

STUDY OF DYNAMIC PROPERTIES OF SOIL IN WOLLO-KOMBOLCHA TOWN



Alex Berhanu Beyene

A Thesis Submitted to The Department of Civil Engineering,
School of Civil Engineering and Architecture
Presented in Partial Fulfillment of the Requirement for the Degree of Master's in Civil
Engineering (specialization in Geotechnical Engineering)

Office of Graduate Studies
Adama Science and Technology University

June 2022
Adama, Ethiopia

STUDY OF DYNAMIC PROPERTIES OF SOIL IN WOLLO-KOMBOLCHA TOWN

Alex Berhanu Beyene

Advisor: Tezera Firew Azmatch (Ph.D)

A Thesis Submitted to The Department of Civil Engineering,
School of Civil Engineering and Architecture
Presented in Partial Fulfillment of the Requirement for the Degree of Master's in Civil
Engineering (specialization in Geotechnical Engineering)

Office of Graduate Studies
Adama Science and Technology University

June 2022
Adama, Ethiopia

DECLARATION

I hereby declare that this Master Thesis entitled “STUDY OF DYNAMIC PROPERTIES OF SOIL IN WOLLO-KOMBOLCHA TOWN” is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

Alex Berhanu

Name of student

Signature

Date

RECOMMENDATION

I, the advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled “STUDY OF DYNAMIC PROPERTIES OF SOIL IN WOLLO-KOMBOLCHA TOWN” prepared under my guidance by Alex Berhanu submitted in partial fulfillment of the requirements for the degree of Master’s of Science in Civil Engineering (specialization in Geotechnical Engineering). Therefore, I recommend the submission of revised version of the thesis to the department following the applicable procedures.

Tezera Firew (Ph.D)

Advisor

Signature

Date

APPROVAL PAGE

I, the advisor of this thesis entitled “STUDY OF DYNAMIC PROPERTIES OF SOIL IN WOLLO-KOMBOLCHA TOWN” and developed by Alex Berhanu, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Tezera Firew (Ph.D)
Advisor

Signature

Date

We, the undersigned, members of the Board of Examiners of the thesis by Alex Berhanu have read and evaluated the thesis entitled “STUDY OF DYNAMIC PROPERTIES OF SOIL IN WOLLO-KOMBOLCHA TOWN” and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Civil Engineering (specialization in Geotechnical Engineering).

Mesfin Benti (Ph.D)
Chairperson

Signature

Date

Srikanth Vadlamoudi (Ph.D)
Internal Examiner

Signature

Date

Siraj Mulugeta (Ph.D)
External Examiner

Signature

Date

Finally, approval and acceptance of the thesis is contingent upon the submission of its final copy to the Office of Postgraduate Studies (OPGS) through the Department Graduate Council (DGC) and School Graduate Committee (SGC).

Department Head

Signature

Date

School Dean

Signature

Date

Office of Postgraduate Studies, Dean

Signature

Date

ACKNOWLEDGEMENT

First of all, I would like to thank God for granting me the courage, strength, and health to finish this research. I am grateful to our institution Adama Science and Technology University (ASTU) for giving me a scholarship opportunity.

I would like to express my deepest gratitude to my advisor Dr. Tezera Firew for his valuable advice, support, and critical comments during my research work. My special thanks to Addis Ababa Institute of Technology (AAiT) for letting me use and carry out relevant tests in their laboratory with special supervision and guidance.

I gratefully acknowledge to Kombolcha town administration, Air Port, Dry Port and Industry park offices for their kind support during sample collection. Finally, I would like to extend my heartfelt thanks to my families especially, my mother Zeyba Reshid and my brother Kedir Reshid for their support and initiation of this work, I am also thankful to my beloved friends for their help.

CONTENTS

CHAPTER	PAGE
DECLARATION.....	ii
RECOMMENDATION.....	iii
APPROVAL PAGE.....	iv
ACKNOWLEDGEMENT.....	v
LIST OF TABLES.....	ix
LIST OF FIGURES	x
LIST OF ACRONYMS AND ABBREVIATIONS	xiii
ABSTRACT	xv
1 INTRODUCTION.....	1
1.1 Background.....	1
1.2 Statement of Problem.....	3
1.3 Objective of The Study	4
1.3.1 General Objective.....	4
1.3.2 Specific Objective	4
1.4 Research Questions.....	4
1.5 Significance of The Study.....	5
1.6 Scope of The Study and Limitation	5
1.7 Structure of The Study	5
2 LITERATURE REVIEW.....	6
2.1 Introduction.....	6
2.2 Basic Index Properties	6
2.3 Cyclic Stress-Strain Behavior of Soil	7
2.4 Shear Modulus and Damping Ratio of Soil	8
2.4.1 Method of determining shear modulus and damping ratio of soil	9
2.4.1.1 Direct determination of stress-strain relationships	9

2.4.1.2	Forced vibration tests.....	10
2.4.1.3	Free vibration tests.....	10
2.4.1.4	Field measurement of wave velocities.....	10
2.4.2	Computation of Shear modulus and Damping ratio Parameters	11
2.4.2.1	Shear modulus.....	11
2.4.2.2	Damping ratio	12
2.4.2.3	Maximum shear modulus ($G_{\max}$)	13
2.5	Parameters Influencing Shear Modulus and Damping Ratio.....	13
2.5.1	Variation of Shear Modulus and Damping Ratio with Confining Pressure	14
2.5.2	Variation of Shear Modulus and Damping Ratio with Cyclic shear strain levels...15	
2.5.3	Variation of Shear Modulus and Damping Ratio with number of loading cycles ..17	
2.5.4	Variation of Shear Modulus and Damping Ratio with plasticity index	18
2.5.5	Variation of Shear Modulus and Damping Ratio with soil type	19
2.5.6	Variation of Shear Modulus and Damping Ratio with void ratio	22
2.6	Previous Studies on The Dynamic Property of Soil	23
3	MATERIALS AND METHODS	27
3.1	Description of The Study Area	27
3.1.1	Location, Topography, and Population size.....	27
3.1.2	Climatic conditions	27
3.2	Experimental Techniques.....	30
3.2.1	Sample Collection and Preparation	30
3.2.2	Summary of Testing Methods	32
3.2.3	Cyclic Simple Shear Test Apparatus.....	33
3.2.3.1	Cyclic simple shear testing procedures used in this study	34
4	RESULT AND DISCUSSION.....	37
4.1	Index Property Tests	37
4.1.1	Field Density and Natural Moisture Content Test	37
4.1.2	Grain Size Distribution Test.....	38
4.1.3	Atterberg Limits Test	39

4.1.4	Specific Gravity Test.....	39
4.2	Soil Classification	39
4.3	One Dimensional Consolidation Test	42
4.4	Cyclic Simple Shear Test Results	42
4.4.1	Determination of Shear Modulus and Damping Ratio	47
4.4.2	Determination of the Initial Shear Modulus/Maximum Shear modulus (G_{max}).....	49
4.4.3	Factors Influencing Shear Modulus and Damping Ratio	50
4.4.3.1	Variation of Shear Modulus and Damping Ratio with Confining pressure.....	50
4.4.3.2	Variation of Shear Modulus and Damping Ratio with cyclic shear strain	51
4.4.3.3	Variation of Shear Modulus and Damping Ratio with number of loading cycles.....	53
4.4.3.4	Variation of Shear Modulus and Damping Ratio with Soil Plasticity	54
4.4.3.5	Variation of Shear Modulus and Damping Ratio with Soil Type.....	55
4.4.3.6	Variation of Shear Modulus and Damping Ratio with Void Ratio.....	56
4.4.4	Comparison of Cyclic Test Results with Previous Studies	56
5	CONCLUSION AND RECOMMENDATION	65
5.1	Conclusion	65
5.2	Recommendation	65
Appendix A	Natural Moisture Content and Field Density Determination.....	72
Appendix B	Specific Gravity Determination.....	74
Appendix C	Grain Size Analysis	76
Appendix D	Atterberg Limit Tests.....	89
Appendix E	Free Swell Test	92
Appendix F	Void Ratio Determination	92
Appendix G	One-Dimensional Consolidation Test	93
Appendix H	Cyclic Simple Shear Test	95
Appendix I	Parameters that affect shear modulus and damping ratio values.....	105

