be deduced from measured hydraulic gradient and flow rate.

2.2 The W.A.C. Bennett Dam sinkhole incident

The 1996 W.A.C. Bennett Dam sinkhole incident has proven to be an important event influencing dam safety risk management of Canadian embankment dams. Moreover, internal erosion is believed to have played a role in the manifestation of the sinkhole incident. The onset, investigation, and subsequent remediation of the two sinkholes that were formed comprise a seminal case study for the development of performance monitoring programs and related analyses. At UBC, studies related to the incident have been ongoing for the better part of the last 15 years (Moffat, 2002). A detailed description of the incident is warranted for a comprehensive understanding of the research need for this study.

2.2.1 Description of the W.A.C. Bennett Dam

The W.A.C. Bennett Dam, or Portage Mountain Dam, was completed in 1967 as part of the Peace River project. At the time of its construction, the dam was the among the largest and highest embankment dams in the world, standing 183 m above bedrock (Stewart and Watts, 2000). A total of 44 million m$^3$ of earthfill material impounds the 360 km long Williston Reservoir (Ripley, 1967), making the W.A.C. Bennett Dam the largest dam operated by BC Hydro. It currently represents 30 percent of the utility’s generating capacity (Stewart and Watts, 2000).

The dam rests on a foundation of flat-lying, interbedded shales and sandstones. The structure of the dam is classified as a zoned sand-gravel fill. The cross-section is comprised of six primary zones (Figure 2.3): a wide central core of silty sand, Zone 1; a transition comprised of sand and gravel, between the core and the drain and between the drain and the downstream
shoulder, Zone 2; a sandy gravel filter between the upstream portion of the transition zone and the drain, Zone 3; a gravel chimney and blanket drain, Zone 4; a wedge of free draining gravel at the top of the upstream face, Zone 5; and shell material comprised of random gravelly sand, Zone 6. The material for the dam fill was sourced mostly from two adjacent terminal moraines, comprised of stratified sands and gravels with an average silt content of less than 10 percent (Ripley, 1967). Notable characteristics of the source moraines include a deficiency of coarser sand size in the 1 to 6 mm diameter range (see Figure 2.1), making gap-graded materials common, and the non-plastic nature of the silt content (Morgan and Harris, 1967). The moraine deposits were able to provide materials for Zone 6 without processing, for Zones 2 – 5 with minimal processing, and for the core after the addition of approximately 10 percent fines (Ripley, 1967).

Prevention of particle migration was recognized as an important design consideration. However, the management of the risk presented by the phenomenon was predominantly limited to simple principles based on judgement (Ripley, 1967). The controls put in place to avoid locally high hydraulic gradients within the dam fill included (Ripley, 1967): (i) a core width equal to water depth; (ii) wide transition zones; and (iii) reasonably gradual increases in permeability between zones.

2.2.2 1996 sinkhole incident

After construction, the W.A.C. Bennett Dam was operated without major incident for almost 30 years; however, in 1996, the dam revealed signs of deterioration. On June 14, a 2 m$^3$ cavity beneath the road surface was discovered atop the crest of the dam (Stewart and Watts, 2000). During subsequent Becker penetration testing to investigate material underlying the cavity, the ground collapsed a further 7 m, creating a 2.5 m diameter cylindrical pit centred around a survey benchmark tube used during construction. This sparked heightened concern and a 24-hour
surveillance program was immediately established. On June 24, precautionary drawdown of the reservoir commenced and 3000 m$^3$/s of water was released down the spillway (Stewart and Watts, 2000).

Under the guidance of Dr. R.B. Peck and Dr. N.R. Morgenstern, a detailed investigation and remediation plan was developed to characterize and treat the sinkhole (Stewart and Watts, 2000). The immediate safety status of the dam was assured through large-scale blanket drain tests, coincident with the sinkhole investigation. To minimize undue risks to dam safety during the investigation, where possible, non-intrusive geophysical methods of investigation were favoured over intrusive methods. Of the total of 14 geophysical techniques attempted, self-potential, downhole seismic velocity, and crosshole shear wave tomography were the most successful (Gaffran et al., 2000). Crosshole shear wave tomography proved particularly useful for delineating the impacted area (Watts et al., 2000). Of the intrusive investigation program, cone penetration testing (CPT) was the most suitable technique for characterizing the in-situ state of the core material, and sonic drilling the most useful technique for sampling (Stewart and Watts, 2000). Ultimately, the investigation program revealed a zone of disturbed, relatively loose zoned core material that extended to a depth of about 80 m, with an average diameter of 2.5 m (Watts et al., 2000). Additionally, during the investigation, a second smaller sinkhole was discovered upstream of the dam crest near the left canyon wall. It was characteristically similar to sinkhole No. 1, but varied in depth, density and lateral extent (Garner et al., 2000). The selected method for remediation of the sinkholes was compaction grouting. The process involves slow injection of a low slump, high friction angle grout into disturbed zones. The grout remains as an intact, cohesive bulb that slowly expands thereby displacing and compacting the surrounding soil in-situ (Garner
et al., 2000). A total of 85 m$^3$ and 57 m$^3$ of grout was injected into sinkholes No. 1 and 2, respectively.

The postulated cause of the sinkholes involves the combined influence of two primary factors: (i) persistently high pore water pressures within the core of the dam attributed to the presence of ex-solved air at the downstream face of the core (Sobkowicz et al, 2000); and (ii) the positioning of a splitter dike comprised of Zone 6 material in direct contact with a portion of the core. It is hypothesized that the resulting hydraulic gradients—up to 4—across the interface of the internally unstable splitter dike and the downstream drain material initiated internal erosion. Then, the mechanism possibly retrogressed into the core of the dam and up the material surrounding the benchmark tube (Stewart and Garner, 2000).

2.2.3 Performance monitoring with shear wave tomography

To track changes to the disturbed zones from compaction grouting, crosshole shear wave tomography was performed before, during, and after remediation. Significant increases to shear wave velocities were observed, indicating increases in density (Garner et al., 2000) and, after the grouting program was complete, the disturbed areas surrounding the sinkholes could no longer be delineated. Shear wave tomography proved such a valuable technique during the investigation and remediation of the W.A.C. Bennett Dam sinkholes that BC hydro implemented the technology as part of the ongoing performance monitoring of the dam (Hoeg et al., 2012). Eight observation wells are used to perform periodic cross-hole shear wave velocity measurements, developing a spatial and temporal database. The information collected provides valuable insight into the in-situ density and effective stress conditions and consequently, the 2012 Expert Engineering Panel (EEP) review of the dam encouraged further development of the technique (Hoeg et al., 2012).
2.3 Laboratory permeameter testing on internal instability phenomena

Although field measurements provide data on the in-situ conditions, the challenge of developing useful and appropriate analyses to reduce the data into representative quantities is best-suited for a controlled laboratory environment. Permeameters are the most common method of studying internal instability phenomena in the laboratory: specimens are reconstituted within a cell and a differential hydraulic pressure is imparted across the specimen using two constant head reservoirs or equivalent. Flumes are another common device used to study internal erosion (e.g. Elkholy et al., 2015; Okeke and Wang, 2016), but permeameters can be used to study a representative soil element and thus, better inform continuum-based approaches to the problem.

Laboratory permeameter technology has progressed. However, the fundamental theoretical concepts still remain founded on the early works of Darcy (1856, as cited in Bear, 1972). Darcy’s law states that the discharge velocity, \( v \), through a granular material is equal to:

\[
v = \frac{Q}{A} = ki
\]  

Where \( Q \) is flow discharge, \( A \) is discharge area, \( k \) is the hydraulic conductivity of the specimen, and \( i \) is hydraulic gradient across the specimen. Hydraulic gradient can be expressed either in terms of the difference in piezometric head, \( \varphi \), or water pressure, \( u \), across the specimen:

\[
i = \frac{\Delta \varphi}{l} = \frac{\Delta u}{\gamma_w l}
\]  

Where \( l \) is specimen length and \( \gamma_w \) is the unit weight of water. In the majority of this study, flow through the specimen is expressed in terms of the average seepage velocity through the pores \( v_s \):

\[
v_s = \frac{v}{n}
\]
Where \( n \) is the porosity of the reconstituted specimen. The validity of Darcy’s law has been found to depend on the calculated Reynolds number, \( R_e \), (Dybbs and Edwards, 1984) defined as the ratio of the inertial forces and the viscous forces of flow:

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

(2.4)

Where \( \rho_w \) is the density of water, \( \mu_w \) is the dynamic viscosity of water, and \( L_s \) is a length scale. Flow with a Reynolds numbers less than 1 typically exhibits laminar flow and is within the Darcian flow regime. Flow with a Reynolds number greater than 1 starts to transition into an inertial flow regime, where the flow is laminar, but the \( v:i \) relation is non-linear. Above \( Re \approx 150–300 \), flow starts to exhibit a highly unsteady turbulent characteristic. Flow through soil typically remains laminar (Mitchell and Soga, 2005), but high velocity flows in coarse-grained material do exhibit non-linear behavior (Giroud et al., 2012).

Two types of permeameter are used to study the phenomenon: rigid wall permeameters, and flexible wall permeameters. The differences between the two devices, and their respective usefulness when studying the internal instability phenomenon, are addressed in Sections 2.3.1 and 2.3.2.

2.3.1 Rigid wall permeameters

The majority of laboratory research conducted on internal instability has been performed with rigid wall permeameters (Åberg, 1993; Kenney and Lau, 1985; ICOLD, 2015; amongst others). Rigid wall permeameters typically incorporate a single cylindrical cell made of plexiglass or equivalent (e.g. Moffat, 2005; Crawford-Flett, 2014). The specimen is reconstituted in direct contact with the cell wall and if required, loading is applied axially to the specimen. The confining pressure on the specimen is governed by the axial load and the influence of sidewall friction and/or adhesion on
the cell wall. Thus, the mean confining stress acting on the specimen is unknown. Moffat (2005) designed the rigid wall permeameter at UBC to study the hydromechanical factors that influence the onset of seepage-induced internal instability.

2.3.2 Flexible wall permeameters

The term “flexible wall permeameter” originates from terminology used by ASTM D5084-10 (ASTM, 2010). The technology is not new, but recent efforts have revitalized its prevalence in the community (Chang and Zhang, 2011; Luo et al., 2012; Ke and Takahashi, 2014). Flexible walls typically comprise rubber membranes that envelop the specimen; relative to rigid-wall permeameters, the benefits include: (i) elimination of preferential seepage flow paths along the soil-wall interface that may adversely impact the results; (ii) the ability to control the confining pressures acting on the specimen; and, (iii) the ability to measure volume change of the specimen.

Slangen (2015) designed the current UBC flexible wall permeameter, introducing a novel measurement of volume change based on a double-walled cell. Slangen’s (2015) testing program included 23 tests on eight glass bead gradations and 16 tests on 10 soil gradations. Key findings from the study include:

- Measurement of total volume change is necessary to properly identify the phenomenological response;
- The hydraulic gradient at the onset of suffosion increases with increasing mean effective stress;
- The portion of non-load bearing fine particles in a gradation is indicative of the potential for suffusion, whereas the susceptibility of a gradation to suffosion can be quantified using state parameters; and
- Sub-angular particles are more resistant to suffosion than spherical particles.
The device is described in greater detail in Section 3.1, and results from Slangen’s (2015) study are used for purposes of baseline comparison in Chapter 6.

2.4 Synthesis

Internal erosion represents a major risk to earth dam safety when not managed appropriately. Internal instability—the transport of fine particles via seepage flow through the pores of coarse particles—is among the four initiating mechanisms of internal erosion. Two distinct internal instability phenomena are suffusion and suffosion. Suffosion is associated primarily with mass loss followed by a rearrangement of the soil structure, whereas suffusion is associated primarily with mass loss followed by an increase in hydraulic conductivity.

Internal erosion is believed to have been a major factor in the development of the W.A.C. Bennett Dam sinkholes. Among the most useful technologies used to delineate and monitor the sinkholes is crosshole shear wave tomography. Laboratory investigation into the sinkhole incident is ongoing at UBC and has included, up to this point, both flexible and rigid wall permeameters. The UBC flexible wall permeameter has recently been developed into a state-of-the art device (Slangen, 2015) capable of measuring volumetric deformations, and thus distinguishing between suffusion and suffosion.
Figure 2.1: Example of gap and widely-graded soils used in dam construction – South Moraine, W.A.C. Bennett Dam (after Morgan and Harris, 1969)
Figure 2.2: Schematic illustration of suffusion and suffosion (after Fannin and Slangen, 2014)

Figure 2.3: Idealised Cross-section of the W.A.C. Bennett Dam (after Morgan and Harris, 1969)
Chapter 3: Apparatus and test procedure

This chapter introduces the flexible wall permeameter that was modified and used for this experimental investigation, the changes made to the device for purposes of shear wave velocity measurement, and the updated test procedure. The test device as designed by Slangen (2015) is introduced in Section 3.1, followed by a detailed description of the upgrades made to the device (see Section 3.2) and test procedures (see Section 3.3) to fulfill research objective No. 1. A chapter summary is presented in Section 3.4, along with the hypothesis examined in the companion laboratory study.

3.1 UBC Flexible wall permeameter

The UBC flexible wall permeameter represents the state of the art for seepage-induced internal instability testing. The device incorporates a double-walled triaxial cell, a seepage control system, and instrumentation. The triaxial cell is assembled for each test in a large water bath prior to applying a confining pressure and imposing upward, unidirectional multi-stage seepage flow. A picture of the assembled device is shown in Figure 3.1, and schematic drawings of the device are given in Figures 3.2 and 3.3.

3.1.1 Double-walled triaxial cell

The basis for double-walled triaxial cell design of the UBC flexible wall permeameter stems from the work of Wheeler (1986). The double-walled configuration enables a measurement of volume change of the cell fluid, from which volume change of the specimen can be derived, independent from the effects of cell pressure. Two transparent acrylic tubes 440 mm in length are used in the setup: an inner tube with an internal diameter of 206 mm and an outer tube with an internal diameter of 236 mm. When placed concentrically between the top and bottom plates of the cell, the tubes enclose an inner chamber, in which the specimen is located, and an outer chamber
between the two tubes (see Figure C.10). The inner and outer chamber ports are connected to a common pressure source such that, when pressurized, the two chambers have an equal cell pressure; and, by maintaining a zero-differential pressure across the inner wall, deformations due to cell pressure changes are eliminated.

The axial loading on the specimen is applied via a rod, referred to as the ‘loading ram’ (Figure 3.2), that rests on the top cap and extends up and outside of the triaxial cell through a water tight U-cup seal in the top plate. Laboratory weights are loaded on top of the rod, to compensate for the combined effect of the buoyancy force from the cell pressure and the friction in the ball bearings feeding the rod through the top plate.

3.1.2 Membrane, base pedestal, and top cap

Within the inner chamber of the triaxial cell, the specimen is situated between a hollow base pedestal and top cap (see Figure 3.2), and enclosed around its diameter by a rubber membrane (see Figure C.9). The membrane is sealed via O-rings to the base pedestal and top cap, such that the specimen is hydraulically isolated from the cell fluid. The arrangement accommodates a cylindrical test specimen with a fixed diameter of 100 mm and height of approximately 100 mm.

The hollow base pedestal and top cap (see Figure 3.2) are designed to allow unimpeded upward seepage flow. The cavity in the base pedestal is cone-shaped, with an inside diameter increasing from 10 mm at the bottom, where the inlet for seepage flow is located, to 90 mm at the top. The top cap contains a cylindrical cavity with an inner diameter of 90 mm and height of 50 mm, with the outlet for seepage flow located at its top. Both the top cap and base pedestal have outside diameters of 100 mm, making them flush with the reconstituted specimen. A system of three primary wire meshes, and three plates perforated with 5 mm holes, support the specimen while allowing for the upward migration of fines under seepage flow. Each wire mesh is
accompanied by a secondary wire mesh which provides either stiffness for the primary wire mesh or spacing for migration (see Appendix C.1 for more details). PVC gaskets are used to secure the plates and wire meshes, and provide a seal around the edges of the wire meshes. The base pedestal supports a perforated plate and a fine wire mesh, the opening size of which is selected to prevent mass loss during specimen reconstitution. The top cap houses two perforated plates which enclose a settling reservoir for any fines that migrate from the specimen during multi-stage seepage flow: a wire mesh (B1 in Table C.1) that retains the coarse particles of the specimen is placed below the primary top perforated plate, and a wire mesh (C1 in Table C.1) that retains all particles of the specimen is placed below the secondary top perforated plate (see Figure C.1). The selection of the opening sizes of the wire meshes is dependent on the particle size distribution of the specimen material. For this study, only the opening size of the primary top wire mesh (B1 in Table C.1) was varied. Post-test observations of the settling reservoir during disassembly of the top cap are used to determine if mass loss from the specimen occurred during multi-stage seepage flow (see Figure 3.4). Finally, the base pedestal houses a connection to measurement point (MP) #1, whereas the top cap houses a port that connects to MP #2 (see Figure 3.3).

3.1.3 Seepage control system

The seepage control system relies on the principle of multi-stage head control with a recirculating water source. The total dynamic head (TDH) of the system is controlled by two constant-head reservoirs: the inflow constant-head device (I-CHD), which connects to the inlet port in the base frame, and the outflow constant-head device (O-CHD), which connects via the outlet port in base frame to the top cap (see Figure 3.3). The head between the two constant-head water surfaces is varied by increasing or decreasing the elevation of the I-CHD via a manual winch (see Figure
C.12). The elevation of O-CHD, however, is fixed. The maximum total dynamic head, $TDH_{\text{max}}$, is limited to 165 cm by the height of the laboratory ceiling.

