EVALUATION AND CONTROL OF COLLAPSIBLE SOILS IN OKANAGAN-THOMPSON REGION

by

Amin Bigdeli

B.Sc., American University of Sharjah, 2010

M.Sc., American University of Sharjah, 2013

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

in

THE COLLEGE OF GRADUATE STUDIES

(Civil Engineering)

THE UNIVERSITY OF BRITISH COLUMBIA

(Okanagan)

October 2018

© Amin Bigdeli, 2018

The following individuals certify that they have read, and recommend to the College of Graduate Studies for acceptance, a thesis/dissertation entitled:

Evaluation and Control of Collapsible Soils in Okanagan-Thompson Region

submitted by Amin Bigdeli in partial fulfillment of the requirements of

the degree of Doctor of Philosophy

Dr. Sumi Siddiqua, School of Engineering

Supervisor

Dr. Abbas Milani, School of Engineering

Supervisory Committee Member

Dr. Mahmudur Fatmi, School of Engineering

Supervisory Committee Member

Dr. Sina Kheirkhah, School of Engineering

University Examiner

Dr. Abdolreza Osouli, Department of Civil Engineering, Southern Illinois University

External Examiner

Abstract

An increase in population levels has led to extensive land development and increased construction on problematic soils. Problematic soils such as collapsible soils are the main reason for many geological hazards that lead to significant maintenance costs. The existing gaps in knowledge regarding the characterization and remediation of collapsible soil have resulted in the amplification of these collapse-associated hazards. Although many studies have investigated collapsible soil, its behavior is not yet fully understood. Few studies have focused on the micro-mechanism of the soil structure during the collapse; consequently, the current methods used to characterize collapsible soil are not entirely reliable. It is essential to bridge this gap to understand collapsible soils better in order to reduce maintenance costs and save lives.

With these research gaps in mind, this dissertation focused on characterizing collapsible soil by understanding the micro-mechanism of collapse, analyzing the pore-size distribution, and studying the relationship between the Soil Water Characteristic Curve (SWCC) and the micro-mechanics of collapse. Further, the outcomes of the study have been used to identify the influence of the pore water pH level on soil collapse. The results also aid in determining the feasibility of using a green stabilizer to control soil collapsibility.

The results showed that the initial moisture content and therefore suction has the highest influence on the collapsibility of the soil. A transformation technique was proposed to constantly update the SWCC. This method showed a satisfactory correlation between total applied pressure and suction of the soil during consolidation of the soil. Further studies showed that infiltration of acidic pore water into the soil results in destruction of the micro/macro pores of the soil which leads to the collapsibility of the soil without any additional load. Finally, the results proved that the acidic environment developed in the soil due to the high solubility of MgCl₂ in the water, force the soil to go under more settlement. It is shown that 7% MgCl₂ solution causes the soil to experience 50% of its collapsibility prior to any loading after 28 days of curing.

Lay Summary

The foundations of all structures lie in the soil. It is essential for the soil beneath the structure to possess enough strength to withstand all load from the structure. However, not all types of soils have adequate properties and high strength.

This research focuses on a particular type of weak soil that undergoes sudden settlement due to the infiltration of water. The primary goal of this study is to establish a better understanding of this type of soil and enhance its properties to reduce its settlement. The soil behavior was studied through micro-structural analysis of soil. In addition, the effect of groundwater with alternated pH levels on the soil collapse was analyzed. Lastly, a green stabilizer was proposed to remediate the collapse problem of the soil. The outcomes of this research provide better understanding of the soil collapse, effect of pH on collapsibility, and a chemical to stabilize the soil.

Preface

This research was performed under the supervision of Dr. Sumi Siddiqua. The laboratory experiments were conducted in the Geo-Material Research Laboratory at the School of Engineering, University of British Columbia (UBC). Ethics approval from the UBC Research Ethics Board was not required for this research study.

The list of publications related to this thesis is presented below. While earning my PhD, I was able to publish and present two conference papers associated with Objective 1 and Objective 2 of this research at peer-reviewed top geotechnical engineering conferences. Two journal papers, based on Chapter 3 and Chapter 4 of this study, have been submitted to the *Bulletin of Engineering Geology and the Environment*. Chapter 5 of this research is in the process of being edited prior to submitting it to the journal of *Environmental Earth Sciences*.

- Bigdeli, A.; Siddiqua, S., "Understand the effect of Magnesium Chloride as a green stabilizer on controlling the collapse settlement", *Environmental Earth Sciences*, under editing. The idea of this research was formed by Dr. Siddiqua and I. I performed all the tests and analysis. In addition, I prepared manuscript, which was further edited by Dr. Siddiqua.
- Bigdeli, A., Siddiqua, S.; "Effect of pore fluid pH level on the microstructure of collapsible soil", *Bulletin of Engineering Geology and the Environment*, under review. The idea of this research was developed by myself. I performed all the experiments and image analysis. Moreover, I wrote the manuscript, which was further edited by Dr. Siddiqua.
- Bigdeli, A., Siddiqua, S., Camapum de Carvalho, J.; "Inclusion of the effect of pore-size distribution and matric suction on the soil collapse studies", *Environmental Earth*

vi

Sciences, under review. The idea of this study was developed by myself. I also performed all the required experiments in the lab. The analysis of the research data was done by Dr. Camapum and I. Dr. Siddiqua guided me through writing the manuscript and finalized the paper.

- Bigdeli, A., Siddiqua, S. (2016); "Assessment and analysis of factors influencing the collapse"; 69th Canadian Geotechnical Conference, Vancouver, BC. The idea of this research was formed by Dr. Siddiqua and I. I performed all the tests and data analysis. In addition, I wrote the manuscript, which was further edited by Dr. Siddiqua. I presented this paper in the conference.
- Bigdeli, A., Siddiqua, S., Williams, N. (2015); "Evaluation and control of collapsible soils in Okanagan-Thompson area"; 68th Canadian Geotechnical Conference, Quebec City, Quebec. The idea of this research was developed by Dr. Siddiqua, Mr. Williams and I. The field experiments on this paper was done by Interior Testing Services LTD. I performed all the laboratory experiments and analysis of data. The manuscript of the conference paper was written by me, which was further edited by Dr. Siddiqua.

Table of Contents

Abstract	iii
Lay Sumn	naryv
Preface	vi
Table of C	Contents viii
List of Ta	bles xi
List of Fig	ures xiii
List of Syı	nbols, Abbreviations and Mathematical Notations
Acknowle	dgmentsxx
Dedication	ı xxi
Chapter 1	: Introduction1
1.1	Overview1
1.2	Motivations 1
1.3	Objectives
1.4	Thesis organization
Chapter 2	: Literature Review
2.1	Overview
2.2	Collapsible soils
2.3	Factors affecting collapse
2.3	.1 Index properties of soil
2.3	.2 Properties of the pore fluid
2.3	.3 Suction of soil

	2.4	Collapse mechanism	11
	2.4.	1 Traditional and macromechanic interpretations of collapse	12
	2.4.2	2 Micromechanic interpretations of collapse	16
	2.5	Collapse remediation	20
	2.5.	1 Mechanical remediation methods	20
	2.5.2	2 Chemical remediation methods	24
Cha	apter 3:	Collapsibility and Suction Behavior of Soil	28
	3.1	Overview	28
	3.2	Soil Suction	28
	3.3	Experimental approach	30
	3.3.	1 Sample collection	30
	3.3.2	2 Laboratory tests	33
	3.3.3	3 Collapse tests	44
	3.4	Analysis of results	54
	3.5	Summary	56
Cha	apter 4:	Effect of Pore Water pH Level on the Microstructure of Collapsible Soil	58
	4.1	Overview	58
	4.2	Soil pH	58
	4.3	Experimental approach	61
	4.3.	1 Material	61
	4.3.2	2 Microstructural analysis	63
	4.4	Collapse analysis	77
	4.5	Summary	80

Chapter 5: Collapse Remediation Using a Green Stabilizer		
5.1	Overview	
5.2	Chemical stabilization of soil	
5.3	Experimental approach	87
5.3.	1 Material	87
5.4	Methodology	
5.5	Analysis of results	
5.6	Summary	101
Chapter 6:	: Conclusions and Recommendations	103
6.1	Summary and conclusions	103
6.2	Originality and contributions	105
6.3	Limitations and recommendations	106
Bibliograp	hy	107
Appendix	A:	

List of Tables

Table 2-1: Summary of famous collapse prediction methods based on the soil properties
Table 2-2: Collapse severity classification (ASTM 2003) 16
Table 2-3: Predicted vs. measured settlement for different treatment methods (Republished with
permission of ASCE, from Mitigation measures for small structures on collapsible
alluvial soils, Kyle M. Rollins and G. Wayne Rogers, 120 (4), 1983; permission
conveyed through Copyright Clearance Center, Inc.)
Table 2-4: Summary of advantages and disadvantages of each method (Republished with
permission of ASCE, from Mitigation measures for small structures on collapsible
alluvial soils, Kyle M. Rollins and G. Wayne Rogers, 120 (4), 1983; permission
conveyed through Copyright Clearance Center, Inc.)
Table 2-5: Different stabilization techniques
Table 3-1: In-situ properties of soil samples for each test pit at two different depths using
densometer
Table 3-2: Index properties of the soil collected in the laboratory 34
Table 3-3: Summary of laboratory testing showing the soil properties
Table 3-4: Summary of the oedometer tests plan 46
Table 4-1: Chemical analysis of soil samples from test pit #1 64
Table 4-2: Summary of the measured versus calculated permeability values of the soil samples
under different pH levels (Short-Term)76
Table 4-3: Summary of the measured versus calculated permeability values of the soil samples
under different pH levels (Long-Term)77
Table 5-1: Summary of Magnesium Chloride attributes 86

Table 5-2: Index properties of the soil	88
Table 5-3: The physical and chemical properties of Magnesium Chloride	90
Table 5-4: Results of single oedometer test on an undisturbed sample	90
Table 5-5: Mix proportions for sample preparation	93
Table 5-6: Summary of the test plan showing studied percentages of MgCl2 solution and t	heir
curing time	95
Table 6-1: Limitations and recommendations	106

List of Figures

Figure 2-1: Schematic view of the characteristics of collapsible soils before and after the collapse Figure 2-2: General classification of collapsible soils. "Republished with permission of Springer Science and Bus Media B V, from Types and distribution of collapsible soils, C.D.F Rogers, 1995; permission conveyed through Copyright Clearance Center, Inc.".....7 Figure 2-3: Soil's structure with (a) the same mineralogy that collapse happens with a change in energy in the whole system (b) different compounds where collapse can happen due Figure 2-4: Different types of soil pores based on their size: (a) intergranular pores; (b) intragranular pores; (c) macropores; (d) micropores 19 Figure 3-1: Coordination of test pits to collect the soil samples at Kelowna International Airport Figure 3-2: Soil sample collection procedure: (a) excavation (b) collecting data from densometer Figure 3-4: Illustrates the complete grain-size distribution of the soil which shows that the soil is Figure 3-5: The SEM image of collapsible soil sample in the natural condition showing the soil Figure 3-6: Pressure plate test sample preparation: (a) fully saturating the soil sample (b) test setup

Figure 3-8: Transformed curve of measured SWCC with the void ratio of the soil at each suction
level
Figure 3-9: Liquid limit and plastic limit moisture contents, obtained from Khalili et al. (2004) and
Fleureau et al. (1993), versus e.pF41
Figure 3-10: Validating the transformed SWCC equation by comparing with Arya-Dierolf (1989)
approach
Figure 3-11: Results of proctor compaction test along with iso-suction curves calculated based on
the equation of transformed SWCC
Figure 3-12: GDS automated oedometer machine
Figure 3-13: Static compaction of the soil sample to reach to the required dry density 46
Figure 3-14: Consolidation results of the soil at 100 kPa inundation with different dry densities48
Figure 3-15: Change in the void ratio of the soil at 100 kPa inundation for different dry densities
of soil sample
Figure 3-16: Consolidation results of the soil at 100 kPa inundation with different initial moisture
contents
Figure 3-17: Change in the void ratio of the soil at 100 kPa inundation as a result of change in
initial moisture content
Figure 3-18: Consolidation results of the soil at 100 kPa inundation under different surcharged
pressures
Figure 3-19: Change in the void ratio of the soil as a result of change in inundation surcharged
pressure
Figure 3-20: Correlation between total applied load and suction of the soil by constantly updating
SWCC

Figure 3-21: Relationship between total collapse of the soil versus total suction prior to inundation
of soil
Figure 4-1: Liquid limit, plastic limit, and plasticity index of the soil sample under different pH
levels 63
Figure 4-2: Sample of SEM image used in ImageJ showing the scale
Figure 4-3: Image processing of the soil 500x zooming demonstrating binarization and
thresholding of the pores (black pixels)
Figure 4-4: Average pore-size distribution of soil sample in its natural condition
Figure 4-5: Spaced pores distribution in the structure of the soil in natural condition that have
significant influence on collapse due to their numbers
Figure 4-6: Macropores distribution in the structure of the soil in natural condition that have low
influence on collapse due to their limited numbers
Figure 4-7: Area of the pores for the short-term effect of different pH level
Figure 4-8: Area of the pores for the long-term effect of different pH level
Figure 4-9: Number of the pores with the area between 50 to 800 μ m ² for short-term exposure of
different levels of pH72
Figure 4-10: Number of the pores with the area between 50 to 800 μ m ² for long-term exposure of
different levels of pH73
Figure 4-11: Macropores distribution in the structure of the soil with short-term exposure to
different pH levels with the area more than 800 μ m ² 74
Figure 4-12: Macropores distribution in the structure of the soil with short-term exposure to
different pH levels with the area more than 800 μ m ²

Figure 4-13: Consolidation test results for short-term exposure of the soil to different pH levels at
100 kPa inundation
Figure 4-14: Consolidation test results for long-term exposure of the soil to different pH levels at
100 kPa inundation
Figure 4-15: Change in void ratio of the soil at 100 kPa inundation for different pH levels and
exposure time
Figure 5-1: Compaction curve of test pit #1 showing maximum dry density and optimum moisture
content of the soil
Figure 5-2: Collapsible soil sample: (a) oven-dried without any chemicals (b) after mixing with
MgCl ₂ solution
Figure 5-3: Collapsible soil sample: (a) prepared in the ring to perform consolidation test (b) after
consolidation and drying in the oven for 24 hours
Figure 5-4: Consolidation results of a test samples mixed with 3% MgCl ₂ solution under different
curing time
Figure 5-5: Consolidation results of a test samples mixed with 7% MgCl2 solution under different
curing time
Figure 5-6: Consolidation results of a test samples mixed with 11% MgCl ₂ solution under different
curing time
Figure 5-7: Collapse potential versus curing period for different amount of MgCl ₂ solutions 99
Figure 5-8: Collapse potential versus curing period for different amount of MgCl ₂ solutions 100
Figure A-1: Regression assumptions analysis of Figure 3-21128

List of Symbols, Abbreviations and Mathematical Notations

SWCC	Soil-water characteristic curve
MgCl ₂	Magnesium Chloride
PSD	Pore-size distribution
SEM	Scanning electron microscopy
i	Collapse potential
Δe	Change in void ratio
<i>e</i> ₀	Initial void ratio
eı	Void ratio at liquid limit
K	Degree of collapse
R	Collapse ratio
WL	Moisture content at liquid limit
WS	Moisture content at saturation
G_S	Specific gravity
γd	Dry unit weight
γw	Unit weight of water
W0	Initial moisture content
I_P	Plasticity index
α	Collapse susceptibility
K_d	Collapse intensity
A	Alfi's collapse potential
I_L	Collapsibility
WP	Moisture content at plastic limit

K_L	Amount of collapse
S_0	Initial degree of saturation
Y0d	Initial dry density
W	Water content
n _o	Initial porosity
C_u	Coefficient of uniformity
I_C	Collapse potential based on ASTM
LL	Liquid limit
PL	Plastic limit
PI	Plasticity index
ef	Final void ratio
USCS	Unified soil classification system
AASHTO	American association of state highway and transportation
SM	Silty-sand
a	Arya-Dierolf empirical parameter
ψ_i	Soil suction
γ	Surface tension of water
θ	Contact angle
$ ho_w$	Density of water
g	Acceleration due to gravity
<i>r</i> _i	Pore radius
AEV	Air-entry value
EDS	Energy-dispersive spectroscopy

ksat	Hydraulic conductivity
C_S	Shape factor
Т	Tortuosity
S_S	Surface area per unit volume of soil solids
μ	Viscosity of water
H_2O	Water
HCl	Hydro Chloric acid
$Mg(OH)_2$	Magnesium Hydroxide

Acknowledgments

I would like to express my sincere gratitude to my advisor and mentor, Dr. Sumi Siddiqua, who has helped me to improve my knowledge and personality throughout my Ph.D. at UBC. Without her patience, advises, and her support, I would never be able to finish this research. Her motivation and immense support have helped me to overcome all the challenges I faced.

I am grateful to all my committee member, Dr. Abbas Milani, Dr. Bahman Naser, and Dr. Mahmudur Fatmi, for their support and insightful comments to improve my research. I would also like to acknowledge all the members of our research group and technicians in the School of Engineering.

Words are not enough to thank my parents for their love, support, and encouragement in every aspect of my life. I am always thankful for all the sacrifices they have made to provide the bests in my life. I am also grateful to my sister who has always loved me and guided me to solve the problems I faced in my life. Sacrifices she has made will always remain in my mind. Finally, I would like to give my special thanks to my grandma for her love, support, and patience. She is the most supportive person in my life who is willing to sacrifice everything to see me happy. In the end, I would like to thank all my friends at UBC who have brought joy and happiness to my life. Their love and support have eased the pain of being far from my family.

Dedication

It is my privilege to dedicate to my compassionate, caring, and thoughtful parents, my sister, and my beloved grandma.

Chapter 1: Introduction

1.1 Overview

Collapsible soils are the origin of many geological hazards in civil engineering projects. Construction on this type of problematic soil has always been a challenge for geotechnical engineers due to existing gaps in knowledge on this topic. This chapter provides brief background information about collapsible soil and the motivations for choosing this research topic. This chapter also presents the four objectives that were identified and defined to advance knowledge about collapsible soils. Finally, the chapter ends with the required tasks to establish each of the research objectives.

1.2 Motivations

An increase in population levels has resulted in the extensive land development and increased construction on problematic soils. Therefore, it is essential for geotechnical engineers to have sufficient knowledge to deal with all types of the soils, including collapsible soils. Although collapsible soils can withstand high amounts of load in an unsaturated condition, the settlements associated with the penetration of water into the system often lead to expensive repairs (Gaaver, 2012). A sudden reduction in volume, due to an increase in the water content, has caused construction on this type of soil to remain as one of the most costly geological hazards in geotechnical engineering. There are many examples of construction failure associated with collapsible soils that have led to tremendous maintenance costs. The development of huge cracks on the Khoda Afarin Channel in Iran (Noutash et al., 2010) and building foundation failure in Mexico are examples of the problems caused by the settlement of collapsible soil. The cost of maintenance of the Khoda Afarin Channel in Iran and the building foundation failure in Mexico

was estimated to be \$0.2 million and \$0.5 million US dollars, respectively (Houston et al., 2001; Noutash et al., 2010). Therefore, the identification, characterization and, prediction of the collapse potential of the soil as well as proposing new solutions to mitigate the problems related to collapsible soils are crucial issues for geotechnical engineers.

Although the study of collapsible soils started as early as 1820s (Smalley et al., 2001), the lack of knowledge on the micromechanics of soil collapse has prevented researchers from fully understandingthe collapse phenomena. In addition, variability in the types and chemical components of these soils has amplified this problem. Therefore, this dissertation aims to advance the current knowledge on collapsible soils and help researchers better understand the behavior of collapsible soils.