LIST OF TABLES

TABLE	PAGE
Table 1.1 Some earthquakes and reported damages in Ethiopia (Kinde et al., 2011).....	2
Table 2.1 Test procedures for measuring moduli and damping characteristics (Das, 2011)	11
Table 2.2 Empirical values of ‘a’ with respect to plasticity index (Hardin & Drnevitch, 1972)	13
Table 2.3 Some influence over stiffness and damping value (Vucetic & Dobry, 1991).....	14
Table 2.4 Summary of some findings on dynamic properties of soils in Ethiopia.....	24
Table 3.1 Location of test pits and their coordinates.....	30
Table 4.1 Summary of index properties test results	41
Table 4.2 Shear stress and shear strain values of DP3 at 250kPa axial stress, 2.5% axial strain, and 5 th cycle.....	43
Table 4.3 Calculation of shear modulus and damping ratio of Figure 4.10	47
Table 4.4 Shear modulus and damping ratio of DP3 at 250kPa of all cycles and all strains	48
Table 4.5 Maximum shear modulus G_{max} and normalized shear modulus $\frac{G}{G_{max}}$ values	49

LIST OF FIGURES

FIGURE	PAGE
Figure 1.1 Ethiopia's Seismic hazard map in terms of peak ground acceleration (CES, 2015)..	3
Figure 2.1 Nature of variation of shear stress versus shear strain (Das, 2011)	7
Figure 2.2 Typical format of dynamic properties of soils of modulus reduction and damping ratio curve (Bedr et al., 2019).....	9
Figure 2.3 Schematic hysteresis loop (Asfaw, 2015)	12
Figure 2.4 Variation of shear modulus with confining pressure (Kumar et al., 2017).....	15
Figure 2.5 Variation of G/G_{max} (a)and D (b) with cyclic shear strain (Jafarzadeh & Sadeghi, 2012).....	16
Figure 2.6 Effect of number of stress cycles on shear modulus (a) and hysteretic damping(b) for medium dense (Das, 2011)	17
Figure 2.7 Correlations between G/G_{max} (a), damping ratio (b) with Plasticity Index (PI) for normally and over consolidated soils (Vucetic & Dobry, 1991).....	18
Figure 2.8 Variation of shear modulus (a) and damping ratio (b) with shear strain for sand (Seed & Idriss, 1970)	20
Figure 2.9 Variation of damping ratio with shear strain for saturated clay (Seed & Idriss, 1970)	21
Figure 2.10 Variation of shear modulus (a) and damping ratio (b) value with void ratio (Sitharam & Vinod, 2010).....	22
Figure 3.1 Location map of Kombolcha Town (Mapcarta, 2022).....	28
Figure 3.2 (a) Average Rainfall (mm) and (b) Maximum, Minimum, and Average Temperature ($^{\circ}$ C) (WorldWheatherOnline, 2022)	29
Figure 3.3 (a) Location of test pits (GPS, 2022) and (b) Typical test pits Dry Port (left) and Medhanialem (right)	31
Figure 3.4 Logged data while the consolidation stage proceeds	34
Figure 3.5 (a) Cyclic simple shear machine found in AAiT (photo credit Controls group) and (b) Schematic of shear deformation of O-rings in the simple shear device	36
Figure 4.1 Summary of grain size distribution curve	38
Figure 4.2 USCS (a) and AASHTO (b) plasticity chart	40

Figure 4.3 Typical Pre-consolidation result of Clay Amar3 soil.....	42
Figure 4.4 Sinusoidal wave shapes of 2.5 % strain of DP3 for three cycles at 400kPa	45
Figure 4.5 Cyclic shear stress (a) and Cyclic shear strain (b) against number of cycles of MD3 at 100kPa axial stress and 2.5 % strain.....	46
Figure 4.6 The hysteresis loops of Amar3 soil under 250kPa axial pressure and 2.5% cyclic shear strain at the 5 th cycle.....	46
Figure 4.7 Hysteresis loop and triangle using stress-strain values of DP3 of 250kPa axial stress and 2.5% axial strain at 5 th cycle	47
Figure 4.8 Variation of shear modulus (a) and damping ratio (b) of Amar3 clay soil with confining pressure.....	51
Figure 4.9 Variation of shear modulus (a) and damping ratio (b) of MD3 silty sand soil with cyclic shear strain amplitude	52
Figure 4.10 Variation of shear modulus (a) and damping ratio (b) with number of loading cycles for 100kPa axial stress and two different strains (0.01% and 5%).....	53
Figure 4.11 Variation of shear modulus (a) of Kombolcha clay soil and damping ratio (b) with soil plasticity at a confining pressure of 100kPa	54
Figure 4.12 Variation of shear modulus (a) and damping ratio (b) with Clay (Amar3) and Silty Sand (MD3) soil type	55
Figure 4.13 Variation of the maximum shear modulus of Kombolcha soil with void ratio.....	56
Figure 4.14 Comparison of (a) Normalized shear modulus and (b) damping ratio values of Kombolcha silty sand soil with the curves developed for sands by Seed and Idriss (1970)	57
Figure 4.15 Comparison of (a) Normalized shear modulus and (b) damping ratio values of Kombolcha clay soil with the curves developed for saturated clay by Seed and Idriss (1970)	58
Figure 4.16 Comparison of Normalized shear modulus(a) and damping ratio(b) values of Kombolcha silty sand soil with the curves developed for Dire Dawa sand, Ziway, Modjo, and Adama silty sand soils at 100kPa	60
Figure 4.17 Comparison of Normalized shear modulus(a) and damping ratio(b) values of Kombolcha silty sand soil with the curves developed for Dire Dawa sand, Ziway, Modjo, and Adama silty sand soils at 400kPa	61

Figure 4.18 Comparison of Normalized shear modulus(a) and damping ratio(b) values of Kombolcha clay soil with the curves developed for Jima, Arbaminch, Addis Ababa Yeka sub-city, and Addis Ababa Gelan sub-city clay soils at 100kPa	63
Figure 4.19 Comparison of Normalized shear modulus(a) and damping ratio(b) values of Kombolcha clay soil with the curves developed for Jima, Arbaminch, Addis Ababa Yeka sub-city, and Addis Ababa Gelan sub-city clay soils at 400kPa.	64

LIST OF ACRONYMS AND ABBREVIATIONS

γ, γ_c	Cyclic shear strain amplitude
τ, τ_c	Cyclic shear stress
σ'_o	Effective confining stress
σ'_v	Vertical effective stress
G_{sec}, G_{eq}	Secant/equivalent shear modulus
G_o, G_{max}	Initial/ Maximum shear modulus
$\frac{G}{G_{max}}$	Normalized shear modulus
ΔW	Dissipated energy
a	Dimensionless parameter which is a function of PI
A	Area
A_{Δ}	Area of triangle
AAiT	Addis Ababa Institute of Technology
AASHTO	American Association of State Highway and Transportation Officials
A_{loop}	Area of the hysteresis loop,
Amar	Amar factory
AP	Air Port
ASTM	American Society for Testing and Materials
ASTU	Adama Science and Technology University
c	Cementation
CES	Compulsory Ethiopian Standard
CH	Highly plastic Clay
CSA	Central Statistical Agency
D	Damping ratio
DP	Dry Port
D_r/R_D	Relative Density

e	Void ratio
EM-DAT	Emergency Events Database
f	Frequency of cyclic loading
F	Shear force
G	Shear modulus
G_s	Specific gravity
Hz	Hertz
IP	Industry Park
K_o	Coefficient of lateral earth pressure
LL	Liquid Limit
LVDT	Linear Variable Differential Transformer/Transducer
MD	Medhanialalem Church
MER	Main Ethiopian Rift valley
MTK	Mitikolo
N	Number of loading cycle
No.	Number
OCR	Over consolidation ratio of the soil
P_c	Pre-consolidation pressure
PGA	Peak Ground Acceleration
PI	Plasticity Index
PL	Plastic Limit
P_o	Present/normal vertical pressure
SM	Silty Sand
USCS	Unified Soil Classification System
USD	United States Dollar
UTS	Universal Testing System
W	Maximum energy

ABSTRACT

Dynamic load due to earthquakes, vibrations from traffic and machines, and blasting cause a major problem in engineering practices and it is required to study the dynamic properties of soil to provide dynamic soil information and to reduce future damages. Kombolcha is one of the earthquake-prone areas and recognized and selected as an industrial development center. However, the dynamic properties of soils have not been investigated in this town so far. The objective of this study is to determine the important dynamic soil parameters (shear modulus and damping ratio). To meet the objective, the representative samples from six excavated pits (a total of 18 samples) were collected and tested for the characterization of soil. From index property test results, classification was made using Unified Soil Classification Systems and American Association of State Highway and Transportation Officials classification systems, the town is dominated by Highly plastic or fat Clay (CH/A-7-5) (four test pits) and (SM/A-2-5) Silty Sand (for two test pits). For the cyclic simple shear test and one-dimensional consolidation test, soil samples were remolded in a field condition from the three selected pits at 3m depth. The cyclic simple shear test was conducted at a confining pressure of 100 kPa, 250kPa, and 400kPa, at a wider strain (0.01%, 0.1%, 1%, 2.5%, and 5%) and a Sinusoidal Shape with 1Hz frequency for 40 cycles. The results were also found in the range of (0.52 MPa to 24.9 MPa) shear modulus and (0.83% to 27.57%) damping ratio, in addition to these values, maximum shear modulus was also determined using an empirical equation. The major factors that influence the values of shear modulus and damping ratio values were discussed and the shear modulus values increased as confining pressure, number of cycles, and plasticity increased, but it decreased with cyclic strain amplitude and void ratio (for G_{max}), whereas damping ratio in contrary for these factors, but not significant for a void ratio. Similar trends were observed by other researchers. The results were also normalized to compare with the curve developed for sand and saturated clay soils. A similar shape was determined and concluded that the result is in good agreement. However, some variations of values at different strain levels from the limits given were observed, these could be due to testing machine and sample preparation differences. On the other hand, results were also compared with local reports and showed a similar shape to all findings, but some variations of values were observed. These variations could be from plasticity, void ratio, and over consolidation ratio differences. From these findings, it is recommended that further work could be made by considering these factors.