A supply of filtered, de-aired water is prepared from tap water, consistent with the process developed by Moffat and Fannin (2006). Suspended solids larger than 3 μm in the tap water are first removed via a sand filter and a carbon filter. The filtered water is then dripped into a de-airing tank under a vacuum of approximately -70 kPa for a minimum of 8 hours. Moffat and Fannin (2006) claim a dissolved oxygen (DO) content of less than 2.5 mg/L could be achieved using this technique. However, DO probe measurements indicate that values of 6.0 mg/L are more realistic with the current state of the equipment. Before a test, the storage reservoir is filled with the filtered de-aired water. During multi-stage seepage flow, this water is pumped to the I-CHD (see Figure C.12), from which it flows through the specimen to the O-CHD, and then drips back into the storage reservoir, completing the circuit.

### 3.1.4 Instrumentation

The instrumentation scheme for the flexible wall permeameter (see Figure 3.3) includes five transducers: a total pressure transducer (TPT) to measure the cell pressure, a TPT to measure the pore water pressure (PWP) in the specimen, a differential pressure transducer (DPT) to measure the differential pore water pressure across the specimen, a DPT to measure water level changes in burette #2 caused by volumetric deformations of the specimen, and a linear variable differential transformer (LVDT) to measure axial deformations of the specimen. Details such as accuracy, precision, and resolution of the instrumentation installed on the flexible wall permeameter are addressed in Appendix A. Output voltages of the transducers are recorded at a frequency of 20 Hz using a computer connected to a data acquisition (DAQ) system, and time-averaged over 1 s.
intervals during data reduction for improved precision. Flow rate through the specimen is determined manually by collecting overflow from O-CHD for a specified interval of time.

Four burettes are included in the flexible wall permeameter setup for purposes of cell pressure control and volume change measurement. The vacuum pressure in the specimen during consolidation is supplied over an air/water interface contained in burette #1 (see Figure 3.3). Conversely, confining pressure is applied to the cell through air/water interfaces in burettes #2, #3, and #4 (see Figure 3.3). Burettes #2 and #3 are connected to the inner chamber, whereas burette #4 connects to the outer chamber. The graduated markings of burette #1 are used for the manual monitoring of specimen volume change during consolidation. The measurements are later corrected for membrane compliance (Vaid and Negussy, 1984). Water levels in burette #2 are recorded automatically to measure volume changes of the fluid in the inner chamber, and the larger burette #3 acts as a refilling reservoir to burette #2. The total volume change of the specimen is derived from the water levels in burette #2 after correcting for the intrusion of the loading ram, membrane penetration, and volume changes due to the dissolution of air and absorption of water. The measurement of total volume change of the test specimen during multi-stage seepage flow is a novel feature of the flexible wall permeameter.

### 3.2 Upgrades to the UBC flexible wall permeameter

Commensurate with research objective No. 1, the UBC flexible wall permeameter (FWP) was upgraded to add the capacity for shear wave velocity measurement. The available technology for measuring shear wave velocity across a laboratory specimen is limited to two widely accepted methods of testing: resonant column and bender elements. Resonant column testing requires a distinct apparatus comprising an axisymmetric cell containing the specimen, a coil magnet assembly to induce excitation, and accelerometers to capture the specimen response (Zavoral,
Bender elements, however, can be installed inside devices used to characterize other soil behaviours, such as a triaxial cell (i.e. Styler, 2014; Kuwano and Jardine, 2002) and oedometer (i.e. Lee et al., 2008; Thomann and Hryciw, 1990). As the flexible wall permeameter is, in essence, a triaxial cell, bender elements were deemed a suitable option for shear wave velocity measurement. A previous effort of installing bender elements in a permeameter at UBC yielded meaningful results; however, the study conducted by Campbell (2006) was performed in a rigid wall permeameter and utilized a simplistic method of measuring and analyzing shear wave velocities. The design for the bender elements, and bender element mounts, of the current study is introduced in Sections 3.2.1 and 3.2.2. The associated upgrades to the companion data acquisition system are described in Section 3.2.3.

### 3.2.1 Bender element design

The design of the bender elements was largely influenced by previous shear wave velocity studies conducted at UBC (Styler, 2014; Campbell, 2006). Two bender elements were fabricated in the Civil Engineering workshop at UBC from Y-poled piezoceramic bender sheets sourced from Piezosystems, Inc. (part number T226-H4-503Y). The sheets are comprised of two plates with aligned polarization sandwiching a conductive centre shim (see Figure 3.5). The bender elements were cut from the sheets to dimensions 10 mm by 14 mm and wired in parallel: the lower corner of one plate was milled off to expose the centre shim and attach a wire leading to the input trigger voltage, and the outside plates were wired to a voltage ground reference (see Figure 3.5). The benefits of parallel-wired Y-poled plates as opposed to the alternative, series-wired X-poled plates, are greater generated deformations and a self-shielding quality (Styler, 2014; Lee and Santamarina, 2005). During excitation, the wiring and polarization of the plate causes one plate to extend and one to contract, inciting a bending moment. When the current is reversed, the element bends in the
opposite direction. Rapid alternation of the current results in oscillation, generating shear waves in the contact medium. One (trigger) bender element triggers a shear wave from a voltage signal, and another (receiving) bender element receives the shear wave after it has travelled through the test specimen, and converts it back to a received voltage signal (see Figure 3.2). The bender elements are coated with polyurethane for waterproofing and mounted on a piece of circuit board within aluminum modules with outside diameters of 20 mm (see Figure B.1). The recess in the aluminum modules, surrounding the bender elements, is filled with RTV silicone, leaving a protruding bender element length of approximately 4 mm (see Figure 3.5).

3.2.2 **Bender element mounting and installation**

Several challenges that were unique to mounting the bender elements within the flexible wall permeameter needed to be overcome: the mounts had to easily disassemble after each test, allow for seepage flow and the migration of fine particles, and protect the bender element circuits from water; additionally, the bender element wiring had to pass through a pressurized cell. The mounting system devised comprises the aluminum bender element modules housed at the centre of new perforated plates (see Figure 3.7 and Appendix B). The modules were designed to screw into the perforated plates, allowing for consistent alignment between bender element and plate. Subsequently, notches in the perforated plates, base pedestal, and top cap can be drawn to ensure overall alignment, which is required to consistently determine shear wave velocity. The sizing and spacing of the perforations in the new plates was kept consistent with the previous plates, however, the cross-sectional area at the exit boundary (csaᵥ) of a specimen is reduced by approximately 6% due to the presence of the bender element module (see Figure 3.9). Additionally, to accommodate the modules, the centres of all wire meshes were clipped away, creating an annular shape. An overhanging lip around the housing (see Figure 3.7 and Appendix B) was designed to seat an O-
ring that seals the inner circumference of the wire mesh annuli and thereby prevents particle migration at this boundary. The wiring for the bender elements extending from the modules is protected using 1/8” diameter nylon tubing (see Figure 3.8), of lengths 145 and 190 cm for the upper and lower bender elements, respectively. The tubing is fixed to the modules by means of 1/16” NPT Swagelok connections (see Figure 3.6). To fit the module, the cavity in the top cap (see Figure 3.2) was drilled an additional 12 mm deeper and, as a result, the mass of the top cap was reduced by 213 g. Accordingly, the mass placed on top of the loading ram during testing was increased to offset the reduced axial pressure. Finally, where the tubing traversed the boundary of the pressurized cell, water-tight seals were maintained around the tubing using a series of No. 006 O-rings (see Figure C.13). The O-ring placed around the lower bender element tubing is seated between the base pedestal and base frame (see Figure C.13). The confining pressure provided by the connection between the two components ensures a proper seal. Four O-rings are placed around the upper bender element tubing (see Figure C.13, Detail A): two on either side of the hole punched in the wire meshes at the secondary top perforated plate, one at the hole in the top cap, and one at the hole in the top plate. The O-rings at the top cap and top plate are placed at the base of a threaded cavity such that that confining stress can be provided by large screws (see Figure C.13), bored-out to accommodate the tubing.

Consideration was also given to mounting the bender elements horizontally within the triaxial membrane and conducting radial measurements (e.g. Cho and Fino, 2010; Montoya et al., 2012) of shear wave velocity, forgoing the need to alter the top cap, base pedestal, or perforated plates; however, the process to install bender elements into disposable triaxial membranes and modify the vacuum mold proved to be too involved.
3.2.3 Data acquisition system

To facilitate the addition of bender elements to the device, the flexible wall permeameter data acquisition (DAQ) system required upgrading. Previously, data flowed from the sensors through a USB-6251 DAQ box, manufactured by National Instruments (NI), to a laboratory PC running NI SignalExpress for data logging. NI SignalExpress is a simplified data-logging software; compared to programmable design platforms such as NI LabVIEW, the software has limited capability. A new, more powerful PC was implemented for the FWP, and a LabView virtual instrument (VI) was developed to run the device, display real-time results in terms of engineering units, and log data collected from the USB-6251 DAQ box. Following the upgrade, the permeameter sensors were re-calibrated, and the Python code used for data-reduction was updated. Aside from the immediate functional improvement to the FWP, the use of LabView also allows for future incorporation of available custom-made LabView programs developed to control bender elements (Styler, 2014).

3.3 Test procedure

The test procedure was modified to allow for the insertion of bender element mounts during apparatus assembly. The three main stages of the previous procedure are maintained (Slangen, 2015): preparation of the specimen, specimen consolidation, and subjection of the specimen to multi-stage seepage flow. The updated procedure is summarized herein with emphasis on the changes made for this study, primarily to the setup of the apparatus; the procedure is presented in greater detail and with accompanying photos in the checklist included in Appendix C.

3.3.1 Specimen preparation

The objective of specimen preparation is to produce a saturated, homogenous specimen suitable for testing in the triaxial permeameter. Two different specimen reconstitution methods are used in
this study, depending on the gradation tested. They are detailed in Section 4.2. Broadly described, the preparation processes involves: (1) mixing the coarse and fine components dry, adding water and de-airing; (2) placing the specimen in a forming mold atop the base pedestal and bottom bender element; (3) leveling the specimen and placing the top cap with top bender element; (4) sealing the membrane containing the specimen against the top cap and applying a vacuum pressure to the specimen of approximately -20 kPa; (5) assembling the double-walled triaxial cell around the specimen; and (6) incrementally increasing the cell pressure to 20 kPa while incrementally releasing the vacuum pressure in the specimen.

The primary difficulty with incorporating the bender elements into the test setup is accommodating the wiring tubes. In the revised setup, the lower bender element wiring tube is fed through the base pedestal and base frame prior to lowering the components into the assembly bath, and the bender element is seated in the lower perforated plate prior to reconstitution of the specimen. The upper bender element is fed through the top cap and the bender element is seated in the top perforated plate prior to positioning on top of the specimen. The top bender element wire tubing must then be fed through the top plate during assembly of the triaxial cell.

### 3.3.2 Consolidation

As an indication of specimen saturation, B-values are determined by closing the drainage valve, locking the loading ram, increasing the cell pressure to 100 kPa, and measuring the change in pore water pressure. All specimens in this study are hydrostatically consolidated at cell pressures of 50 or 100 kPa. Excess pore water pressures generated are dissipated through an upward, one-way drainage path through the top cap.
3.3.3 Multi-stage seepage flow

Specimens are subjected to multi-stage, upward seepage flow. Hydraulic head across the specimen is incrementally increased by raising the elevation of I-CHD (see Figure C.12), and the imposed differential water pressure across the specimen is measured using a DPT. Small increments of $\Delta TDH = 1$ to $2.5$ cm are applied in the initial 5-6 stages of a test, followed by larger increments of $\Delta TDH = 5$ cm in the intermediate stages of a test, finally increasing up to $\Delta TDH = 20$ cm at the end of a test. The stage durations, $\Delta t$, vary according to the hydraulic conductivity of the specimen, but at minimum, are 5 minutes or sufficiently long to permit at least two separate representative measurements of flow rate. Flow rates are not measured until the differential pore water pressures across the specimen, monitored using the FWP VI, have stabilized for a given stage. The mean effective stress, $p'$, is derived from measurement of the cell pressure, calculated from TPT1, and the mean pore water pressure in the specimen, calculated from DPT1.

3.4 Summary

The state-of-the-art flexible wall triaxial permeameter designed by Slangen (2015) to study seepage-induced internal instability was upgraded to add the capacity for shear wave velocity measurement and thereby fulfill research objective No.1. The device incorporates a double-walled triaxial cell, a seepage control system, instrumentation, and parallel-wired bender elements. The DAQ system was upgraded with a new LabView VI to drive the device and store data. Custom perforated plates were designed and manufactured to mount the bender elements within the permeameter. Finally, the test procedure including preparation of a saturated specimen, consolidation, and multi-stage seepage flow was altered to accommodate the bender element wire tubing.
3.4.1 Hypothesis of current permeameter laboratory study

The hypothesis of the current permeameter study is that the insertion of bender element mounts in the UBC flexible wall permeameter will not affect the measured seepage regime or internal erosion response of a specimen subjected to seepage flow and thus, will not affect the ability to reproduce past results using the device (see Figure 3.9). To make an evidence-based claim, this hypothesis must be tested in a variety of different conditions: if changes to the specimen response or seepage regime are observed due to the inclusion of bender element mounts, it is postulated that the relative magnitude of the changes may differ for internally stable specimens, internally unstable specimens exhibiting suffusion, and internally unstable specimens exhibiting suffosion.
Figure 3.1: Assembled flexible wall permeameter in water bath

Figure 3.2: Schematic view of the double-walled triaxial cell with bender element configuration (after Slangen, 2015)
Figure 3.3: Schematic plan view of double-walled triaxial cell base ports and instrumentation (after Slangen, 2015)

Figure 3.4: Post-test evidence of mass loss retained on wire mesh C1
Figure 3.5: Schematic view of a bender element wired in parallel with polarization comparison

Figure 3.6: Bender element modules with swageloks
Figure 3.7: Bender element mounts (module inserted in perforated plate)

Figure 3.8: Bender element module with wire tubing
Figure 3.9: Flexible wall permeameter flow diagram with and without bender element mounts

\[ v_s = \frac{Q}{cse_a \ast n} \]

\( cse_a = 73.6 \text{ cm}^2 \quad \text{and} \quad cse_a = 78.5 \text{ cm}^2 \)
Chapter 4: Materials and testing program

Laboratory experiments were conducted to investigate the effects of installing bender element mounts in the flexible wall permeameter. The structure and components of the testing program designed to meet the objectives outlined in Section 3.4 are introduced in this chapter: the details of the materials tested and the reasoning behind their selection are discussed in Section 4.1, the methods used to reconstitute specimens comprised of the materials are detailed in Section 4.2, and finally, the testing program implemented to meet the objectives of the study is explained in Section 4.3.

4.1 Materials

As the objectives of this study included examining the intra-laboratory reproducibility of past results (see Section 1.2), the type of materials that could be used were limited to those previously tested in the flexible wall permeameter: silica glass beads and scalped gradations of W.A.C. Bennett Dam transition soil (Slangen, 2015). All tests for this study were conducted on silica glass beads. As opposed to natural soils, glass beads have consistent, engineered properties – a desirable characteristic when attempting to examine features like repeatability or when calibrating DEM models (e.g. Shire and O’Sullivan, 2013). Moreover, other permeameter studies previously conducted in the UBC Graduate Soils Laboratory have also used the same glass beads, expanding the comparable dataset for purposes of commissioning the device (Moffat and Fannin, 2006; Crawford-Flett, 2014). The drawbacks, however, to using glass beads instead of natural soils include the fact that they provide an idealized representation of in-situ conditions, and that they are relatively more prone to segregation during specimen reconstitution due to their high sphericity. The latter of these drawbacks can lead to specimen heterogeneity.
4.1.1 Glass bead specifications

The glass beads, manufactured by Potters Industries Inc. (see Figure 4.1), have a soda-lime silica glass composition, with roundness $R = 0.8$ to $0.9$, density $\rho = 2.5 \text{ g/cm}^3$, and coefficient of static friction $\mu_{sf} = 0.9$ to $1.0$. Additionally, the minimum index void ratio, $e_{min} = 0.57$, the maximum index void ratio, $e_{max} = 0.67$, and the specific gravity, $G_s = 2.49$, were determined for the glass bead particles (Slangen, 2015). When examined using the QicPic apparatus (Sympatec, 2008), the particles were observed to be almost perfectly spherical (Slangen, 2015). Of the five uniform glass bead component-fractions used by Slangen (2015), three were required to create the gradations tested in this study: GB-F, the fine component with $d_{50} = 0.17 \text{ mm}$; and GB-C2 and GB-C3, the coarse components with $d_{50} = 0.96 \text{ mm}$ and $d_{50} = 1.21 \text{ mm}$, respectively (see Table 4.1 and Figure 4.2). The uniform gradation tested in the current study was comprised solely of GB-F and correspondingly, was labelled as GB-F. The gap-graded gradations tested (see Figure 3.3) were produced by mixing a certain portion of GB-F, comprising the finer fraction content, $S_f$, with one of GB-C2 or GB-C3. The code adopted from Slangen (2015) for the gap-graded gradations is 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) and ended with two numbers representing the percentage fine fraction. For example, gradation 6.0GB35 is a gap-graded gradation comprised of glass bead components GB-C3 and GB-F, with $D'_{15}/d'_{85} = 6.0$ and $S_f = 0.35$. The basis for the selection of the gradations tested in the current study is discussed in Section 4.3.
4.2 Specimen reconstitution methods

Two different specimen reconstitution methods were used in the current study. In accordance with Slangen (2015), water pluviation was used for the uniformly-graded specimens and a modified slurry deposition method was used for gap-graded specimens.