1.3 Objectives

The primary goal of this research study is to develop a better understanding of the behavior of collapsible soils to predict the collapse settlement and minimize the geological hazards associated with this type of problematic soil. In order to achieve this goal, the following objectives must be met:

- Characterize natural collapsible soil to develop an understanding of the micro-mechanism of collapse
- Determine the relationship between the micro-mechanism of collapse and the Soil Water Characteristic Curve (SWCC) of natural soil
- 3) Identify the influence of pore water pH level on the collapse settlement
- Understand the effect of Magnesium Chloride as a green stabilizer on controlling the collapse settlement

These objectives are accomplished by implementing the following primary tasks:

- Study the macro-mechanism of soil collapse by determining the one factor that is responsible for the collapse. This task was done by analyzing the effects of factors, such as dry density, moisture content, and surcharge pressure, on the soil while keeping all the other factors constant. A series of oedometer tests were performed under this task.
- Study the micro-mechanism of soil collapse by analyzing the pore-size distribution and identifying its correlation with soil suction under different experimental conditions. A pressure plate test was performed on the SWCC of natural collapsible soil.
- 3) Investigate the effect of pore water pH level on collapse potential by analyzing the change in the pore-size distribution of the soil. This task was done by performing image analysis on SEM photos of the soil, under varying levels of pH and exposure time, before and after the tests.
- 4) Performe the feasibility study to identify the effectiveness of green soil stabilizer (Magnesium Chloride, MgCl₂) on controlling the collapse. Oedometer tests were performed with samples prepared with different percentages of MgCl₂ solution for five different curing durations.

1.4 Thesis organization

In order to fulfill the objectives mentioned above, this dissertation consists of six chapters, as follows:

Chapter One presents a brief background on the unsaturated soils with a focus on problematic soil. Further, it highlights the importance of studying the behavior of problematic soils and the gap of knowledge in this area. This chapter emphasizes the objectives of this study that can advance the knowledge of collapsible soils. Finally, the tasks needing to be accomplished to achieve the objectives are listed.

Chapter Two reviews background information and previous studies on collapsible soil to characterize and understand the collapse mechanism. Empirical methods to predict the collapse are also presented in this chapter. Finally, chapter ends with background information about the current techniques to remediate the collapse.

Chapter Three refers to the first part of laboratory work, and it focuses on the first and second objective of this dissertation. Preliminary geotechnical experiments were performed to measure the index properties of the collected soil. Moreover, SEM images of the soil's structure were taken to study the micro-structure of the soil. In addition, SWCC of the soil was measured and verified with the analytical model. Finally, a correlation between total applied load, global void ratio, and suction of the soil was provided and verified under varying soil conditions such as dry density, moisture content, and surcharge load.

Chapter Four presents the results for the third objective of this study by investigating the effect of pore water pH level on the collapsibility of the soils. It studies the microstructure of the soil exposed to the pore water with different levels of pH and exposure time. The pore-size distribution of the soil was measured and associated with the results of a single oedometer test.

Chapter Five reviews a brief background of the chemical soil stabilizing methods and focuses on the fourth objective of this dissertation. This chapter analyzes the effect of one of the most common soil stabilizers and de-icing agents, Magnesium Chloride (MgCl₂), on the collapse potential of the soil. The collected soil was mixed with different percentages of MgCl₂ under different curing times, and the collapse potential of the mixture was measured using the oedometer tests.

Chapter Six contains a summary of this dissertation and presents the outcomes of each objective. Moreover, this chapter presents the limitations of this study and the recommendations for future studies in this area of research.

Chapter 2: Literature Review

2.1 Overview

Expansion, dispersion, and collapsibility of soil give rise to many geotechnical difficulties including inadequate bearing capacity, the potential for unacceptable settlements, and slope instability. Soil composition, mineralogy, structure, and nature of the pore fluid are the factors responsible for such characteristics (Briscolland and Chown, 2001). The present study is focused on collapsibility problems of soil.

This chapter reviews background information and the previous studies on characterizing collapsible soils. Empirical methods to predict the collapse are also presented in this chapter. Finally, this chapter ends with background information about the current techniques to remediate the collapse.

2.2 Collapsible soils

Collapsible soils have been the subject of many studies for more than 70 years. As the name indicates, this type of soil undergoes a sudden volume change when the water content increases; this change, which occurs with or without the presence of additional loading, causes the soil particles to move to a denser structure (Sultan, 1969; Jennings and Knight, 1957). Due to the sensitivity of this type of the soil to water, collapsible soils are also called moisture-sensitive soils (Houston et al., 2002).

Cementing agents that exist in the structure of collapsible soils stabilize the open and partially unstable fabric, and thereby give the soil high bearing capacity in the unsaturated state (Rust et al., 2010). However, the addition of water to the system, along with high pressure on top of the soils, softens the inter-particle bindings and leads to a critical reduction in volume (Barden et al., 1973).

Common features associated with collapsible soils are: high porosity, high void ratio, sensitivity to water, low dry density, low inter-particle bonds, loosely cemented and geologically younger deposits. Figure 2-1 is a schematic view of the characteristics of collapsible soils.



Figure 2-1: Schematic view of the characteristics of collapsible soils before and after the collapse

Various types of natural soil with the same features mentioned above can be categorized as collapsible soils. Researchers have shown that even the compacted soils, at the dry side of optimum water content, have an open and meta-stable structure that undergoes settlement in the presence of additional water and load (Sun et al., 2007; Pereira and Fredlund, 2000; Lawton et al., 1989). Rogers (1994) provided a classification for all different soils with their collapsibility behavior.

Figure 2-2 shows the classification of collapsible soils which include both compacted and natural soils, such as Alluvial, Aeolian, Residual, and Colluvial deposits.



Figure 2-2: General classification of collapsible soils. "Republished with permission of Springer Science and Bus Media B V, from Types and distribution of collapsible soils, C.D.F Rogers, 1995; permission conveyed through Copyright Clearance Center, Inc."

Loess is one of the most common types of collapsible soils. Covering more than 10 percent of earth's landmass, Loess is composed of sub-angular silt-size particles that are the result of air-fall sedimentation (Indraratna et al., 2005; Rogers, 1995). Loess is an Aeolian deposit often found in arid and semi-arid regions (Houston et al., 2002); Aeolian collapsible soils can also be found in environments with medium rainfall, where the impermeable top layers' crust protects the lower layers of soil from saturation. The mid-west United States is an example of such an environment, where fine Aeolian deposits experience a large amount of collapse (Clemence and Finbarr, 1981).

Loess is a reddish-brown silt-size soil with adequate strength and stiffness in the dry-state; it has a relatively low dry density and cohesion (Rogers, 1995). This type of soil commonly comprises a significant amount of sand and silt with a small portion of clay (Bigdeli et al., 2015; Al-Rawas, 2000; Clevenger, 1958). The metastable structure of Loess soil consists mainly of calcium carbonate (calcite) as cementitious material for inter-particle binding; this binding is created during the post-depositional processes as a result of weathering (Tabarsa et al., 2018; Smalley et al., 2006a; Smalley and Vita-Finzi, 1968).

2.3 Factors affecting collapse

Traditionally, macromechanics methods to study soil collapse only considered one factor such as dry density, moisture content, atterberg limits, or loss of suction responsible for the collapse (Barden et al., 1973; Dudley, 1970). The concepts of soil mechanics were used to study the collapsible soil in the macromechanics methods. Most of the work carried out on the parameters that govern collapse behavior had focused on initial dry density, water content, degree of saturation, and applied load. Brief background is provided below on the factors affecting collapse.

2.3.1 Index properties of soil

Soil type: As explained previously, the structure of collapsible soils consists of silt-size particles bound together with clayey-bridge (Lawton et al., 1989). In the unsaturated state, the clayey-bridge works as a cementitious agent between the soil particles which increases the shear strength of the soil. The higher the amount of clayey material, the higher the void ratio of the soil. Upon the addition of water to the system, the clayey-bridges dissolve and the soil experiences collapse. Therefore, a higher amount of clayey content results in a greater amount of collapse (Basma and Tuncer, 1992). However, Lawton et al. (1989) showed that after a certain point, the addition of clayey to the soil leads to expansibility behavior. Later studies on collapsible soils with a high amount

of clay (more than 30%) proved that clay content is not the key factor and there is no monotonic relation to the collapse potential of soil (Li et al., 2016; Ruilin and Lizhong, 1999; Krayev, 1969). **Dry unit weight:** This feature has a significant effect on the collapse potential of soil (Bigdeli and Siddiqua, 2016; Houston et al., 2002; Rogers, 1995). Generally, higher values of dry unit weight result in a denser structure with a lower void ratio. In addition, densifying the soil forces the particles to rearrange into a more stable structure by destroying the weak cementitious interparticle bonds (Basma and Tuncer, 1992). Therefore, when additional water infiltrates the system,

the influence of weak bindings on the collapsibility is less profound (Vanapalli et al., 1999).

Water content: Collapse triggering saturation degree varies between different types of soil. This factor depends on the initial moisture content of the soil as well as the applied pressure on soil structure. Increasing the moisture content of the soil results in dissolution of cementitious agents and therefore weakening the meta-stable structure of collapsible soils (Chen et al., 2006); consequently, the structure of soil fails and triggers the collapse. It is noteworthy that an increase in moisture content and applied load increases the collapse potential to a certain point beyond which no substantial settlement happens (Li et al., 2016). This collapse behavior is explained by the fact that there is a maximum densification level for any type of soil, including collapsible soils (Basma and Tuncer, 1992).

2.3.2 Properties of the pore fluid

Population over-burst has necessitated the world for rapid urbanization and industrialization. This has resulted in a significant increase in acid precursor emissions and environmental pollution (Pankaj et al., 2012). One of the most critical problems caused by industrialization is acid rain. Stalin and Muthukumar (2002) identified that acid precursor emissions could reduce the pH level of precipitation to as low as 5.6. They reported severe acidification of soil due to acid rain which

altered the physico-chemical properties of the studied soil (Pankaj et al., 2012; Stalin and Muthukumar, 2002). Acidification of the environment has been the subject of many studies in Eastern Canada (Scott et al., 2010), and awareness of acid rain and deposition of acid precursors in soil have recently increased in Western Canada (Hazewinkel et al., 2008; Shewchuk, 1983). Studies on the effect of acid rain on the properties of lime and cement stabilized soils reported a tremendous change in the strength of the soil (Kamon et al., 1996). A high concentration of Hydrogen ions in the soil changes the cation exchange capacity and chemical reactions (Gupta and Singh, 1997). Sunil et al. (2006) reported that soil pollution as a result of landfill leachate changes the pH level of the soil and consequently alters the mechanical properties of compacted clay by rearranging the clay particles.

A low pH level of the pore fluid can also affect the structure of the soil and result in shifting the grain-size-distribution of the soil toward the silt fraction and increasing the angularity of the particles (Pankaj et al., 2012). In addition, studies on the effect of various pH levels on the structure of montmorillonite indicate a significant increase in micropores and mesopores and decrease in surface area of the soil structure (Pin-Hua et al., 2006; Lebron et al., 2002; Altin et al., 1999). New studies are focused on the effect of initial pH level, initial solute concentration, and temperature of the pore fluid on the adsorption capacity of loess (Wang et al., 2009).

2.3.3 Suction of soil

Stress state principal of soils can be used to describe the mechanical behavior of soils in both saturated and unsaturated conditions (Li et al., 2016). Terzaghi (1943) was the first one who introduced the principle of effective stress equation for saturated soils. Later, this equation was modified to be used for unsaturated soils (Bishop, 1959). Stress state principal has been widely acknowledged to describe the collapse mechanism of unsaturated soils by introducing net normal

stress and matric suction as the two stress state variables (Sun et al., 2007a & b; Khalili et al., 2004; Sun et al., 2004; Fredlund and Morgenstern, 1977). other researchers have proven the application of the effective stress principle to describe the behavior of collapsible soils (Khalili et al., 2004; Barden et al., 1973; Bishop and Donald, 1961). The outcome of these studies has shown that the reduction in the matric suction of a soil due to wetting results in the change in effective stress and loss of strength (Pereira and Fredlund 2000; Fredlund and Morgenstern 1977). Tadepalli and Fredlund (1991) and Tadepalli et al. (1992) verified the one-to-one relationship between matric suction and total volume change due to collapse. It is shown that any increase in moisture content of a collapsible soil not only decreases the matric suction, it also affects some other phenomena such as dissolving soluble salts which are considered to act as bonds in unsaturated soil (Houston et al. 1988; Guan 1986). As a result, more collapse can be generated due to the solubility of the bonds and loss of strength.

2.4 Collapse mechanism

The topic of collapsible soil has been the subject of many studies. In general, all the studies on this topic can be classified into three main categories:

Macromechanics methods or traditional methods in which the concepts of soil mechanics are used and only one factor, such as dry density, Atterberg limits, moisture content or loss of suction was considered as the main reason behind the collapsibility of the soil (Barden et al., 1973; Dudley, 1970). In addition, many empirical equations were developed to correlate the amount of soil collapse to soil properties (Noor et al., 2013; Ayadat and Hanna, 2007; Gibbs and Bara, 1967; Feda, 1964; Clevenger, 1958).

However, variety in the chemical components and microstructure of collapsible soils has limited the use of empirical methods to local soil only.

- Micromechanics methods in which soil collapse is studied based on pores distribution in the soil structure. Recent advancements in the image processing tools have abled researchers to analyze the collapse through microstructural vital factors such as contact relation, particle pattern, bonding material, and pore formation (Li et al., 2016). The last two factors have the greatest impact on the collapse process (Lommler and Bandini, 2015; Jing-bo and Yun, 1994; Gao, 1980a).
- A combination of the first two methods in which the mechanics of unsaturated soil along with a microstructural analysis of the collapsible soil are used to interpret the behavior of the soil during the collapse (El-Ehwany and Houston, 1990). Recently, researchers have developed a relationship between the total collapse of the soil and a suction transform matrix, using the void ratio. In this proposed method, pore size distribution was calculated using image analysis software under different factors, such as dry density, moisture content, and surcharged load, to have a better understanding of collapse behavior.

2.4.1 Traditional and macromechanic interpretations of collapse

Based on this approach, various methods were developed to predict and measure the collapsibility of soil. The collapsibility potential of soil was first identified by Abelev (1948). Single oedometer tests were performed to measure the decrease in volume at constant load after flooding the soil sample. This method defines collapsibility potential as a relationship between the reduction of void ratio after inundation with respect to the void ratio of the soil in an unsaturated condition.

$$i = \frac{\Delta e}{1 + e_0} \tag{2.1}$$

Where Δe is the reduction of void ratio due to wetting; e_0 is the initial void ratio of the soil in an unsaturated condition. If the value of "i" after performing the oedometer test is greater than 0.02, it indicates that the sample soil is susceptible to collapse. This approach was among the first which

could calculate collapsibility potential. However, due to an increase in the water content of the soil, it only indicates the volume change tendency under an applied load. Therefore, this approach does not provide any measure of rheological change. Denisov (1963) was among the first researchers to recognize the effect of natural porosity on the potential subsidence of soils. Denisov's method considered the void ratios at the natural and liquid limit moisture contents to evaluate the collapsibility of the soil. Based on Denisov's method, the soil is considered collapsible if it can absorb enough water to reach or exceed its liquid limit.

$$\mathbf{K} = \frac{\mathbf{e}_1}{\mathbf{e}_0} \tag{2.2}$$

In this equation, e₁ and e₀ are the void ratios at the liquid limit and initial condition, respectively. The soil is classified as highly collapsible if the value of "K" is less than 1. Denisov's method was a suitable approach to identify the collapse potential of the soils, but it was not consistent with different types of collapsible soils. Therefore, more factors needed to be considered in his equation. Gibbs and Bara (1967) utilized the outcome of Denisov's method to develop a new approach to relate the moisture content at liquid limit and saturation to the collapse potential of the soil. The equation presented by Gibbs and Bara (1967) is:

$$R = \frac{W_l}{W_s} = \frac{W_l}{\left(\frac{\gamma_w}{\gamma_d} - \frac{1}{G_s}\right)}$$
(2.3)

Where R is collapse ratio, w_1 is the moisture content at the liquid limit, w_s is the moisture content at saturation, G_s is the specific gravity of soil, γ_w and γ_d are the unit weight of water and dry soil respectively. Based on this criterion, the soil sample is susceptible to collapse if the value of R is less than unity. A new method for identifying the collapsible soils was first introduced into the new Soviet building code by Priklonskij in 1952. This method was based on the initial moisture content and Atterberg limits of the soil.

$$K_{d} = \frac{w_{l} - w_{0}}{I_{P}}$$
 (2.4)

Where w_1 is the moisture content at the liquid limit, w_0 is initial moisture content, and I_p is plasticity index. Based on this equation if $K_d < 0$, the soil is categorized as highly collapsible, and if K_d is larger than 1, it is a soil with swelling potential. Any values of K_d between 0 and 1 indicate the soil is normal and there is no significant amount of collapse (Ayadat and Hanna, 2011).

Markin (1969) was the first to propose an interval of the degree of saturation between 60% and 65%, beyond which collapse no longer appears. Researchers such as Booth (1975) and Lawton et al. (1989) confirmed that in soils with saturation above Markin's limit, the amount of collapse becomes independent of the applied load for a given dry density. In other words, the natural moisture content of the soil is inversely proportional to the surcharged load that causes collapse (Alfi, 1984).

$$\alpha = \frac{\mathbf{e}_0 - \mathbf{e}_1}{1 + \mathbf{e}_0} \tag{2.5}$$

In the above equation, if the degree of saturation is less than 60% and α is larger than -0.1, the soil is susceptible to collapse. Alfi introduced a new model based on the void ratio of the soil in natural and liquid limit conditions. Based on Alfi's criterion, the soil is collapsible if the void ratio is more than 0.67 and the value of A, obtained from the equation below, is larger than -0.67:

$$A = \frac{(e_0 - e_1)\gamma_w}{(1 + e_0)(w_0\gamma_d)}$$
(2.6)

Where e_0 and e_1 are the void ratio at natural and liquid limit condition, respectively and the rest of the parameters have been defined. A summary of some of the most important studies to measure collapse is shown in Table 2-1:

Equation	Reference	Collapsibility condition
$K = \frac{e_1}{e_0}$	Denisov (1963)	$K = 0.5 - 0.75 \rightarrow \text{Highly}$ collapsible
$R = \frac{W_l}{W_s} = \frac{W_l}{\left(\frac{\gamma_w}{\gamma_d} - \frac{1}{G_s}\right)}$	Gibbs and Bara (1967)	R < 0.1
$K_{d} = \frac{w_{l} - w_{0}}{I_{P}}$	Priklonskij (1952)	K _d <0
$I_{L} = \frac{w_{o} - w_{p}}{I_{P}}$	Skempton and Northey (1952)	Higher I _L \rightarrow Higher CP
$\alpha = \frac{\mathbf{e}_0 - \mathbf{e}_1}{1 + \mathbf{e}_0}$	Markin (1969)	$\alpha > -0.1 \ \& \ S_0 < 60\%$
$A = \frac{(e_0 - e_l)\gamma_w}{(1 + e_0)(w_0\gamma_d)}$	Alfi (1984)	$e_0 > 0.67 \& A > -0.67$
$K_{L} = \frac{\left[\frac{W_{0}}{S_{0}} - w_{p}\right]}{I_{p}}$	Feda (1966)	$K_L > 0.85 \ \& \ S_0 < 60\%$
$\gamma_{0d} < 1.28 \text{ g/cm}^3$	Clevenger (1958)	Large settlement
$\gamma_{0d} * w < 15$	Kassiff and Henkin (1967)	Susceptible to collapse
n ₀ > 40%	Feda (1966)	Large settlement
$4 < C_u < 12$ $C_u \ge 12$	Ayadat and Belouahri (1998)	Collapse may happen Susceptible to collapse
$\rm I_P < 20$, 15 $< \rm ~w_L < 35$	Ayadat and Ouali (1999)	Susceptible to collapse
$I_{C} = \frac{\Delta h}{h_{o}}$	ASTM D-5333 (2003)	Table 2-2

Table 2-1: Summary of famous collapse prediction methods based on the soil properties
The most common method to calculate the collapse potential of soil is proposed in ASTM D-5333 (2003). This test method consists of placing the soil sample in natural moisture content in the oedometer machine. The stress on top of the soil sample is applied incrementally to reach to the required testing load. Soil sample gets fully saturated by inundating the cell with distilled water which induces the collapse. Table 2-2 shows the classification of collapse potential based on the intensity.