Keywords: - Cyclic simple shear test, Dynamic properties, Shear modulus, Damping ratio, and Index properties

1 INTRODUCTION

1.1 Background

The analysis of foundation vibrations and geotechnical earthquake engineering problems in civil engineering requires the characterization of dynamic soil properties. Among the dynamic loading, earthquake is one of the natural hazards that destroy billions of dollars' worth and kill countless lives annually. The ground motion due to earthquake may lead to permanent settlement, tilting of footing, and, thus, failure of the structure supported by them. The nature and distribution of earthquake damage are strongly influenced by the response of soils to cyclic loading. Different soil properties influence the behavior of the soil for different problems. The behavior of soils subjected to dynamic loading is influenced by dynamic soil properties (Kramer, 1996). It is a critical task in the solution of geotechnical earthquake engineering problems to measure the dynamic soil properties. The important dynamic soil properties are known as shear modulus and damping variations with cyclic strains. The dynamic soil properties can be used as an input parameter for the design of foundations for machinery and vibrating equipment, analysis of slope stability of embankments under earthquake loading conditions, and also used to model soil behavior under dynamic loading.

The Great Rift Valley region of Ethiopia is an earthquake-prone area. According to the EM-DAT database – from 1900 to 2013 there were a total of seven earthquakes, killing a total of 24 people, affecting 585 people, and causing more than 7 million USD in economic damage (Wilks et al., 2017) (see Table 1.1 for some earthquakes and reported damages in Ethiopia). Recently, a significant earthquake occurred on the 24th of January 2016 in the Hawassa caldera basin and close to the Cobette volcanic complex. The event was felt up to 100 Km away and caused structural damage and public anxiety in the city of Hawassa itself (Wilks et al., 2017). Kombolcha is one of the earthquake-prone areas and is located on the Western margin of the Main Ethiopian Rift valley (MER). The town is categorized under seismicity zone three (CES, 2015) and Figure 1.1 illustrates this based on Peak Ground Acceleration (PGA) value.

Table 1.1 Some earthquakes and reported damages in Ethiopia (Kinde et al., 2011)

Year	Earthquake	Intensity	Structural damage
1979	Akaki	4.1	No damage to Aba Samuel hydroelectric power station a few kilometers away. Cracks are seen in poorly built masonry structures.
1985	Oitu Bay (Langano)	5.1	Strongly felt in Lake Langano camp, central main Ethiopian rift, and cracks in buildings in resort area hotels.
1989	Mekelle	5.3	Felt by many causing some panic.
1989	Dichotto	5.8	Dining people were thrown off the table, the masonry house collapsed, landslides killed 4 people and 300 cattle, and 6 bridges were destroyed in Dichotto.
1989	Soddo	5.0	Widespread panic, broken windows, and some injured in Soddo.
1993	Nazareth	5.0	Several adobe buildings collapsed in Nazareth town's northern Ethiopian main rift. Felt as far as Debre Zeit and Addis Ababa
2005	Afar Triangle		Fumes as hot as 400°C shoot up from some of them; the sound of bubbling magma and the smell of sulfur rise from others. The larger crevices are dozens of meters deep and several hundred meters long. Traces of recent volcanic eruptions are also visible. Followed by a weeklong series of earthquakes. During the months that followed, hundreds of further crevices opened up in the ground, spreading across an area of 345 square miles.
2009	Ankober	5.0	Earthquake strikes near Ankober Town and was widely felt in Addis, especially by residents who live in multistory buildings.
2010	Hosanna	5.3	Damage sustained by reinforced concrete frame dormitory building at Jimma University with in-filled walls at where as many as 26 students were injured. Structural damage to slab and column joints and damage to too many buildings in Hosanna.
2011	Ethio-Somali Border	6.1	In Dire Dawa, Jijiga and Somalian towns' buildings were shaken.
2011	Abosto/ Yirga Alem	5.0	Damage to unreinforced cinder 100 houses was destroyed and two people were injured.

At Kombolcha, there are major infrastructural facilities for the whole railway network of Ethiopia and also a new airport just 2 Km away from the railway station. Due to highly

industrialization of this town, in the future, so many high-rise buildings, roads, bridges, and other projects will be done. So, to build a structure that is enough to resist the dynamic load, investigating the soil behavior under cyclic loading is important. Therefore, this study is conducted to determine the important dynamic soil properties which are shear modulus and damping ratio of soils in Kombolcha town. There are a variety of laboratory and field methods that measure the low and high-strain soil behavior under cyclic loading. For this study, the cyclic simple shear test was used.

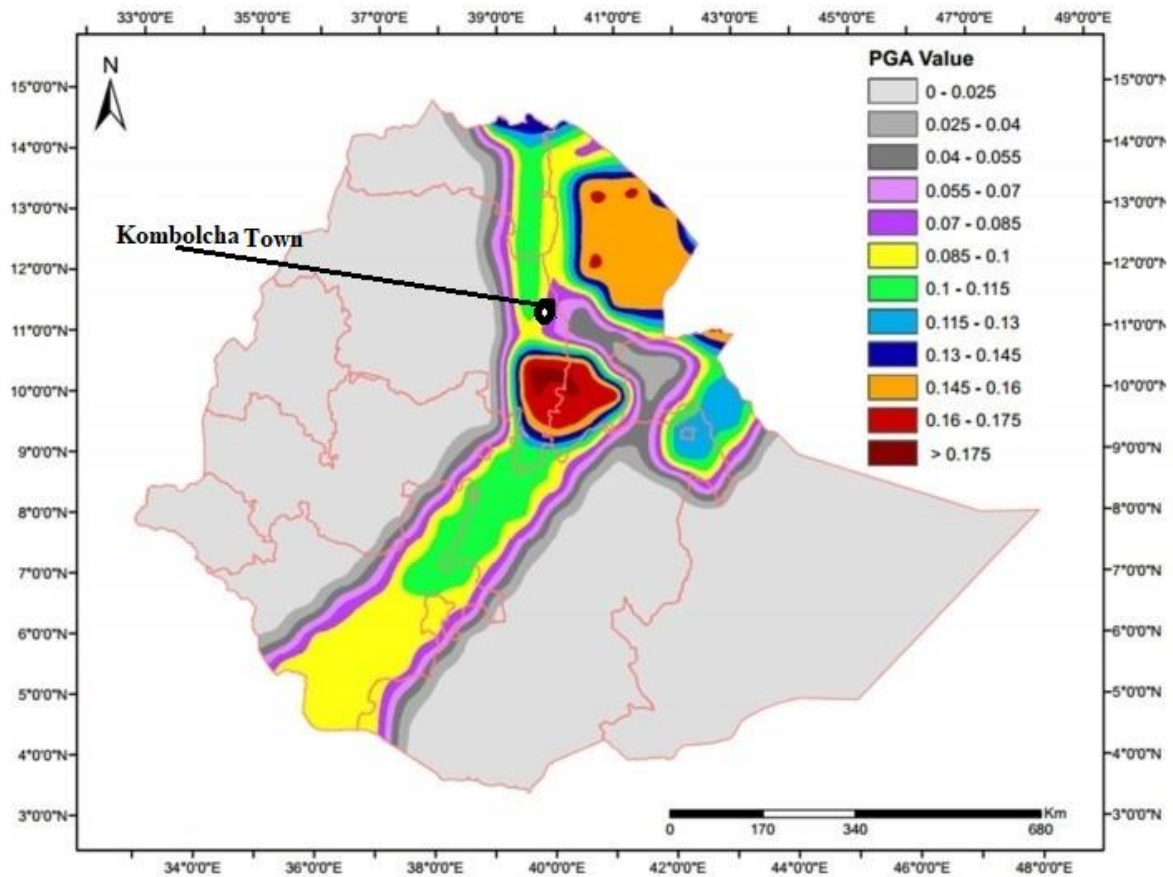


Figure 1.1 Ethiopia's Seismic hazard map in terms of peak ground acceleration (CES, 2015)