The water pluviation technique adopted (Fannin et al., 1994; Vaid and Negussey, 1988) involves: (1) depositing three 450 g uniform batches of dry glass beads into round-bottom flasks and filling the flasks with de-aired water to a level 2 cm above the glass beads; (2) boiling the batches for a minimum of 30 min, then allowing the batches and flasks to cool to room temperature before placing under a vacuum pressure of -60 kPa for at least 12 hrs; (3) filling the flasks and the membrane-lined split mold cavity to the brim with de-aired water; and (4) individually rotating the flasks while maintaining a seal at the flask opening before releasing the seal underwater and depositing the glass beads into the split mold cavity, repeating the process for all three batches.

The modified slurry deposition technique adopted (Moffat and Fannin, 2006) involves: (1) preparing a 1.6 kg batch of dry glass beads with a composition of coarse and fine fractions that corresponds to the target fines content of the specimen; (2) thoroughly mixing the batch of glass beads and then saturating the mixture by boiling it in de-aired water for a minimum of 30 min and, after allowing the mixture to cool to room temperature, storing it under a vacuum pressure of -60 kPa for at least 12 hrs; and (3) placing the saturated slurry in discrete quantities with the aid of a bent spoon into the split mold cavity while maintaining a thin film of standing water over the placed material to prevent segregation and preserving saturation.

4.3 Testing program

A testing program with the selected materials was designed to meet research objectives No. 2 and No. 3, and thereby determine if the presence of the bender element mounts in the flexible wall
permeameter alters the seepage regime or the internal erosion response of specimens reconstituted in the flexible wall permeameter. To make this determination, data of tests conducted with and without the bender element mounts present were compared. To expand the database and expedite the testing process, the merit of importing results from a previous study was explored. Thus, the results of the Slangen (2015) dataset were used for two purposes: (i) first, as a basis of comparison for affirming the operator’s ability to operate the device in accordance with the developed methods, and (ii) second, where appropriate, to serve as the “without bender element mounts” case in a comparison of results. It was decided that, if a significant difference was observed between the Slangen (2015) test results and the results of the current study with bender element mounts present, the device would be reconfigured to remove the bender element mounts and an additional test would be performed as a check of the findings.

The two main test variables in the Slangen (2015) study were the particle gradation and the target cell pressure. The Slangen (2015) glass bead test program incorporated one uniform gradation, and nine gap-graded gradations. The tests yielded one of three internal erosional responses: pre-critical (or stable), suffusion, or suffosion. Tests on the uniform gradation yielded a stable response, whereas tests on gap-graded gradations yielded either a suffusive or suffosive internal erosion response. The gradations GB-F, 4.8GB20, and 6.0GB35, each yielding a distinct erosional response in the Slangen (2015) study, were selected for testing in the current study. Slangen’s (2015) commissioning test was conducted on gradation GB-F, at a target confining pressure of 100 kPa, and yielded a stable response. The gradation GB-F has also been tested in other permeameter studies (Moffat and Fannin, 2006; Crawford-Flett, 2014) and is the only uniform gradation tested in Slangen’s (2015) program. Additionally, in examining repeatability, Slangen (2015) conducted two tests on the gradation 4.8GB20 (see Figure 4.3) at a target confining
pressure of 50 kPa, yielding a suffusive response, and two tests on the gradation 6.0GB35 (see Figure 4.3) at a target confining pressure of 100 kPa, yielding a suffusive response. To expand the basis for comparison, the gap-graded gradations and target confining pressures in Slangen’s (2015) repeat tests were also included in the testing program of the current study. Target cell pressure was not selected as a test variable in this study as it has a relatively smaller effect on the erosion response of the specimen (Slangen, 2015); however, an additional test variable was added: the presence of bender element mounts.

The composition and resulting microstructure of the selected gradations influence the erosional response exhibited when the gradations are subjected to multi-stage seepage flow. Gradation GB-F is comprised of the fine component GB-F (see Table 4.2). The uniform gradation has a fine-particle dominated matrix. Gradation 4.8GB20 is comprised of the fine component GB-F and coarse component GB-C2 (see Table 4.2). The gap-graded gradation has a microstructure dominated by inter-coarse particle contacts with a large portion of non-load bearing fine particles, and a potential for the rearrangement of coarse particles (Slangen, 2015). Finally, gradation 6.0GB35 is comprised of the fine component GB-F and coarse component GB-C3 (see Table 4.2). The gap-graded gradation has a relatively loose micro-structure with no dominant fraction, and relatively high potential for contractive particle rearrangement or even collapse of the micro-structure (Slangen, 2015).

An overview of the testing program is presented in Table 4.3. The test codes used were compiled as follows: “gradation” + “target cell pressure” + “M” or “NM” + “(R)” (optional), where “M” designates a test with bender element mounts present, “NM” designates a test conducted with no bender element mounts present, and “(R)” designates a repeated test. A total of seven tests were successfully conducted as part of this study. Before the flexible wall permeameter
device was configured for bender element mounting, test GB-F-100-NM was performed to affirm the author’s ability to operate the device in accordance with the developed test methods. After the device was configured (see Section 3.2), tests GB-F-100-M, 4.8GB20-50-M, 4.8GB20-50-M (R), 6.0GB35-100-M, and 6.0GB35-100-M (R) were performed. As a significant deviation was noted between current and past results (Slangen, 2015) for tests conducted on the 6.0GB35 gradation (see Section 6.4 for discussion), the device was reconfigured to its previous state and test 6.0GB35-100-NM was added.
### Table 4.1: Characteristics of glass bead components

<table>
<thead>
<tr>
<th>Component Label</th>
<th>Material</th>
<th>$d_{0}$ (mm)</th>
<th>$d_{15}$ (mm)</th>
<th>$d_{50}$ (mm)</th>
<th>$d_{85}$ (mm)</th>
<th>$d_{100}$ (mm)</th>
<th>$C_{u}$ (-)</th>
<th>$C_{c}$ (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GB-F</td>
<td>P-0070</td>
<td>0.12</td>
<td>0.14</td>
<td>0.17</td>
<td>0.19</td>
<td>0.20</td>
<td>1.25</td>
<td>1.03</td>
</tr>
<tr>
<td>GB-C2</td>
<td>A-100</td>
<td>0.80</td>
<td>0.90</td>
<td>0.96</td>
<td>1.03</td>
<td>1.20</td>
<td>1.10</td>
<td>1.00</td>
</tr>
<tr>
<td>GB-C3</td>
<td>A-120</td>
<td>1.00</td>
<td>1.13</td>
<td>1.21</td>
<td>1.29</td>
<td>1.40</td>
<td>1.11</td>
<td>1.00</td>
</tr>
</tbody>
</table>

**Notes:**
1. Potters Industries Inc. designation

### Table 4.2: Characteristics of tested glass bead gradations

<table>
<thead>
<tr>
<th>Gradation</th>
<th>Fine Component</th>
<th>Coarse Component</th>
<th>$D'<em>{15}/d'</em>{85}$ (mm)</th>
<th>$S_{f}$ (mm)</th>
<th>$D'_{50}^1$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GB-F</td>
<td>GB-F</td>
<td>-</td>
<td>-</td>
<td>1.00</td>
<td>0.17</td>
</tr>
<tr>
<td>4.8GB20</td>
<td>GB-F</td>
<td>GB-C2</td>
<td>4.8</td>
<td>0.20</td>
<td>0.96</td>
</tr>
<tr>
<td>6.0GB35</td>
<td>GB-F</td>
<td>GB-C3</td>
<td>6.0</td>
<td>0.35</td>
<td>1.21</td>
</tr>
</tbody>
</table>

**Notes:**
1. Equal to the $d_{50}$ of the coarse component in a gap-graded gradation

### Table 4.3: Testing program

<table>
<thead>
<tr>
<th>Bender Element Mounts</th>
<th>Expected internal erosion response</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Stable</td>
</tr>
<tr>
<td>With</td>
<td>GB-F-100-M</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Without</td>
<td>GB-F-100-NM 1</td>
</tr>
<tr>
<td></td>
<td>GB-F-100 2</td>
</tr>
</tbody>
</table>

**Notes:**
1. Tests shown in bold have been conducted in the current study.
2. Tests shown in italics have been imported from Slangen (2015).
Figure 4.1: Potters Industries Inc. soda-lime silica glass beads
Figure 4.2: Particle size distributions of glass bead components

Figure 4.3: Particle size distributions of test gradations
Chapter 5: Results and analysis

Chapter 5 contains the results of laboratory work completed during the testing program and the associated analysis of seepage regime and internal erosion response conducted for each of the seven tests. The analysis performed on the tests is first detailed in Section 5.1. Subsequently, the results and analysis of the laboratory tests performed on the three gradations of glass beads are presented in Sections 5.2 – 5.4. The results are shown in terms of the variables \( i, v, \varepsilon_a \) and \( \varepsilon_v \), where contractive strains are shown as positive. All tests involved multi-staged, upward-directed seepage flow. Some tests were conducted with the presence of the bender elements and some without, in accordance with the testing program (see Table 4.3). For purposes of comparison, plots of the results are shown with consistent axes in Figures 5.1 – 5.5. Additional plots, with greater resolution to show individual test results, are included in Appendix D. Finally, an analysis of test repeatability, followed by a synthesis of the findings of the experiments are provided in Sections 5.5 and 5.6, respectively.

5.1 Analysis of seepage regime and internal erosion response

In the context of permeameter studies (Slangen, 2015; Moffat and Fannin, 2011) the seepage regime is the distribution of fluid velocities within a porous medium. In this study, with a single measuring point for fluid velocities, the seepage regime of each test is described in terms of hydraulic conductivity. Thus, a change in seepage regime can be indicated by a change in hydraulic conductivity. Seepage flow in this study is presented in terms of seepage velocity (see Equation 2.3) to eliminate the effects of differing porosity when comparing results. Hydraulic conductivity is calculated from the \( v:i \) relation using Equation 2.1, where \( v \) is discharge velocity. Most stages of seepage flow during a test were characterized by several measurements of discharge; in these cases, the measurements are averaged to calculate a representative fluid velocity (i.e. seepage
velocity or discharge velocity) for each stage. The hydraulic gradient is calculated using Equation 2.2, from the differential pore water pressure across the specimen and the specimen length.

The cross-sectional area selected for the determination of seepage velocity is that of the specimen at the exit boundary (csa_e): the value of the csa_e depends on the presence (or otherwise) of bender element mounts (see Figure 3.9). The csa_e was selected because internal erosion initiates, and is often most prevalent, at the exit boundary of a specimen: without mounts present, the csa_e = 78.5 cm²; and, with mounts present, the csa_e = 73.6 cm². Conversely, hydraulic conductivity is deemed representative of flow along the whole specimen length, for which fluid velocity is determined using the cross-sectional area at the mid-height of the specimen (78.5 cm²).

Changes to the fabric of a porous medium influence the tortuosity of flow paths, and thus yield a change in hydraulic conductivity. Particle loss from a test specimen, in the absence of volume change, results in an increase in void space and a corresponding increase in hydraulic conductivity. Contractive volume change, in the absence of particle loss, reduces void space and yields a corresponding decrease of hydraulic conductivity. Post-consolidation, contractive deformations during a test are associated with the rearrangement of particles, or even collapse of a low-density fabric (Mitchell and Soga, 2005). In the absence of any change to the fabric of the porous medium, seepage flow is controlled by the flow regime. The transition from a Darcian flow regime to a laminar-inertial flow regime generally occurs at relatively low fluid velocities, at Reynolds numbers $R_e = 1$ to 10 (Bear, 1972). In the laminar-inertial flow regime, the $v:i$ relation is no longer expected to be linear. As an approximation to the seepage velocity at which the transition occurs, $v_s$ at $R_e = 1$ is determined for each test, using Equation 2.4 with $L_s = D’_{50}$ (see Table 4.2). Thus, an increase in hydraulic conductivity is attributed to particle loss, and a decrease in hydraulic conductivity is attributed to either (i) the transition from Darcian flow to a laminar-inertial flow
regime, or (ii) a contractive volume change during particle rearrangement. The occurrence of mass loss is verified from forensic observations (see Figure 3.4).

Suffusion is associated with mass loss, minimal volume change, and an increase in hydraulic conductivity. Suffosion is associated with mass loss, substantial volumetric contraction, and a change in hydraulic conductivity (Slangen and Fannin, 2014). In this study, volumetric strains, $\varepsilon_v$, greater than 1.00% are considered substantial. This demarcation is generally consistent with Slangen (2015).

5.2 Gradation GB-F

Gradation GB-F was the only uniform gradation examined in the test program. Based on previous tests conducted on the gradation (Slangen, 2015), it was expected to demonstrate a stable response to seepage flow. Two tests were conducted on the gradation GB-F with a target cell pressure of 50 kPa. The specimens were reconstituted by water pluviation. The first test was conducted without bender element mounts present in the flexible wall permeameter (test GB-F-100-NM), and the second test was conducted with the presence of the bender element mounts (test GB-F-100-M).

5.2.1 Test GB-F-100-NM

The specimen was reconstituted by water pluviation and hydrostatically consolidated to a mean effective stress, $p'_c$, of 98 kPa; specimen height, $l$, of 98 mm; and void ratio, $e_v$, of 0.67 (see Table 5.1). The B-value for the test was measured to be 0.70. The test was initiated at $TDH = 3$ cm for $\Delta t = 40$ min, yielding $i = 0.22$ and $v_s = 0.0067$ cm/s; the test was terminated after 13 stages of seepage flow at $TDH_{max}$ after $t = 138$ min, with $i = 7.4$ and $v_s = 0.33$ cm/s (see Table 5.2). No evidence of mass loss was observed during post-test forensic examination.

The seepage velocity, $v_s$, was directly proportional to the hydraulic gradient, $i$, across the specimen throughout the duration of the test, producing a linear relation (see Figure 5.1a). A
negligible axial strain of $\varepsilon_a = 0.002\%$, and a small volumetric strain of $\varepsilon_v = 0.11\%$, were recorded at the end of the test (see Figures 5.1b and 5.1c).

### 5.2.2 Test GB-F-100-M

The specimen was reconstituted by water pluviation and hydrostatically consolidated to $p' = 98$ kPa, $l = 100$ mm, and $e = 0.63$ (see Table 5.1). The B-value was measured to be 0.75. The test was initiated at $TDH = 3$ cm for $\Delta t = 7$ min, yielding $i = 0.16$ and $v_s = 0.0100$ cm/s; the test was terminated after 13 stages of seepage flow at $TDH_{max}$ after $t = 85$ min, with $i = 7.0$ and $v_s = 0.36$ cm/s (see Table 5.2). No evidence of mass loss was observed during post-test forensic examination (see Table 5.2).

The $v_s:i$ relation was linear throughout the duration of the test (see Figure 5.2a). A very small axial strain of $\varepsilon_a = 0.02\%$, and a very small volumetric strain of $\varepsilon_v = 0.03\%$, were recorded at the end of the test (see Figures 5.2b and 5.2c). Expansive volumetric strains up to $\varepsilon_v = -0.07\%$ were measured mid-test. Volumetric strains were negative for stages 8 and 9.

### 5.2.3 Analysis of gradation GB-F tests

The seepage flows in tests GB-F-100-NM and GB-F-100-M yield average hydraulic conductivities of $k = 0.017$ cm/s (see Figure D.2) and $k = 0.019$ cm/s (see Figure D.6), respectively (see Table 5.3). No substantial axial or volumetric deformation developed in either test. The negative volumetric strains measured in stages 8 and 9 is potentially the result of the uncertainty of the measurement (see Appendix A), air bubbles within the tubing or the burette #2 valve, or a combination thereof. The seepage velocity in the last stage of each test, $v_s = 0.33$ cm/s and $v_s = 0.36$ cm/s, respectively, was below the calculated upper limit of 0.59 cm/s for seepage velocity within the Darcian flow regime (at $Re = 1$). The response of the test specimen to the imposed
seepage flow in tests GB-F-100-NM and GB-F-100-M is deemed stable (see Table 5.4). The Low B-values measured for the GB-F gradation are discussed in Section 6.1.2.

5.3 Gradation 4.8GB20

Two nominally identical tests were conducted on the gradation 4.8GB20 with a target cell pressure of 50 kPa. The specimens were reconstituted by slurry deposition. Both tests were conducted with bender element mounts present in the flexible wall permeameter.

5.3.1 Test 4.8GB20-50-M

The specimen was hydrostatically consolidated to $p'_c = 52$ kPa, $l = 100$ mm, and $e_c = 0.49$ (see Table 5.1). The B-value was measured to be 0.95. The test was initiated at $TDH = 1$ cm for $\Delta t = 40$ min, yielding $i = 0.01$ and $v_s = 0.0010$ cm/s; the test was terminated after 20 stages of seepage flow at $TDH_{max}$ after $t = 337$ min, with $i = 5.2$ and $v_s = 0.50$ cm/s (see Table 5.2). Post-test forensic observations revealed evidence of mass loss.