Collapsibility, I _C (%)	Intensity of Collapse
0	None
0.1 to 2.0	Slight
2.1 to 6.0	Moderate
6.1 to 10.0	Moderately severe
>10	Severe

Table 2-2: Collapse severity classification (ASTM 2003)

Although many studies have been done to identify factors for measuring the collapsibility of soil, the challenges to measure the suction of the soil as well as microstructure study of the soil require more investigations. Therefore, recent research is focused on micro-mechanism of collapse.

2.4.2 Micromechanic interpretations of collapse

Collapse should be analyzed as a problem of soil's structural stability. Collapsible soil is a metastable structure in which the structural stability of the soil depends on external and internal factors affecting soil condition. Loss of stability in the structure of collapsible soils can be due to:

a) Change in external energy, such as overburden pressure or vibration.

- b) Change in internal energy, such as a change in the stress state, temperature, or moisture content.
- c) Weakening of the bonds between soil particles as a result of chemical attack and change in the pH level of the soil.

A change of energy can also happen within the aggregate of a soil. Therefore, Mineralogy of the aggregates within a soil structure has also a significant impact on the collapsibility of the soil. Figure 2-3a illustrates the porous structure and collapse procedure of soil only composed of a mineral such as quartz, which is attached by cementing agents. Soil structural collapse may result from a rupture of aggregates due to a change in external/internal energy, such as with a simple change in the stress-state. Figure 2-3b shows the same structure; however, the aggregates are a compound of different minerals such as a combination of quartz and clay. In this latter case, the rupture of aggregates that causes the collapse can also occur due to a change in external/internal energy within the soil particles, such as with a change in temperature when the coefficient of thermal expansion of these minerals varies with the type of mineral. This problem can only be addressed through microstructural analysis of the soil. In addition, the difference in the structure of the soil, such as dispersed and flocculated structures, can cause collapse (Vanapalli et al., 1999). This phenomenon can be observed during compaction of soil on the dry side of optimum density (Tadepalli and Fredlund, 1991). However, compaction of the same soil at wet of optimum with the same dry density and void ratio does not experience the same collapse behavior (Lawton et al., 1992; Tadepalli et al., 1992; Lawton et al., 1989).



Figure 2-3: Soil's structure with (a) the same mineralogy that collapse happens with a change in energy in the whole system (b) different compounds where collapse can happen due to a change of energy in a single particle.

Oedometer machine is the common test to perform on soil to measure the amount of collapse. However, less attention is paid to the changes of energy such as inundation of soil and applying pressure that disturb the stability of the soil during testing. These factors can alter the suction of the soil which is directly related to the collapse. Therefore, analyzing the mechanism of collapse to find a relationship between suction of the soil with applied pressure can solve this problem.

One of the crucial factors in microstructural analysis of collapsible soils is porosity, which consists of pore formation and distribution within the soil. The collapsible structure of a soil is generally provided with macropores generated during the formation process or compaction of the soil. Gao (1980a, 1981) has divided pore forms into four different categories namely intragranular, intergranular, spaced, and macropores (Munoz-Castelblanco et al., 2011). In the process of collapse, these macropores are filled with soil particles, resulting in a sudden reduction of the volume of voids in the soil (Gao, 1980b). Figure 2-4 shows the different types of pores within the structure of a collapsible soil.



Figure 2-4: Different types of soil pores based on their size: (a) intergranular pores; (b) intragranular pores; (c) macropores; (d) micropores

As shown in Figure 2-4, the structure of collapsible unsaturated loess deposits is highly porous. Collapse behavior of loess soils is greatly dependent on its microstructure, which includes bonding material, pore formation, particle pattern, and contact relation (Kozubal and Steshenko, 2015). Although bonding material and pore formation have a more profound effect on collapse behavior, a comprehensive study of loess soil behavior cannot be fundamentally characterized considering one single factor (Kozubal and Steshenko, 2015). Although many studies have been performed to show how soil collapsibility is directly related to porosity, limited studies have considered the importance of pore size distribution in soil. Camapum et al. (2002), in their study on the collapsibility of soils in tropical weather conditions, showed that the total void ratio of the soil does not have a significant effect on collapse. However, by considering the inter- and intragranular pores within soil particles, a direct relationship can be developed between the coefficient of collapse and the void ratio. Information regarding changes in pore size distribution due to loading and wetting provides better evidence that different kinds of pores contribute differently to collapse (Jiang et al., 2014a; Jiang et al., 2014b; Jiang et al., 2012)

2.5 Collapse remediation

Generally, the methods for treating collapsibility of soils fall into two groups: (i) Mechanical remediation methods, which are mainly focused on increasing the compaction of loess soil and rearranging the soil particles to reduce collapse; and (ii) chemical remediation methods, which use chemicals to alter the behavior and improve the strength and stability of collapsible soils. Recently, a combination of the two methods using compaction of soil followed by chemical stabilization has been used to treat problematic soils. Below are some of the most common techniques with an explanation of the advantages and disadvantages of each method (Jefferson et al., 2008; Al-Rawas, 2000):

2.5.1 Mechanical remediation methods

Soil replacement: One of the simplest methods to deal with collapsible soils is to excavate, remove the collapsible soil, and replace it with a compacted soil with better mechanical properties. This method can only be used if the layer of problematic soil is thin and close to the surface (Anayev and Volyanick, 1986). Prewetting: In this method the collapsible soil is flooded with water via boreholes, trenches, or ponding to dissolve the cementitious inter-particle bindings without exerting any additional load. This method is used mainly in the construction of canals and roads, as prewetting is not an effective method for the foundation of the buildings where an increase in overburden pressure of the soil after construction will result in further collapse (Rollins and Rogers, 1994; Houston et al., 1988; Gibbs and Bara, 1967).

Controlled wetting: This method is similar to prewetting, but in controlled wetting the additional water is introduced to the system once construction is complete and the soil should be wet in a carefully-monitored manner to prevent failure in the surrounding soils (Al-Rawas, 2000).

Moisture control: This method limits and controls water infiltration into the soil structure. This can be done through (i) installation of a drainage system, (ii) using impermeable materials on the soil, (iii) restricting landscape vegetation, or (iv) decreasing the permeability of the soil (Manckenchinie, 1980).

Heat treatment and small explosions: In this method, gas and fuel are burned in pressurized boreholes to a temperature up to 1000^{oC}. This technique destroys the structure of the loess to develop a more stabilized soil for construction projects (Bell and Bruyn, 1997).

Compaction control: Compaction is the most common and cheapest method to remediate collapsibility problems. This technique can greatly decrease the degree of collapse in compacted zones while decreasing the induced stress to which collapsible soil is subjected (Rollins and Rogers, 1994). Compaction can solve the collapsibility problem for soil layers up to 10 meters in depth; however, it can only deal with collapsible soils above the groundwater table with a saturation level of less than 60% (Kozubal and Steshenko, 2015; Wang et al., 2011).

In order to better remediate the collapsibility of loess soils, a combination of two or more mechanical methods can be used together. Table 2-3 compares the measured and predicted settlement of different treatment methods. Moreover, the advantages and disadvantages of each method are summarized in Table 2-4:

Table 2-3: Predicted vs. measured settlement for different treatment methods (Republished with permission of ASCE, from Mitigation measures for small structures on collapsible alluvial soils, Kyle M. Rollins and G. Wayne Rogers, 120 (4), 1983; permission conveyed through Copyright Clearance Center, Inc.)

	Treatment	Predicted collapse after loading		Measured settlement after loading	
Test Cell Method	Before treatment (mm)	After treatment (mm)	Collapse (mm)	Creep (mm)	
1	No treatment	267	N/A	282	12
2	Prewetting	270	300	243	12
3	Soil replc.	267	183	114	9
4	Compaction control	254	31	3	14
5	Dynamic compaction after prewetting	396	15	11	18

Table 2-4: Summary of advantages and disadvantages of each method (Republished with permission of ASCE, from Mitigation measures for small structures on collapsible alluvial soils, Kyle M. Rollins and G. Wayne Rogers, 120 (4), 1983; permission conveyed through Copyright

Clearance Center, Inc.)

Test Cell	Treatment Method	Advantages	Disadvantages
1	No treatment	N/A	N/A
2	Prewetting	Low cost Ease of application	Settlement upon loading No uniform settlement
3	Soil replacement	Relatively low cost Removal of differential settlement Ease of application	Applicable to the layers near the surface
4	Compaction control	Highly effective Improves soil properties Effective for the layers up to 10 m depth	Higher cost Not easy to use Nonuniformity of treatment
5	Dynamic compaction after prewetting	Siginificant decrease in collapse Greater uniformity of densification Increase compaction efficiency applicable for the layers up to 10 m depth	Huge cost Not easy to use Potential for liquefaction Increase creep settlement

2.5.2 Chemical remediation methods

Problematic soils have given rise to many geological hazards. Among them, collapsible loess soils are notoriously difficult to deal with due to the collapse potential variability across even a small site (Jefferson et al., 2005). Therefore, a carefully-performed site investigation prior to any ground improvement is mandatory to prevent failure due to collapse (Basma and Tuncer, 1992).

In general, chemical remediation methods have been used to change and improve the engineering properties of natural soils. There are four factors that can be enhanced using chemical stabilization techniques (Ingles and Metcalf, 1972):

a) Durability: The resistance of the soil to short-term weathering, erosion, and water infiltration.

b) Volume stability: The resistance of the soil to any change in its structure due to swelling, collapsibility, change in temperature and water table.

c) Strength: The amount of load soil can withstand before it suffers deformation in its structure.

d) Permeability: The ease of infiltration of water between the soil particles.

Stabilizers can improve the properties of the soil through one or more of the following scenarios: (i) Permeating into the soil to strengthen and stiffen it if the chemical viscosity is low and soil permeability is high; (ii) Compressing and densifying the surrounding soil if the chemical viscosity is high and soil permeability is low; and (iii) Reinforcing the soil at different locations and carrying the load of the unstabilized soil structure (Houston et al., 2001). It should be noted that collecting enough information about the chemical composition and its interaction with soil particles is essential when chemical stabilization techniques are used. Failure to perform a pretreatment assessment may result in engineering hazards (Hunter, 1988). Much research has been done on the suitability of stabilizing additives such as cement, lime, fly-ash, polymers, silicates, etc. to remediate collapse potential (Tabarsa et al., 2018; Jefferson et al., 2008; Basma and Tuncer, 1992). Traditional stabilizers: Cement-based stabilizers were among the first chemicals used to stabilize collapsible soils (Clemence and Finbarr, 1981). Cement-type stabilizers such as fly ash, cement kiln dust, and a mixture of fly ash and rice husk ash have shown promising results in remediating soil collapse (Sreekrishnavilasam et al., 2007; Punrattanasin et al., 2002; Zia and Fox, 2000). These types of stabilizers are more applicable for fine sand deposits, including collapsible soils, and they can be used after construction is complete. However, a careful check must be done to ensure the cementitious materials have penetrated to the desired depth to strengthen the particles' bonding upon wetting (Jefferson et al., 2008).

New chemical stabilizers: New chemicals such as sodium silicate, calcium chloride, sodium hydroxide, ammonium acryloyl, and chrome lignin paper pulp waste and slurry are recent advancements in chemical stabilizers. These materials form gel-like cementing agents, either through a chemical reaction in the solution itself or through a reaction between the solution and the chemical composition of the soil and result in structural stabilization of the collapsible soils (Tabarsa et al., 2018; Jefferson et al., 2008). Although many studies have proven the effectiveness of these materials in collapse potential remediation of loess soil, the huge cost of this technique and its associated environmental pollution have limited their use to specific areas such as mining (Bahloul et al., 2014; Fattah et al., 2014; Kalantari, 2012; Abbeche et al., 2010).

Polymers: The short-comings and disadvantages of previous materials have led researchers to focus on finding new chemicals and techniques. There are some examples of polymers used in the field of loess solidification, such as urea-formaldehyde rosin and hydroquinone-formaldehyde rosin, but the high price and high toxicity of polymers have limited their usage (Larson et al.,

2012). The introduction of biopolymers as a new stabilizing agent, however, has overcome these problems (Khatami and O'Kelly, 2012; Martin et al., 1996). Studies indicate that soil solidification with biopolymers is promising and the effect is significant. The most outstanding advantage of loess solidification with biopolymers is that it uses less solidified material and it is degradable (Ayeldeen et al., 2017). Besides, it has higher strength, good water resistance, and effectively eliminates liquefaction of saturated loess (Wang et al., 2011). Table 2-5 summarizes some of the important studies on the stabilization of loess soil:

Cement-based Stabilizers			
Chemical	Reference	Remarks	
- Cement	- Evstatiev et al. (2002)	- Reduce the collapse	
- Fly ash	- Zia & Fox (2000)	- Hard workability	
-Waste cement kiln dust	- Sreekrishnavilasam et al. (2007)	- Cheap	
- Fly ash and rice husk	- Gasaluck & Nantasarn (2002)	- High polluting impact	
	Chemical Stabilizers	L	
- Sodium silicate	- Clemence & Finbarr (1981)	- Effective against collapse	
- Calcium chloride	- Pengelly et al. (1997)	- Costly	
- Sodium hydroxide	- Pengelly et al. (1997)	- Not easy to apply	
- Ammonia	- Al-Rawas (2000)	- Toxic	
	Polymers		
- Nanoclay	- Tabarsa et al. (2018)	- Effective against collapse	
- Xanthan gum	- Ayeldeen et al. (2017)	- Highly cost	
- Guar Gum	- Aveldeen et al. (2017)	- Environmental friendly	
	Ayeldeen et al. (2017)	- Degradable	

Table 2-5: Different stabilization techniques

A suite of improvement approaches is available to mitigate the collapse potential of these soils, and these include either pre-construction or post-construction on loess, depending on the project requirements. This chapter provided brief background on the collapsible soils, the factors affecting the collapse, and the remediation methods. By highlighting the gap of knowledge in this topic, the next chapters provide experimental analysis to better understand collapsible soils.

Chapter 3: Collapsibility and Suction Behavior of Soil

3.1 Overview

The research on the collapse mechanism of collapsible soil is mainly focused on analyzing the factors governing the collapse. Less attention is given to the change in stress-state of the soil during the oedometer test due to the variation in applied pressure and saturation of the soil. In this study, the soil water characteristic curve (SWCC) of the collected collapsible soil was measured using pressure plate device. A relationship between pore-size distribution and suction of the soil was developed by transformation of SWCC which was verified by fitting to Arya-Dierolf SWCC prediction method. In the second part of this study, a series of oedometer tests under 3 different criteria (dry density, moisture content, and surcharge load) were performed to verify the new relationship. The results show that the consideration of total void (e) and matric suction (pF) leads to a satisfactory correlation with the total collapse of the soil which can be used for future studies.

3.2 Soil Suction

The Soil-Water Characteristic Curve (SWCC) is one of the popular means to analyze the behavior of unsaturated soils. It was originally developed for agricultural-related projects. Later on, it was gradually adopted for geotechnical engineering studies (Fredlund, 2002; Fredlund and Rahardjo, 1993). Although this characterization provides information for engineering judgment about the unsaturated condition of the soil, obtaining accurate data to develop SWCC relationship is a challenging task due to the assumptions used in this experiment. One such assumption in calculating the volumetric water content is that the soil sample does not undergo any volume change during the experiment (Clevenger, 1958). However, in the case of collapsible soils which

experience significant volume change, obtaining accurate data for SWCC is extremely difficult (Feda, 1964).

Many studies have been performed to predict the SWCC relationship based on different properties of soil (SY et al., 2013; Aubertin et al., 2003; Fredlund et al., 2002). Arya-Paris (1981) and Arya-Dierolf (1989) provided a physico-empirical model to relate SWCC to grain-size distribution of the soil. Moreover, other studies focused on describing the relationship between water content and the soil suction and correlating it to the soil behavior (Xie et al., 2018; Malaya and Sreedeep, 2011). The influence of the suction on hardening of the soil can be used to explain the collapsibility process in terms of effective stress principles (Xie et al., 2018; Fredlund and Houston, 2013; Khalili et al., 2004). However, most of these methods have limitations to predict the relationship for extremely low as well as high suction levels.

The SWCC and soil structure of collapsible soils are highly dependent on the porosity and pore size distribution of the soil (Xie et al., 2018). Camapum de Carvalho and Leroueil (2004) proposed a new relationship between the volumetric water content of the soil versus multiplication of void ratio (e) and the logarithm of soil suction (pF), in the form of e.pF. According to these authors, the technique provides satisfactory results for a soil with similar pore distributions. Further investigations have shown that the structural collapse due to an increase in moisture content of soils in a tropical weather can be explained with this method by considering the macropores in calculating the void ratio of the soil (Camapum de Carvalho et al., 2002).

As a result, analyzing the three factors: suction, porosity, and pore size distribution has a great importance in the study of the collapsible soil behavior (Camapum de Carvalho et al., 2015). The current study focuses on the characterization of collapsible soils and understanding the factors that control the collapse settlement by performing experimental analysis on the soil samples collected

29

from Okanagan-Thompson region. SWCC of the collected soil was measured using pressure plate SWCC Device. Moreover, the image analysis technique was performed on SEM images to study pore shape and pore-size distribution of the soil. In addition, a series of single oedometer tests were performed under different criteria. Finally, the updated technique provided by Camapum de Carvalho and Leroueil (2004) is adopted in this article in order to obtain better understandings on collapsibility of the soil in respect of the matric suction and pore-size distribution within the soil structure.

3.3 Experimental approach

Experiments were designed to reach to the objectives can be categorized as:

- a) Preliminary tests: experiments such as sieve size analysis, hydrometer test, Atterberg limit, and compaction test were performed to collect index properties of the soil
- b) Collapse tests: advance experiments were performed on the soil to study the behavior of the soil and measure and understand the collapsibility. Tests such as image analysis to study the microstructure of the soil, pressure plate to measure the suction behavior, and consolidation to measure the collapse potential are the examples.

This section provides the brief explanation of the test methods and present the result.

3.3.1 Sample collection

Soil samples were collected from Okanagan-Thompson valley where the collapse problem had been identified by local geotechnical companies (Bigdeli et al., 2015). Figure 3-1 shows the coordination of each test pit locations at the airport site.



Figure 3-1: Coordination of test pits to collect the soil samples at Kelowna International Airport

In order to analyze the airport's soil behavior, three test pits, 10 meters apart from each other, were excavated at the east side of the airport using a truck mounted excavator. Campbell and Troxler's nuclear densometers were used at each excavated point with 0.15 meters depth and 1-minute duration of the shots to collect in-situ density and moisture content of the soil. Sample collection steps are shown in Figure 3-2:





(b)



Figure 3-2: Soil sample collection procedure: (a) excavation (b) collecting data from densometer

(c) undisturbed sample collection

Preliminary in-situ experiments on the soil provided some information about the properties of the collected soil. Table 3-1 presents the in-situ moisture content and wet/dry density of the soil at each depth:

		Moisture	Wet Density	Dry Density
Test Hole	Depth (m)	content (%)	(kg/m ³)	(kg/m ³)
#1	0.5	9.3	1486	1359.6
	1	6.2	1399	1317.3
#2	0.5	11.2	1478	1329.1
	1	7.8	1465	1359.0
#3	0.7	6.4	1423	1337.4
	1	5.4	1598	1516.1

Table 3-1: In-situ properties of soil samples for each test pit at two different depths using

densometer

3.3.2 Laboratory tests

Several studies indicated strong relationships between in-situ or as compacted dry density with collapsibility of soil (Houston and El-Ehwany, 1991; Houston et al., 1988). Based on the soil properties from Table 3-1, test pit #1 has the lowest dry density which makes this soil to be more prone to collapsibility. As such, test pit #1 was chosen for all the laboratory testing. Physical and index properties of the soil measured in the laboratory are presented in Table 3-2. This table also shows liquid limit (LL), plastic limit (PL), plasticity index (PI), initial void ratio (e₀) and final void ratio (e_f) of the soil after performing collapse test on undisturbed soil sample.