1.2 Statement of Problem

Earthquakes, vehicular traffic, blasting, pile-driving, and machine vibrations are the major causes of the dynamic loads that lead to problems in engineering practices. For all geotechnical problems, it is very important to study the dynamic properties of the soils, especially in earthquake-prone regions. Kombolcha town is an earthquake-prone area and classified as

seismic zone three according to CES-160, highly growing infrastructures especially, after the town is selected as an industrial development center became more attractive for the investors and workers and many projects and constructions are started. The town has Kombolcha Steel products, a metalworking factory, an industrial park, a beer factory, a Kombolcha textile factory, a dry port, and an airport. Kombolcha is served by a station for the Awash to Weldiya railway project which will boost the growth of the town. Due to this industrialization, proximity to earthquakes, and dramatic growth of the town the determination of the response of soil deposits are needed to reduce future damages. However, the dynamic soil properties have not been investigated yet. To fill this gap, this research studied the determination of the dynamic properties of soils (shear modulus and damping ratio) found in Kombolcha. After characterizing the soils, three typical disturbed soil sample was remolded in field condition and a cyclic simple shear test was used in wide strains (0.01% to 5%) to determine the dynamic soil properties. The results from this study will help geotechnical engineers to know the behavior of soil in wide strains. It will be applicable in designing foundations for machines and other large-scale civil engineering structures and geotechnical activities in the town as well as seismic design.

1.3 Objective of The Study

1.3.1 General Objective

The major objective of this research is to determine the Shear modulus and Damping ratio values of typical soils found in Kombolcha town using the cyclic simple shear test.

1.3.2 Specific Objective

- To determine the index properties, and to classify the soil in Kombolcha town.
- To determine the field density using sand-cone replacement method.
- To study the effect of various parameters on shear modulus and damping ratio of the typical soils of Kombolcha town.

1.4 Research Questions

1. Which type of soil is dominant in Kombolcha town?
2. What are the values of shear modulus and damping ratio in the area?
3. To what extent the shear modulus and damping ratio values will be affected by confining stress, number of loading cycles, cyclic strain amplitude, plastic index, void ratio, and soil type?

1.5 Significance of The Study

This study will provide valuable information for the basic index properties in addition to shear modulus and damping ratio values of the town and could be used for a feasibility study of geotechnical engineering problems. The obtained results will provide input for the design of earthquake-resistant foundations, earth retaining structures, embankments, and machinery and vibratory equipment foundations. Also, for numerical and analytical modeling of soil deposit, analysis of soil-structure interactions and mechanical behaviors in the study area. The outcome of this study will help in a better understanding of the major factors that influence the dynamic properties of soil. Furthermore, the study can be used as an input for other researchers or institutions as literature.

1.6 Scope of The Study and Limitation

The scope of this study is limited to the investigation of shear modulus and damping ratio values of soils that are collected from Kombolcha town. The method used in the determination of these parameters is limited to the cyclic simple shear test. The samples were taken from six pits and excavated up to 3 meters in depth. The typical three samples were used for the cyclic and one-dimensional consolidation tests that were performed by a remolded soil using field density and natural moisture content.

1.7 Structure of The Study

This research is organized into five chapters and appendices. The first chapter gives the thesis background, statement of the problem, objectives, research questions, significance of the study, and scope and limitation of the study. The second chapter presents the literature review which includes the cyclic stress-strain behavior of soils, the method of determination and computation of shear modulus and damping characteristics, the parameters that affect the dynamic properties of soils, and a summary of previous studies on the dynamic property of soil. Chapter three describes the study area, experimental techniques, a summary of testing procedures, an overview of cyclic simple shear apparatus, and its experimental program. Chapter four presents the results in tabular form and figures. The interpretation of the results obtained from the field and laboratory tests and discusses test results and some comparison with the previous study is presented. Chapter five presents the conclusion of findings and recommendations for future studies. Finally, tables and figures with some calculations are presented in the appendices.

2 LITERATURE REVIEW

2.1 Introduction

The behavior of soils subjected to cyclic loading is becoming increasingly more important for the modern geotechnical engineer. It is very important to know the critical dynamic properties of soil deposits in the field of geotechnical engineering. Dynamic properties of soil especially shear modulus (G) and damping ratio (D) are frequently considered for evaluating the ground response to dynamic stimulants such as earthquake loads, ocean waves, machine foundations, traffic vibrations, and soil-structure interaction (Fakharian et al., 2019). Shear modulus (or, more precisely, secant shear modulus) represents the stiffness of soil, whereas damping ratio is described as the percentage of energy loss per cycle of vibration. Since the early 1970s, considerable research has been undertaken to investigate the influence of various factors on the dynamic properties of soils. The key parameters identified based on laboratory test results are cyclic shear strain, soil type, plasticity index, mean effective confining stress, loading frequency, number of loading cycles and other factors (e.g., the void ratio, over consolidation ratio) generally play a secondary role on the variation of G and D versus cyclic shear strain curves (Bedr et al., 2019).

In this chapter, dynamic properties of the soil are reviewed. The methods of determination of shear modulus and damping ratio and factors that influence the dynamic characteristics of the soil are summarized. Finally, summary of previous literatures are provided.

2.2 Basic Index Properties

Basic physical (index) properties, which are necessary for the determination of the dynamic soil properties are; field density and moisture content, specific gravity, Atterberg's limits, and grain size distribution. These properties are important in cyclic loadings for shear modulus and damping ratio determination (Kumar et al., 2014). Hence, the determination of the dynamic soil properties requires consideration of the index parameters. In this study, the representative six test pits were taken from the study area and a total of 18 samples were investigated in the field and laboratory for the determination of these index properties and characterization of the soil.

2.3 Cyclic Stress-Strain Behavior of Soil

The stress-strain response of soil to cyclic loading is nonlinear and hysteretic and commonly characterized by a hysteresis loop (Kramer, 1996). The hysteresis loop is the loop that shows the stress-strain relationship in cyclic loading. This loop is obtained from plotting shear stress against shear strain values determined from the cyclic test. For this study, the loop was plotted from 50 sample points for each cycle obtained from the cyclic simple shear test. Some empirical models have been proposed for the behavior of soils subjected to cyclic loading. The equivalent-linear model is the most common model used to represent the hysteretic behavior of soil in the seismic analysis. This model represents non-linear hysteretic soil behavior using an equivalent shear modulus, G , equal to the slope of the line connecting the tips of the hysteresis loop, and an equivalent damping ratio, D , proportional to the enclosed area of the loop (Das, 2011). Figure 2.1 shows the hysteretic stress-strain relationships at different strain amplitudes.

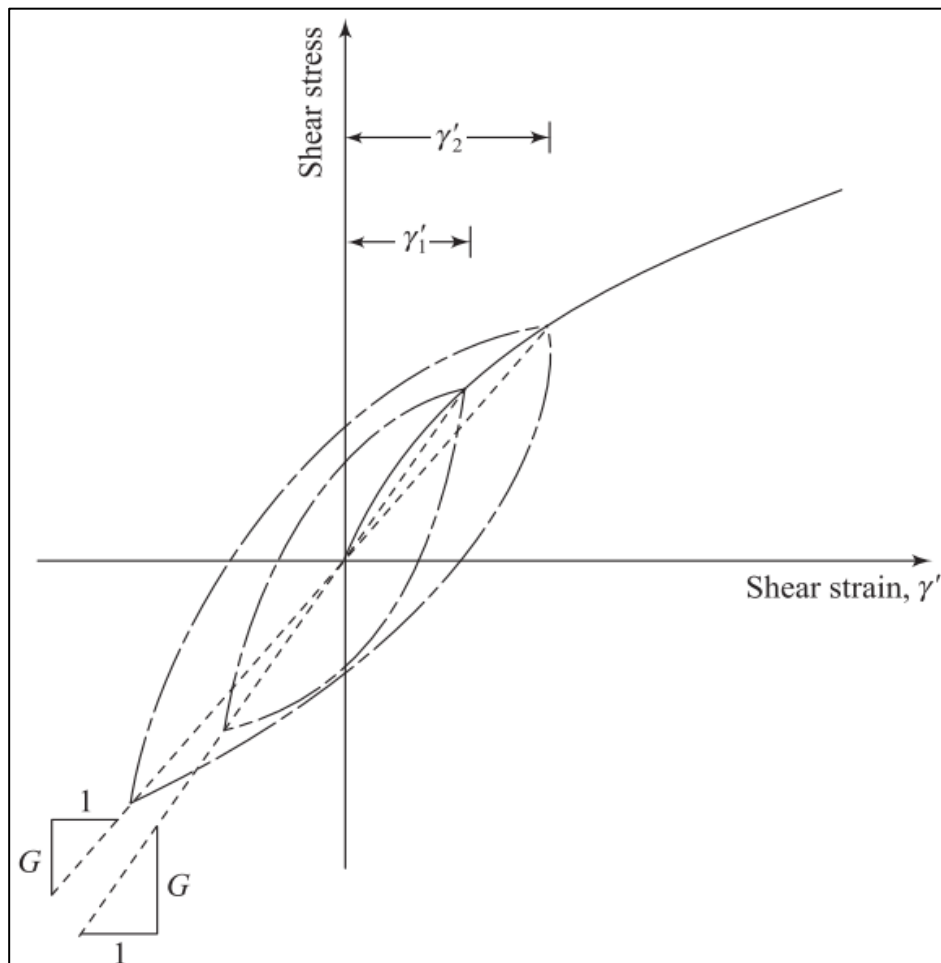


Figure 2.1 Nature of variation of shear stress versus shear strain (Das, 2011)