The $v_s:i$ relation exhibited a three-part curvilinear response (see Figures 5.3a and D.9): (i) the relation was linear for the first two stages of seepage flow up to $i = 0.07$ and $v_s = 0.017$ cm/s; (ii) this was followed by a period of increasing seepage velocity, initially at an increasing rate and subsequently at a decreasing rate; (iii) through the final four stages of the test, above $i = 2.8$ and $v_s = 0.34$ cm/s, the relation was linear. The $\varepsilon_a:i$ relation exhibited a three-part curvilinear response (see Figures 5.3b and D.11): (i) from the start of the test until $i = 1.4$, axial strain increased at a decreasing rate to a value of $\varepsilon_a = 0.01$ %; (ii) between $i = 1.4$ and $i = 3.6$, axial strain increased in two stepwise increments to a very small value of $\varepsilon_a = 0.08$ %; (iii) from $i = 3.6$ until test termination, axial strain remained approximately constant at $\varepsilon_a = 0.08$ %. Finally, the $\varepsilon_v:i$ relation exhibited a three-part curvilinear response (see Figures 5.3c and D.12): (i) from the start of the test until $i = 1.4$, volumetric strain increased at a decreasing rate to a very small value of $\varepsilon_v = 0.07$ %;
(ii) between \(i = 1.4\) and \(i = 3.6\), volumetric strain increased in three stepwise increments to a moderately large value of \(\varepsilon_v = 0.59\%\); (iii) from \(i = 3.6\) until test termination, volumetric strain remained approximately constant at \(\varepsilon_v = 0.59\%\).

### 5.3.2 Test 4.8GB20-50-M (R)

The specimen was hydrostatically consolidated to \(p' = 50\) kPa, \(l = 96\) mm, and \(e_c = 0.51\) (see Table 5.1). The B-value for the test was measured to be 0.99. The test was initiated at \(TDH = 1\) cm for \(\Delta t = 22\) min, yielding \(i = 0.01\) and \(v_s = 0.0046\) cm/s; the test was terminated after 23 stages of seepage flow at \(TDH_{\text{max}}\) after \(t = 662\) min, with \(i = 5.0\) and \(v_s = 0.50\) cm/s (see Table 5.2). Post-test forensic observations revealed evidence of mass loss.

The \(v_s:i\) relation exhibited a two-part curvilinear response (see Figures 5.3a and D.13): (i) for the first 14 stages of the test up to \(i = 1.7\) and \(v_s = 0.24\) cm/s, seepage velocity increased at a slightly decreasing rate with hydraulic gradient; (ii) through the final nine stages of the test the relation was linear. The \(\varepsilon_a:i\) relation exhibited a three-part curvilinear response (see Figures 5.3b and D.15): (i) from the start of the test until \(i = 0.26\), no axial strain developed; (ii) between \(i = 0.26\) to \(i = 1.7\), axial strain increased in two stepwise increments to a very small value of approximately \(\varepsilon_a = 0.03\%\); (iii) from \(i = 1.7\) until test termination, axial strain remained approximately constant at \(\varepsilon_a = 0.03\%\). Finally, the \(\varepsilon_v:i\) relation exhibited a four-part curvilinear response (see Figures 5.3c and D.16): (i) from the start of the test until \(i = 0.48\), volumetric strain increased at a decreasing rate to a small value of \(\varepsilon_v = 0.17\%\); (ii) between \(i = 0.48\) and \(i = 1.4\), volumetric strain increased slightly at a constant rate to \(\varepsilon_v = 0.20\%\); (iii) this period was followed immediately by a rapid increase between \(i = 1.5\) and \(i = 1.7\), to a small volumetric strain \(\varepsilon_v = 0.28\%\); (iv) from \(i = 1.7\) until test termination, volumetric strain remained approximately constant at \(\varepsilon_v = 0.28\%\).
5.3.3 Analysis of gradation 4.8GB20 tests

The seepage flow in test 4.8GB20-50-M yields an initial sequence of relatively constant hydraulic conductivity \( k_i = k_{\text{min}} = 0.026 \text{ cm/s} \) (see Figure D.10 and Table 5.3) to \( i = 0.31 \), in the absence of any axial or volumetric deformation (see Figure 5.3). It is followed by a sequence of increasing hydraulic conductivity to \( k_{\text{max}} = 0.037 \text{ cm/s} \) at \( i = 0.86 \), again in the absence of any substantial axial or volumetric deformation. The increase in hydraulic conductivity is thus attributed to the migration of finer fraction particles out of a stable, coarse-particle dominated micro-structure. At \( i = 1.0 \) and \( v_s = 0.12 \text{ cm/s} \), a sequence of decreasing hydraulic conductivity initiates and continues to \( k_f = 0.030 \text{ cm/s} \), at the end of the test, and is accompanied by small increases in axial and volumetric strains to values of \( \varepsilon_a = 0.03 \% \) and \( \varepsilon_v = 0.59 \% \). The initiation of this sequence corresponds well with the theoretical transition to non-Darcian flow in the specimen, \( v_s Re = 1 = 0.11 \text{ cm/s} \). Thus, the decrease in hydraulic conductivity is attributed primarily to the effects of inertial flow and partially to a slight rearrangement of particles. Accordingly, the response of the specimen to seepage flow is characterized by an initial sequence where the fabric remains unchanged, a subsequent sequence of migration of fine particles out of a stable, coarse-particle dominated micro-structure that yields negligible volume change, and a final sequence where a slight rearrangement of the coarse-particle matrix occurred: the response is deemed suffusive. The hydraulic gradient at the onset of suffusion is \( i_{su} = 0.3 \) (see Table 5.4), corresponding to the onset of the increase in hydraulic conductivity (see Figure D.10).

The seepage flow in test 4.8GB20-50-M (R) is characterized generally by a sequence of relatively high hydraulic conductivity \( k_i = k_{\text{max}} = 0.075 \text{ cm/s} \) (see Table 5.3) decreasing at a slightly increasing rate to \( k_f = k_{\text{min}} = 0.032 \text{ cm/s} \) (see Figure D.14), and accompanied by small increases in axial and volumetric strains to values of \( \varepsilon_a = 0.03 \% \) and \( \varepsilon_v = 0.28 \% \). The calculated upper limit of
the Darcian flow regime, \( v_s \, Re = i = 0.11 \) cm/s, was exceeded at a relatively low hydraulic conductivity, \( i = 0.6 \). The decrease in hydraulic conductivity is attributed primarily to the effects of inertial flow and partially to a slight rearrangement of particles. Given the flow rate during the first stage of seepage flow of test 4.8GB20-50-M (R) exceeds that of test 4.8GB20-50-M by nearly half an order of magnitude, it is postulated that some migration of fine particles occurred during the reconstitution or consolidation of the specimen of test 4.8GB20-50-M (R) and the test started at or near a post-critical condition. However, given the relatively small and stable nature of the volumetric and axial deformations, the response of test 4.8GB20-50-M (R) was deemed suffusive, but the onset of suffusion was not characterized.

5.4 Gradation 6.0GB35

Three tests were performed on the gradation 6.0GB35, with a target cell pressure of 100 kPa. The first two tests were conducted with the presence of the bender element mounts (tests 6.0GB35-100-M and 6.0GB35-100-M (R)). The third test was conducted without the presence of the bender element mounts (test 6.0GB35-100-NM).

5.4.1 Test 6.0GB35-100-M

The specimen was hydrostatically consolidated to \( p'_c = 99 \) kPa, \( l = 100 \) mm, and \( e_c = 0.38 \) (see Table 5.1). The B-value was measured to be 0.97. The test was initiated at TDH = 1 cm for \( \Delta t = 32 \) min, yielding \( i = 0.03 \) and \( v_s = 0.0033 \) cm/s; the test was terminated after 13 stages of seepage flow at TDH = 60 cm after \( t = 195 \) min, with \( i = 3.2 \) and \( v_s = 0.23 \) cm/s (see Table 5.2). Post-test forensic observations revealed evidence of mass loss.

The \( v_s : i \) relation exhibited a two-part curvilinear response (see Figures 5.4a and D.17): (i) for the first 11 stages of the test up to \( i = 2.4 \) and \( v_s = 0.19 \) cm/s, seepage velocity increased with hydraulic gradient at an approximately constant rate; (ii) through the final two stages of the test,
seepage velocity increased with hydraulic gradient at a decreasing rate. The $\varepsilon_a : i$ relation exhibited a curvilinear response (see Figures 5.4b and D.19); from the beginning of the test to test termination, axial strain increased at an increasing rate to a very small value of $\varepsilon_a = 0.08\%$. Finally, the $\varepsilon_v : i$ relation exhibited a two-part curvilinear response (see Figures 5.4c and D.20): (i) from the start of the test until $i = 1.4$, volumetric strain increased at a slightly increasing rate to $\varepsilon_v = 0.23\%$; (ii) between $i = 1.4$ and $i = 3.2$, volumetric strain increased rapidly in a stepwise manner to a relatively large value of $\varepsilon_v = 2.6\%$. The test was terminated at this point because the capacity of the device to measure volumetric strain measurement was exceeded.

5.4.2 Test 6.0GB35-100-M (R)

The specimen was hydrostatically consolidated to $p_c' = 98$ kPa, $l = 99$ mm, and $\varepsilon_c = 0.32$ (see Table 5.1). The B-value for the test was measured to be 0.97. The test was initiated at $TDH = 2$ cm for $\Delta t = 12$ min, yielding $i = 0.11$ and $v_s = 0.014$ cm/s; the test was terminated after 17 stages of seepage flow at $TDH = 77.5$ cm after $t = 194$ min, with $i = 4.33$ and $v_s = 0.31$ cm/s (see Table 5.2). Post-test forensic observations revealed evidence of mass loss.

The $v_s : i$ relation exhibited a two-part curvilinear response (see Figures 5.4a and D.21): (i) for the first 12 stages of the test up to $i = 1.9$ and $v_s = 0.22$ cm/s, seepage velocity increased with hydraulic gradient at an approximately constant rate; (ii) through the final five stages of the test, seepage velocity increased with hydraulic gradient at a decreasing rate. The $\varepsilon_a : i$ relation exhibited a negligible response (see Figure 5.4b), increasing slightly during the test to a very small value of $\varepsilon_a = 0.04\%$. Finally, the $\varepsilon_v : i$ relation exhibited a two-part curvilinear response (see Figures 5.4c and D.24): (i) from the start of the test until $i = 1.2$, volumetric strain increased at a decreasing rate to a small value of $\varepsilon_v = 0.43\%$; (ii) between $i = 1.2$ and $i = 4.3$, volumetric strain increased rapidly in a stepwise manner until reaching a large value of $\varepsilon_v = 3.0\%$. The test was terminated at this point.
point because, as for the 6.0GB35-100-M test, the capacity for volumetric strain measurement was exceeded.

5.4.3 Test 6.0GB35-100-NM

The specimen was hydrostatically consolidated to \( p' = 103 \text{ kPa}, l = 100 \text{ mm}, \text{ and } e_c = 0.35 \) (see Table 5.1). The B-value was measured to be 0.83. The test was initiated at \( TDH = 1 \text{ cm for } \Delta t = 25 \text{ min} \), yielding \( i = 0.05 \) and \( v_s = 0.0047 \text{ cm/s} \); the test was terminated after 12 stages of seepage flow at \( TDH = 47.5 \text{ cm after } t = 138 \text{ min} \), with \( i = 2.2 \text{ and } v_s = 0.24 \text{ cm/s} \) (see Table 5.2). Post-test forensic observations revealed evidence of mass loss.

The \( v_s:i \) relation exhibited a two-part curvilinear response (see Figures 5.5a and D.25): (i) for the first 3 stages of the test up to \( i = 0.19 \) and \( v_s = 0.0093 \text{ cm/s} \), seepage velocity increased at an approximately constant rate; (ii) through the final 9 stages of the test, seepage velocity increased with hydraulic gradient at a slightly increasing rate. The LVDT was not seated correctly in this test and, as a result, meaningful axial strain measurements were not obtained over the duration of the test, and therefore the \( e_a:i \) relation could not be determined. Finally, the \( e_v:i \) relation exhibited a two-part curvilinear response (see Figures 5.5c and D.27): (i) from the start of the test until \( i = 1.5 \), volumetric strain increased at a decreasing rate to a small value of \( e_v = 0.44 \% \); (ii) between \( i = 1.5 \) and \( i = 2.2 \), volumetric strain increased rapidly in a stepwise manner until reaching a large value of \( e_v = 3.0 \% \). The test was again terminated at this point, because of exceeding the capacity for volumetric strain measurement.

5.4.4 Analysis of gradation 6.05GB35 tests

The seepage flow in test 6.0GB35-100-M yields an initial sequence of approximately constant hydraulic conductivity \( k_i = k_{\text{max}} = 0.023 \text{ cm/s} \) (see Table 5.3), in the absence of any axial or volumetric deformation (see Figure 5.4). It is followed by a sequence of slightly decreasing
hydraulic conductivity to $k_f = k_{\min} = 0.018$ cm/s starting at $i = 1.2$ and $v_s = 0.098$ cm/s (see Figure D.18), accompanied by substantial axial and volumetric deformations. The initiation of this sequence corresponds well with the calculated transition into non-Darcian flow, at $v_s \, Re = i = 0.091$ cm/s. Additionally, once initiated, the deformation and associated mass loss of the specimen due to seepage flow did not stabilize during the test and when the range of volumetric measurement was exceeded. Thus, the decrease in hydraulic conductivity is attributed to combined effect of inertial flow and a rearrangement of particles. Accordingly, the response of the specimen to seepage flow is characterized by an initial sequence where the fabric remains unchanged and a subsequent sequence where fine particle migration and significant rearrangement of the coarse-particle matrix occurred: the response is deemed suffosive. The hydraulic gradient at the onset of suffosion is $i_{so} = 1.2$ (see Table 5.4 and Figure D.20).

The seepage flow in test 6.0GB35-100-M (R) yields an initial sequence of approximately constant hydraulic conductivity $k_i = k_{\max} = 0.024$ cm/s (see Table 5.3), in the absence of any axial or volumetric deformation (see Figure 5.4). It is followed by a sequence of decreasing hydraulic conductivity to $k_f = k_{\min} = 0.016$ cm/s starting at $i = 1.7$ and $v_s = 0.19$ cm/s, that is similarly accompanied by substantial axial and volumetric deformations. The initiation of this sequence occurs after the calculated transition into non-Darcian flow, $v_s \, Re = i = 0.091$ cm/s and after the initiation of volumetric and axial strains (see Figure 5.4). Again, once initiated, the deformation and associated mass loss of the specimen did not stabilize during the remainder of the test. The decrease in hydraulic conductivity at $i = 1.9$ is attributed to the combined effect of inertial flow and the rearrangement of particles. Accordingly, the response of the specimen to seepage flow is characterized by an initial sequence where the fabric remains unchanged and a subsequent sequence where fine particle migration and significant rearrangement of the coarse-particle matrix
occurred: the response is deemed suffosive. The hydraulic gradient at the onset of suffosion is $i_{so} = 1.2$ (see Table 5.4 and Figure D.24).

The seepage flow in test 6.0GB35-100-NM yields a short initial sequence of constant hydraulic conductivity $k_i = 0.021$ cm/s (see Table 5.3), in the absence of any axial or volumetric deformation (see Figure 5.4). It is followed by a brief sequence of decreasing hydraulic conductivity to $k_{min} = 0.013$ cm/s starting at $i = 0.1$ and $v_s = 0.008$ cm/s, accompanied by a small volumetric deformation, $\varepsilon_v = 0.14\%$. The initiation of this sequence occurs well before the calculated transition to non-Darcian flow, $v_s Re = i = 0.091$ cm/s. Thus, the decrease in hydraulic conductivity is attributed to a slight rearrangement of particles. In the final sequence of the test, hydraulic conductivity is increasing. Initially, it is not accompanied by volumetric strain, but at $i = 1.5$, substantial volumetric deformations commenced. The increase in hydraulic conductivity is attributed to the migration of fine particles out of a coarse-particle dominated micro-structure that was subject to particle rearrangement. Accordingly, the response of the specimen to seepage flow is characterized by an initial sequence where minor changes to the fabric occurred, a subsequent sequence where fine particle migration occurred in the absence of course-particle rearrangement, and a final sequence where significant rearrangement of the coarse-particle matrix occurred in concert with fine particle migration: the response is deemed suffosive. The hydraulic gradient at the onset of suffosion is $i_{so} = 1.5$ (see Table 5.4 and Figure D.27).

The axial strains measured in the tests conducted on gradation 6.0GB35 are small considering the large volumetric strains measured. Similarly small end-of-test axial strains, $\varepsilon_a \leq 0.10\%$, were also observed in some of the tests exhibiting suffosion conducted by Slangen (2015). The phenomenon is attributed to seepage-induced rearrangement of the particle packing.
5.5 Test repeatability

In accordance with research objective No. 2, repeat tests were carried out for tests 4.8GB20-50-M and 6.0GB20-50-M. To differentiate between random variation in test results and potential systematic variation caused by alterations to the test equipment, the baseline variability of the permeameter must first be established. Ideally, examination of the baseline variability would be conducted entirely with the device in its original state, but the repeatability tests in the current study are conducted with bender elements installed. These tests can still provide valuable insight on the baseline variability of results obtained with the test device if it is assumed the changes to it have little effect on the random variation of its results. Two aspects of repeatability are examined: void ratio of the reconstituted specimens, and response of the specimen to seepage flow.

The specimen void ratios were $e_c = 0.51$ and $e_c = 0.49$ for the 4.8GB20 tests, and $e_c = 0.38$ and $e_c = 0.32$ for the 6.0GB35 tests. The repeatability of void ratios was lower for the gradation with a larger particle size ratio, $D'_{15}/D'_{85}$, and larger finer fraction content, $S_f$. Given the relatively sensitive micro-structure of the 6.0GB35 gradation, achieving consistent particle arrangements during reconstitution is expected to be more challenging. The difference in void ratio could also be attributed to the inhomogeneity of fines content in the specimen (see Appendix E). The repeatability of the void ratios for the 4.8GB20 gradation suggests that the modified test procedure is capable of producing reasonably consistent specimens.