Depth (m)	Moisture content (%)	Wet Density (kg/m ³)	Dry Density (kg/m ³)	LL (%)	PL (%)	PI (%)	eo	ef
0.5	4.9	1377	1312.7	25.2	21.4	3.8	1.03	0.67
1	4.6	1325	1266.7	24.7	20	4.7	1.11	0.66

Table 3-2: Index properties of the soil collected in the laboratory

Sieve and hydrometer analysis were performed to determine the grain-size distribution of the soil. Sieves were stacked on top of each other in ascending order based on their openings. Oven-dried soil sample was sieved using a mechanical shaker and grain-size distribution graph was generated based on ASTM D6913. The result showed that 20 percent of the soil consists of silt and clay. ASTM D7928 was used to analyze particle-size distribution of silt and clay using hydrometer apparatus. This test indirectly measures the diameter of the fine-grained soil based on their sedimentation time. Figure 3-3 shows the hydrometer test setup and Figure 3-4 demonstrates the full grain-size analysis of the soil.



Figure 3-3: Hydrometer test setup to find the gradation of fine-grained soil



Figure 3-4: Illustrates the complete grain-size distribution of the soil which shows that the soil is classified as "Silty-Sand".

The soil classification systems do not provide any guidelines for collapsibility of different soil with the same grain-size distribution (Smalley et al., 2001). This clearly identifies a need for microscopic analysis, which was performed using Scanning Electron Microscopy (SEM) on the oven-dried samples. SEM image in Figure 3-5 shows the presence of large aggregates due to the grouping of smaller particles via clay-bridge or other cementing agents which creates micropores within the particles and macropores between the particles.



Figure 3-5: The SEM image of collapsible soil sample in the natural condition showing the soil particles forming the honey-comb structure

Preliminary analysis on the SEM images showed that the soil consisted of 63% of the aggregated grains and the remaining 37% is formed by individual particles. These results are important to find the total void ratio of the soil to use in the future tests.

The standard compaction test was carried out to find the optimum moisture content and maximum dry density of the soil in accordance to ASTM D698. Oven-dried soil samples were mixed with different percentages of water (starting from 2 until 18 percent with 2% increments) and were compacted in the standard mold. Based on the compaction curve, the optimum moisture content and maximum dry density are equal to 13% and 1865 Kg/m³, respectively. The summary of the soil sample properties is shown in Table 3-3 below:

Soil ID	TH2
Depth	1 m
Soil Type	Silty-Sand
Moisture Content	7.8 %
In-situ Dry Density	1325 kg/m ³
Optimum Moisture Content	13 %
Target Pressure	100 KPa

Table 3-3: Summary of laboratory testing showing the soil properties

In order to study the suction behavior of unsaturated soil, GCTS pressure plate device was used to develop SWCC of the studied soil (Fredlund and Houston, 2013; Padilla et al., 2005). Soil sample was mixed with 7.8% of water and mechanically compacted in the ring to reach to in-situ dry density. Compacted soil was then left to become fully saturated before starting the test. Figure 3-6 presents the prepared sample and test setup for this device.



(a)



(b)

Figure 3-6: Pressure plate test sample preparation: (a) fully saturating the soil sample (b) test setup to measure SWCC

Drying part of SWCC was developed by measuring the volumetric water content of the soil under each suction. The ranges of suction for this test started from 4 kPa and finished with 500 kPa as it is shown in Figure 3-7. It is noteworthy that each test took 4 weeks to cover all the suction ranges.

In addition, this test was repeated 4 times on different soil samples to assure the accuracy of the results.



Figure 3-7: Laboratory measurement of SWCC of the soil using pressure plate device

Camapum de Carvalho and Leroueil (2004) proposed a transformation method for SWCC to incorporate pore-size distribution of a soil. In this approach, logarithm of suction in centimeters of water column times 10 is multiplied by void ratio of the soil. The new axis (e.pF) is developed to study the suction behavior of the soil by constantly updating the void ratio. Figure 3-8 shows the results of e.pF versus saturation degree (S_r).



Figure 3-8: Transformed curve of measured SWCC with the void ratio of the soil at each suction level

This approach was tested for different types of soil. Figure 3-9 presents the relationship between the liquid limit and plastic limit, obtained from Khalili et al. (2004) and Fleureau et al. (1993), versus e.pF. It shows that for soils with plastic behavior, there is a direct relationship between the liquidity and plasticity limits and air-entry value (AEV) of the SWCC. It should be noted that the points correspond to montmorillonite were excluded because:

• The moisture determined on the liquid limit and plastic limit corresponds to water between layers of expansive minerals, which does not contribute effectively on the soil plasticity and should be excluded from the limits of liquidity and plasticity (Campos et al., 2008).

• Montmorillonite is considered as highly active soil which causes this soil to not follow the same trend as any other types of soil.



Figure 3-9: Liquid limit and plastic limit moisture contents, obtained from Khalili et al. (2004) and Fleureau et al. (1993), versus e.pF

Arya and Paris (1981) and Arya and Dierolf (1989) proposed a model to estimate the SWCC based on the grain-size distribution of the soil. They introduced an empirical parameter, a, to consider the pore formation in the natural structure of the soil (SY et al., 2013). Further studies on this method improved the prediction of the SWCC (Vaz et al., 2005). In the current study, Figure 3-10 is developed to compare experimental and predicted SWCC values using Arya-Dierolf's (1989) proposed a relationship as follows:

$$\Psi_{i} = 2\gamma \cos\theta / \rho_{w} gr_{i} \tag{3.1}$$

where ψ_i is the soil suction, γ is the surface tension of water, θ is the contact angle, ρ_w is the density of water, g is the acceleration due to gravity, and r_i is the pore radius. Based on the index properties of the soil, SWCC of the soil was developed using Arya-Dierolf approach.

Figure 3-10 demonstrates an agreement between the experimental data points and the estimated curve using Arya-Dierolf model for void ratio equal to 0.78. It can be concluded that the transformed characteristic curve presented in Figure 3-8 is able to estimate the suction of the studied soil samples for different ranges of void ratio of the test specimens.



Figure 3-10: Validating the transformed SWCC equation by comparing with Arya-Dierolf (1989)

approach

The estimated Air-Entry Value (AEV) from Figure 3-7 was calculated to be equal to 5 kPa. The AEV was also predicted using Arya-Dierolf (1989) method and the value was found to be equal to 3.6 kPa. The AEV value obtained from the experimental data is in agreement with Arya-Dierolf (1989) method.

Figure 3-11 presents the standard Proctor compaction curve of the collapsible soil collected from the testing site at the depth of 1 meter. This figure contains the saturation curve and iso-suction curves obtained from the SWCC of the compacted soil at the optimum condition. Iso-suction curves were plotted by knowing the moisture content of the soil using the SWCC transformation technique presented in Figure 3-8. Figure 3-11 also includes the initial conditions (i.e. dry density and moisture content) of the specimens used in the collapse tests in the next section. It is clear from this figure that the data points chosen for conducting the oedometer test have not been overcompacted to potentiate the collapse.



Figure 3-11: Results of proctor compaction test along with iso-suction curves calculated based on the equation of transformed SWCC

In order to study the collapsibility of the soil, a series of single oedometer tests were performed in the next section to measure the effect of different factors on collapsibility. Further, the results of these tests were combined and analyzed with the transformed SWCC.

3.3.3 Collapse tests

The collapse potential of a soil was first identified by Jennings and Knight (1957) where authors used an oedometer to measure changes in volume at constant load after flooding the soil sample with water. This method defines collapse potential as a relationship between the reductions of void ratio after inundation with respect to the void ratio of the soil in an unsaturated condition. Equation 2.1 in the previous chapter is the mathematical expression of this method.

Based on several studies (Ali, 2011; Abbeche et al., 2010), a combination of many factors such as mineralogy, applied stress, the degree of saturation, nature of cementing agents, amount of wetting up under stress, and chemistry of pore fluid affect the collapsibility of the soil. The effect of different factors such as dry density, moisture content, and surcharge pressure on collapsibility of the soil sample was analyzed through conducting a series of single oedometer tests. Figure 3-12 shows the GDS Automated Oedometer Machine used for conducting the experiments.



Figure 3-12: GDS automated oedometer machine

In order to control tests conditions and minimize any variation in results, reconstituted soil samples were prepared carefully to perform single oedometer test in accordance to ASTM standard D5333 (ASTM, 1994; Day, 1990). The reconstituted soil sample was passed through sieve #4 to remove all the large aggregates. The sieved soil was then kept in the oven with the temperature 105 ± 5 for at least 24 hours to get completely dry. A total number of 32 samples were used to measure and

verify the collapsibility results of studied soil. It is noteworthy that the samples were prepared using static compaction and the oedometer cell was covered with plastic wrap during the test to keep the moisture of the soil. Figure 3-13 illustrates the static compaction device to monitor the exerted load on the sample.



Figure 3-13: Static compaction of the soil sample to reach to the required dry density

Prior to any testing, dried sample was removed from the oven, sealed, and kept outside for 10 mins to cooldown. Table 3-4 summarizes the oedometer test plan.

Dry Density (kg/m ³)	Moisture Content (%)	Inundation Pressure (kPa)
1300	7.8	100
1325	7.8	100
1350	7.8	100
1375	7.8	100
1325	5	100
1325	9	100
1325	7.8	50
1325	7.8	200

Table 3-4: Summary of the oedometer tests plan

Dry Density: Low values of dry density are one of the key features of the collapsible soil. Holtz and Hilf (1961) have proven that the collapse potential of the soil can be estimated using the dry density of the soil together with its liquid limits. Moreover, Basma and Kallas (2004) also confirmed the accuracy of the results. Based on these studies and the liquid limit value measured in the laboratory, the collected soil sample is classified as a collapsible soil. In order to investigate more about the effect of dry density on collapse, four different values for dry density (1300, 1325, 1350, and 1375 kg/m³) were chosen in a way to cover all varieties of dry densities available in test pits. By knowing the dimensions of oedometer ring, the amount of dry soil needed to reach to specific dry density was calculated. Then, the soil was mixed thoroughly with distilled water to achieve the in-situ moisture content of the soil (7.8%). The moist soil was then immediately transferred to the oedometer ring and was compacted to reach to the required dry density by using static compactor. The effect of dry density under different loadings and the amount of collapse at flooding point are shown in Figure 3-14 and Figure 3-15 respectively.



Figure 3-14: Consolidation results of the soil at 100 kPa inundation with different dry densities



Figure 3-15: Change in the void ratio of the soil at 100 kPa inundation for different dry densities of soil sample

Figure 3-14 proves the inverse relation between the dry density of the soil and the amount of collapse. As the dry density of the soil is increased, the collapse decreases as it has been expected due to having more compacted structure. In addition, Figure 3-15 shows that the relationship between the amount of collapse and dry density of the soil is linear with R-square equal to 0.978. **Moisture content:** Collapsible soils are moisture sensitive in that any increase in their moisture contents, with or without loading, results in a sudden change in volume and collapse (Abbeche et al., 2010). It has been proved that the increase in the moisture content of the soil which reduces the soil suction, results in an increase in the collapse settlement (Houston et al., 2001). Three different values of moisture content were chosen to analyze the effect of moisture content on the amount of collapse at a specific pressure. In order to do that, dry density of the soil was kept

constant (1325 kg/m³) and different percentages of water were added and mixed with the soil with the same procedure for dry density analysis. Then the consolidation test was performed using the oedometer machine till 400 kPa with a flooding point at 100 kPa. Figure 3-16 and Figure 3-17 below show the results of these tests:



Figure 3-16: Consolidation results of the soil at 100 kPa inundation with different initial moisture

contents



Figure 3-17: Change in the void ratio of the soil at 100 kPa inundation as a result of change in initial moisture content

Figure 3-16 shows that as the initial moisture content of the soil increases, the collapsibility of the soil is also increased. Moreover, as Figure 3-17 shows, the amount of collapse and the moisture content of the soil have a linear relationship with R-square equal to 92.7%.

Surcharge pressure: All types of soil undergo settlement when the surcharged load is applied to them (Cerato et al., 2009). This situation is the same for collapsible soils. Therefore, another important criterion in the collapsibility of the soil is the effect of surcharged pressure (Basma and Tuncer, 1992; Booth, 1975).

Three different pressures (50, 100, and 200 kPa) were chosen as a flooding point to study the effect of pressure on collapsibility. In order to do that, all other factors such as dry density and moisture content were kept constant (1325 kg/m³ and 7.8% respectively) and the amount of collapse was a
measure for different flooding pressures using oedometer machine. The collapse results for each flooding pressure under different loadings steps and the amount of collapse at flooding point are shown in Figure 3-18 and Figure 3-19 respectively.



Figure 3-18: Consolidation results of the soil at 100 kPa inundation under different surcharged

pressures



Figure 3-19: Change in the void ratio of the soil as a result of change in inundation surcharged pressure

As Figure 3-18 shows, increasing the surcharged pressure from 50 to 200 kPa will result in having more collapse. It is a logical conclusion since applying more energy will cause the destruction of the soil structure and replacement of the soil particles in the more compacted way at the flooding point. In addition, Figure 3-19 proves that there is a linear relationship (with R-square equal 95.8%) between amounts of collapse and different surcharged pressure at flooding point. It is important to mention that among these three factors, change in initial moisture content of the soil has the highest impact on collapsibility with the rate of 1.2 percent change in void ratio per percentage of moisture content.

At each stage of the oedometer test, total collapse, void ratio, and saturation of the soil were measured and calculated to be used for future analysis.

3.4 Analysis of results

By assuming that the soil is fully saturated after the inundation and collapse, the values for void ratio, saturation, and total collapse of the soil at each stage of oedometer test were recorded. As mentioned earlier, a transformed SWCC in Figure 3-8 shows a correlation between the saturation level of the soil with values derived by multiplying the void ratio and the logarithmic of suction (e.pF). This correlation has R-square equal to 0.95. This approach further expanded to incorporate the effect of soil suction and porosity on the collapsibility of the soil. As such, all data points collected at the oedometer experiments were used to back-calculate the suction of the soil by knowing the void ratio and saturation that corresponded to a given data point using the equation presented on Figure 3-8.

Figure 3-20 was developed by converting the experimental data from the oedometer tests into the e.pF form. The figure shows that the total applied pressure and the e.pF are proportional. Figure 3-20 demonstrates the correlation between total applied pressure, calculated matric suction, and measured void ratio from the transformed SWCC plot presented in Figure 3-8. It is clear from the figure that the change in total applied pressure has significant influence on suction and void ratios. This correlation can be used to approximate the volume change of the soil for a specific suction level and loading. Recent numerical studies by Pasha et al. (2017) supports the outcome of this study. Although variations in the soil structure and therefore the void ratio of a sample in a test affect the accuracy of the results, the results can be used for future studies to develop a regression model to predict the suction or void ratio by knowing the applied pressure acting on the soil.



Figure 3-20: Correlation between total applied load and suction of the soil by constantly updating SWCC

Figure 3-20 visibly establish the interdependency of applied stress, suction, and void ratio. This indicates the soil collapse studies should not be limited to only applied stress, rather it should combine traditional oedometer and SWCC data to develop a complete behavior of collapsible soil. Figure 3-21 demonstrates the relationship between total collapse on the soil versus total suction of the soil prior to inundation of the soil. The equation presented in Figure 3-8 was used to calculate the suction of the soil at each stage of consolidation testing. Figure 3-20 not only shows the relationship between the suction and total collapse of the soil, it also proves that by using the proposed method to transform SWCC, suction control collapse test can be performed with a normal oedometer machine. The regression assumptions of this figure are presented in Appendix A.



Figure 3-21: Relationship between total collapse of the soil versus total suction prior to inundation of soil

3.5 Summary

This study aims to provide a better understanding of the collapse settlement by considering changes in internal (micro level) and external (macro level) energies of the soil. In order to understand these phenomena, experiments were performed on soil samples collected from the Okanagan-Thompson region. The SWCC was developed using experimental data which was compared against fitted points using the Arya-Dierolf model. Experiments were further performed using single oedometer machine to study the effects of dry density, moisture content, and

surcharged pressure on the collapsibility of the studied soil samples. Among these three factors, change in initial moisture content of the soil had the highest impact on collapsibility at 1.2 percent change in void ratio per percentage of moisture content. All data points collected from the oedometer experiments were used to back-calculate the suction of the soil by knowing the void ratio and degree of saturation that correspond to a given data point.

Experimental results show that the consideration of the void ratio (e) and the logarithmic of matric suction (pF), by means of transforming e.pF, leads to satisfactory correlations with total applied pressure during the collapse of the soil. Moreover, it clearly demonstrates that the collapse of soil depends on the suction, void ratio and the stress state of the soil when it is subjected to saturation. Moreover, results show that it is possible to predict the collapsibility of the soil using the total suction.

This study presents an approach to combine traditional oedometer and SWCC data which can be used to predict the matric suction behavior of the soil by knowing the void ratio and the total applied pressure. This approach can be an alternate for suction controlled collapse test and save huge amount of time and money for the study of unsaturated soils.

Chapter 4: Effect of Pore Water pH Level on the Microstructure of Collapsible Soil

4.1 Overview

Results of Chapter 3 showed the importance of analyzing the microstructure of the collapsible soils. Pore-size distribution of the soil is one of the governing factor responsible for the collapsibility of the soil which can be dramatically changed by pH level of the pore fluid. Therefore, this chapter investigates the impact of the pore water pH level on the microstructure of collapsible soil. Experiments were performed to study the short and long-term (pretreated) exposure of the soil to four pH levels of 5, 7, 9, and 11. Series of oedometer test were performed and Image processing methods were applied on SEM images of the studied soil before each test. The outcome of this chapter shows that the pore-size distribution of the studied soil samples varied significantly for different scenarios. In addition, reducing the pH level of the soil resulted in having higher number of micropores in the soil's structure which forced the soil to undergo settlement before the collapse test.

4.2 Soil pH

Environmental impacts due to the rapid urbanization and industrialization have always been the subject of research (Bigdeli et al., 2015). In recent years, much attention has been paid to acidification of rain which forms due to continuous addition of air pollutants like sulfur dioxide and nitrogen oxides to the atmosphere (Sunil et al., 2006). These gases not only cause air pollution but also indirectly contaminate soil. It is reported in the literature that the atmospheric pollution can reduce the precipitation pH levels as low as 5.6 which results in acidification of soil and thus

altering soil's physical and engineering properties (Sunil et al., 2006; Stalin and Muthukumar, 2002; Gupta and Singh, 1997).

Acid rain or polluted rainfall is one of the age-old global environmental problems. The impact of acid rain on natural ecosystems, and remediation techniques have been studied by several researchers (Reuss and Johnson, 2012; Menz and Seip, 2004; Skjelkvale et al., 2001; Rabl and Spadaro, 1999; Burtraw et al., 1997; Reuss et al., 1986). Particularly, in Canada, many researchers have studied the harmful effects of elevated depositions of nitrogen (N) and sulfur (S) from the oil sands industry (Morrison and Carou, 2004; Duchesne et al., 2002; Beamish and Harvey, 1972). Sulfate ions along with NO₃⁻ and CO₃²⁻ presented in the atmosphere, become partially balanced with the Hydrogen (H) ions to form H₂SO₄, HNO₃, and H₂CO₃ which create acidic precipitations that may alter physico-chemical and engineering properties of soil (Pankaj et al., 2012; Beamish and Harvey, 1972). For example, studies on boreal ecosystems in northwest Saskatchewan have shown that the ecosystem is highly susceptible to acidification due to the production of oil sands (Scott et al., 2010). The pH level of precipitation due to the natural resource extractions was measured as low as 2.9 (Beamish and Harvey, 1972). Recently, researchers have focused more on the effect of acid rain on the environment of western provinces in Canada (Mongeon et al., 2010; Beamish and Harvey, 1972).