2.4 Shear Modulus and Damping Ratio of Soil

The properties that are most important for dynamic analysis are the stiffness and material damping of the soil under dynamic loading. The parameters which can express these properties of soil are dynamic shear modulus and damping ratio. These parameters can be determined from the stress-strain behavior of soils under cyclic loading (Kramer, 1996).

The shear modulus is an important parameter of the dynamic characteristics of soils. It is an essential parameter for in-situ seismic response analysis calculations. The stress-strain relationships of soils are curvilinear. The shear modulus that is experimentally determined is the secant modulus obtained by joining the extreme points on the hysteresis loop. Note that when the amplitude of strain is small (that is, $\gamma'=\gamma'_1$; Figure 2.1), the value of G is larger compared to that for the larger strain level (that is, $\gamma'=\gamma'_2$) and it is known as the initial shear modulus or maximum shear modulus ($G_{\max}$) (Das, 2011). The $G_{\max}$ of the soil is generally defined at a very low shear strain ($\gamma \leq 5 \times 10^{-6}$) (Okur & Ansal, 2007). The use of measured shear wave velocities is generally the most reliable means of evaluating the in-situ value of maximum shear modulus, $G_{\max}$ for a particular soil deposit (Kramer, 1996). It can be used for several purposes such as seismic site classification, liquefaction susceptibility analysis, subsurface mapping, and subgrade strength estimation (Hussien & Kararay, 2016). When shear wave velocity measurement is not available, the maximum shear modulus, $G_{\max}$ can be estimated in different ways. $G_{\max}$ is used to normalize the shear modulus (G) versus shear strain relationships. These normalized relationships allow the engineer to use well-established degradation curves and scale them to the measured in-situ value of $G_{\max}$ (Luna & Jadi, 2000). The relation between the normalized shear modulus and cyclic shear strain is shown as G_{eq}/G_o versus γ_c in Figure 2.2.

Damping Ratio (D) is used in several dynamic analysis procedures to provide realistic motion attenuation. This ratio is based on the material damping properties. The damping ratio represents the ability of a material to dissipate dynamic load or to dampen the system. As the soil elements lose stiffness with the amplitude of strain, their ability to dampen dynamic forces increases (Luna & Jadi, 2000). This is due to the energy dissipated in the soil by friction, heat, or plastic yielding. Thus, the breadth of the hysteresis loop is related to the area, which as a measure of energy dissipation, can conveniently be described by the damping ratio (Kramer, 1996).

A modulus reduction curve is used to represent the degradation of shear modulus with shear strain in terms of reduction in modulus ratio ($G/G_{\max}$) (Kramer, 1996). Dynamic properties of soils are commonly represented by the variation of equivalent shear modulus (G_{eq}), normalized to the initial shear modulus (G_0), and damping ratio (D) with cyclic shear strain amplitude (γ_c) (Bedr et al., 2019) (Figure 2.2).

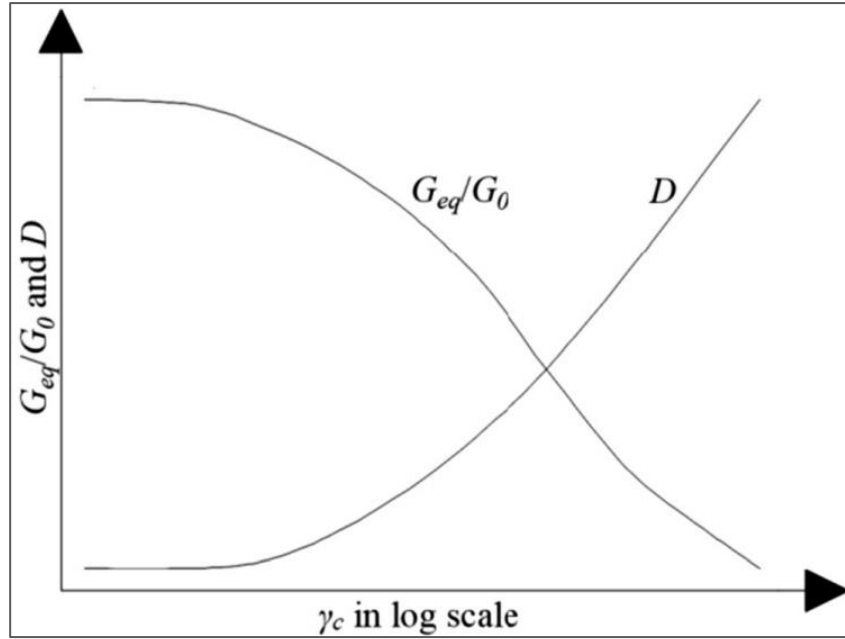


Figure 2.2 Typical format of dynamic properties of soils of modulus reduction and damping ratio curve (Bedr et al., 2019)

2.4.1 Method of determining shear modulus and damping ratio of soil

There are various procedures, including laboratory and field tests that have been used to determine shear modulus and damping characteristics of soils. A wide variety of laboratory apparatuses are available, each with different merits and limitations concerning different problems (Karray & Chekired, 2019). A summary of the procedure and the approximate range of strain within which they have been used are presented in Table 2.1 below. There are different strain ranges for which the shear modulus and damping ratio are determined. These strain ranges are very low strains ($\gamma \leq 10^{-3}$ percent), medium strains ($10^{-3} < \gamma < 10^{-1}$ percent), and large strains ($10^{-1} < \gamma < 5$ percent). The methods were given by (Seed & Idriss, 1970) and discussed below.

2.4.1.1 Direct determination of stress-strain relationships

Hysteretic stress-strain relationships can be determined in the laboratory using triaxial compressional tests, simple shear tests, or torsional shear tests conducted under cyclic loading

conditions. In general, these procedures are useful for measuring moduli and damping factors under moderate to relatively high strain levels (Seed & Idriss, 1970).

2.4.1.2 Forced vibration tests

Forced vibration tests, involving the determination of resonant frequencies and measurement of response at other frequencies have been used to determine both moduli and damping factors. In the laboratory; these test conditions have included the application of torsional vibrations and longitudinal vibrations to cylindrical samples or shear vibrations to layers of soil placed on a shaking table. But in the field, shear vibrations of dams have been induced by large shaking machines; it is difficult to interpret the results of field tests to determine damping factors. These procedures are useful for determining properties at relatively low to moderate strain levels (Seed & Idriss, 1970).

2.4.1.3 Free vibration tests

Free vibration tests, in which measurements are made of the decay in response to a soil sample or soil deposits, have been used to measure both moduli and damping factors for soils. Methods of excitation are similar to those used for forced vibration tests, but the procedure can be used for the measurement of soil characteristics at relatively low to moderately high strain levels (Seed & Idriss, 1970).

2.4.1.4 Field measurement of wave velocities

In situ (field) tests have been used to measure the velocity of propagation of body waves (compressional waves, shear waves) and surface waves (Rayleigh waves) from which values of soil modulus can readily be determined for low strain conditions (Seed & Idriss, 1970). However, these procedures have not provided values of damping factors.

Researchers have used different testing methodologies (e.g., resonant column test, piezoelectric bender element test, cyclic triaxial test, and cyclic simple shear test) to determine the dynamic properties of different soils at varying strain levels ((Sas et al., 2017), (Abdellaziz et al., 2019), (Gabryś et al., 2021), (Zhang et al., 2021), (Bedr et al., 2019), (Sezer et al., 2019), (Fakharian et al., 2019)). In this thesis, the determination of hysteretic stress-strain relationships was used, using the cyclic simple shear apparatus to determine the basic parameters of dynamic properties of soil (Shear modulus and Damping ratio). The cyclic simple shear test apparatuses are often

superior to triaxial test devices as they allow for a smooth and continuous rotation of the principal stress directions during shearing (Karray & Chekired, 2019).