When compared visually, the results of the two repeat tests match closely with the initial tests (see Figures 5.3 and 5.4); for both gradations, the repeat tests demonstrate the same type of internal erosion responses as the original tests. Additionally, the results of the repeat tests are quantitatively similar to the initial tests (see Tables 5.2, 5.3, and 5.4): the variation of final hydraulic conductivities is $\pm 0.001 \text{ cm/s}$ for both gradations, the variation of measured volumetric
strain for the suffusive tests was ± 0.15%, and the critical hydraulic gradients for suffosive tests are identical. The only notable deviation between repeat and initial tests occurs in the seepage regime parameters for 4.8GB20-50-M (R). As noted in Section 5.3.3, these differences are attributed to pre-test particle migration.

5.6 Synthesis

Results of the seven tests on glass bead specimens, each of which was subjected to upward seepage flow inside a flexible wall permeameter (FWP) device, have been presented and analyzed. The tests were conducted on three different gradations: GB-F, 4.8GB20, and 6.0GB35. Additionally, two configurations of FWP-device were used in the testing program: one with the presence of bender element mounts, and the other without bender element mounts. Analysis of the tests has considered the variation of hydraulic conductivity, axial and volumetric strains, and changes to the specimen fabric inferred from changes in hydraulic conductivity and/or specimen deformation.

Two tests were conducted on the uniform gradation GB-F, one with bender element mounts present and one without mounts. In both tests, the $v_s:i$ relation was found linear. The seepage regimes of GB-F-100-NM and GB-F-100-M are both characterized by single hydraulic conductivities: $k = 0.017$ cm/s and $k = 0.019$ cm/s, respectively. No significant deformations were measured during either test. Accordingly, the response in each test is deemed stable.

Two tests were conducted on gradation 4.8GB20, both with bender element mounts present. The $v_s:i$ relation exhibited a three-part curvilinear response in 4.8GB20-50-M and a two-part curvilinear response in 4.8GB20-50-M (R). The maximum hydraulic conductivity of test 4.8GB20-50-M (R), $k_{\text{max}} = 0.075$ cm/s, was approximately twice the magnitude of the maximum hydraulic conductivity of test 4.8GB20-50-M, $k_{\text{max}} = 0.037$ cm/s. It is postulated that some pre-test particle migration occurred in test 4.8GB20-50-M (R). Small and relatively stable seepage-induced
volumetric and axial deformations developed during both tests. The response of both tests was deemed suffusive, initiating at a hydraulic gradient below \( i = 0.3 \).

Three tests were conducted on gradation 6.0GB35, two with bender element mounts present, and one without bender element mounts present. The \( v_r:i \) relation exhibited a two-part curvilinear responses in all three tests. The maximum hydraulic conductivities of tests 6.0GB35-100-M, 6.0GB35-100-M (R), and 6.0GB35-100-NM were \( k_{\text{max}} = 0.023 \text{ cm/s} \), \( k_{\text{max}} = 0.027 \text{ cm/s} \), and \( k_{\text{max}} = 0.027 \text{ cm/s} \), respectively. Large seepage-induced volumetric deformations developed in all three specimens and consequently, each test was terminated before \( TDH_{\text{max}} \). The response in tests 6.0GB35-100-M, 6.0GB35-100-M (R), and 6.0GB35-100-NM were deemed suffusive, initiating at hydraulic gradients of \( i_{so} = 1.2 \), \( i_{so} = 1.2 \), and \( i_{so} = 1.5 \), respectively.
Table 5.1: Initial test condition

<table>
<thead>
<tr>
<th>Test code</th>
<th>$l$ (mm)</th>
<th>$e_c$ (-)</th>
<th>$p'_c$ (kPa)</th>
<th>$c_s a_e$ (cm$^2$)</th>
<th>$B$-value (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GB-F-100-NM</td>
<td>98</td>
<td>0.67</td>
<td>98</td>
<td>78.5</td>
<td>0.70</td>
</tr>
<tr>
<td>GB-F-100-M</td>
<td>100</td>
<td>0.63</td>
<td>98</td>
<td>73.6</td>
<td>0.75</td>
</tr>
<tr>
<td>4.8GB20-50-M</td>
<td>100</td>
<td>0.49</td>
<td>52</td>
<td>73.6</td>
<td>0.95</td>
</tr>
<tr>
<td>4.8GB20-50-M (R)</td>
<td>96</td>
<td>0.51</td>
<td>50</td>
<td>73.6</td>
<td>0.99</td>
</tr>
<tr>
<td>6.0GB35-100-M</td>
<td>100</td>
<td>0.38</td>
<td>99</td>
<td>73.6</td>
<td>0.97</td>
</tr>
<tr>
<td>6.0GB35-100-M (R)</td>
<td>99</td>
<td>0.32</td>
<td>98</td>
<td>73.6</td>
<td>0.97</td>
</tr>
<tr>
<td>6.0GB35-100-NM</td>
<td>100</td>
<td>0.35</td>
<td>103</td>
<td>78.5</td>
<td>0.83</td>
</tr>
</tbody>
</table>

Notes:
1 Axial strain for 6.0GB35-100-NM was not recorded.
2 Based on forensic observations of the top cap at the end of the test.

Table 5.2: End test condition

<table>
<thead>
<tr>
<th>Test code</th>
<th>$i$ (-)</th>
<th>$v_s$ (cm/s)</th>
<th>$\varepsilon_a^1$ (%)</th>
<th>$\varepsilon_v$ (%)</th>
<th>$t$ (min)</th>
<th>Mass loss$^2$ (Yes/No)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GB-F-100-NM</td>
<td>7.4</td>
<td>0.33</td>
<td>0.00</td>
<td>0.11</td>
<td>138</td>
<td>N</td>
</tr>
<tr>
<td>GB-F-100-M</td>
<td>7.0</td>
<td>0.36</td>
<td>0.02</td>
<td>0.03</td>
<td>85</td>
<td>N</td>
</tr>
<tr>
<td>4.8GB20-50-M</td>
<td>5.2</td>
<td>0.50</td>
<td>0.08</td>
<td>0.58</td>
<td>337</td>
<td>Y</td>
</tr>
<tr>
<td>4.8GB20-50-M (R)</td>
<td>5.0</td>
<td>0.50</td>
<td>0.03</td>
<td>0.27</td>
<td>662</td>
<td>Y</td>
</tr>
<tr>
<td>6.0GB35-100-M</td>
<td>3.2</td>
<td>0.23</td>
<td>0.08</td>
<td>2.62</td>
<td>195</td>
<td>Y</td>
</tr>
<tr>
<td>6.0GB35-100-M (R)</td>
<td>4.3</td>
<td>0.31</td>
<td>0.04</td>
<td>3.00</td>
<td>194</td>
<td>Y</td>
</tr>
<tr>
<td>6.0GB35-100-NM</td>
<td>2.2</td>
<td>0.24</td>
<td>-</td>
<td>3.00</td>
<td>138</td>
<td>Y</td>
</tr>
</tbody>
</table>
### Table 5.3: Seepage regime parameters

<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>$k_f^2$ (cm/s)</th>
<th>$v_s^3$ (cm/s)</th>
<th>$v_s Re = 1^4$ (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GB-F-100-NM</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
<td>0.33</td>
<td>0.59</td>
</tr>
<tr>
<td>GB-F-100-M</td>
<td>0.019</td>
<td>0.019</td>
<td>0.019</td>
<td>0.019</td>
<td>0.36</td>
<td>0.59</td>
</tr>
<tr>
<td>4.8GB20-50-M</td>
<td>0.026</td>
<td>0.026</td>
<td>0.037</td>
<td>0.030</td>
<td>0.50</td>
<td>0.11</td>
</tr>
<tr>
<td>4.8GB20-50-M (R)</td>
<td>0.075</td>
<td>0.032</td>
<td>0.075</td>
<td>0.032</td>
<td>0.50</td>
<td>0.11</td>
</tr>
<tr>
<td>6.0GB35-100-M</td>
<td>0.023</td>
<td>0.018</td>
<td>0.023</td>
<td>0.018</td>
<td>0.23</td>
<td>0.09</td>
</tr>
<tr>
<td>6.0GB35-100-M (R)</td>
<td>0.024</td>
<td>0.016</td>
<td>0.027</td>
<td>0.016</td>
<td>0.31</td>
<td>0.09</td>
</tr>
<tr>
<td>6.0GB35-100-NM</td>
<td>0.021</td>
<td>0.013</td>
<td>0.027</td>
<td>0.027</td>
<td>0.24</td>
<td>0.09</td>
</tr>
</tbody>
</table>

**Notes:**
1. Initial hydraulic conductivity $k_i$.
2. Hydraulic conductivity at the last stage of seepage flow $k_f$.
3. Seepage velocity during the last stage of seepage flow, from Table 5.2.
4. Using Eq. 2.4 with $L_s = D'_{50}$, $p_w = 988.2 \text{ kgm}^{-3}$, and $\mu_w = 1.002 \times 10^{-3} \text{ Nsm}^{-2}$ (for water at 20 ºC).

### Table 5.4: Characterization of specimen response

<table>
<thead>
<tr>
<th>Test code</th>
<th>$k_{min} / k_i^1$ (-)</th>
<th>$k_{max} / k_i^2$ (-)</th>
<th>$\varepsilon_v^3$ (%)</th>
<th>Phenomenon</th>
<th>$i_{su}^4$ (-)</th>
<th>$i_{so}^6$ (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GB-F-100-NM</td>
<td>1.0</td>
<td>1.0</td>
<td>0.11</td>
<td>Stable</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>GB-F-100-M</td>
<td>1.0</td>
<td>1.0</td>
<td>0.03</td>
<td>Stable</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4.8GB20-50-M</td>
<td>1.0</td>
<td>1.4</td>
<td>0.58</td>
<td>SU</td>
<td>0.3</td>
<td>-</td>
</tr>
<tr>
<td>4.8GB20-50-M (R)</td>
<td>0.4</td>
<td>1.0</td>
<td>0.27</td>
<td>SU</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>6.0GB35-100-M</td>
<td>0.8</td>
<td>1.0</td>
<td>2.62</td>
<td>SO</td>
<td>-</td>
<td>1.2</td>
</tr>
<tr>
<td>6.0GB35-100-M (R)</td>
<td>0.7</td>
<td>1.1</td>
<td>3.00</td>
<td>SO</td>
<td>-</td>
<td>1.2</td>
</tr>
<tr>
<td>6.0GB35-100-NM</td>
<td>0.8</td>
<td>1.2</td>
<td>3.00</td>
<td>SO</td>
<td>-</td>
<td>1.5</td>
</tr>
</tbody>
</table>

**Notes:**
1. Calculated from Table 5.3.
2. Calculated from Table 5.3.
3. Volumetric strain at end of test.
4. SU = Suffusion; SO = Suffosion.
5. Hydraulic gradient at the onset of suffusion.
6. Hydraulic gradient at the onset of suffusion.
Figure 5.1: GB-F-100-NM test results
Figure 5.2: GB-F-100-M test results
Figure 5.3: 4.8GB20-M test results
Figure 5.4: 6.0GB35-M test results
Figure 5.5: 6.0GB35-NM test results
Chapter 6: Discussion

Chapter six compares the results of the laboratory investigation to previous studies and tests the hypothesis that insertion of bender element mounts (BEMs) into the UBC flexible wall permeameter (FWP) will not affect the seepage regime or internal erosion response of a specimen subjected to seepage flow (research objective No. 3). The comparisons are made in terms of volumetric strain and seepage velocity. Limitations of the investigation are also discussed in the chapter, which is organized into six subsections. The commissioning of the device is discussed in Section 6.1; the influence of the BEMs on stable, suffusive, and suffosive specimen responses is characterized in Sections 6.2, 6.3, and 6.4, respectively, by comparing tests conducted with and without the BEMs present; next, the potential impact of specimen inhomogeneity on the test results is discussed in Section 6.5; and finally, the effect of the modifications on the intra-laboratory reproducibility of the FWP is summarized in Section 6.6.

6.1 Device commissioning

Tests performed on gradation GB-F were used to commission the test device and troubleshoot setup issues early in the testing program. In Section 6.1.1, the results of a commissioning test are compared to results from previous studies and to expected values calculated from empirical correlations. Next, a commentary on challenges with specimen saturation and the resulting mitigation steps developed is included in Section 6.1.2. Finally, a synthesis is provided in Section 6.1.3.

6.1.1 Comparison to previous studies and empirical correlations

Test GB-F-100-NM was performed to affirm the writer’s ability to operate the device in accordance with the developed test method and produce results in reasonable agreement with previous studies conducted on gradation GB-F. Accordingly, the affirmation is based on initial
properties of the reconstituted specimen, and on the resulting hydraulic properties of the specimen determined under multi-stage seepage flow. The GB-F-100-NM specimen length \( (l) \), and void ratio after completion of consolidation \( (e_c) \), are compared to those reported for specimen GB-F-100 (Slangen, 2015) using the same flexible wall permeameter. The hydraulic conductivity of GB-F-100-NM is compared to results from three laboratory tests performed on gradation GB-F in previous studies at UBC: GB-F-100 (Slangen, 2015), C-GB-100-0 (Crawford-Flett, 2014), and test F (Moffat and Fannin, 2006). Notably, C-GB-100-0 and test F were conducted in a different test device: a large rigid-wall permeameter.

The GB-F-100-NM specimen length, \( l = 98 \) mm, and void ratio, \( e_c = 0.67 \), compare favorably to the corresponding values for the GB-F-100 specimen (Slangen, 2015), \( l = 97 \) mm and \( e_c = 0.65 \) (see Table 6.1). Thus, the test method used in test GB-F-100-NM successfully reproduced a specimen with dimensions and particle arrangement comparable to previous specimens reconstituted using the same method.

Although the tests of Crawford-Flett (2014) and Moffat and Fannin (2006) were conducted in a rigid-wall permeameter under significantly lower confining stresses (see Table 6.1), the void ratios of the reconstituted GB-F specimens are comparable to those of the current study – a phenomenon most likely explained by the differing reconstitution methods. Accordingly, the data from tests F and C-GB100-0 provide a corroborating context to the analysis of GB-F-100-NM. The average hydraulic conductivity from the three past laboratory studies ranges from \( 0.014 \) cm/s to \( 0.019 \) cm/s; the average hydraulic conductivity of test GB-F-100-NM, \( k_{avg} = 0.017 \) cm/s, is near the centre of that range. As an additional check, the average hydraulic conductivity of test GB-F-100-NM is compared to those obtained from commonly-used methods of estimating hydraulic
conductivity (see Table 6.2; and Appendix F). The value of 0.017 cm/s in test GB-F-100-NM is in the middle of the range of values estimated from the methods: 0.007 to 0.029 cm/s.

6.1.2 Challenges with B-value measurement and resulting mitigation efforts

Skempton’s B-value, the index value of specimen saturation, is defined as the ratio of the increase in pore water pressure to the increase in confining pressure under isotropic undrained loading (Budhu, 2011). Typically, a specimen is deemed saturated when \( B \geq 0.95 \). The B-values for GB-F-100-NM and its companion test, GB-F-100-M, were measured to be 0.70 and 0.75, respectively (see Table 5.1). During a follow-up investigation into the issue, a cavity was discovered at the end of one of the horizontal drill holes made into the base frame for the DPT1/TPT2 port. It is hypothesized that air bubbles formed in said cavity and distorted the B-value measurement. New practices for de-airing the base frame and preliminary checks of DPT1 and TPT2 (see Appendix C) read-outs during test setup were implemented prior to the tests on gap-graded gradations. Apart from test 6.0GB35-100-NM, B-values above 0.95 were successfully achieved.

The theoretical relation between degree of saturation and hydraulic conductivity is well established: hydraulic conductivity reduces with decreasing saturation (Lambe, 1951). A specimen with lower saturation should exhibit a value of hydraulic conductivity less than that of a specimen with greater saturation. The B-values measured for tests GB-F-100-NM, GB-F-100-M, or 6.0GB35-100-NM were deemed unrepresentative of specimen saturation for two reasons: (i) the measured hydraulic conductivities were either equal to or greater than comparable tests with B-values greater than 0.95; and, (ii) no obvious signs of unsaturation were observed during test setup (i.e. air bubbles in transducer lines; air emitting from the specimen after application of vacuum pressure; large displacements of the top cap during consolidation).
6.1.3 Synthesis

Test GB-F-100-NM was performed at the beginning of the test program to commission the upgraded flexible wall permeameter device. The initial specimen properties of test GB-F-100-NM are in excellent agreement with a previous test performed on the specimen in the flexible wall permeameter (Slangen, 2015). Additionally, the average hydraulic conductivity of test GB-F-100-NM is within the range of values established from past laboratory tests performed on the gradation and from widely-used correlations. Finally, issues encountered with B-value measurements were investigated and addressed early in the test program. Methods to improve the reliability of B-value measurement were successfully implemented for the tests on gap-graded gradations.

Based on the agreement obtained between test GB-F-100-NM and the expected results established from past studies and empirical correlations, it is reasonable to believe that the device is yielding results that are independent of the operator.