Along with environmental impacts, acid rain also influences soil's strength properties due to the dispersion-flocculation processes of the clay particles within the soil (Li et al., 2005; Dontsova and Norton, 2002). On the other hand, acidic condition (pH < 6) can dissolve and remove CaCO₃ from soil and result in developing sodic soil (El-Swaify, 1973). In this condition, the chemical composition of a soil alters over time without any change in its texture. This chemical alteration within a soil can weaken bonds between soil particles and lead to self-arrangements of the particles

and structural collapse. In addition, infiltration of wastewater in the landfills, sewage, and usage of de-icing agents can change the pH level. Several investigations have been conducted to study the effect of pH level of pore water on the properties of soil (Sunil et al., 2006; Pin-Hua et al., 2006; Abdullah et al., 1999; Altin et al., 1999; Suarez et al., 1984), however, in case of problematic soil, in particularly for collapsible soil the gap of knowledge is still there.

Research has been performed to study the effect of pore fluid pH on the properties such as Atterberg limits, cation exchange capacity, hydraulic conductivity of soil (Pankaj et al., 2012; Sunil et al., 2006; Abdullah et al., 1999; Suarez et al., 1984). Most of these research focuses on the properties of clayey soil and only a few considered the influence of pH level on pore-size distribution, pore geometry, clogging and porosity of the subjected soil (Altin et al., 1999). There are also some studies on the change in porosity and pore-size distribution of the collapsible soil due to loading and wetting process (Jiang et al., 2014a & b; Jiang et al., 2012; Camapum de Carvalho et al., 2002), however, up to this date, in the knowledge of the author, there is no study on developing the relationship between the pH level of pore fluid, pore-size distribution, and collapsibility of the soil. This study attempts to address this knowledge gap. The objectives of the present research are: (i) to investigate the effect of synthetic acid rain and sewage on porosity, pore-size distribution and pore geometry of the collapsible soil at short and long-term periods by changing the pH level of pore water; (ii) to measure the collapsibility of the soil by performing series of single oedometer tests at short and long-term scenarios; and (iii) to quantify pore characteristics with changes in pH level before and after collapse of soil and (iv) to advance understanding of parameters likely to intervene the collapse phenomenon of soil.

4.3 Experimental approach

A combined study of physical testing and microscopic image analysis were used to investigate the effect of pH on soil's structure and collapse potential. Different pH levels of pore water were prepared, and experiments were performed at the short and long-term exposure of the soil to different pH levels. In this section, detailed experimental approach is presented.

4.3.1 Material

Vast land area of North America is covered by loess deposits which typically corresponds to the collapsible soil (Rogers, 1995; Rogers et al., 1994; Sweeney and Smalley, 1988). Glacial grinding and cold weathering along with cryogenic process are the main reasons behind the highly productive loess material in this region (Smalley, 1966). Okanagan-Thompson region is an intermountain valley which is dominated mostly by glaciolacustrine silts and collapsible soil (Bigdeli and Siddiqua, 2016; Bigdeli et al., 2015; Fulton, 1975). Collapsible soil samples were collected, and preliminary soil mechanics experiments were conducted to characterize the soil as described in the previous chapter.

Altin et al. (1999) in their study on the effect of pH on montmorillonite concluded that the pH values lower than 3 results in dissolution of protons and destroys the structure of the soil. Therefore, different batches of buffer solutions with pH levels of 5, 7, 9, and 11 were prepared using H_2SO_4 and NaOH to study the effect of pore water pH level on the structure of the collapsible soil. Two sets of soil specimens were analyzed in this study:

 a) Short-term or untreated: reconstituted soil samples were studied in their natural in-situ condition. The samples were then inundated with pore fluid with different pH level during the consolidation test. b) Long-term or pretreated: soil samples were exposed to pore fluid of different pH levels and left to cure for 24 hours prior to performing any test. The samples were then inundated with pore fluid with different pH level during the experiments.

ASTM D 4972 method was used to measure the average pH of the three samples of the collected soil. In the test, 10 g air-dried sample passing sieve #10 was collected into a glass container and then approximately 10 ml of distilled water was added. The average pH level of the collected soil from the airport site was measured with a pH probe and it was equal to 8.3. Index tests such as Atterberg limits were measured at different pH levels by mixing the oven-dried soil with different buffer solutions. Figure 4-1 presents the liquid and plastic limits, as well as the plasticity index of the soil.



Figure 4-1: Liquid limit, plastic limit, and plasticity index of the soil sample under different pH levels

4.3.2 Microstructural analysis

Image processing is one of the new methods in geotechnical engineering to investigate the poresize and grain-size distribution as well as pore and grain geometry (Kumara et al., 2012; Hue et al., 2010; Aydilek et al., 2002). SEM images of the soil samples were taken for both short and long-term effect of pH on the soil structure. A small amount of dried soil sample was mounted on Aluminum stubs and was coated with a thin layer of epoxy to prevent the accumulation of electrostatic charges. In addition, SEM images at different magnifications (50X to 10,000X) were captured and 500X magnified images were selected to better analyze the pore-size distribution and geometry of the macropores within the collapsible soils. Figure 4-2 demonstrates the SEM image settings, magnification, and scale that was used for image processing in this chapter. In addition, chemical analysis data from energy-dispersive spectroscopy (EDS) indicated the presence of higher concentration of Aluminum and Calcium Oxides in the soil. Therefore, It was concluded that the bonding between the particles are mainly clayey-bridges.



Figure 4-2: Sample of SEM image used in ImageJ showing the scale

	Weight %							
Element	0	Na	Mg	Al	Si	K	Ca	Ti
Max	56.02	5.08	4.96	11.68	24	14.89	7.24	5.47
Min	27.64	0.19	0.37	2.61	5.91	0.18	0.65	0.15
Average	45.79	1.96	1.27	7.97	18.08	2.96	3.48	1.21
SD	9.07	1.84	1.52	3.04	5.27	4.84	2.47	1.72

Table 4-1: Chemical analysis of soil samples from test pit #1

ImageJ, an open source image analysis tool, was used to pre-process and analyze the images (Ferreira and Rasband, 2010). Images obtained from SEM were converted to 8-bit grayscale and the scale of the images was converted from pixel into µm using a scale factor. The contrast and brightness of the pictures were automatically adjusted by ImageJ to increase the quality of the picture. Further, Despeckle filter to reduce the noise, as well as Bandpass filter to smoothen the particles perimeter were applied on the images. Finally, thresholding was performed using Shanbhag, Yen, and Renyi Entropy functions as suggested by the researchers (Cherian et al., 2014). Renyi Entropy was chosen as the best thresholding function for this material to select the pixels within a desired range of brightness value which belong to the foreground (particles of interest) and reject all the other pixels in the background (Cherian et al., 2014). At the end, images were converted to binary and different processes such as erode, dilate, watershed, and etc. were applied to reduce the errors during the analysis. The black and white (B & W) binary images were produced following the image analysis steps through the transformation of the micrograph. Once the binary images were created, the pixels were counted using ImageJ. The B &W scale was used to differentiate pores from the soil particles. Figure 4-3 demonstrates the processed image where the dark pixels are the pores and the bright pixels are the soil particles.



Figure 4-3: Image processing of the soil 500x zooming demonstrating binarization and thresholding of the pores (black pixels)

After transformation of the pixels shape into circular, ImageJ was used to measure the area (A) and perimeter (P) of each particle and pores. The Pore/particle-size distribution is represented by plotting a histogram on area of the pores. Figure 4-4 shows the histogram of the pore-size distribution of the soil in its natural condition. It is noteworthy that the SEM image analysis was performed on different locations of a given sample and Figure 4-4 provides the average area of the pores from all locations.



Figure 4-4: Average pore-size distribution of soil sample in its natural condition

Li et al. (2016) characterized all kinds of pores in Loess soils and they concluded that the pores with average radius of 4 to 16 μ m have significant influence on collapsibility. It is noteworthy that the pores with larger radius than 16 μ m can increase the collapse potential of the soil; however, their limited numbers in the structure of the soil and their unstable condition reduce their effect (Li et al., 2016). Therefore, Figure 4-5 and Figure 4-6 demonstrate pore-size distribution of the soil in natural condition for the pores with area between 50 to 800 and larger than 800 μ m², respectively. It is noteworthy that the pores with the area larger than 800 μ m² are few in the structure of collapsible soils as it is shown in Figure 4-6. These pores are commonly found in shallow depth and their contribution to the collapse is not significant (Li et al., 2016).



Figure 4-5: Spaced pores distribution in the structure of the soil in natural condition that have

significant influence on collapse due to their numbers



Figure 4-6: Macropores distribution in the structure of the soil in natural condition that have low influence on collapse due to their limited numbers

The image analysis method was then applied to all the tested range of pH levels and a relationship between area of the pores versus the pH level of pore fluid was developed. Figure 4-7 and Figure 4-8 present the average area of the pores for both short and long-term conditions, respectively.



Figure 4-7: Area of the pores for the short-term effect of different pH level



Figure 4-8: Area of the pores for the long-term effect of different pH level

In order to better compare the results of image analysis for different scenarios, Figure 4-9 and Figure 4-10 focus on the pore-sizes which have significant influence on collapse for short and long-term effect of pH exposure, respectively. The results of these two figures show that the effect of reduction in the pH level is more significant on the micropores of the soil. Moreover, as the pH level increases, the number of the pores of with larger diameter get increased. The only exception is observed for pH 5 which shows lower porosity within the soil structure due to the effect of acidic environment in the system.



Figure 4-9: Number of the pores with the area between 50 to 800 μm^2 for short-term exposure of

different levels of pH



Figure 4-10: Number of the pores with the area between 50 to 800 μm^2 for long-term exposure of different levels of pH

More studies were performed on the image analysis results to investigate the effect of pore water pH level on the pores with larger area of 800 μ m². Figure 4-11 and Figure 4-12 show the macropores distribution in the structure of the soil exposed to different pH levels. Although there are limited number of macropores in the structure of the studied soil, the results prove that exposure time has significant influence on the macroporosity of the soil. Moreover, Figure 4-12 show that increasing pH level of pore fluid increases the number of the macropores in the structure of the soil. Therefore, it is safe to expect higher collapse for higher pH levels and for the long-term exposure.





different pH levels with the area more than 800 μm^2



Figure 4-12: Macropores distribution in the structure of the soil with short-term exposure to different pH levels with the area more than 800 μ m²

Many studies have shown the importance of measuring pore-size distribution to predict the saturated hydraulic conductivity of the soil (k_{sat}) (Gimenez et al., 1997; Ahuja et al., 1989;). Kozeny-Carman equation is widely used to predict the hydraulic conductivity of the soil. Later, Lebron et al. (1999) have used a neural network to predict the hydraulic conductivity and suggested new factors, called hydraulic radius and form factor, in the Kozeny-Carman equation to predict k_{sat} . The hydraulic radius can be calculated by dividing the median of area (A) by the median perimeter (P) of each pore. Moreover, form factor can be predicted using the neural network by

knowing the grain-size distribution, bulk density, pH, and roughness of the soil. Below is the Kozeny-Carman equation for calculating the hydraulic conductivity:

$$k = \frac{1}{C_{s}S_{s}^{2}T^{2}} \frac{\gamma_{w}}{\mu} \frac{e^{3}}{1+e}$$
(4.2)

Where C_S is the shape factor, T is tortuosity, S_S is the surface area per unit volume of soil solids, γ_w is the unit weight of water, μ is the viscosity of water, and e is the void of the soil sample.

Researchers have shown that realistic calculation of hydraulic conductivity of the soil is not possible without considering the capillarity and adsorption phenomena within the soil structure (Jongerius and Bisdom, 1981). One way to express the pore shape is by dividing the area of the pore by the square of the perimeter (A/P^2) (Lebron et al., 2002; Mason and Morrow, 1991; Jongerius and Bisdom, 1981). Table 4-2 and Table 4-3 summarize the measured values from soil samples under different pH levels. In this table k_{exp} was calculated using Kozeny-Carmen equation using the image analysis results and k_{calc} was measured through consolidation tests. These values can be used to predict the hydraulic conductivity of the soil.

Table 4-2: Summary of the measured versus calculated permeability values of the soil samples under different pH levels (Short-Term)

рН	Median of Area (µm²)	Median of Perimeter (µm)	k _{exp} (cm/s)	k _{calc.} (cm/s)
5	11.47	12.01	2.23E-05	3.60E-04
7	13.17	12.85	1.40E-05	3.68E-04
9	12.98	12.77	1.52E-05	3.68E-04
11	12.08	12.32	1.01E-05	3.74E-04

рН	Median of Area	Median of Perimeter	kexp (cm/s)	k _{calc.} (cm/s)	
	(μm²)	(μm)			
5	9.96	11.19	1.94E-05	4.00E-04	
7	11.77	12.16	2.07E-05	3.62E-04	
9	10.87	11.69	1.52E-05	3.67E-04	
11	10.26	11.36	1.32E-05	3.70E-04	

Table 4-3: Summary of the measured versus calculated permeability values of the soil samples under different pH levels (Long-Term)

4.4 Collapse analysis

Series of single oedometer tests were performed on oven-dried reconstituted soil samples to measure the influence of pore fluid pH level on the soil's collapsibility. Sieved soil was removed from the oven and kept in the room temperature at least for 10 minutes prior to sample preparation. The weight of the dry soil was calculated by knowing the dimensions of the oedometer ring, to maintain the in-situ dry density of the soil (i.e. 1325 kg/m³). Then, the soil was mixed thoroughly with liquid (distilled water for short-term effect and pore fluid with different pH for long-term effect) to achieve the in-situ moisture content of the soil (i.e. 7.8%). The moist soil was then immediately transferred to the oedometer ring and was compacted to reach to the required dry density by using static compactor. The sample was then placed inside the oedometer cell and it was sealed with the plastic wrap to avoid any loss of moisture during the test. It is noteworthy that the test on the soil samples shown 0.05% and 0.37% adsorption of water after 30 and 1440 minutes, respectively. Single oedometer tests were performed based on ASTM standard D-5333 on the reconstituted soil samples in order to measure collapsibility of soil at 100 kPa (ASTM D-5333, 2003; Day, 1990). The samples were then flooded using different pH level of buffer solutions and

waited 16 to 18 hours to reach fully saturation. At the end of the test, soil samples were carefully collected from the oedometer cell to measure their weight and dimensions for moisture content and void ratio readings. The similar readings were also taken for the samples after 24 hours of oven drying. The dry samples were used for SEM tests and image analysis.

In long-term analysis, soil samples were mixed with buffer solutions at different pH levels and cured for 24 hours at $23 \pm 2^{\circ}$ C temperature in an airtight ziplock bag prior to placing them in the oven. Next, a similar testing procedure was followed for both short and long-term studies. Results of short-term and long-term collapsibility behavior of the soil are presented in Figure 4-13 and Figure 4-14 respectively.



Figure 4-13: Consolidation test results for short-term exposure of the soil to different pH levels

at 100 kPa inundation



Figure 4-14: Consolidation test results for long-term exposure of the soil to different pH levels at 100 kPa inundation

The effect of pH level on the collapsibility of the soil was calculated by subtracting the settlement of the soil at 100 kPa before and after the inundation of the soil with buffer solutions. Figure 4-15 demonstrates this effect on the soil at the short-term and long-term exposures. In both testing conditions, the collapsibility of the soil increased with an increase in the pH. This behavior of the soil can be explained by analyzing the pore-size distribution of the soil. It can be concluded that lower values of pH level increase the microporosity of the studied soil which results in weakening the clayey-bridges between the soil particles, this clayey-bridges are responsible for the honeycomb structure of the soil. This effect destroys the macropores within the soil structure and it results in having less collapse in the oedometer tests. On the other hand, higher values of pH level do not have a significant effect as lower pH values on the soil structure. The preserved macroporous structure of the collapsible soil will be destroyed during the oedometer test. Therefore, higher changed in the void ratio of the soil can be seen for higher pH values.



Figure 4-15: Change in void ratio of the soil at 100 kPa inundation for different pH levels and

exposure time

4.5 Summary

This chapter investigates the impact of the pore fluid pH level on the microstructure of collapsible soil. Experiments were performed to study the short and long-term exposure of the soil at four different pH levels of 5, 7, 9, and 11. Series of oedometer tests were conducted and image processing methods were applied on SEM images of the soil before the oedometer tests. Based on

the image analysis after the collapse test, it is concluded that both spacepores and macropores have significant influence on the soil collapse.

According to the results and discussions presented in this study, the following conclusions can be made:

- 1. Pretreatment of the soil with different pH levels has a significant effect on the porosity of the soil and changes the number of micro and macropores within the soil structure.
- Decreasing the pH level of pore fluid destroys the larger pores while increases number of smaller pores within the soil structure.
- 3. Structure of the soil with pH level equal to 5 showed the lowest porosity among all test specimens due to the effect of acidic environment on the clayey-bonds between the particles. The acidic environment not only creates dispersion-flocculation on the clay particles, it also dissolves CaCO₃ which weakens the chemical bonds between the particles (Li et al., 2005; Dontsova and Norton, 2002; El-Swaify, 1973).

The results of this section are important to study the effect of a green-stabilizer, MgCl₂, on collapse remediation. The results of the next chapter can only be explained using the results of Chapter 4 due to the high solubility of this salt in the water and developing an acid environment in the system.

Chapter 5: Collapse Remediation Using a Green Stabilizer

5.1 Overview

After understanding the importance of microstructural analysis in soil collapse and the factors such as pH level that can alter that, this chapter is focused on stabilizing the collapsible soils. Three different percentages of Magnesium Chloride solution (3%, 7%, 11%) and a control sample were chosen to be mixed with the collected soils. In addition, to study the time-dependent effect of this chemical, five curing times (0, 1, 3, 7, 28 days) were selected to measure the collapsibility of soil. The collapse potential of each mixture was measured by performing a series of single oedometer tests and the results were compared. The results of the collapse test for different percentages of MgCl₂ indicate that as the amount of MgCl₂ increases, the harsh acidic environment caused by reaction between this salt and pore water, destroys the soil collapsible structure. The soil mixture undergoes gradual settlement prior to inundation due to the increase in surcharge pressure. As a result, the sudden settlement of the soil during inundation (collapse) is less significant. The increase in the soil collapse is more dramatic in early stages of mixing where MgCl₂ is highly reactive to the water and results in significant volume reduction of the collapsible soils.

5.2 Chemical stabilization of soil

Most of the problems raised in geotechnical engineering are initiated due to the unfavorable interaction between the soil particles and water (Kezdi, 2016). Problems such as collapsibility, expansibility, strength and cohesion reduction, and freeze-thaw cycles are all the examples of such interactions (Latifi et al., 2016). Preservation or improvement of properties of the soil during soil-water interaction is called stabilization (Fang, 2013). The purpose of the soil stabilization is to

improve the engineering characteristics and performance of the subjected soil. This can be done by using different additives such as cementing agents (ex. Lime), special type of a soil (ex. Nanoclay), and chemical additives (ex. MgCl₂) to the natural soil (Latifi et al., 2016; Gualtieri et al., 2015; Marto et al., 2014; Marto et al., 2013; Liu et al., 2011). These stabilizers improve the properties of the soil by interacting with soil particles or independently with only their inert involvement through cation exchange, flocculation, crystallization, and dissociation (Muhammad and Siddiqua, 2017). Stabilizers can be added to the disturbed soil by using mechanical mixing or can be injected and permeated through the voids of undisturbed soil (Kezdi, 2016).