From the preceding discussions, a summary of the general procedure, test conditions, range of strain, and the properties that can be obtained are given in Table 2.1.

Table 2.1 Test procedures for measuring moduli and damping characteristics (Das, 2011)

General procedure	Test condition	Approximate strain range	Properties can be determined
Determination of hysteretic stress-strain relationships	Triaxial compression	10^{-2} to 5 %	Modulus; Damping
	Simple shear	10^{-2} to 5 %	Modulus; Damping
	Torsional shear	10^{-2} to 5 %	Modulus; Damping
Forced vibration	Longitudinal vibrations	10^{-4} to 10^{-2} %	Modulus; Damping
	Torsional vibrations	10^{-4} to 10^{-2} %	Modulus; Damping
	Shear vibration-lab	10^{-4} to 10^{-2} %	Modulus; Damping
	Shear vibration-field	10^{-4} to 10^{-2} %	Modulus
Free vibration tests	Longitudinal vibrations	10^{-3} to 1 %	Modulus; Damping
	Torsional vibrations	10^{-3} to 1 %	Modulus; Damping
	Shear vibration-lab	10^{-3} to 1 %	Modulus; Damping
	Shear vibration-field	10^{-3} to 1 %	Modulus
Field wave velocity measurement	Compression waves	$\sim 5 \times 10^{-4}$ %	Modulus
	Shear waves	$\sim 5 \times 10^{-4}$ %	Modulus
	Rayleigh waves	$\sim 5 \times 10^{-4}$ %	Modulus

2.4.2 Computation of Shear modulus and Damping ratio Parameters

2.4.2.1 Shear modulus

An important utility of the shear modulus is that because most soils have curvilinear stress-strain relationships, its average value over the entire loop can be approximated by the secant shear modulus, G_{sec} , which is commonly called equivalent shear modulus (G_{eq}) (Kramer, 1996). Thus, G_{sec} describes the general inclination of the hysteresis loop. Using the equivalent-linear analysis method, the secant shear modulus can be determined by the extreme points on the hysteresis loop (see Equation 2.1 below and Figure 2.3).

$$G_{\text{sec}} = \frac{\Delta\tau}{\Delta\gamma} \text{-----Equation 2.1}$$

$\Delta\tau$ is the difference between the maximum and the minimum values of shear stress and $\Delta\gamma$ is the difference between the maximum and the minimum values of shear strain.

The shear stress and shear strain from the cyclic simple shear test can be determined as

$$\text{Shear stress, } \tau = \frac{\text{Shear Force}}{\text{Area of sample}} = \frac{F}{A} \text{----- Equation 2.2}$$

$$\text{Shear strain, } \gamma = \frac{\text{Lateral LVDT}}{\text{Height of sample}} \text{----- Equation 2.3}$$

Where, LVDT is Linear Variable Differential Transducer, a deformation measurement.

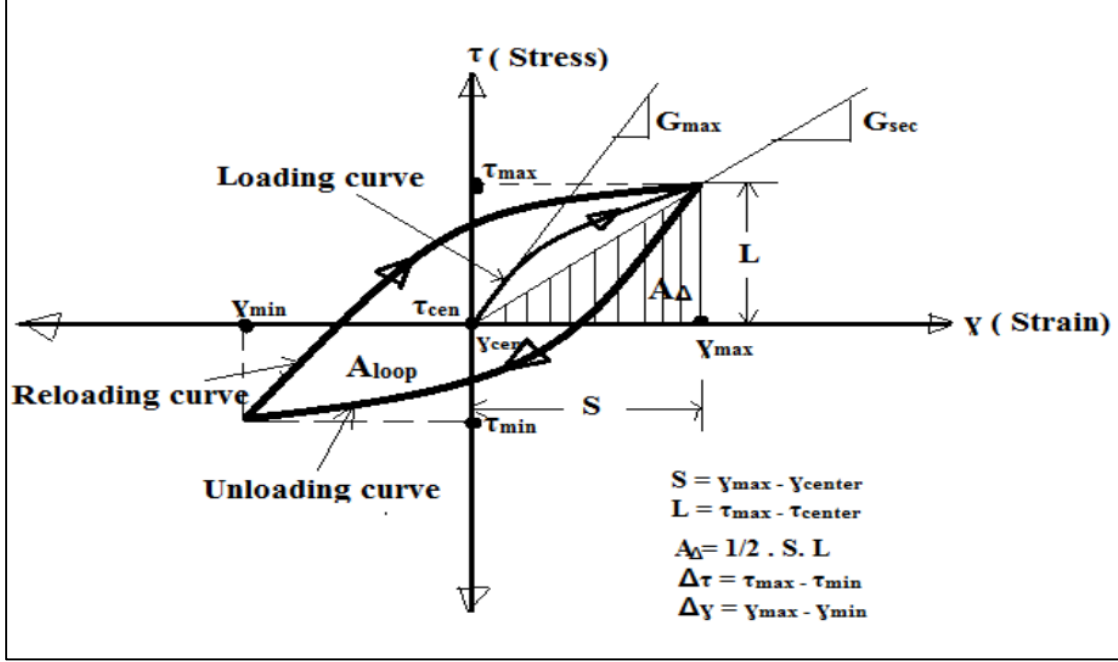


Figure 2.3 Schematic hysteresis loop (Asfaw, 2015)

2.4.2.2 Damping ratio

Damping is the dissipation of strain energy during cyclic loading in the soil and the damping ratio is determined from the dissipated energy divided by the maximum stored (i.e., elastic) energy per cycle. The damping ratio at a given shear strain amplitude can be obtained from the hysteretic stress-strain properties. Referring to Figure 2.3 and Figure 2.1, the damping ratio can be given as

$$D = \frac{\Delta W}{2\pi W} = \frac{A_{\text{loop}}}{4\pi A_{\Delta}} \text{----- Equation 2.4}$$

Where: D is the damping ratio, ΔW is the dissipated energy, W is maximum energy = $2 \cdot A_{\Delta}$, A_{loop} is the area of the hysteresis loop, and A_{Δ} is the area of the triangle.

$$A_{\text{loop}} = \frac{1}{2} \sum_{i=1}^n (\tau_i - \tau_{i+1}) \times (\gamma_i + \gamma_{i+1}) \text{----- Equation 2.5}$$

2.4.2.3 Maximum shear modulus ($G_{\max}$)

$G_{\max}$ is the maximum shear modulus of the soil that is generally defined at a very low shear strain ($\gamma \leq 5 \times 10^{-6}$) (Okur & Ansal, 2007). For the present study, in the absence of availability of such experimental data at sufficiently low strain ($\gamma \approx 10^{-6}$), the empirical correlation proposed by (Hardin & Drnevitch, 1972) has been used for evaluating $G_{\max}$ and it is shown below.

$$G_{\max} = 3230 * \left(\frac{(2.97-e)^2}{(1+e)} \right) (\text{OCR})^a (\sigma'_o)^{1/2} \text{----- Equation 2.6}$$

Where $G_{\max}$ = maximum shear modulus in kPa, OCR = over consolidation ratio, e is the void ratio of the soil $e = \frac{G_s}{\gamma_d} - 1$ ----- Equation 2.7

a is constant = f(plasticity index, PI). Following are the recommended values of 'a' for use in the preceding equation.

Table 2.2 Empirical values of 'a' with respect to plasticity index (Hardin & Drnevitch, 1972)

PI	0	20	40	60	80	≥ 100
a	0	0.18	0.3	0.41	0.48	0.5

σ'_o is means effective confining pressure in kPa

For field conditions σ'_o can be determined as $\sigma'_o (\text{kPa}) = \frac{(\sigma'_v + 2k_o \sigma'_v)}{3}$ ----- Equation 2.8

σ'_v = Vertical effective stress

K_o = Coefficient of lateral earth pressure at rest and it is often taken as 0.5 (Seed et al., 1986)

2.5 Parameters Influencing Shear Modulus and Damping Ratio

When subjected to earthquake or cyclic loading, the shear modulus and damping ratio of the soil are affected by many parameters such as the soil type, cyclic shear strain level, plasticity index, mean effective confining stress, loading history, frequency of loading, number of loading cycles, over-consolidation ratio, void ratio, degree of saturation, and grain characteristics ((Hardin & Drnevitch, 1972), (Vucetic & Dobry, 1991), (Ishihara, 1996), (Kramer, 1996), (Kumar et al., 2014), (Seed and Idriss, 1970), (Hsiao et al., 2016) (Jia, 2018), (Fakharian et al., 2019)). The following table summarizes some factors affecting the stiffness and damping of soils.