6.2 Influence of BEMs on stable specimen responses

An intra-study comparison is made to determine the effect of the presence of bender element mounts on the response of a specimen that is internally stable. The results of GB-F-100-NM and GB-F-100-M are compared (see Figure 6.1), with GB-F-100-NM serving as the baseline for the comparison. The two reconstituted specimens have similar dimensions and void ratios (see Table 5.1). Additionally, both GB-F-100-NM and GB-F-100-M yielded linear $v_s:i$ relations (see Figure 6.1) with very comparable hydraulic conductivities (see Table 6.4). The volumetric deformations were not significant in either test, and both tests are deemed stable (see Table 6.5). Accordingly, there is no evidence to suggest that the bender element mounts have a measurable effect on the response of gradation GB-F to seepage flow under the test conditions.
6.3 Influence of BEMs on suffusive specimen responses

An inter-study comparison is made to determine the effect of the presence of bender element mounts on the response of a specimen with potential for suffusion. The results of 4.8GB20-50-M and the repeated test 4.8GB20-50-M (R), both of which were conducted with bender element mounts present, are compared to the results of tests 4.8GB20-50 and 4.8GB20-50 (R), which were conducted by Slangen (2015) in the same flexible wall permeameter without the presence of bender element mounts (see Figure 6.2). The four test specimens were consolidated to comparable lengths and void ratios (see Table 6.3).

The mean final hydraulic conductivity for the two tests conducted without bender element mounts (Slangen, 2015) is \( k_f = 0.024 \pm 0.004 \) cm/s (see Table 6.4), whereas the mean final hydraulic conductivity for the two tests conducted with bender element mounts is \( k_f = 0.031 \pm 0.001 \) cm/s (see Table 6.4). If the repeat tests from both studies are removed from the evaluation, and 4.8GB20-50-M is compared to 4.8GB20-50, the differences in measured hydraulic conductivity values are less distinguishable. The \( n_i: i \) relations of the two tests exhibit a similar pattern (see Figure 6.1a) and the maximum variation of key hydraulic conductivity parameters (\( k_i, k_{\text{min}}, k_{\text{max}} \), and \( k_f \)) between the two tests is \( \pm 0.0025 \) cm/s (see Table 6.4). Given the variation observed between the two tests conducted by Slangen (2015) without BEMs present is greater than the variation between test 4.8GB20-50-M and 4.8GB20-50, the insertion of the bender element mounts is deemed to not have caused a distinct change in the seepage response of the specimen.

The mean final volumetric strains of the 4.8GB20 tests conducted with and without bender element mounts are \( \varepsilon_v = 0.08 \pm 0.05 \% \) (Slangen, 2015) and \( \varepsilon_v = 0.42 \pm 0.16 \% \) (see Table 6.4), respectively. Although the strains differed by over a factor of four, the volumetric strains for tests conducted without bender element mounts were still within the defined limits for suffusion,
\( \varepsilon_v = 1.00\% \) (see Section 5.1). Additionally, the final volumetric strains of other tests conducted by Slangen (2015) on the 4.8GB20 gradation at cell pressures of 100 and 150 kPa were \( \varepsilon_v = 0.50\% \) and \( \varepsilon_v = 0.48\% \), respectively. Examining the full context of Slangen’s four tests on the 4.8GB20 gradation, the increase in measured volumetric strain between the 4.8GB20-50 tests is likely associated with the challenges of reconstituting gap-graded glass bead specimens rather than the presence of bender element mounts (see Section 6.5 for further discussion). Additionally, the hydraulic gradients at the onset of suffusion for 4.8GB20-50-M, 4.8GB20-50, and 4.8GB20-50 (R), were nominally identical (see Table 6.5), denoting a consistency within the observed phenomenon.

In summation, the differences between the results of the tests conducted on gradation 4.8GB20 with and without bender element mounts present are attributed to random variation. No systematic effects on the specimen response to seepage flow from the insertion of bender element mounts were observed.

### 6.4 Influence of BEMs on suffosive specimen responses

Both inter and intra-study comparisons are made to determine the effect of the presence of bender element mounts on the response of a specimen with potential for suffosion. Tests 6.0GB35-100-M and 6.0GB35-100-M (R) are compared to tests 6.0GB35-100, 6.0GB35-100 (R), and, finally, 6.0GB35-100-NM. The five test specimens were consolidated to comparable lengths and void ratios (see Table 6.3).

#### 6.4.1 Comparison with previous laboratory results

The results of 6.0GB35-100-M and 6.0GB35-100-M (R), conducted in the current study with bender element mounts present, are first compared with 6.0GB35-100 and 6.0GB35-100 (R), performed by Slangen (2015) without the presence of bender element mounts (see Figure 6.3). The
two tests of the current study exhibited notably different behaviour than the two tests of the previous study, including greater seepage velocities and volumetric strains occurring at smaller hydraulic gradients. The tests of the current study exceeded the volumetric strain measurement capacity, $\varepsilon_v = 3.00\%$, at a mean hydraulic gradient of $i = 3.8$ and were subsequently terminated. The tests of the previous study were terminated at TDH$_{\text{max}}$ at a mean hydraulic gradient of $i = 5.3$ with a mean volumetric strain of $\varepsilon_v = 1.86 \pm 0.32\%$. All four tests exhibited suffosive responses that initiated at similar hydraulic gradients: 1.2, 1.8, 1.2, and 1.2 for tests 6.0GB35-100, 6.0GB35-100 (R), 6.0GB35-100-M, and 6.0GB35-100-M (R), respectively (see Table 6.4). However, the subsequent erosional responses of 6.0GB35-100-M and 6.0GB35-100-M (R) are more pronounced.

Overall, the tests conducted in the current study on gradation 6.0GB35 with bender element mounts present have poor agreement to previous laboratory tests conducted on gradation 6.0GB35 without bender element mounts present. In accordance with the testing program for this study (see Section 4.3), an additional test was conducted on gradation 6.0GB35 without bender element mounts present before asserting whether the insertion of bender elements was responsible for the changes in specimen behavior observed.

6.4.2 Intra-study comparison with and without bender element mounts

The flexible wall permeameter was reconfigured to remove the bender element mounts and the associated hardware. 6.0GB35-100-NM was then performed. The test is compared with 6.0GB35-100-M and 6.0GB36-100-M (R) (see Figure 6.4).

The variations of $k_i$, $k_{\text{min}}$, $k_{\text{max}}$, and $k_f$ between the three tests are relatively small: $\pm 0.002$ cm/s, $\pm 0.002$ cm/s, $\pm 0.002$ cm/s, and $\pm 0.006$ cm/s, respectively. Moreover, the $v_s : i$ relations of the three tests are similar (see Figure 6.4a).
Test 6.0GB35-100-NM exhibited a similarly pronounced suffosive response as the two tests conducted with bender element mount present, initiating at a hydraulic gradient of $i_{so} = 1.5$ (see Table 6.4). The volumetric strain measurement capacity, $\varepsilon_v = 3.00\%$, was exceeded for test 6.0GB35-100-NM at a hydraulic gradient of $i = 2.2$, and the test was terminated.

The comparison with the added test indicates that the differences in the results between the current and previous study are not likely associated with the presence of bender elements, but instead likely to be associated with the challenges of reconstituting gap-graded glass bead specimens (see Section 6.5 for further discussion) and the sensitive nature of suffosion. Similarly pronounced erosional responses—where sudden continuing volumetric strains were encountered—were noted in Slangen’s (2015) study during tests on gradation 6.5GB35. Ultimately, the intra-study comparison of the results takes precedence when considering the hypothesis of this study (see Section 2.4). When solely considering the results of the three suffosive specimens tested in this study, there are no observable systematic effects caused by the insertion of bender element mounts.

### 6.5 Specimen inhomogeneity

Specimen inhomogeneity is suspected to be the main limitation of the study. Two sources of inhomogeneity were identified: one during specimen reconstitution and another during specimen consolidation.

Most of the testing program of the current study was conducted on gap-graded, internally unstable specimens of glass beads. Glass bead particles are nearly perfectly spherical and experience negligible interlocking. When mechanically agitated, the gap-graded mixture is prone to segregation. As a result, some degree of sorting is expected when mixing two fractions together during specimen reconstitution (see Figure E.2). To evaluate the effectiveness of the specimen
reconstitution technique in producing homogenous specimens, homogeneity tests were conducted using trial specimens of 4.8GB20 (see Appendix E). The average variation of fines content along the height of two trial specimens, of nominal fines content $S_f = 0.20$, was measured in the current study to be $S_f = \pm 0.035$, compared to the $S_f = \pm 0.03$ achieved by Slangen (2015). This small variation in localized fines content might explain some of the differences observed between the results of the two studies.

The specimens are also susceptible to finer-fraction extraction occurring when vacuum pressure is applied during consolidation. Vacuum pressure is only applied to the top of the specimen and takes time to equalize throughout the specimen. If applied too quickly, a hydraulic gradient is imparted across the specimen prior to the imposition of multi-stage seepage flow, and due to the inherently unstable nature of the gap-graded glass bead gradations: some finer-fraction beads may migrate out of the specimen, resulting in specimen inhomogeneity. The likelihood of this occurring was mitigated during the study through a very slow application of the vacuum pressure; however, the results of Test 4.8GB20-50-M (R) indicate that the phenomenon may have still have affected some tests.

6.6 Effect of the BEMs on intra-laboratory reproducibility of FWP tests

The laboratory investigation was designed to examine the intra-laboratory reproducibility of UBC flexible wall permeameter (FWP) tests after the device was modified to accommodate bender elements. In the comparisons of test results shown for stable, suffusive, and suffosive specimens (see Figures 6.1, 6.2, and 6.4) no systematic effects from the presence of the bender elements are observed. The minor differences observed in an intra-study comparison for suffusive specimens and inter-study comparisons for stable and suffosive specimens are deemed to be within the expected variation of the flexible permeameter test results established from repeatability tests.
Notably, the presence of the bender elements did not alter the nature of the erosional response or the hydraulic gradient at the onset of instability, $i_{su}$ or $i_{so}$. Accordingly, it is believed the inclusion of bender elements in the flexible wall permeameter has no appreciable effect on the specimen response to seepage flow and, correspondingly, the intra-laboratory reproducibility of FWP tests.
Table 6.1: Test properties of comparable GB-F tests from previous studies

<table>
<thead>
<tr>
<th>Test code</th>
<th>Study</th>
<th>l (mm)</th>
<th>e_c (-)</th>
<th>p'_c (kPa)</th>
<th>k_avg (cm/s)</th>
<th>i_max (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GB-F-100-NM¹</td>
<td>Current</td>
<td>98</td>
<td>0.67</td>
<td>98</td>
<td>0.017</td>
<td>7.4</td>
</tr>
<tr>
<td>GB-F-100¹</td>
<td>Slangen (2015)</td>
<td>97</td>
<td>0.65</td>
<td>102</td>
<td>0.014</td>
<td>8.6</td>
</tr>
<tr>
<td>C-GB100-0²</td>
<td>Crawford-Flett (2014)</td>
<td>320</td>
<td>0.65</td>
<td>0</td>
<td>0.019</td>
<td>0.95</td>
</tr>
<tr>
<td>Test F²</td>
<td>Moffat and Fannin (2006)</td>
<td>430</td>
<td>-</td>
<td>25</td>
<td>0.015</td>
<td>15.2</td>
</tr>
</tbody>
</table>

Notes:
¹ Reconstituted using water pluviation in the flexible wall permeameter.
² Reconstituted using slurry deposition in the large rigid wall permeameter.

Table 6.2: Hydraulic conductivity estimations from commonly-used methods

<table>
<thead>
<tr>
<th>Source</th>
<th>k_avg (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GB-F-100-NM</td>
<td>0.017</td>
</tr>
<tr>
<td>Hazen equation (Hazen, 1911)</td>
<td>0.007 – 0.020¹</td>
</tr>
<tr>
<td>Kozeny-Carman equation (Carman, 1939)</td>
<td>0.029¹</td>
</tr>
<tr>
<td>Prugh method (Powers et al., 2007)</td>
<td>0.018 – 0.028¹</td>
</tr>
</tbody>
</table>

Notes:
¹ Calculations for values included in Appendix F.

Table 6.3: Initial test conditions in Slangen (2015) and the current study

<table>
<thead>
<tr>
<th>Test code</th>
<th>l (mm)</th>
<th>e_c (-)</th>
<th>p'_c (kPa)</th>
<th>csa_e (cm²)</th>
<th>B-value (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slangen (2015)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.8GB20-50</td>
<td>103</td>
<td>0.48</td>
<td>54</td>
<td>78.5</td>
<td>0.96</td>
</tr>
<tr>
<td>4.8GB20-50 (R)</td>
<td>102</td>
<td>0.45</td>
<td>53</td>
<td>78.5</td>
<td>0.95</td>
</tr>
<tr>
<td>6.0GB35-100</td>
<td>100</td>
<td>0.37</td>
<td>102</td>
<td>78.5</td>
<td>0.95</td>
</tr>
<tr>
<td>6.0GB35-100 (R)</td>
<td>102</td>
<td>0.37</td>
<td>102</td>
<td>78.5</td>
<td>0.97</td>
</tr>
<tr>
<td>Current Study</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.8GB20-50-M</td>
<td>100</td>
<td>0.49</td>
<td>52</td>
<td>73.6</td>
<td>0.95</td>
</tr>
<tr>
<td>4.8GB20-50-M (R)</td>
<td>96</td>
<td>0.51</td>
<td>50</td>
<td>73.6</td>
<td>0.99</td>
</tr>
<tr>
<td>6.0GB35-100-M</td>
<td>100</td>
<td>0.38</td>
<td>99</td>
<td>73.6</td>
<td>0.97</td>
</tr>
<tr>
<td>6.0GB35-100-M (R)</td>
<td>99</td>
<td>0.32</td>
<td>98</td>
<td>73.6</td>
<td>0.97</td>
</tr>
<tr>
<td>6.0GB35-100-NM</td>
<td>100</td>
<td>0.35</td>
<td>103</td>
<td>78.5</td>
<td>0.83</td>
</tr>
</tbody>
</table>
Table 6.4: Comparison of seepage regime parameters with and without BE mounts

<table>
<thead>
<tr>
<th>Phenomenon</th>
<th>Test code</th>
<th>$k_i^1$ (cm/s)</th>
<th>$k_{\text{min}}$ (cm/s)</th>
<th>$k_{\text{max}}$ (cm/s)</th>
<th>$k_f^2$ (cm/s)</th>
<th>$v_s^3$ (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internally stable</td>
<td>GB-F-100-NM⁴</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
<td>0.334</td>
</tr>
<tr>
<td></td>
<td>GB-F-100-M</td>
<td>0.019</td>
<td>0.019</td>
<td>0.019</td>
<td>0.019</td>
<td>0.364</td>
</tr>
<tr>
<td>Internally unstable</td>
<td>4.8GB20-50</td>
<td>0.022</td>
<td>0.022</td>
<td>0.032</td>
<td>0.028</td>
<td>0.450</td>
</tr>
<tr>
<td>(suffusion)</td>
<td>4.8GB20-50 (R)</td>
<td>0.025</td>
<td>0.020</td>
<td>0.028</td>
<td>0.020</td>
<td>0.409</td>
</tr>
<tr>
<td></td>
<td>4.8GB20-50-M</td>
<td>0.026</td>
<td>0.026</td>
<td>0.037</td>
<td>0.030</td>
<td>0.504</td>
</tr>
<tr>
<td></td>
<td>4.8GB20-50-M (R)</td>
<td>0.075</td>
<td>0.032</td>
<td>0.075</td>
<td>0.032</td>
<td>0.504</td>
</tr>
<tr>
<td>Internally unstable</td>
<td>6.0GB35-100</td>
<td>0.014</td>
<td>0.006</td>
<td>0.014</td>
<td>0.006</td>
<td>0.103</td>
</tr>
<tr>
<td>(suffosion)</td>
<td>6.0GB35-100 (R)</td>
<td>0.016</td>
<td>0.006</td>
<td>0.016</td>
<td>0.006</td>
<td>0.130</td>
</tr>
<tr>
<td></td>
<td>6.0GB35-100-NM</td>
<td>0.021</td>
<td>0.013</td>
<td>0.027</td>
<td>0.027</td>
<td>0.235</td>
</tr>
<tr>
<td></td>
<td>6.0GB35-100-M</td>
<td>0.023</td>
<td>0.018</td>
<td>0.023</td>
<td>0.018</td>
<td>0.227</td>
</tr>
<tr>
<td></td>
<td>6.0GB35-100-M (R)</td>
<td>0.024</td>
<td>0.016</td>
<td>0.027</td>
<td>0.016</td>
<td>0.307</td>
</tr>
</tbody>
</table>

Notes:
1 Initial hydraulic conductivity $k_i$.
2 Hydraulic conductivity at the last stage of seepage flow $k_f$.
3 Seepage velocity at the discharge boundary during the last stage of seepage flow.
4 Bolded tests are from the current laboratory investigation.
5 Italicized tests are from Slangen (2015).
Table 6.5: Comparison of internal erosion response parameters with and without BE mounts