The history of using chemical stabilizers goes back to around 80 years ago when Calcium and Sodium Chlorides were used as a dust suppression on Macadam road. Magnesium Chloride is one of the common dust suppression products (Palmer et al., 1995; Landon and Williamson, 1983). It has been widely used as a green binder due to its natural source which is sea water (Latifi et al., 2016). New studies on MgCl₂ have shown the possibility of using this chemical as a soil stabilizer (Latifi et al., 2015). It has been used for the improvement of subgrade soil in road construction to reduce the cost of maintenance and rehabilitation (Monlux and Mitchell, 2007). Stabilizers can be more effective in the cases where the subgrade of a road consists of problematic soils (Turkoz et al., 2014; Al-Rawas et al., 2002). Only in British Columbia, Canada, the cost of maintenance and rehabilitation of roads was estimated at 270M\$ to improve the road conditions including dust control and pavement stabilization (Muhammad and Siddiqua, 2017). Therefore, many researchers have focused on the study of different chemical stabilizers which can be used for road construction to reduce the material, cost, and time.

Generally, there are four approaches to stabilize the soil particles as explained below (Kezdi, 2016):

83

- a) Filling the intergranular voids with a water-repellent chemical which has a good adherence to the soil particles.
- b) Increasing the intergranular surface forces to increase the cohesion and shearing strength.
- c) Strengthening the connection between the soil particles at certain points. This technique is called "spot-welding".
- d) Embedding the soil particles in a continuous matrix to preserve the properties of the soil.

In addition to the points mentioned above, another technique to stabilize the soil is through precipitation of chemicals which can stabilize the soil structure (Kezdi, 2016). Some chemical stabilizers such as a mixture of Sodium Silicate and Calcium Chloride, during their reaction with water, produce Calcium Silicate which is water-insoluble and suitable for soil stabilizing (Arulrajah et al., 2009).

Based on the techniques to stabilize the soil, failure in the soil matrix can happen when: 1) fracture occurs on the contact point between the additive and soil particles 2) fracture happens in the stabilizer or soil particles 3) displacement of the soil particles due to a reduction of shear strength. It is noteworthy that in the first case, the cohesive forces between the particles exceeds the adhesion force and in the second failure scenario, the adhesion is much stronger than the cohesion of stabilizer and soil particles.

Magnesium Chloride (MgCl₂) is one of the common de-icing materials (Act, 1993). It can be applied to the roads during the winter to reduce the freezing point (Bolander and Yamada, 1999). The study has shown that use of MgCl₂ not only reduce the freezing point to -32.7 °C, but it also develops gradual freezing of water which leads to not having complete freezing-thaw cycles (Bolander, 1997). This chemical has also been used as a dust suppressant for the unpaved roads in semi-arid regions (Bushman et al., 2005; Giummarra et al., 1997). Upon the application of Magnesium Chloride, it starts to absorb the humidity of the surrounding air and increase the surface tensions of the soil particles (Sutter et al., 2006). Therefore, the soil surface will be very hard and loss of moisture will be reduced during the re-compaction of the soil layers (Palmer et al., 1995). as a result, Magnesium Chloride has been extensively used as a stabilizer in recent years (Nixon and Williams, 2001; Ketcham et al., 1996).

Although the application of MgCl₂ as a stabilizer has many advantages, it has some drawbacks that limit the usage of this material that has been listed below (Lohnes and Coree, 2002):

- a) High solubility in the water results in washing off from the soil during the rainfall. The leachate materials will infiltrate in the groundwater and the salt will be carried from treated layers at the top to the greater depth (Fay and Shi, 2012). Under dry weather condition, the solution will move upward through capillary effect and the salt crystals will be formed after evaporation of water (Bolander and Yamada, 1999).
- b) High percentages of MgCl₂ solution is needed to increase the effectiveness. Solutions with less than 20% of salt, have the same performance as adding water to the system (Bolander and Yamada, 1999).
- c) Solutions with high concentrations of MgCl₂ are very corrosive to the steels and metals (Hoover et al., 1981). This is mainly a result of the high solubility of this salt in the water and developing an acidic environment as shown below:

$$MgCl_2 + 2H_2O \leftrightarrow Mg(OH)_2 + 2HCl$$
(5.1)

This chemical reaction results in having a weak base and a strong acid which lowers the pH level of the water as low as 3.5 (Shi et al., 2009; Lohnes and Coree, 2002). Therefore, free Hydrogen created in this reaction accelerates the rate of corrosion.

 d) Polluted groundwater with a high concentration of Magnesium and Chloride is taken up by the trees and accumulated in their leaves. Once inside the plant, Chloride moves through the water-conducting system which results in weakening the leaves and the death of the tree (Goodrich et al., 2009).

Table 5-1 below summarizes the advantages, disadvantages, application, and origin of Magnesium Chloride (Bolander and Yamada, 1999).

Chemical	Magnesium Chloride		
	- Starts to absorb water from the air at 32% relative		
	humidity.		
	- More effective than Calcium Chloride solutions for		
Advantages	increasing surface tension.		
	- Treated site can be re-compacted without the concern		
	of losing moisture		
	- Effectiveness when less than 20% solution has		
	performance similar to water		
Disadvantages	- Highly corrosive against metals		
	- High solubility in water and washing off with rainfall		
Origin	Sea Water		
	- Does not have a significant effect on aquatic life		
Environmentel Impact	- High concentration of Chloride will be accumulated in		
Environmentai impaci	the leaves of trees		
	- Results in the death of some species of trees		

Table 5-1: Summary of Magnesium Chloride attributes

Many studies have been done to apply Magnesium Chloride to improve the mechanical properties of different types of soils (Latifi et al., 2016; Latifi et al., 2016; Latifi et al., 2015; Jianli et al., 2010; Abood et al., 2007; Thenoux and Vera, 2003). Results of these research proved that Magnesium Chloride can be used as a stabilizer and its effectiveness depends on the concentration of this salt (Latifi et al., 2016). In addition, mineralogical and morphological as well as the development of the mineral molecules could alter mechanical properties of problematic soils when mixing it with the MgCl₂ (Latifi et al., 2016; Santoni et al., 2005). However, there is no study on the effect of MgCl₂ on collapsibility of Loess soils. Therefore, this research tends to investigate the feasibility of using MgCl₂ to reduce the collapse potential of the collapsible soil.

5.3 Experimental approach

Three different percentages of Magnesium Chloride solution (3%, 7%, 11%) were chosen to be mixed with the collected soils. In addition, five curing periods (0, 1, 3, 7, 28 days) were selected to study the time-dependent effect of this chemical on collapsibility. The collapse potential of each mixture was measured by performing a series of single oedometer tests and the results were compared.

5.3.1 Material

Soil samples were collected from Kelowna International Airport where the collapsibility of the soil foundation was reported by local geotechnical companies (Bigdeli et al., 2015). Preliminary geotechnical experiments were conducted on the collected sample as it was presented on Chapter 3. Summary of the results are presented in Table 5-2 below:
Depth (m)	1
Moisture Content (%)	4.6
Wet Density (kg/m ³)	1325
Dry Density (kg/m ³)	1266.7
LL (%)	24.7
PL (%)	20
PI (%)	4.7
рН	8.3
Sand (%)	81.6
Silt (%)	16.9
Clay (%)	1.5

Table 5-2: Index properties of the soil

The compaction test was carried out to find the optimum moisture content and maximum dry density of the soil. Based on the compaction curve, the optimum moisture content is 13% which relates to a maximum dry density equal to 1865 Kg/m³. The result indicates susceptibility of the soil to collapse due to very low dry density. Figure 5-1 shows the result of compaction curve.



Figure 5-1: Compaction curve of test pit #1 showing maximum dry density and optimum moisture content of the soil

The MgCl₂ used in this study was obtained from Thermo Fisher Scientific Chemicals Inc., Massachusetts, as a white powder. The physical and chemical properties of this chemical are presented in Table 5-3.

Properties	Magnesium Chloride
Physical state	Solid
Appearance	White
Odor	Odorless
рН	5-6.5, 5% aq. Solution
Solubility	540 g/L (20 °C)
Molecular weight	95.21
Molecular formula	MgCl ₂

Table 5-3: The physical and chemical properties of Magnesium Chloride

The method to perform single oedometer test was explained earlier in Chapter 3. Table 5-4 summarizes the result of oedometer test performed on the undisturbed soil sample at 100 kPa inundation pressure. It indicates that the collected soil sample is suffering from the sever collapse and improvement of soil properties is essential. In the next section, the effect of Magnesium Chloride, as a green stabilizer, on collapsibility of the soil will be studied.

Initial void ratio (e ₀)	1.1
Change in void during the collapse (Δe)	0.3
Collapse potential	15
Inundation pressure (kPa)	100

Table 5-4: Results of single oedometer test on an undisturbed sample

5.4 Methodology

Prior to any tests, the soil sample was oven-dried for at least 24 hours at 105±5 °C temperature to completely dry the sample. The oven-dried sample was then hand-grounded and passed through sieve #4 to remove large aggregates and obtain a uniform distribution. By knowing the in-situ dry density of our sample (1350 kg/m^3) and volume of the oedometer ring, required the dry weight of the soil sample was calculated. In order to investigate the effect of MgCl₂ on the collapse potential, different amounts of Magnesium Chloride solution were prepared and added to the soil (3, 7, and 11% by dry weight of the soil). The compaction characteristics of the soil sample were used to calculate the amount of MgCl₂ solution needed to add to each test specimen. Attention was given during the hand-mixing of the soil with MgCl₂ solution to obtain a homogeneous mixture. It is noteworthy that the time was controlled during the preparation of the sample due to the high absorbency of humidity of Magnesium Chloride from the surrounding air. The soil was mixed thoroughly with varying amounts of MgCl₂ solution to achieve the in-situ moisture content of the soil (7.8%). The moist soil was then immediately transferred to the oedometer ring and was compacted to reach to the required dry density by the means of the static compactor. Figure 5-2 illustrates the sieved soil sample before and after mixing with MgCl₂ solution. Moreover, Table 5-5 summarizes the mix proportions used for sample preparation.



(a)



(b)

Figure 5-2: Collapsible soil sample: (a) oven-dried without any chemicals (b) after mixing with

 $MgCl_2$ solution

Type	Dry soil	Required	MgCl ₂	Added water (a)		
Type	needed (g)	water (g)	Solid (g)	Water (g)	fuucu water (g)	
0%	86.1	6.72	0	0	6.72	
3%	85.75	6.69	1.11	1.47	5.22	
7%	85.4	6.66	2.57	3.41	3.25	
11%	85.2	6.65	4.03	5.34	1.31	

Table 5-5: Mix proportions for sample preparation

One important aspect that needs to be considered when using a soil stabilizer, is the curing time. After preparation of samples in oedometer ring, they were covered completely in plastic wrap and tapped all over to prevent the loss of moisture during the curing time. Wrapped samples were then kept in the closed plastic box and cured for 0, 1, 3, 7, and 28 days at controlled room temperature $(25\pm2 \ ^{\circ}C)$. It is important to mention that the control samples were made to measure the moisture absorbed after curing time. The maximum value of moisture absorbed was measured for 11% MgCl₂ solution cured for 28 days. The amount of moisture absorbed was equal to 0.36% which shows the reliability of the curing method.

The collapse potential of the mixture was measured by gradually loading the specimen to 100 kPa where at the soil was inundated with distilled water. Figure 5-3 demonstrates the soil sample before and after performing the oedometer test. Results of oedometer test for varying percentages of MgCl₂ solution and different curing periods are presented and compared in the next section.



(a)



(b)

Figure 5-3: Collapsible soil sample: (a) prepared in the ring to perform consolidation test (b) after consolidation and drying in the oven for 24 hours

5.5 Analysis of results

Three different percentages of MgCl₂ solutions were mixed with the collected soil and each one was cured for 0, 1, 3, 7, and 28 days before performing any experiment. Series of single oedometer tests were conducted on soil mixture to measure the collapse potential. In order to check the accuracy of the results, at least three samples for each soil mixture were prepared and tested. Therefore, a total number of 50 samples were used to measure and verify the collapsibility results. Table 5-6 summarizes the oedometer test plan.

Table 5-6: Summary of the test plan showing studied percentages of MgCl2 solution and their

curing time

Levels																			
		0					3%					7%					11%		
		0 370				770				1170									
0	1	3	7	28	0	1	3	7	28	0	1	3	7	28	0	1	3	7	28
	0	0 1	0 0 1 3	0 1 3 7	0 1 3 7 28	0 1 3 7 28 0	0 1 3 7 28 0 1	0 1 3 7 28 0 1 3	0 1 3 7 28 0 1 3 7	0 1 3 7 28 0 1 3 7 28	Levels 0 1 3 7 28 0 1 3 7 28 0	Levels 0 1 3 7 28 0 1 3 7 28 0 1	U 3% 7% 0 1 3 7 28 0 1 3 7 28 0 1 3 3 7 28 0 1 3 7 28 0 1 3 3 7 28 0 1 3<	Levels 0 1 3 7 28 0 1 3 7 28 0 1 3 7	Levels 0 1 3 7 28 0 1 3 7 28	Levels 0 1 3 7 28 0 1 3 7 28 0	Levels 0 1 3 7 28 0 1 3 7 28 0 1	Levels 0 1 3 7 28 0 1 3 7 28 0 1 3 7 28 0 1 3 7 28 0 1 3 7 28 0 1 3 7 28 0 1 3 3 7 28 0 1 3	Levels 0 1 3 7 28 0 1 3 7 28 0 1 3 7

Figure 5-4, Figure 5-5, and Figure 5-6 show the results of the collapse test performed on 3, 7, and 11 percent mixture of MgCl₂ solution under varying curing time, respectively.



Figure 5-4: Consolidation results of a test samples mixed with 3% MgCl₂ solution under

different curing time



Figure 5-5: Consolidation results of a test samples mixed with 7% MgCl2 solution under

different curing time



Figure 5-6: Consolidation results of a test samples mixed with 11% MgCl₂ solution under different curing time

Many research has shown the ability of Magnesium Chloride on improving the properties of different types of soils (Latifi et al., 2016; Latifi et al., 2016; Latifi et al., 2015). However, the addition of MgCl₂ to the collapsible soil, in case of 0, 1, 3, and 7 days curing time, has increased the collapse potential. This can be explained as a dramatic decrease in the pH value of the pore water due to the high solubility of MgCl₂ which lead to having more pores in the structure of the soil as concluded from Chapter 4. In case of 11% addition of MgCl₂ to the system, the harsh acidic environment reduces the pH level of system below 6 where sodic soil is going to be developed due to the removal of CaCO₃ by acid from soil (El-Swaify, 1973). Results have been presented in

Figure 5-7. This graph shows that among all mixtures, 11% MgCl₂ has reduced the collapse potential of the soil, even in the early stages of curing, by almost 50%. In case of addition of 3% and 7% of MgCl₂ solution to the soil with no curing time, the collapse was increased by 60% and 20%, respectively. However, after 28 days of curing of soil sample mixed with 3% and 7% MgCl₂ solution, the collapse was reduced by 17% and 50% comparing to the untreated soil sample, respectively. Therefore, it can be observed that the curing has significant impact on the collapsibility of the soil in lower percentages of MgCl₂ (3 and 7%).



Figure 5-7: Collapse potential versus curing period for different amount of MgCl₂ solutions

Figure 5-8 illustrates the bar chart of the effect of different percentages of magnesium chloride under varying curing time on collapse potential of the soil. In general, extending the curing time from 0 day to 1, 3, 7 to 28 days can reduce the collapse potential. In the early stages of the curing time, Magnesium Chloride crystals fill the porous structure of the collapsible soil and dissolve in water during the inundation which increase the collapse. However, as the time passes, the high solubility of magnesium chloride results in adsorbing the water inside the voids of the soil and producing acidic environment that destroys the cementing agents that hold the soil particles together. This phenomenon will cause the soil structure to become weaker and undergo more settlement during the early stages of collapse test prior to inundation. Therefore, the sudden settlement of the soil during the inundation is reduced. In other words, addition of MgCl₂ to the soil and curing the mixture, can significantly remediate the soil collapse problem.



Figure 5-8: Collapse potential versus curing period for different amount of MgCl₂ solutions

5.6 Summary

This study aims to provide a better understanding of the effect of Magnesium Chloride as one of the most common de-icing agents and green stabilizers, on collapse potential. Collapsible soil samples were collected from Okanagan-Thompson Valley and mixed with 3, 7, and 11 percent of MgCl₂ solution to the dry weight of the soil. Moreover, five different curing durations (0, 1, 3, 7, and 28 days) were defined to investigate the effect of this salt on the soil structure over the time. Series of single oedometer tests were performed on each mixture to measure the collapse potential. Result of this study indicates although excessive research has shown the improvement of soil properties with the addition of low percentages of Magnesium Chloride, this solution increases the collapse potential of the silty-sand collapsible soil due to the dramatic decrease in the pH of pore water. The results of the collapse test for different percentages of MgCl₂ indicate that as the amount of MgCl₂ increases, the harsh acidic environment caused by reaction between this salt and pore water, destroys the soil collapsible structure. The soil mixture undergoes gradual settlement prior to inundation due to the increase in surcharge pressure. As a result, the sudden settlement of the soil during inundation (collapse) is less significant.

Comparing the results of the oedometer test for different curing time indicate the importance of the curing time on the collapsibility. It shows that as the curing time increases, the crystals of MgCl₂ within the voids, adsorb the moisture from the soil and create an acidic environment in the soil. The produced acid weakens the structure of the soil by destroying the cementing agents that hold the soil particles together. Therefore, any small increase in the surcharge pressure of the soil, without the addition of water, will lead to collapse. This phenomenon can be seen in the early stages of the oedometer test where the addition of the pressure has a significant effect on the settlement of the soil.

101

This study helps to better understand the advantages as well as shortcomings of using MgCl₂ as a soil stabilizer and a de-icing agent. The results show that as the percentage of MgCl₂ and curing time increase, soil collapse decreases. It can be concluded that lower percentages of MgCl₂ require longer curing time to remediate the collapse potential. Therefore, among all the combinations of MgCl₂ percentages and curing time, soil samples with 7% of MgCl₂ and 28 days curing time have the best stabilization effect.

Chapter 6: Conclusions and Recommendations

6.1 Summary and conclusions

Problematic soils are the origin of most geological hazards which lead to high cost of maintenance. Collapsible soil is one of the types of problematic soils and the construction on this type of the soil is a challenge for geotechnical engineers. Collapsible soil covers 10 percent of the earth's land. Understanding the collapse mechanism results in mitigating this problem, saving huge cost of maintenance, and even saving human life. Therefore, this research highlights the key aspects affecting the collapse by analyzing the macro and micro-mechanism of collapsible soils. The goal of this dissertation is to provide a better understanding of the collapse phenomenon and the factors affecting it. To fulfil this goal, the investigations included three main tasks: 1) understanding of the collapse settlement by considering changes in internal and external energies of the soil as the major cause for altering the equilibrium state of the soil; 2) analyzing the microstructure of the collapsible soils and the effect of pore water chemistry on it; and 3) remediating the collapse by using a green stabilizer. After finishing these tasks, the results were obtained and analyzed, and the conclusions are summarized below:

A new approach to transform SWCC by constantly updating the total void ratio of the soil resulted in a satisfactory correlation with applied pressure and collapsibility of soil. To verify, a series of single oedometer tests were performed on the factors affecting the collapse such as dry density, water content, and surcharge pressure. Experimental results proved that the collapsibility of the soil is directly related to the suction, index of voids, and the total applied load on the soil. The outcome of the first task can be used to predict the total collapsibility of the soil by knowing the void ratio and measuring the SWCC. Moreover, it can be used as an alternative method for a suction-controlled collapse test which requires a significant amount of time to be performed. The second task of this research showed the significant effect of pore fluid pH level and the exposure time on the microstructure of collapsible soil. Based on the results of experimental work, it was concluded that pretreatment of the soil under different pH levels increases the number of micro and macropores within the soil structure. Moreover, Structure of the soil with pH level equal to 5 showed the lowest porosity among all test specimens due to the effect of acidic environment on the clayey-bonds between the particles. The acidic environment not only creates dispersion-flocculation on the clay particles, it also dissolves CaCO₃ which weakens the chemical bonds between the particles. These results were verified by analyzing the SEM images before and after the collapse and measuring the pore-size distribution. The outcome of this task was adopted for performing feasibility study of soil stabilizer to remediate collapse and the effect of a green-stabilizer, MgCl₂, on collapse remediation could only be explained with the results of this task. The final task of this study was to stabilize the soil to control its collapsibility. Therefore, the

effect of one of the most common green stabilizers as well as de-icing agents, Magnesium Chloride (MgCl₂), on collapsibility of the soil was investigated. The outcomes proved that MgCl₂ can improve the mechanical behavior of the collapsible soil in its dry condition. Due to the high solubility of this chemical in water, during the consolidation test and saturation of the soil, Magnesium Chloride dissolved into water and developed acidic environment with pH levels below 6. Based on the results of Chapter 4, desolvation of the soil particles as well as the cementing agents between them in an acidic environment increased the collapsibility of the soil. Moreover, it was concluded that increasing the curing time results in gradual settlement of the soil prior to inundation which causes the reduction in the collapsibility of the soil during flooding.