Table 2.3 Parameters influencing stiffness and damping value (Vucetic & Dobry, 1991)

Increasing Factors	$G_{\max}$	$G/G_{\max}$	D
Confining pressure, σ_c	Increases with σ_c	Stay constant or increase with σ_c	Stay constant or decrease with σ_c
Void ratio, e	Decreases with e	Increase with e	Decrease with e
Geological age, t	Increases with t	May increase with t	Decrease with t
Cementation, c	Increases with c	May increase with c	May decrease with c
Over consolidation ratio, OCR	Increases with OCR	Not affected	Not affected
Plasticity index, PI	- Increases with PI if OCR > 1 - Stays about constant if OCR=1	Increase with PI	Decrease with PI
Cyclic strain, γ_c	-	Decrease with γ_c	Increase with γ_c
Stress rate (Frequency of cyclic loading), f	Increase with f	Not affected if G and $G_{\max}$ are measured at the same f	Stay constant or may increase with f
Number of loading cycles, N	Decreases after N cycles of large with recovers later with time	Decreases with N at large	Not significant for moderate γ_c and N

Out of these parameters the variation of confining pressure, cyclic shear strain levels, the number of loading cycles, soil type, plasticity index, and the void ratio were addressed in this study.

2.5.1 Variation of Shear Modulus and Damping Ratio with Confining Pressure

It is observed that for a given shear strain amplitude, the shear modulus increases with the increase of confining pressure (Fig. 2.4 depicts the variation of G with γ for the first loading cycle (N = 1)); similar observations were also reported by other researchers ((Seed & Idriss, 1970)), (Chattaraj & Sengupta, 2016), (El Mohtar et al., 2013), (Qiao et al., 2020), (Zhang et al., 2021)). whereas, the damping ratio decreases with the increase of confining pressure. Confining pressure is more significant for soils with low plasticity (Jia, 2018).

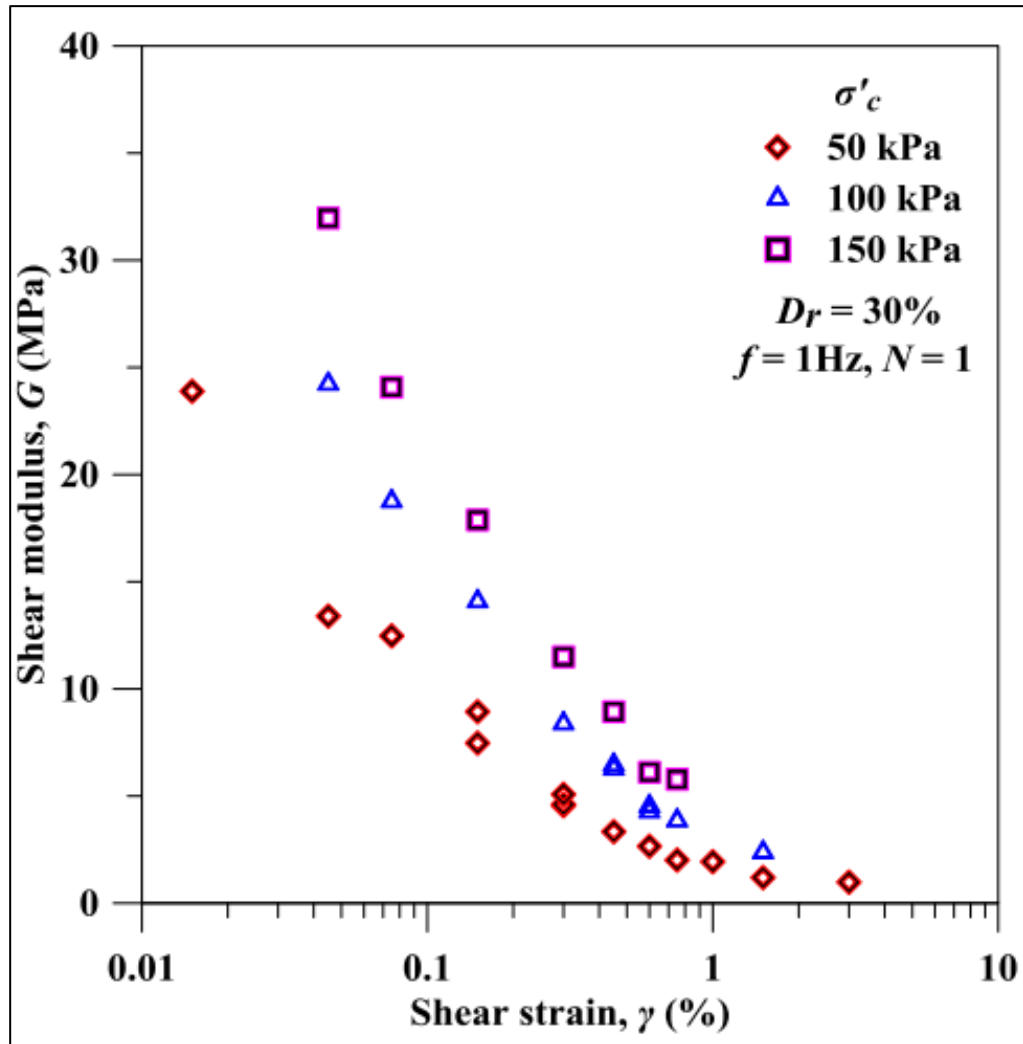


Figure 2.4 Variation of shear modulus with confining pressure (Kumar et al., 2017)

2.5.2 Variation of Shear Modulus and Damping Ratio with Cyclic Shear Strain Levels

Shear modulus degradation with an increase in cyclic strain amplitude has generally been observed in many studies while the damping ratio behaves on the contrary. For example, (Jafarzadeh & Sadeghi, 2012) collected and compared a variety of experimental cyclic test results from different studies indicating that normalized shear modulus ($G/G_{\max}$) decreases with an increase in cyclic strain (Figure 2.5 a) and the damping ratio (Figure 2.5 b) ascents proportionally. For a given number of cycles and mean effective stress, the magnitude of Damping ratio (D) decreases with the decrease of shear strain.