<table>
<thead>
<tr>
<th>Phenomenon</th>
<th>Test code</th>
<th>$k_{\text{min}} / k_i$</th>
<th>$k_{\text{max}} / k_i$</th>
<th>$\varepsilon_v$</th>
<th>Phenomenon</th>
<th>$i_{\text{su}}$</th>
<th>$i_{\text{so}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internally stable</td>
<td>GB-F-100-NM</td>
<td>1.0</td>
<td>1.0</td>
<td>0.11</td>
<td>Stable</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>GB-F-100-M</td>
<td>1.0</td>
<td>1.0</td>
<td>0.03</td>
<td>Stable</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Internally unstable (suffusion)</td>
<td>4.8GB20-50</td>
<td>1.0</td>
<td>1.5</td>
<td>0.12</td>
<td>SU</td>
<td>0.2</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>4.8GB20-50 (R)</td>
<td>0.8</td>
<td>1.1</td>
<td>0.03</td>
<td>SU</td>
<td>0.2</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>4.8GB20-50-M</td>
<td>1.0</td>
<td>1.4</td>
<td>0.58</td>
<td>SU</td>
<td>0.3</td>
<td>-</td>
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<td>4.8GB20-50-M (R)</td>
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<td>1.0</td>
<td>0.27</td>
<td>SU</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Internally unstable (suffosion)</td>
<td>6.0GB35-100</td>
<td>0.4</td>
<td>1.0</td>
<td>1.54</td>
<td>SO</td>
<td>-</td>
<td>1.2</td>
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<tr>
<td></td>
<td>6.0GB35-100 (R)</td>
<td>0.4</td>
<td>1.0</td>
<td>2.19</td>
<td>SO</td>
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<td>1.8</td>
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<td>6.0GB35-100-NM</td>
<td>0.8</td>
<td>1.2</td>
<td>3.00</td>
<td>SO</td>
<td>-</td>
<td>1.5</td>
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<tr>
<td></td>
<td>6.0GB35-100-M</td>
<td>0.8</td>
<td>1.0</td>
<td>2.62</td>
<td>SO</td>
<td>-</td>
<td>1.2</td>
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<tr>
<td></td>
<td>6.0GB35-100-M (R)</td>
<td>0.7</td>
<td>1.1</td>
<td>3.00</td>
<td>SO</td>
<td>-</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Notes:
1 Volumetric strain at end of test.
2 SU = Suffusion; SO = Suffosion.
3 Hydraulic gradient at the onset of suffusion.
4 Hydraulic gradient at the onset of suffusion.
5 Italicized tests are from Slangen (2015).
Figure 6.1: Intra-study comparison of GB-F test results with and without BEMs
Figure 6.2: Inter-study comparison of 4.8GB20 test results with and without BEMs
Figure 6.3: Inter-study comparison of 6.0GB35 test results with and without BEMs
Figure 6.4: Intra-study comparison of 6.0GB35 test results with and without BEMs
Chapter 7: Conclusions and recommendations

The aim of this study is to examine the feasibility of mounting bender elements in a flexible wall permeameter. Three companion research objectives were developed: (1) upgrade the flexible wall permeameter with the capacity for shear wave velocity measurement; (2) examine the repeatability of the flexible wall permeameter test results; and, (3) determine if the modifications made affect the ability to reproduce past results using the device. Following review of pertinent literature, custom-made bender elements and related mounts were added to the UBC flexible wall permeameter, thus fulfilling research objective No. 1. A test program of limited scope, with variables of material gradation and presence of bender elements, was then completed. Intra-study comparisons of the results were used to address research objective No. 2. Both intra- and inter-study comparisons of the results were used to complete research objective No. 3. Conclusions arising from the findings of the research are reported herein. Recommendations for future related works are also discussed.

7.1 Upgrades to the flexible wall permeameter

Bender elements, mounted in custom-made perforated plates, were installed in the flexible wall permeameter. The triaxial frame, top cap, and base pedestal were altered to accommodate the necessary wiring for the bender elements. Along with the physical upgrades to the device, new data-logging and improved data-reduction systems were implemented. In support of these changes, a working test procedure was successfully developed that integrated the bender elements and associated hardware and software upgrades.
7.2 Test repeatability

Two sets of repeated tests were included in the test program, with the objective of examining repeatability of the results. Analysis of the repeated tests in the current study yields the following conclusions:

- The modified test procedure is capable of producing specimens with reasonably consistent dimensions and void ratios.
- The repeat tests show good qualitative and quantitative agreement with respective initial tests. The repeatability demonstrated in the current study is comparable to that of previous studies conducted with the flexible wall permeameter.

7.3 Effects of installing bender elements on test results

The hypothesis of the current study was that the insertion of bender element mounts in the UBC flexible wall permeameter would not affect the seepage regime within the permeameter or the measured internal erosion response of specimens. Comparison of test results, with and without the presence of bender elements in the flexible wall permeameter, for specimens yielding stable, suffusive, and suffosive internal erosion responses after imposition of multi-stage seepage flow establish the following:

- The studied hypothesis is confirmed. The presence of bender elements and associated mounts in the flexible wall permeameter do not have an appreciable effect on the seepage regime or the internal erosional response of the tested specimens.
- The modifications made to the flexible wall permeameter do not affect the ability to reproduce past results using the device. Therefore, the mounting of bender elements in a flexible wall permeameter appears feasible.
7.4 Recommendations for future work

The device is currently equipped for a study of the relation between the micromechanics of internal erosion and changes in shear wave velocity. As this work is at the onset of a larger research endeavor, there remains a large body of future related work. Key recommendations of the author for future work include:

- Maintaining strict saturation practices during specimen reconstitution and consolidation. Additionally, the merits of altering the drilled transducer ports on the base frame and replacing the PPT2 transducer should be explored.

- Adding the capacity of the flexible wall permeameter for mass loss measurements to aid in characterization of the erosional responses.

- Increasing the capacity of the flexible wall permeameter for volumetric deformation measurements to better characterize suffosion.
**Bibliography**


Sympatec (2008). “Windex-operating instructions release 5.4.1.0.”


Appendix A Instrumentation and Measurement Uncertainty

In this study, three uncertainty terms are reported: precision, defined as the standard deviation of the measured value around the mean measured value; resolution, the smallest significant change of a measured value that can be detected, taken as four times the precision (Slangen, 2015); and accuracy, defined as the standard deviation of the calibrated data around the linear regression line.

Accuracy of measured quantities can be determined from calibration data using Equation A.1:

\[ (s_i)^2 = \frac{1}{n-1} \sum_{i=1}^{n} (z_i - \bar{z}_i)^2 \]  

Where:
- \( s_i \) – standard deviation of calibrated data around the linear regression line
- \( n \) – number of calibration measurements
- \( z_i \) – base variable
- \( \bar{z}_i \) – predicted value of base variable

The accuracies of the transducers in the FWP instrumentation scheme, as calculated using A.1, are presented in Table A.1. Also listed in Table A.1 are the general specifications of each transducer.

The uncertainties of derived quantities are determined using the method of propagation suggested by ASTM E2655 (ASTM, 2008). Derived parameters such as \( p' \), \( e_c \), and \( i \) are calculated using combinations of measured quantities. Correspondingly, the accuracy of a derived quantity is dependent on the uncertainties of the variables that comprise the quantity, as dictated by Equation A.2:

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

Where:
- \( s_x \) – standard variation of derived variable \( z_x \)
- \( n \) – number of base variables in derived variable function
- \( z_x \) – base variable
- \( s_i \) – standard deviation of base variable \( z_i \)
The uncertainty of the derived variable is evaluated at the mean values of base variables, $z_i$. A full reporting of the uncertainties of the measured quantities of the flexible wall permeameter device can be found in Slangen’s (2015) thesis; however, the accuracies of derived parameters and key measured parameters used to present the results of this thesis (see Chapter 5) are included in Table A.2. An example showing the use of Equation A.2 is shown below for axial strain, $\varepsilon_a$:

$$\varepsilon_a = \frac{\Delta l}{l}$$  \hspace{1cm} (A.3)

*Where:*

$\Delta l$ – axial deformation

$l$ – height of the specimen

The standard deviation of axial strain is defined as:

$$(s_{\varepsilon_a})^2 = \left(\frac{\partial \varepsilon_a}{\partial \Delta l}\right)^2 (s_{\Delta l})^2 + \left(\frac{\partial \varepsilon_a}{\partial l}\right)^2 (s_l)^2$$

The partial derivatives for each base variable are:

$$\frac{\partial \varepsilon_a}{\partial \Delta l} = \frac{1}{l} \quad \frac{\partial \varepsilon_a}{\partial l} = -\frac{\Delta l}{l^2}$$

The standard deviation and mean values of base variables are:

$$\bar{\Delta}l = 0 \ mm, 1 \ mm \quad s_{\Delta l} = 0.01 \ mm$$

$$\bar{l} = 100 \ mm \quad s_l = 1 \ mm$$

Calculating the standard deviation of axial strain:

$$s_{\varepsilon_a} = \sqrt{\left(\frac{1}{(100 \ mm)^2}\right) (0.01 \ mm)^2 + \left(-\frac{\Delta l}{(100 \ mm)^2}\right)^2 (1 \ mm)^2}$$

$$s_{\varepsilon_a} = 1.4 \times 10^{-4} \ mm = 0.01 \%$$
Table A.1: Flexible wall permeameter instrumentation (after Slangen, 2015)

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Instrument name</th>
<th>Measurement port(s)</th>
<th>Model</th>
<th>Manufacturer</th>
<th>Range</th>
<th>Accuracy / Precision / Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell pressure</td>
<td>TPT #1</td>
<td>IC-P</td>
<td>PDCR 130/w/c</td>
<td>Druck</td>
<td>0 – 700 kPa</td>
<td>± 0.2 / 0.02 / 0.08 kPa</td>
</tr>
<tr>
<td>PWP of specimen</td>
<td>TPT #2</td>
<td>MP #1</td>
<td>111</td>
<td>GP:50</td>
<td>0 – 1050 kPa</td>
<td>± 0.5 / 0.1 / 0.4 kPa</td>
</tr>
<tr>
<td>Differential PWP across specimen</td>
<td>DPT #1</td>
<td>MP #1 MP #2</td>
<td>PDW/E972-05-01</td>
<td>Sensotec</td>
<td>± 70 kPa</td>
<td>± 0.1 / 0.003 / 0.012 kPa</td>
</tr>
<tr>
<td>Axial deformation</td>
<td>LVDT</td>
<td>-</td>
<td>TS 25</td>
<td>Novotechnik</td>
<td>0 – 25 mm</td>
<td>± 0.01 / 0.0008 / 0.0032 mm</td>
</tr>
<tr>
<td>Volume change ¹</td>
<td>DPT #2</td>
<td>IC-P</td>
<td>316</td>
<td>GP:50</td>
<td>0 – 14 kPa</td>
<td>± 0.02 / 0.004 / 0.012 kPa</td>
</tr>
<tr>
<td>Flow rate ²</td>
<td>-</td>
<td>O-CHD</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>± 0.0004 / - / - cm³/s</td>
</tr>
</tbody>
</table>

Notes:
1 Derived from fluid level in burette #2 after correcting for intrusion of loading ram, membrane penetration, and volume changes due to the dissolution of air and absorption of water.
2 Mass of water discharged from O-CHD over an increment of time; quantified using a scale and stopwatch.
Table A.2: Uncertainty in key quantities

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Type</th>
<th>Symbol</th>
<th>Unit</th>
<th>Typical value</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydraulic gradient across the specimen</td>
<td>Derived</td>
<td>$i$</td>
<td>(-)</td>
<td>0.00</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10.00</td>
<td>0.02</td>
</tr>
<tr>
<td>Void ratio</td>
<td>Derived</td>
<td>$e$</td>
<td>(-)</td>
<td>0.50</td>
<td>0.03</td>
</tr>
<tr>
<td>Axial strain</td>
<td>Derived</td>
<td>$\varepsilon_a$</td>
<td>%</td>
<td>0.00</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.00</td>
<td>0.01</td>
</tr>
<tr>
<td>Volumetric strain</td>
<td>Derived</td>
<td>$\varepsilon_v$</td>
<td>%</td>
<td>0.00</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.00</td>
<td>0.07</td>
</tr>
<tr>
<td>Hydraulic conductivity</td>
<td>Derived</td>
<td>$k$</td>
<td>cm/s</td>
<td>0.020</td>
<td>0.002</td>
</tr>
<tr>
<td>Seepage velocity</td>
<td>Derived</td>
<td>$v_s$</td>
<td>cm/s</td>
<td>0.012</td>
<td>0.0012$^1$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.60</td>
<td>0.06$^1$</td>
</tr>
<tr>
<td>Mean effective stress</td>
<td>Derived</td>
<td>$p'$</td>
<td>kPa</td>
<td>50</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100</td>
<td>0.2</td>
</tr>
<tr>
<td>Total dynamic head</td>
<td>Measured</td>
<td>$TDH$</td>
<td>cm</td>
<td>N/A</td>
<td>0.5</td>
</tr>
<tr>
<td>Specimen length</td>
<td>Measured</td>
<td>$l$</td>
<td>mm</td>
<td>100</td>
<td>1</td>
</tr>
<tr>
<td>Test duration</td>
<td>Measured</td>
<td>$t$</td>
<td>min</td>
<td>240</td>
<td>1/60</td>
</tr>
</tbody>
</table>

Notes:
$^1$ For simplicity, porosity was taken as a constant quantity
Appendix B  Bender Element Mounts Drawings

Figure B.1: Drawing of bender element modules
Figure B.2: Drawing of updated top perforated plate
Figure B.3: Drawing of updated bottom perforated plate (perforations not shown)
Appendix C  Updated test procedure checklist

The test procedure checklist, originally created by Slangen (2015), was modified for this study to incorporate the bender element mounts, modules, and wiring. Additionally, the checklist has been updated to align with the most recent methods and terminology associated with the device. Of note, the checklist is tailored for the modified slurry deposition technique. Some deviations are required when using the water pluviation technique instead.

Section C.1 includes guidelines for selecting wire mesh sizes for the gradations used in this study. A diagram is included to show the order each wire mesh should be placed when assembling the permeameter. Section C.2 includes select photos of the permeameter setup. The photos are referenced in the checklist where useful as a visual aid.
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The following test checklist has been updated by Adam Silvester in 2017.
Flexible wall permeameter test procedure checklist

Day 1: Cleaning permeameter and Specimen Preparation

☐ Apply vacuum pressure between 65 to 75 kPa to de-airing water reservoir and with water through the sand and carbon filters to $M_{\text{max}} = 330$ kg at least 24h prior to permeameter setup. Maintain vacuum pressure until permeameter setup.

☐ Wash perforated plates and appropriate wire meshes (see Section C.1) and store in de-aired water.

☐ Weigh 1800 g of dry glass beads with the desired mass fractions. Add de-aired water into stainless steel bowl and boil for 30 minutes. Let it cool down and place in vacuum desiccator overnight.

☐ If dry, carefully saturate tubing connected to transducers using syringe.

☐ Fill burettes with de-aired water using suction and purge lines. Ensure water does not overfill vacuum chamber and enter vacuum line.

☐ Clean all grooves, surfaces, and ports of top cap, bottom frame, top plate, and base pedestal with cotton swabs, cloths, and air pressure.

☐ Place lubricated base pedestal O-rings in appropriate grooves.

☐ Feed lower BE wiring (attached to BE) tube through base pedestal, No. 006 O-ring, and base frame, leaving around 20 cm of slack in BE wiring tube above hole in base pedestal. Attach base pedestal to base frame.

☐ Lubricate large acrylic tube O-rings and place in appropriate grooves on top plate and base pedestal, cover with paper towels overnight.

☐ Soak rubber membrane in de-aired water and leave covered overnight to protect from light.
Day 2: Setting up permeameter