6.2 Originality and contributions

The research on understanding the behavior of collapsible soil has mainly focused on the factors affecting the collapse. However, less attention has been given to the analysis of the soil microstructure of collapsible soil as well as the change in stress-state of this type of soil during the collapse test. In addition, by considering the global void of the soil, and constantly updating the SWCC with void ratio, the transformed SWCC has been able to predict the complete hydraulic path followed by a soil during mechanical loading. The outcome of the first part of this dissertation provides an alternative to suction-controlled collapse test. Also, it will enable future researchers to measure the suction value of the soil during the consolidation test which is not currently being measured.

Pore-size distribution of the soil is one of the key features responsible for soil collapse which can be significantly altered by pore water properties such as pH levels. Many studies have been done to understand the effect of the pH level of the pore water on the properties of the soil, however, to the author's knowledge, there have been no investigations of collapsible soil. Therefore, this research highlights the influence of different levels of pH on the microstructure and pore-size distribution of the collapsible soil. The results are important to study the chemical remediation methods for soil collapse.

Magnesium Chloride is one of the most common soil stabilizers which is being used extensively as a de-icing agent. Previous studies have shown the capability of this chemical to improve the properties of the problematic soils in their dry condition. However, there was still a gap in the knowledge to check the feasibility of MgCl₂ in the reduction of collapse. This investigation studied the effect of different percentages of MgCl₂ as well as the curing time on the collapse potential of

105

subjected soil and showed the advantages and drawbacks of using this chemical on the environment.

6.3 Limitations and recommendations

A few limitations and their recommendation for future studies have been listed in the Table 6-1 below:

No.	Limitation	Recommendation
1	The studies were performed only on collapsible	The properties, chemical components, and structure
	soil in the Okanagan.	of collapsible soils are different based on their origin.
		The studies should be performed on collapsible soils
		from different locations to compare results.
2	The collapsibility of the soil was investigated	Future research can conduct the experiment under
	through one-dimensional consolidation tests.	cyclic loading. Moreover, the effect of freeze-thaw
		on the soil suction, pore-size distribution, and
		collapse potential can be studied.
3	This research is limited to the experimental	Field testing should be performed, and the efficiency
	methods in the laboratory testing conditions.	of the method should be compared to the current
		techniques
4	The effect of Magnesium Chloride on the collapse	Curing temperature has a significant impact on the
	was only investigated at a certain temperature.	soil stabilizer. The effect of Magnesium chloride can
		be investigated at varying temperatures.

Table 6-1: Limitations	s and rec	commendations
------------------------	-----------	---------------

Bibliography

- Abbeche, K., Bahloul, O., Ayadat, T., & Bahloul, A. (2010). Treatment of collapsible soils by salts using double consolidation method. *International Conference GeoShanghai*.
- Abdullah, W. S., Alshibli, K. A., & Al-Zou'bi, M. S. (1999). Influence of pore water chemistry on the swelling behavior of compacted clays. *Applied Clay Science*, *15*(5), 447 462.
- Abelev, M. (1948). The essentials of designing and building on microporous soils. *Stroitel'naya Promyshelmast, 10.*
- Abood, T., Kasa, A., & Chik, Z. (2007). Stabilisation of silty clay soil using chloride compounds. *Journal of Engineering Science and Technology*, 2(1), 102 110.
- Act, C. (1993). *Priority substances list assessment report*. Ottawa: Environment Canada and Health Canada.
- Ahuja, L. R., Cassel, D. K., Bruce, R. R., & Barnes, B. B. (1989). Evaluation of spatial distribution of hydraulic conductivity using effective porosity data. *Soil Science*, *148*(6), 404 411.
- Alfi, A. S. (1984). MECHANICAL AND ELECTRON OPTICAL PROPERTIES OF A STABILIZED COLLAPSIBLE SOIL IN TUCSON, ARIZONA. Tucson: The University of Arizona.
- Ali, M. M. (2011). Identifying and analyzing problematic soils. Geotech Geol Eng, 343-350.
- Al-Rawas, A. A. (2000). State-of-the-Art-Review of Collapsible Soils. *Sultan Qaboos University Journal for Science [SQUJS], 5*, 115 - 135.

- Al-Rawas, A., Taha, R., Nelson, J., Al-Shab, B., & Al-Siyab, H. (2002). A comparative evaluation of various additives used in the stabilization of expansive soils. *Geotechnical Testing Journal*, 25(2), 199 - 209.
- Altin, O., Özbelge, H. Ö., & Dogu, T. (1999). Effect of pH in an aqueous medium on the surface area, pore size distribution, density, and porosity of montmorillonite. *Journal of colloid and interface science*, 217(1), 19 - 27.
- Anayev, V. P., & Volyanick, N. V. (1986). Engineering geologic peculiarities of construction work on loessial soils. 5th International Congress of the Association of Engineering Geologists, 2, 659 - 665.
- Arulrajah, A., Abdullah, A., Bo, M., & Bouazza, A. (2009). Ground improvement techniques for railway embankments. *Proceedings of the Institution of Civil Engineers-Ground Improvement*, 162(1), 3 - 14.
- Arya, L., & Dierolf, T. (1989). Predicting soil moisture characteristics by particle-size distributions: an improved method to calculate pore radii from particle radii. *Int. Workshop on Indirect Methods for Estimating the Hydraulic Properties of Unsaturated Soils*, 115 124.
- Arya, L., & Paris, J. (1981). A physicoempirical model to predict the soil moiture characteristic from particle-size distribution and bulk density data. *Soil Science of America Journal*, 45, 1023 - 1030.
- ASTM D-698. (2012). Standard test methods for laboratory compaction characteristics of soil using standard effort (12,400 ft-lbf/ft³ (600 kN-m/m³)). *ASTM International*.

ASTM D-4972. (2018). Standard test methods for pH of soils. ASTM International.

- ASTM D-5333. (2003). Standard test method for measurement of collapse potential of soils (Withdrawn 2012). *ASTM International*.
- ASTM D-6913. (2017). Standard test methods for particle-size distribution (gradation) of soil using sieve analysis. *ASTM International*.
- ASTM D-7928. (2017). Standard test method for particle-size distribution (gradation) of finegrained soils using the sedimentation (hydrometer) analysis. *ASTM International*.
- Aubertin, M., Mbonimpa, M., Bussiere, B., & Chapuis, R. P. (2003). A model to predict the water retention curve from basic geotechnical properties. *Canadian Geotechnical Journal*, 40(6), 1104 - 1122.
- Ayadat, T., & Belouahri, B. (1998). Migration of fine size particles as a collapse mechanism of soils. *Revue Française de Géotechnique*, 83, 73 - 83.
- Ayadat, T., & Hanna, A. M. (2011). Assessement of soil collapse prediction methods.*International Journal of Engineering-Transactions B: Applications*, 25(1), 19 26.
- Ayadat, T., & Hanna, M. (2007). Identification of collapsible soil using the fall cone apparatus. *Journal of Geotechnical Engineering*, *30*(4), 1 - 12.
- Ayadat, T., & Ouali, S. (1999). Identification des sols affaissables basée sur les limites d'Atterberg. *Revue française de géotechnique*, 86, 53 - 56.
- Aydilek, A. H., Seyfullah, H. O., & Tuncer, B. E. (2002). Digital image analysis to determine pore opening size distribution of nonwoven geotextiles. *Journal of Computing in Civil Engineering*, 280 - 290.
- Ayeldeen, M., Negm, A., El-Sawwaf, M., & Kitazume, M. (2017). Enhancing mechanical behaviors of collapsible soil using two biopolymers. *Journal of Rock Mechanics and Geotechnical Engineering*, 9(2), 329 - 339.

- Bahloul, O., Abbeche, K., Bahloul, A., & Halitim, A. (2014). Effect of sodium chloride on the wetting induced collapse strain of soils. *Malaysian Journal of Civil Engineering*, 26(2), 119 135.
- Barden, L., McGown, A., & Collins, K. (1973). The collapse mechanism in partly saturated soil. *Engineering Geology*, 7, 49 - 60.
- Basma, A. A., & Tuncer, E. R. (1992). Evaluation and control of collapsible soils. *Journal of Geotechnical Engineering*, 118(10), 1491-1504.
- Basma, A., & Kallas, A. (2004). Modeling soil collapse by artificial neural networks. *Geotechnical and Geological Engineering*, 22(3), 491 - 504.
- Beamish, R. J., & Harvey, H. H. (1972). Acidification of the La Cloche Mountain Lakes,
 Ontario, and resulting fish mortalities. *Journal of the Fisheries Board of Canada, 29*(8),
 1131 1143.
- Bell, F. G., & Bruyn, I. D. (1997). Sensitive, expansive, dispersive and collapsive soils. *Bulletin* of the International Association of Engineering Geology, 56, 19 38.
- Bigdeli, A., & Siddiqua, S. (2016). Assessment and analysis of factors influencing the collapse.69th Canadian Geotechnical Conference. Vancouver.
- Bigdeli, A., Siddiqua, S., & Williams, N. (2015). Evaluation and control of collapsible soils in
 Okanagan-Thompson area. 68th International Conference of Canadian Geotechnical
 Engineering. Quebec.
- Bishop, A. W., & Donald, I. B. (1961). The experimental study of partly saturated soil in the triaxial apparatus. 5th international conference on soil mechanics and foundation engineering, (pp. 13 - 21). Paris.

- Bishop, A., & Blight, G. (1959). Some aspects of effective stress in saturated and partly saturated soils. *Géotechnique*, 13(3), 177 - 197.
- Bolander, P. (1997). Chemical additives for dust control what we have learned. *Journal of the Transportation Research Board*, 1589, 42 - 49.
- Bolander, P., & Yamada, A. (1999). *Dust palliative selection and application guide*. (No. 9977 1207-SDTDC).
- Booth, A. R. (1975). The factors influencing collapse settlement in compacted soils. *6th Regional Conf. for Africa on Soil Mechanics and Foundation Engineering*. 2, pp. 57-63.
 South Africa: South African Institute of Civil Engineers.
- Briscolland, R., & Chown, R. (2001). Problem soils: a review from a british perspective,. *Proceeding of Problematic Soils Conference*, (pp. 53 - 66). Nottingham.
- Burtraw, D., Krupnick, A., Mansur, E., Austin, D., & Farrell, D. (1997, September). The Costs and Benefits of Reducing Acid Rain. *Resources for the Future*.
- Bushman, W., Freeman, T., & Hoppe, E. (2005). Stabilization techniques for unpaved roads.
 ransportation Research Record: Journal of the Transportation Research Board, 1936, 28
 33.
- Camapum de Carvalho, J., & Leroueil, S. (2004). Transformed soil-water characteristic curve. Soils and Rocks, 231 - 242.

Camapum de Carvalho, J., de Rezende, L., Cardoso, F., de FL Lucena, L., Guimaraes, R., & Valencia, Y. (2015). Tropical soils for highway construction: Peculiarities and considerations. *Transportation Geotechnics*, 5, 3 - 19.

- Camapum de Carvalho, J., Guimaraes, R., & Pereira, J. (2002). Courbes de retention d'eau d'un profil d'alteration. *3rd Int. Conf. on Unsaturated Soils* (pp. 289 294). UK: Taylor and Francis.
- Chen, C., Gao, P., & Hu, Z. (2006). Moistening deformation characteristic of loess and its relation to structure. Yanshilixue Yu Gongcheng Xuebao/Chinese Journal of Rock Mechanics and Engineering, 25(7), 1352 - 1360.
- Cherian, C., Arnepalli, D. N., Dogga, T. S., Raviteja, N. B., Gorle, S. V., & Balraj, N. M. (2014).
 Assessment of grain-size and pore-size distribution using digital image analysis. *Proceedings of Indian Geotechnical Conference IGC-2014*, (pp. 240 -249). Kakinada,
 India.
- Clemence, S., & Finbarr, A. (1981). Design considerations for collapsible soils. *Journal of Geotechnical Engineering*, *107*(3), 301 305.
- Clevenger, W. (1958). Experiences with loess as foundation material. *Transactions of the American Society of Civil Engineering*, *123*(1), 151 - 169.
- Day, R. W. (1990). Sample disturbance of collapsible soil. *Journal of Geotechnical Engineering*, *116*(1), 158-161.
- Denisov, Y. (1963). About the nature of high sensitivity of Quick clays. Osnov. Fudam. Mekh. Grunt, 5, 5 - 8.
- Dontsova, K. M., & Norton, L. D. (2002). Clay dispersion, infiltration, and erosion as influenced by exchangeable Ca and Mg. *Soil Science*, *167*(3), 184 193.
- Duchesne, L., Quimet, R., & Houle, D. (2002). Basal area growth of sugar maple in relation to acid deposition, stand health, and soil nutrients. *Journal of Environmental Quality*, *31*(5), 1676 1683.

- Dudley, H. (1970). Review of collapsing soils. *Journal of Soil Mechanics and Foundations Division*, 97(SM3), 925 - 947.
- El-Ehwany, M., & Houston, L. (1990). Settlement and moisture movement in collapsible soils. *Journal of geotechnical engineering*, *116*(10), 1521 - 1535.
- El-Swaify, S. A. (1973). Structural changes in tropical soils due to anions in irrigation water. *Soil Sci.*, *43*(1), 64 72.

Fang, H. Y. (2013). Foundation engineering handbook. Springer Science & Business Media.

- Fattah, M. Y., Al-Ani, M. M., & Al-Lamy, M. T. (2014). Studying collapse potential of gypseous soil treated by grouting. *Soils and Foundations*, 54(3), 396 - 404.
- Fay, L., & Shi, X. (2012). Environmental impacts of chemicals for snow and ice control: state of the knowledge. *Water, Air, & Soil Pollution, 223*(5), 2751 - 2770.
- Feda, J. (1964). Colloidal activity, shrinking and swelling of some clays. Proceedings of the Soil Mechanics Seminar, (pp. 531 - 564). Illinois.
- Feda, J. (1966). Structural stability of subsident loesses from PrahaDejvice. *Engineering Geology*, 1(3), 201 219.
- Ferreira, T. A., & Rasband, W. (2010). The ImageJ user guide V 1.5.
- Fleureau, J. M., Kheirbek-Saoud, S., Soemitro, R., & Taibi, S. (1993). Behavior of clayey soils on drying–wetting paths. *Canadian geotechnical journal*, *30*(2), 287 - 296.
- Fredlund, D. G. (2002). Use of soil-water characteristic curve in the implementation of unsaturated soil mechanics. *3rd International Conference on Unsaturated Soils* (pp. 20-23). Recife: Brazil.
- Fredlund, D. G., & Houston, S. L. (2013). Interpretation of soil-water characteristic curves when volume change occurs as soil suction is changed. *Advances in unsaturated soils*, 1 15.

- Fredlund, D., & Morgenstern, N. (1977). Stress State Variable for Unsaturated Soils. Journal of Geotechnical Engineering, 103, 447 - 466.
- Fredlund, D., & Rahardjo, H. (1993). *Soil mechanics for unsaturated soils*. New York: John Wiley and Sons.
- Fredlund, M. D., Wilson, G. W., & Fredlund, D. G. (2002). Use of the grain-size distribution for estimation of the soil-water characteristic curve. *Canadian Geotechnical Journal*, 39(5), 1103 - 1117.
- Fulton, R. J. (1975). Quaternary geology and geomorphology, Nicola-Vernon area, British Columbia (82 LW 1/2 and 92 IE 1/2). Geological Survey of Canada.
- Gaaver, K. (2012). Geotechnical properties of Egyptian collapsible soils. *Alexandria Engineering Journal, 51*, 205 - 210.

Gao, G. (1980a). The microstructures of loess in China. Chinese Science Bulletin, 20, 945 - 948.

- Gao, G. (1980b). Classification for microstructure of loess and its collapsibility. *Chinese Science Bulletin, 12,* 1203 - 1212.
- Gibbs, J., & Bara, P. (1967). Stability problems of collapsing soil. *Journal of Soil Mechanics and Foundation Engineering*, 93(1), 577 - 594.
- Gimenez, D., Allmaras, R. R., Huggins, D. R., & Nater, E. A. (1997). Prediction of the saturated hydraulic conductivity-porosity dependence using fractals. *Soil Science*, 61(5), 1285 -1292.
- Giummarra, G., Foley, G., & Cropley, S. (1997). Dust control: Australasian experiences with various chemical additives. *Journal of the Transportation Research Board*, *1589*, 50 53.

- Goodrich, B., Koski, R., & Jacobi, W. (2009). Condition of soils and vegetation along roads treated with magnesium chloride for dust suppression. *Water, air, and soil pollution, 198*(1-4), 165 188.
- Gualtieri, M., Romagnoli, M., Pollastri, S., & Gualtieri, A. (2015). Inorganic polymers from laterite using activation with phosphoric acid and alkaline sodium silicate solution: mechanical and microstructural properties. *Cement and Concrete Research*, 67, 259 -270.
- Guan, W. (1986). On soluble salts and the mechanism of loess collapsibility. *Journal of Guilin College Geology*, 6(3), 271 - 278.
- Gupta, A. K., & Singh, D. N. (1997). Interaction of contaminants with soils: A review. *Indian Geotechnical Journal*, 27, 75 - 87.
- Hazewinkel, R. O., Wolfe, A. P., Pla, S., Curtis, C. J., & Hadley, K. (2008). Have atmospheric emissions from the Athabasca Oil Sands impacted lakes in northeastern Alberta, Canada? *Can. J. Fish. Aquat. Sci.*, 65, 1544 - 1567.
- Holtz, W., & Hilf, J. (1961). Settlement of soil foundation due to saturation. *5th International SMFE*. Paris.
- Hoover, J., Pitt, J., Lustig, M., & Fox, D. (1981). *Mission-oriented dust control and surface improvement processes for unpaved roads.*
- Houston, S., & El-Ehwany, M. (1991). Sample disturbance of cemented collapsible soils. *Journal of Geotechnical Engineering*, *117*(5), 731 - 752.
- Houston, S., Houston, W., & Lawrence, C. (2002). Collapsible soil engineering in highway infrastructure development. *Journal of Transportation Engineering*, *128*(3), 295 300.

- Houston, S., Houston, W., & Spadola, D. (1988). Prediction of field collapse of soils due to wetting. *Journal of Geotechnical Engineering*, 114(1), 40-58.
- Houston, S., Houston, W., Chen, C., & Febres, E. (1998). Site characterication for collapsible soil deposits. *2nd International Conference on Unsaturated Soils*. Beijing.
- Houston, S., Houston, W., Zapata, C., & Lawrence, C. (2001). Geotechnical engineering practice for collapsible soils. *Geotechnical and Geological Engineering*, *19*, 333 355.
- Houston, S., Houston, W., Zapata, C., & Lawrence, C. (2001). Geotechnical engineering practice for collapsible soils. *Geotechnical and Geological Engineering*, *19*(1), 333-355.
- Hue, D. M., Phien-Wej, N., & Giao, P. H. (2010). Evaluation of the changes in stiff clay microstructure by SEM digital image processing. *Geotechnical Journal*, 97 - 104.
- Hunter, D. (1988). Lime-induced heave in sulfate-bearing clay soils. *Journal of geotechnical* engineering, 114(2), 150 167.
- Indraratna, B., Chu, J., & Rujikiatkamjorn, C. (2005). *Ground improvement case histories*. Oxford, UK: Elsevier.
- Ingles, O. G., & Metcalf, J. B. (1972). Soil stabilization principles and practice (Vol. 11).
- Jefferson, I., Evstatiev, D., & Karastanev, D. (2008). The treatment of collapsible loess soils using cemented materials. *GeoCongress*, 662-669.
- Jefferson, I., Rogers, C., Evstatiev, D., & Karastanev, D. (2005). Treatment of metastable loess soils: lessons from eastern Europe. In *Elsevier geo-engineering book series* (pp. 723 -762). Elsevier.
- Jennings, J. E., & Knight, K. (1957). The additional settlement of foundations due to collapse of sandy soils on wetting. 4th International Conference on Soil Mechanics and Foundation Engineering, (pp. 316-319). London.

- Jiang, M., Hu, H., Peng, J., & Yang, Q. (2012). Pore changes of loess before and after stress path tests and their links with mechanical behaviors. *Chinese Journal of Geotechnical Engineering*, 34(8), 1369 - 1378.
- Jiang, M., Li, T., Hu, H., & Thornton, C. (2014b). DEM analyses of one-dimensional compression and collapse behaviour of unsaturated structural loess. *Journal of Computers and Geotechnics*, 60, 47 - 60.
- Jiang, M., Zhang, F., Hu, H., Yujun, C., & Peng, J. (2014a). Structural characterization of natural loess and remolded loess under triaxial tests. *Journal of Engineering Geology*, 181, 249 -260.
- Jianli, M., Youcai, Z., Jinmei, W., & Li, W. (2010). Effect of magnesium oxychloride cement on stabilization/solidification of sewage sludge. *Construction and Building Materials*, 24(1), 79 - 83.
- Jing-bo, O., & Yun, N. (1994). Study on pores and collapsibility of loess. *Journal of Engineering Geology*, 2(2), 76 - 83.
- Jongerius, A., & Bisdom, A. B. (1981). Porosity measurements using the Quantimet 720 on backscattered electron scanning images of thin sections of soils. *Submicroscopy of Soils and Weathered Rocks*, *1*, 207.
- Kalantari, B. (2012). Foundations on collapsible soils: a review. ICE, 166(FE2), 57-63.
- Kamon, M., Ying, C., & Katsumi, T. (1996). Effect of acid rain on lime and cement stabilized soils. *Soils and Foundations*, *36*(4), 91 99.
- Ketcham, S., Minsk, L., Blackburn, R., & Fleege, E. (1996). *Manual of practice for an effective anti-icing program: a guide for highway winter maintenance personnel.*

Kezdi, A. (2016). Stabilized earth roads. Elsevier.

- Khalili, N., Geiser, F., & Blight, G. (2004). Effective stress in unsaturated soils: Review with new evidence. *International Journal of Geomechanics*, *4*(2), 115 126.
- Khatami, H. R., & O'Kelly, B. C. (2012). Improving mechanical properties of sand using biopolymers. *Journal of Geotechnical and Geoenvironmental Engineering*, *139*(8), 1402 1406.
- Kozubal, J., & Steshenko, D. (2015). The complex compaction method of an unstable loess substrate. *Arabian Journal of Geosciences*, 8(8), 6189 6198.
- Krayev, V. F. (1969). On subsidence of loess soils of the Ukraine. *Actes du Colloque de Tokyo*, 321 324.
- Kumara, G. J., Hayano, K., & Ogiwara, K. (2012). Image analysis Techniques on evaluation of particle size distribution of gravel. *International Journal of GEOMATE: Geotechnique, Construction materials and Environment, 3*(1), 290 - 297.
- Landon, B., & Williamson, R. (1983). Dust-abatement materials: evaluation and selection. *Transportation Research Record*, 898, 250 - 257.
- Larson, S. L., Newman, J. K., Griggs, C. S., Beverly, M., & Nestler, C. C. (2012). Biopolymers as an Alternative to Petroleum-Based Polymers for Soil Modification. ENGINEER RESEARCH AND DEVELOPMENT CENTER VICKSBURG MS ENVIRONMENTAL LAB.
- Latifi, N., Horpibulsuk, S., Meehan, C., Abd Majid, M., Tahir, M., & Mohamad, E. (2016).
 Improvement of problematic soils with biopolymer—an environmentally friendly soil stabilizer. *Journal of Materials in Civil Engineering*, 29(2), 04016204.

- Latifi, N., Rashid, A., Ecemis, N., Tahir, M., & Marto, A. (2016). Time-dependent physicochemical characteristics of Malaysian residual soil stabilized with magnesium chloride solution. *Arabian Journal of Geosciences*, 9(1), 58.
- Latifi, N., Rashid, A., Marto, A., & Tahir, M. (2016). Effect of magnesium chloride solution on the physico-chemical characteristics of tropical peat. *Environmental Earth Sciences*, 75(3), 220.
- Latifi, N., Rashid, A., Siddiqua, S., & Horpibulsuk, S. (2015). Micro-structural analysis of strength development in low-and high swelling clays stabilized with magnesium chloride solution—A green soil stabilizer. *Applied Clay Science*(118), 195 - 206.
- Lawton, E., Fragaszy, R., & Hardcastle, J. (1989). Collapse of compacted clayey sand. *Journal* of Geotechnical Engineering, 115(9), 1257 1267.
- Lawton, E., Fragaszy, R., & Hetherington, M. (1992). Review of wetting-induced collapse in compacted soil. *Journal of Geotechnical Engineering*, *118*(9), 1376 1394.
- Lebron, I., Schaap, M. G., & Suarez, D. L. (1999). Saturated hydraulic conductivity prediction from microscopic pore geometry measurements and neural network analysis. *Water Resources Research*, 35(10), 3149 - 3158.
- Lebron, I., Suarez, D. L., & Schaap, M. G. (2002). Soil pore size and geometry as a result of aggregate-size distribution and chemical composition. *Soil Sci.*, *167*(3), 165 172.
- Li, P., Vanapalli, S., & Li, T. (2016). Review of collapse triggering mechanism of collapsible soils due to wetting. *Journal of Rock Mechanics and Geotechnical Engineering*, 8(2), 256 274.

- Li, Z. X., Cai, C. F., Shi, Z. H., & Wang, T. W. (2005). Aggregate stability and its relationship with some chemical properties of red soils in subtropical China. *Pedosphere*, 15(1), 129 -136.
- Liu, J., Shi, B., Jiang, H., Huang, H., Wang, G., & Kamai, T. (2011). Research on the stabilization treatment of clay slope topsoil by organic polymer soil stabilizer. *Engineering Geology*, 117(2), 114 - 120.
- Lohnes, R., & Coree, B. (2002). *Determination and evaluation of alternate methods for managing and controlling highway-related dust.* Iowa Department of Transportation.
- Lommler, J., & Bandini, P. (2015). Characterization of collapsible soils. *IFCEE 2015*, (pp. 1834 1841).
- Malaya, C., & Sreedeep, S. (2011). Critical Review on the Parameters Influencing soil-water characteristic curve. *Journal of Irrigation and Drainage Engineering*, *138*(1), 55 62.
- Manckenchinie, W. (1980). Foundation investigation and design techniques for volumetrically active clays and collapsing sands. *7th Regional Conference for Africa on Soil Mechanics and Foundation Engineering*, 2, pp. 769 774. Accra.
- Markin, B. P. (1969). Discussion on standard criteria of Sag in Loess soils. *Soil Mechanics and Foundations Engineering*, 2, 137.
- Martin, G. R., Yen, T. F., & Karimi, S. (1996). Application of biopolymer technology in silty soil matrices to form impervious barriers. *7th Australia New Zealand Conference on Geomechanics: Geomechanics in a Changing World* (p. 814). Australia: Institution of Engineers.

- Marto, A., Latifi, N., & Eisazadeh, A. (2014). Effect of non-traditional additives on engineering and microstructural characteristics of laterite soil. *Arabian Journal for Science and Engineering*, 39(10), 6949 - 6958.
- Marto, A., Latifi, N., & Sohaei, H. (2013). Stabilization of laterite soil using GKS soil stabilizer. *Electron. J. Geotech. Eng*, *18*, 521 - 532.
- Mason, G., & Morrow, N. R. (1991). Capillary behavior of a perfectly wetting liquid in irregular triangular tubes. *Journal of Colloid and Interface Science*, *141*(1), 262 274.
- Menz, F. C., & Seip, H. M. (2004). Acid rain in Europe and the United States: an update. *Environmental Science & Policy*, 7(4), 253 - 265.
- Mongeon, A., Aherene, J., & Watmough, S. A. (2010). Steady-state critical loads of acidity for forest soils in the Georgia Basin, British Columbia. *Journal of Limnology*, 69(1s), 193 -200.
- Monlux, S., & Mitchell, M. (2007). Chloride stabilization of unpaved road aggregate surfacing.
 Transportation Research Record: Journal of the Transportation Research Board, 1989, 50 58.
- Morrison, H. A., & Carou, S. (2004). Canadian acid deposition science assessment. *Environment Canada–Meteorological Service of Canada*, 4905.
- Muhammad, N., & Siddiqua, S. (2017). Investigation of the strength development using magnesium alkalinization for subgrade. *Leadership in Sustainable Infrastructure*. Vancouver.
- Munoz-Castelblanco, J., Delage, P., Pereira, J. M., & Cui, Y. J. (2011). Some aspects of the compression and collapse behaviour of an unsaturated natural loess. *Géotechnique Letters*, 1 - 6.

- Nixon, W., & Williams, A. (2001). *A guide for selecting anti-icing chemicals, version 1.0.* IIHR Technical Rep.
- Noor, T., Hanna, A., & Mashhour, I. (2013). Numerical modeling of piles in collapsible soil subjected to inundation. *International Journal of Geomechanics*, *13*(5), 514 526.
- Noutash, M., Hajialilue, B., & Cheshmdoost, M. (2010). Prepounding of canals as a remediation method for collapsible soils. *4th International Conference on Geotechnical Engineering and Soil Mechanics*. Tehran.
- Padilla, J. M., Perera, Y. Y., Houston, W. N., & Fredlund, D. G. (2005). A new soil-water characteristic curve device. *Advanced Experimental Unsaturated Soil Mechanics*, 15-22.
- Palmer, J., Edgar, T., & Boresi, A. (1995). Strength and density modification of unpaved road soils due to chemical additives.
- Pankaj, S., Sameer, V., Manorma, K., Mahure, N. V., Sivakumar, N., Ranjan, K., & Murari, R. (2012). Understanding the effect of acid rain on physico-chemical and engineering properties of black cotton soil. *International Journal of Environmental Sciences*, 2(3), 1291.
- Pasha, A. Y., Khoshghalb, A., & Khalili, N. (2017). Hysteretic Model for the Evolution of Water Retention Curve with Void Ratio. *Journal of Engineering Mechanics*, 143(7).
- Pereira, J., & Fredlund, D. (2000). Volume change behaivior of collapsible compacted Gneiss soil. *J. Geotech. Geoenviron. Eng.*, *126*(10), 907 916.
- Pin-Hua, R., He, M., Xiao-Hui, M., Xian, Y., & Ming, Y. (2006). Effect of surfactants on the stability of clay suspensions with special reference to the change of pH. *Soil Science*, *171*(10), 764 - 771.
- Priklonskij, V. A. (1952). Gruntovenedie-Utoraiva Chast. Gosgeolizdat, 371.

- Punrattanasin, P., Subjarassang, A., Kusakabe, O., & Nishimura, T. (2002). Collapse and erosion of Khon Kaen loess with treatment option. *First International Conference on Scour of Foundations*, (pp. 1081 - 1095). College Station.
- Rabl, A., & Spadaro, J. (1999). Damages and costs of air pollution: an analysis of uncertainties. *Environ. Pollut.*, 25(1), 29 - 46.
- Reuss, J. O., & Johnson, D. W. (2012). Acid deposition and the acidification of soils and waters. Springer Science & Business Media, 59.
- Reuss, J. O., Christophersen, N., & Seip, H. M. (1986). A critique of models for freshwater and soil acidification. *Acidic Precipitation*, 909 - 930.
- Rogers, C. (1995). Types and distribution of collapsible soils. *Genesis and Properties of Collapsible Soils*, 1 - 17.
- Rogers, C. F., Dijkstra, T. A., & Smalley, I. J. (1994). Hydroconsolidation and subsidence of loess: studies from China, Russia, North America and Europe: in memory of Jan Sajgalik. *Engineering Geology*, 37(2), 83 - 113.
- Rollins, K. M., & Rogers, G. W. (1994). Mitigation measures for small structures on collapsible alluvial soils. *Journal of Geotechnical Engineering*, *120*(9), 1533 1553.
- Ruilin, H., & Lizhong, G. G. (1999). Microstructure effect on the subsduce of loess. *Journal of Engineering Geology*, 17(2), 161 167.
- Rust, E., Heymann, G., & Jones, G. (2010). Collapsible soils-an overview. *Civil Engineering*, *18*(3), 22 24.
- Santoni, R., Tingle, J., & Nieves, M. (2005). Accelerated strength improvement of silty sand with nontraditional additives. *Transportation Research Record: Journal of the Transportation Research Board*, 1936, 34 - 42.
- Scott, K. A., Wissel, B., Gibson, J. J., & BIRKS, J. S. (2010). Chemical characteristics and acid sensitivity of boreal headwater lakes in northwest Saskatchewan. *Journal of Limnology*, 69(1s), 33 - 44.
- Shewchuk, S. R. (1983). snowpack and surface water chemistry survey of small lakes in northern Saskatchewan. *Saskatchewan Research Council*, *155*, 62.
- Shi, X., Akin, M., Pan, T., Fay, L., Liu, Y., & Yang, Z. (2009). Deicer impacts on pavement materials: Introduction and recent developments. *Open Civil Engineering Journal*, *3*, 16 -27.
- Skempton, A. W., & Northey, R. D. (1952). The sensivity of clays. Geotechniques, 3, 30 53.
- Skjelkvale, B. L., Mannio, J., Wilander, A., & Andersen, T. (2001). Recovery from acidification of lakes in Finland, Norway and Sweden. *Hydrology and Earth System Sciences*, 5, 327 -337.
- Smalley, I. J. (1966). The properties of glacial loess and the formation of loess deposits. *Journal of Sedimentary Research, 36*(3).
- Smalley, I. J., & Vita-Finzi, C. (1968). The formation of fine particles in sandy deserts and the nature of desert loess. *Journal of Sedimentary Research*, 38(3), 766 - 774.
- Smalley, J., Jefferson, F., Dijkstra, A., & Derbyshire, E. (2001). Some major events in the development of the scientific study of loess. *Earth-Science Reviews*, 54(1), 5 - 18.
- Smalley, J., Jefferson, F., O'hara-dhand, K., & Evans, D. (2006 a). An approach to the problem of loess deposit formation: Some comments on the 'in situ' or 'soil-eluvial' hypothesis. *Quaternary International*, 152(1), 109 - 117.

- Sreekrishnavilasam, A., Rahardja, S., Kmetz, R., & Santagata, M. (2007). Soil treatment using fresh and landfilled cement kiln dust. *Construction and Building Materials*, 21(2), 318 -327.
- Stalin, V. K., & Muthukumar, M. (2002). Effect of acid permeation on the chemical characteristics of soil and fly ash. *Indian Geotechnical Conference*, 1, pp. 301 - 304. Allahabad.
- Suarez, D. L., Rhoades, J. D., Lavado, R., & Grieve, C. M. (1984). Effect of pH on saturated hydraulic conductivity and soil dispersion. *Soil Sci.*, *48*(1), 50 55.
- Sultan, A. (1969). Collapsing soils. Proceedings Seventh International Conference on Soil Mechanics and Foundation Engineering. Mexico City.
- Sun, D. A., Sheng, D., & Xu, Y. (2007). Collapse behaviour of unsaturated compacted soil with different initial densities. *Canadian Geotechnical Journal*, 44(6), 673 - 686.
- Sun, D., Sheng, D., & Xu, Y. (2007a). Collapse behaviour of unsaturated compacted soil with different initial densities. *Canadian Geotechnical Journal*, 44(6), 673 686.
- Sunil, B. M., Nayak, S., & Shrihari, S. (2006). Effect of pH on the geotechnical properties of laterite. *Engineering geology*, 85(1), 197 - 203.
- Sutter, L., Dam, T., Peterson, K., & Johnston, D. (2006). Long-term effects of magnesium chloride and other concentrated salt solutions on pavement and structural portland cement concrete: Phase I results. *Transportation Research Record: Journal of the Transportation Research Board*, 1979, 60 - 68.
- Sweeney, S. J., & Smalley, I. J. (1988). Occurrence and geotechnical properties of loess in Canada. *Engineering Geology*, 25(2-4), 123 134.

- Tabarsa, A., Latifi, N., Meehan, C. L., & Manahiloh, K. N. (2018). Laboratory investigation and field evaluation of loess improvementusing nanoclay – A sustainable material for construction. *Construction and Building Materials*, 158, 454 - 463.
- Tadepalli, R., & Fredlund, D. (1991). The collapse behavior of a compacted soil during inundation. *Canadian Geotechnical Journal*, 28(4), 477 - 488.
- Tadepalli, R., Rahardjo, H., & Fredlund, D. (1992). Measurement of matric suction and volume changes during inundation of collapsible soil. *Geotechnical Testing Journal*, 15(2), 115 -122.
- Terzaghi, K. (1943). Theoretical soil mechanics. New York: John Wiley and Sons.
- Thenoux, G., & Vera, S. (2003). Evaluation of hexahydrated magnesium chloride performance as chemical stabilizer of granular road surfaces. *Transportation Research Record: Journal of the Transportation Research Board, 1819*, 44 - 51.
- Turkoz, M., Savas, H., Acaz, A., & Tosun, H. (2014). The effect of magnesium chloride solution on the engineering properties of clay soil with expansive and dispersive characteristics. *Applied Clay Science*, 101, 1 - 9.
- Vanapalli, S. K., Fredlund, D. G., & Pufahl, D. E. (1999). The influence of soil structure and stress history on the soil-water characteristics of a compacted till. *Géotechnique*, 49(2), 143 - 159.
- Vanapalli, S., Fredlund, D., Pufahi, D., & Clifton, A. (1999). Model for the prediction of shear strength with respect to soil suction. *Canadian Geotechnical Journal*, *33*(3), 379 392.
- Vaz, C. M., de Freitas lossi, M., de Mendonca Naime, J., Macedo, A., Reichert, J. M., Reinert, D. J., & Cooper, M. (2005). Validation of the Arya and Paris water retention model for Brazilian soils. *Soil Science Society of America Journal*, 69(3), 577 583.

- Wang, Y. M., Li, C., Teng, F., & Gao, L. C. (2011). New research on chemical solidification of collapsible loess foundation. *Applied Mechanics and Materials*, 90, 2466 - 2471.
- Wang, Y., Tang, X., Chen, Y., Zhan, L., Li, Z., & Tang, Q. (2009). Adsorption behavior and mechanism of Cd(II) on loess soil from China. *Journal of Hazardous Materials*, 172(1), 30 - 37.
- Xie, W. L., Li, P., Vanapalli, S. K., & Wang , J. D. (2018). Prediction of the wetting-induced collapse behaviour using the soil-water characteristic curve. *Journal of Asian Earth Sciences*, 151, 259 - 268.
- Zia, N., & Fox, P. J. (2000). Engineering properties of loess-fly ash mixtures for roadbase construction. *Trans. Research Record*, 1714, 49 - 56.

Appendix A:



Figure A-1: Regression assumptions analysis of Figure 3-21