- Clean constant-head, assembly, and storage reservoirs with cloths.
- Move I-CHD to maximum height and fill with de-aired water and purge line.
- Attach inflow tubes and vacuum line to base frame.
- Move base frame into assembly reservoir and open all ports, rotate base frame such that O-CP (see Figure 3.3) points towards burette board. Use hand pump to remove air bubbles in ports and recesses.
- Fill assembly tank to around 20 cm above top of base pedestal with water from the de-airing water reservoir.
- Feed upper BE tube wiring (attached to BE) through No. 006 O-ring, mesh C2, mesh C1, No. 006 O-ring, smaller top perforated plate, and top cap (see Figure C.2 and C.13). Leave arrangement loose.
- Secure end of top BE wiring out of water and place top cap and BE arrangement underwater in assembly reservoir. Tumble/vibrate components along tube wiring prior to securing arrangement using two PVC gaskets. Leave around 15 cm of slack in BE wiring tube above mesh C2.
- Place top and bottom perforated plates, and meshes A1, A2, B1, and B2 underwater in assembly tank. Tumble/vibrate items. Arrange meshes in appropriate order (see Figure C.1) and secure to perforated plates using O-ring around center lip.
- Remove top BE protective cap and screw the BE into threads of perforated plate. Place perforated plate with wire meshes into seating in top cap while looping slack BE wiring tube (see Figure 3.2). Secure with PVC gasket. Screw BE confining screw with No. 006 O-ring into threading at top of top cap to create seal (see Figure C.13).
- Saturate tips of tubing connected to transducers for air bubbles.
- Connect all lines to base plate, close valves once connected, stabilize lines.
- Turn on DAQ computer. Launch Flexible Wall Permeameter VI in LabView. Run VI.
- Conduct test of DPT1: place one end in assembly tank and another in a raised beaker (keep height consistent between tests), record DPT1 reading.
- Remove bottom BE cap and Screw BE into threads of perforated plate. Place perforated plate with wire meshes in base pedestal, making sure to not breach the water surface, while looping slack BE wiring tube (see Figure 3.2). Secure with PVC gasket (see Figure C.3)
- Roll membrane around base pedestal, leaving 2 fingers of the base pedestal free and place O-ring (using expander) approximately 1 finger below top of base pedestal (see Figure C.4).
- Lower water level in assembly tank to below O-ring on rubber membrane (move water to storage reservoir).
- Place support cylinders and split-mold (see Figure C.5), and connect to vacuum (-20 kPa).
- Set placement reservoir on top of split mold, ensuring proper seal.
- Measure height of top of outflow wire mesh (R1)
- Ensure that water levels above base pedestal and above prepared material are equal to the depth of the bent spoon. Place specimen using bent spoon (see Figure C.6). Stir prepared material in bowl often (using varied motions), while ensuring air is not introduced.
- Fill placement reservoir with de-aired water. Level top of specimen using siphoning device (-20 kPa), end of rod approximately 85 mm. Collect excess glass beads in bowl used to prepare material.
- Measure height of top of specimen (R2). Re-fill placement reservoir (see Figure C.7).
- Cover ports of top cap with cap nuts and lift the assembled top cap vertically (wire meshes and BE pointing up), while minimizing air introduced into wire meshes (also mind that the BE wire end does not enter the water). Lower top cap into placement reservoir and rotate it underwater (placement reservoir must be full) (see Figure C.7).
- Place top cap on top of levelled specimen, measure R3 (check if R3 < R2 -0.5 mm). Check if level.
- Collect particles in placement reservoir and on base plate with levelled off particles and empty placement reservoir using siphon. Remove placement reservoir.
- Use O-ring expander to feed BE wiring tube through O-ring. Apply a very gentle pressure on the top cap while flipping the flexible membrane around the top cap (try to minimize air bubbles in top of membrane. Release O-ring from expander to create seal (see Figure C.8). Re-secure end of BE wiring.
- Connect inflow and vacuum lines with dripping water.
- Measure height of top cap after connecting lines (R4) and record water level in Burette #1 (RB1).
- Disconnect the vacuum to the split mold and lower vacuum pressure to 0 kPa.
- Open vacuum valve and proceed to apply vacuum to the top cap very slowly using a manual regulator to -20 kPa.
- Release split mold and remove support cylinders (Figure C.9).
- Measure height of top cap (R5) and record water level in Burette #1 (RB2).
- Put steel ball on top of top cap.
- Raise water level to near top of assembly reservoir (recommend filling storage reservoir and transferring to assembly via bucket).
- Place acrylic tubes onto O-rings in grooves on base frame (if they float off, cleaning of grooves/O-rings was insufficient) (see Figure C.10).
- Feed top BE wiring tubing through top plate. Place top plate in assembly reservoir, use hand pump to de-air. Adjust top plate atop acrylic tubes and screw in to tie rods. Screw in second confining screw with No. 006 O-ring around protruding BE wire tubing.
- Lower water level to just below top of top plate. Dry top plate.
- Place loading ram, connect LDVT.
- Check ground cables from data acquisition system, pump, inflow reservoir and triaxial cell.
- Open appropriate valves (DPT2 open, TPT1 open, TPT2 open, cell pressure open, outer chamber open).
- Start data recording for consolidation: voltage readings at 20 Hz.
- Increase the cell pressure and decrease the vacuum pressure in similar intervals (+5 kPa / -5 kPa) until cell pressure reaches slightly above 20 kPa. Disconnect the vacuum pressure and close vacuum line (undrained specimen).
- Measure B-value: lock loading ram (see Figure C.11), increase cell pressure to 100 kPa and record TPT1 and TPT2.
- After 5 min, reduce pressure to 20 kPa, open drainage (vacuum) line and slowly increase cell pressure to target.
- Unlock loading ram and replace with appropriate weight of confining stress.
- Adjust the inflow CHD to head “5 cm” (see Figure C.12).
- Reset Burette # 2 water level to maximum.
- Place bowl with excess specimen material in oven.
- Record water level in burette (RB3).
- Stop recording. Stop VI process. Start VI process and change DAQ settings to 5 Hz. Start recording for overnight readings.
Day 3: Multi-stage seepage flow

☐ Stop recording. Stop VI process.
☐ Read water level in burette after consolidation (RB4) and close drainage line.
☐ Make sure pump is on at low speed and reservoirs are full and in starting positions.
☐ Open DPT1 valves and check all other pressure and flow valves.
☐ Open outlet and open inlet.
☐ Start VI process and change DAQ settings to 20 Hz. Start recording for test. Use test time from VI dash, it will be slightly slower than actual time.

Day 3: Shutdown and Reset:

☐ Stop DAQ to keep data clean.
☐ Close inflow valve.
☐ Shut off pump.
☐ Close port valves on base frame.
☐ Switch to Burette #3 (never have one side of DPT2 pressurized and the other connected to atmosphere).
☐ Depressurize system by disconnecting air.
☐ Close DPT 2 valves on front and backside of board.
☐ Take off LDVT and ground wire.
☐ Close outflow valve.
☐ Disconnect all lines.
☐ Remove top plate
☐ Remove outer acrylic cylinder
☐ Lift permeameter with inner acrylic cylinder still on, allow for water to drain out of cylinder. Place on work bench and then remove cylinder.
☐ Remove top cap from specimen (protect BE) prior to flipping permeameter (while pinching membrane) and pouring specimen into a bowl (release membrane).
☐ Cover BEs with protective caps.
C.1 Wire mesh selection

Table C.1: Wire mesh sizes for varying specimen gradations

<table>
<thead>
<tr>
<th>Label</th>
<th>Purpose</th>
<th>4.8GB</th>
<th>6.0GB</th>
<th>1.0GF</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>Prevent fines loss during specimen reconstitution</td>
<td>0.033 mm</td>
<td>0.033 mm</td>
<td>0.033 mm</td>
</tr>
<tr>
<td>A2</td>
<td>Provide stiffness for A1</td>
<td>0.6 (or 0.4) mm</td>
<td>0.6 (or 0.4) mm</td>
<td>0.6 (or 0.4) mm</td>
</tr>
<tr>
<td>B1</td>
<td>Retain coarse particles while allowing fines to pass during seepage flow</td>
<td>0.8 mm</td>
<td>1.0 mm</td>
<td>0.033 mm</td>
</tr>
<tr>
<td>B2</td>
<td>Provide spacing between B1 and primary top perforated plate</td>
<td>2.8 mm</td>
<td>2.8 mm</td>
<td>2.8 mm</td>
</tr>
<tr>
<td>C1</td>
<td>Retain fines during seepage flow</td>
<td>0.033 mm</td>
<td>0.033 mm</td>
<td>0.033 mm</td>
</tr>
<tr>
<td>C2</td>
<td>Provide stiffness for C1</td>
<td>1.4 mm</td>
<td>1.4 mm</td>
<td>1.4 mm</td>
</tr>
</tbody>
</table>

Notes:
1 A, B, and C assigned according to direction of flow (see Figure C.1); 1 and 2 assigned according to wire mesh purpose.

Figure C.1: FWP wire mesh schematic
C.2 Test setup photos and schematics

Figure C.2: Inside top cap with BE, O-ring, wire mesh, and PVC gasket (should be underwater when assembled)

Figure C.3: Top cap and base pedestal with BEs
Figure C.4: Using O-ring expander around rubber membrane

Figure C.5: Vacuum mold and rubber membrane
Figure C.6: Placing glass bead specimen into expanded rubber membrane

Figure C.7: Filling placement reservoir and placing top cap
Figure C.8: Flipping rubber membrane and positioning O-ring

Figure C.9: Specimen after being released from split mold
Figure C.10: Acrylic tubes and top cap with lines attached

Figure C.11: Assembled FWP with top plate, LVDT, and locked loading ram
Figure C.12: Inflow constant head device (I-CHD) with manual winch for elevation control

Figure C.13: Schematic view of FWP with bender element wiring and water-tight seals
Appendix D  Individual Test Result Plots

Figure D.1: Test GB-F-100-NM $v_s:i$ relation

Figure D.2: Test GB-F-100-NM $k:i$ relation
Figure D.3: Test GB-F-100-NM $\varepsilon_a$ vs. $i$ relation

Figure D.4: Test GB-F-100-NM $\varepsilon_v$ vs. $i$ relation
Figure D.5: Test GB-F-100-M $v_s:i$ relation

Figure D.6: Test GB-F-100-M $k:i$ relation
Figure D.7: Test GB-F-100-M $\varepsilon_a:i$ relation

Figure D.8: Test GB-F-100-M $\varepsilon_v:i$ relation
Figure D.9: Test 4.8GB20-50-M $v_s:i$ relation

Figure D.10: Test 4.8GB20-50-M $k:i$ relation
Figure D.11: Test 4.8GB20-50-M $\varepsilon_a:i$ relation

Figure D.12: Test 4.8GB20-50-M $\varepsilon_v:i$ relation
Figure D.13: Test 4.8GB20-50-M (R) $v_s$:$i$ relation

Figure D.14: Test 4.8GB20-50-M (R) $k$:$i$ relation
Figure D.15: Test 4.8GB20-50-M (R) $\varepsilon_a:i$ relation

Figure D.16: Test 4.8GB20-50-M (R) $\varepsilon_v:i$ relation
Figure D.17: Test 6.0GB35-100-M $v_i$ relation

Figure D.18: Test 6.0GB35-100-M $k_i$ relation
Figure D.19: Test 6.0GB35-100-M $\varepsilon_a:i$ relation

Figure D.20: Test 6.0GB35-100-M $\varepsilon_v:i$ relation
Figure D.21: Test 6.0GB35-100-M (R) \(v_s:i\) relation

Figure D.22: Test 6.0GB35-100-M (R) \(k:i\) relation
Figure D.23: Test 6.0GB35-100-M (R) $\varepsilon_a : i$ relation

Figure D.24: Test 6.0GB35-100-M (R) $\varepsilon_v : i$ relation
Figure D.25: Test 6.0GB35-100-NM \( v_s:i \) relation

Figure D.26: Test 6.0GB35-100-NM \( k:i \) relation
Figure D.28: Test 6.0GB35-100-NM $\varepsilon_a; i$ relation

Figure D.27: Test 6.0GB35-100-NM $\varepsilon_v; i$ relation
Appendix E  Specimen homogeneity tests

To evaluate specimen homogeneity produced by the slurry deposition technique described in Section 4.2, two trial glass bead specimens were reconstituted using the technique, exhumed in stages, and separated into mass fractions by means of dry sieving.

Trial specimen #1 – 4.8GB20:

A trial specimen of the 4.8GB20 gradation was reconstituted in the flexible wall permeameter split mold atop the base pedestal and exhumed with a bent spoon. The specimen was dissected into five equal layers of approximately 20 mm thickness. A #35, with opening size of 0.5 mm, sieve was used to separate the five layers into coarse and fine fractions. The average fines content of the five layers was $S_f = 0.16$ with a variation of the finer fraction of $S_f = \pm 0.04$ (see Figure E.1).

![Figure E.1: #35 sieve analysis of layers in trial specimen #1](image)

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Trial specimen #2 – 4.8GB20:

A second trial specimen of the 4.8GB20 gradation was reconstituted using the slurry deposition technique in a 1000 mL glass beaker (see Figure E.2). The glass beaker, with an inside diameter of approximately 100 mm, allows for visual observations of the reconstituted glass bead specimen while maintaining typical specimen dimensions. The specimen was exhumed in four layers, 200 mL in volume, using the siphoning device (see Section 3.3.1) connected to a vacuum pressure of approximately -20 kPa, and the coarse and fine fractions of each layer were separated using a #35 sieve. The average fines content of the four layers was $S_f = 0.17$ with a variation of the finer fraction of $S_f = \pm 0.03$ (see Figure D.3).

Figure E.2: Front and back views of a 4.8GB20 specimen reconstituted in a 1000 mL glass
Figure D.3: #35 sieve analysis of layers in trial specimen #2
Appendix F Calculation of theoretical hydraulic conductivities

The hydraulic conductivity of gradation GB-F under the conditions of test GB-F-100-NM is determined using three different empirical relations: the Hazen equation (Hazen, 1911), the Kozeny-Carman equation (Carman, 1939), and Prugh’s method (Powers et al., 2007). The properties of test GB-F-100-NM and gradation GB-F used as inputs to the relations are listed in Table F.1.

Table F.1: Inputs for hydraulic conductivity relations

<table>
<thead>
<tr>
<th>Property</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter at 10% mass passing</td>
<td>$d_{10}$</td>
<td>0.13 mm</td>
</tr>
<tr>
<td>Diameter at 50% mass passing</td>
<td>$d_{50}$</td>
<td>0.17 mm</td>
</tr>
<tr>
<td>Diameter at 60% mass passing</td>
<td>$d_{60}$</td>
<td>0.17 mm</td>
</tr>
<tr>
<td>Density of water</td>
<td>$\rho_w$</td>
<td>998.2 kg/m$^3$</td>
</tr>
<tr>
<td>Dynamic viscosity of water</td>
<td>$\mu_w$</td>
<td>$1.002 \times 10^{-3}$ Ns/m$^2$</td>
</tr>
<tr>
<td>Particle density</td>
<td>$\rho_s$</td>
<td>2.5 g/cm$^3$</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>$G_s$</td>
<td>2.49</td>
</tr>
<tr>
<td>Void ratio</td>
<td>$e$</td>
<td>0.67</td>
</tr>
</tbody>
</table>

Notes:
1 Associated with a water temperature $T = 20 ^\circ$C, maintained constant in a controlled laboratory environment.

F.1 Hazen equation

A widely-used empirical correlation relating the hydraulic conductivity to index grain size was proposed by Hazen in 1911, as reported by Holtz and Kovacs (1981):

$$ k = C \ast (d_{10})^2 $$

(F.1)

Where:
- $k$ – hydraulic conductivity (in cm/s)
- $C$ – constant to account for particle shape, path tortuosity, sediment sorting, and porosity
- $d_{10}$ – particle diameter at 10% mass passing in a sieve analysis (in mm)
The empirical relation is considered valid for clean sands with $d_{10}$ sizes between 0.1 and 3.0 mm. The constant $C$ typically varies from 0.4 to 1.2, with a typical value of 1 (Holtz and Kovacs, 1981; Craig, 2004), and incorporates the conversion of units.

\[
k = 0.4 \times (0.13 mm)^2 \quad k = 1.2 \times (0.13 mm)^2
\]

\[
k = 0.007 \text{ cm/s} \quad k = 0.020 \text{ cm/s}
\]

Thus, the theoretical range of hydraulic conductivity established using Hazen’s relation is $0.007 \text{ cm/s} - 0.020 \text{ cm/s}$.

### F.2 Kozeny-Carman equation

Another widely used correlation is the Kozeny-Carman equation. The basis for its development was formulated by Kozeny (1929) and further extended by Carman (1939). The form of the equation presented in this study is taken from Chapuis and Aubertin (2003):

\[
k = C \times \frac{g}{\mu_w \rho_w} \times \frac{e^3}{S^2 G_s^2 (1+e)}
\]  

Where:
- $k$ – hydraulic conductivity
- $C$ – constant to account for the shape and tortuosity of channels
- $g$ – gravitational constant
- $\mu_w$ – dynamic viscosity of water
- $\rho_w$ – density of water
- $e$ – void ratio
- $S$ – specific surface
- $G_s$ – specific weight ($p_s/p_w$)

Chapuis and Legare (1992) proposed a method for determining specific surface area ($m^2/kg$) of a non-plastic soil by assuming a spherical particle shape:

\[
S = 6/d\rho_s
\]

\[
S = \frac{6}{(1.70 \times 10^{-4} \text{ m})(2.5 \text{ g/cm}^3)} \times \frac{1000 \text{ g}}{kg} \times \frac{1 \text{ m}^3}{10^6 \text{ cm}^3} \times \frac{1}{10^6 \text{ cm}^3} = 14 \text{ m}^2/kg
\]
Where:

d – diameter of spheres, assumed to be equal to $d_{50}$

$\rho_s$ – density of spheres

The spherical shape assumption is appropriate given the near-perfectly spherical glass beads tested in this study. Using the specific surface calculated in Equation F.3, inputs from Table F.1, and an assumed value for C, an estimate for hydraulic conductivity can be calculated. Per Carman (1939), a value of $C = 0.2$ provides the best fit for the empirical correlation (Chapuis and Aubertin, 2003).

$$k = 0.2 \times \frac{9.81 \text{ N/kg}}{(1.002 \times 10^{-3} \text{ Ns/m}^2)(998.2 \text{ kg/m}^3)} \times \frac{0.67^3}{(14 \text{ m}^2/\text{kg})(2.5)^2(1.63)}$$

$$k = 2.9 \times 10^{-4} \text{ m/s} = 0.029 \text{ cm/s}$$

F.3 Prugh’s Method

Synthesizing laboratory and field investigations, Byron Prugh developed a series of charts for Moretrench American Coporation that relate hydraulic conductivity to soil gradation and in-situ density. These charts are published in *Construction Dewatering: New Methods and Applications* (Powers et al. 2007). Three charts are presented in the textbook: a chart for dense soils, a chart for soils with 50% relative density, and a chart for loose soils. GB-F-100-NM has a void ratio of $e = 0.67$, and thus, to determine the relative density of the specimen, a value for the minimum and maximum void ratio is also required (Taylor, 1948). Based on theoretical particle packing, the maximum and minimum void ratios for a fabric of equally-sized spheres are $e_{max} = 0.91$ and $e_{min} = 0.35$ (Slangen, 2015); however, laboratory investigations have revealed that in practice, randomly packed spherical particles have a much narrower range of void ratios, closer to $e_{max} = 0.67$ and $e_{min} = 0.60$ (McGeary, 1961; Scott and Kilgour, 1969). To counteract the uncertainty of the relative density of GB-F-100-NM, charts for 50% relative density soils and loose soils were used to
calculate a range of hydraulic conductivity estimates. Other inputs for the charts include $d_{50}$ and uniformity coefficient:

$$C_u = D_{60}/D_{10}$$ (E.4)

$$C_u = \frac{0.17 \text{ mm}}{0.13 \text{ mm}} = 1.3$$

The output for the 50% relative density soils and loose soils estimation charts were 0.018 cm/s and 0.028 cm/s, respectively.