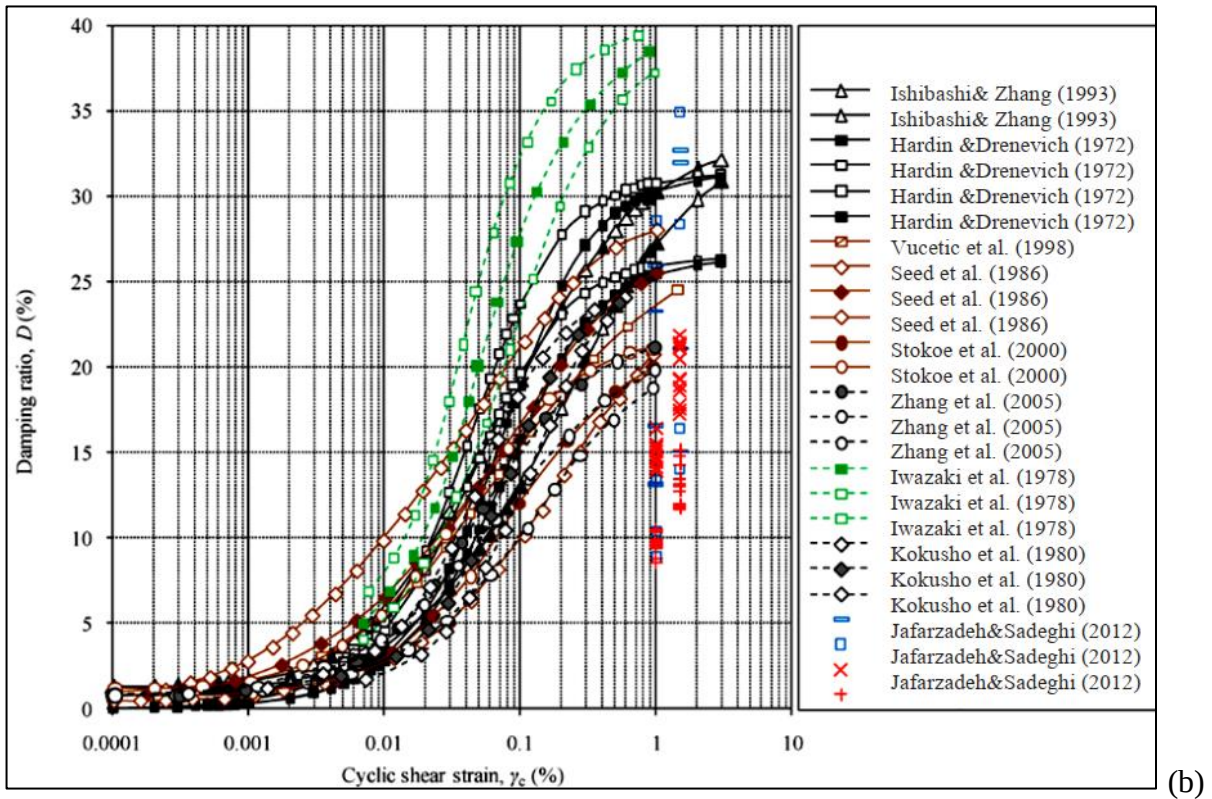
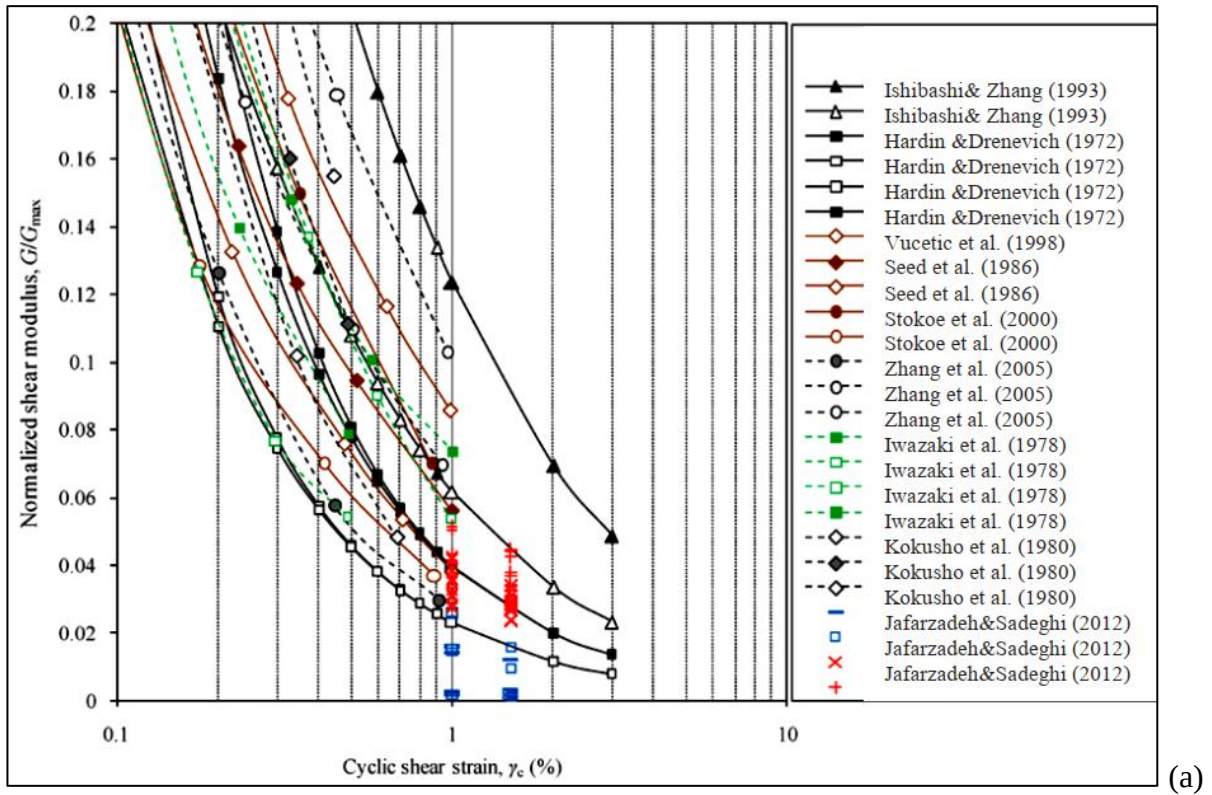


Figure 2.5 Variation of G/G_{max} (a) and D (b) with cyclic shear strain (Jafarzadeh & Sadeghi, 2012)

2.5.3 Variation of Shear Modulus and Damping Ratio with Number of Loading Cycles

For a given value of mean effective stress and shear strain, the shear modulus slightly increases and the damping ratio decreases with the number of cycles. For most seismic events, the number of significant cycles is likely less than 20. The value determined at the 5th cycle provides reasonable values for all practical purposes (Das, 2011). The following figures illustrate the effect of number of loading cycles on the shear modulus and damping ratio values.

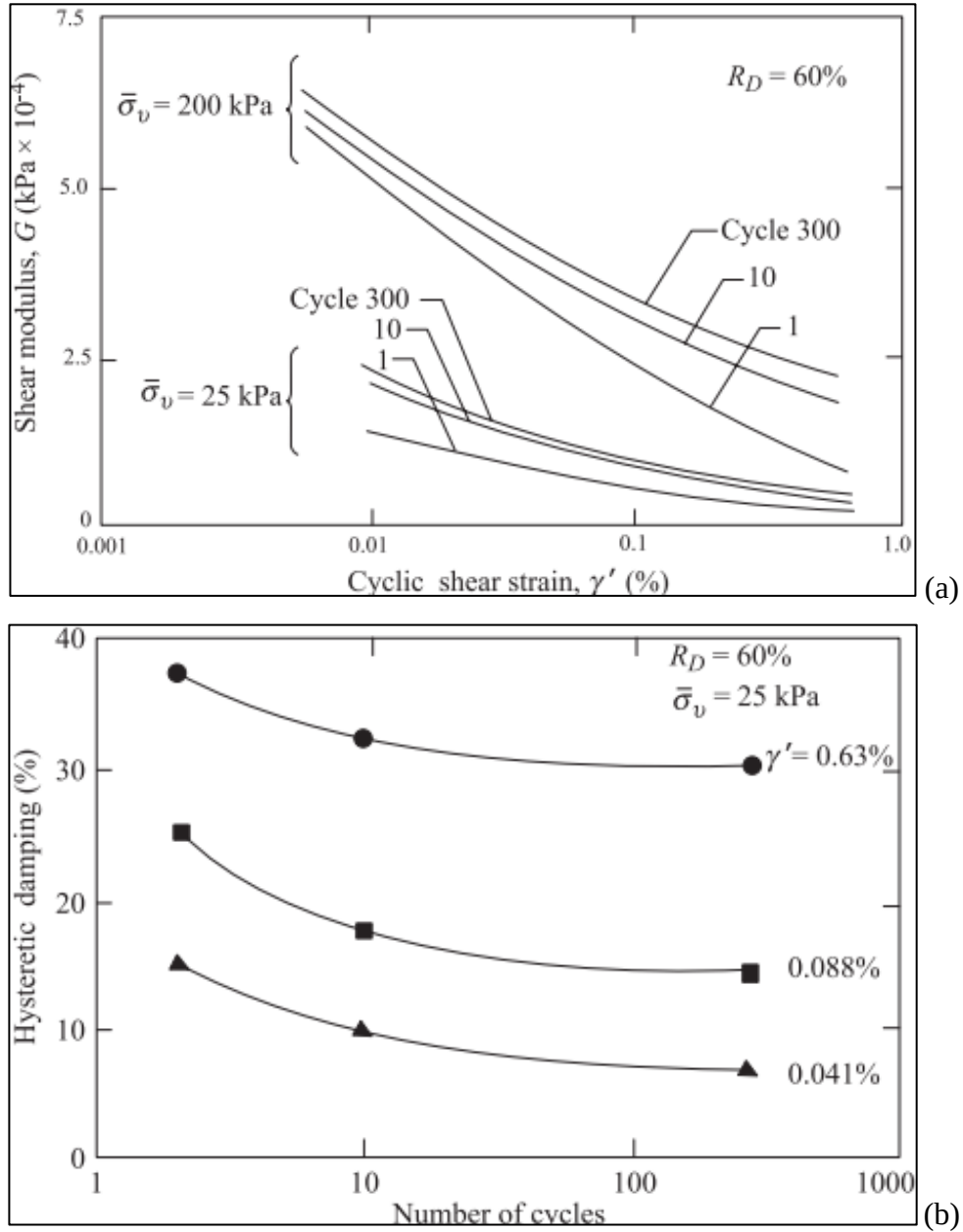


Figure 2.6 Effect of number of stress cycles on shear modulus (a) and hysteretic damping(b) for medium dense (Das, 2011)

2.5.4 Variation of Shear Modulus and Damping Ratio with Plasticity Index

(Vucetic & Dobry, 1991) studied the influence of the plasticity index (PI) on the cyclic stress-strain parameters over normally consolidated and over-consolidated ($OCR = 1-15$) clay (Figure 2.7 a and 2.7 b) explained that, compared to the soils with a lower PI, soils with higher plasticity tend to have a more linear cyclic stress-strain response at smaller strains and degrades less at larger shear strain (γ_c). The soil stiffness is significantly influenced by soil plasticity, i.e., the stiffness of soils with high plasticity decreases more slowly with the increase in shear strain than that of the low-plasticity soils (Jia, 2018).

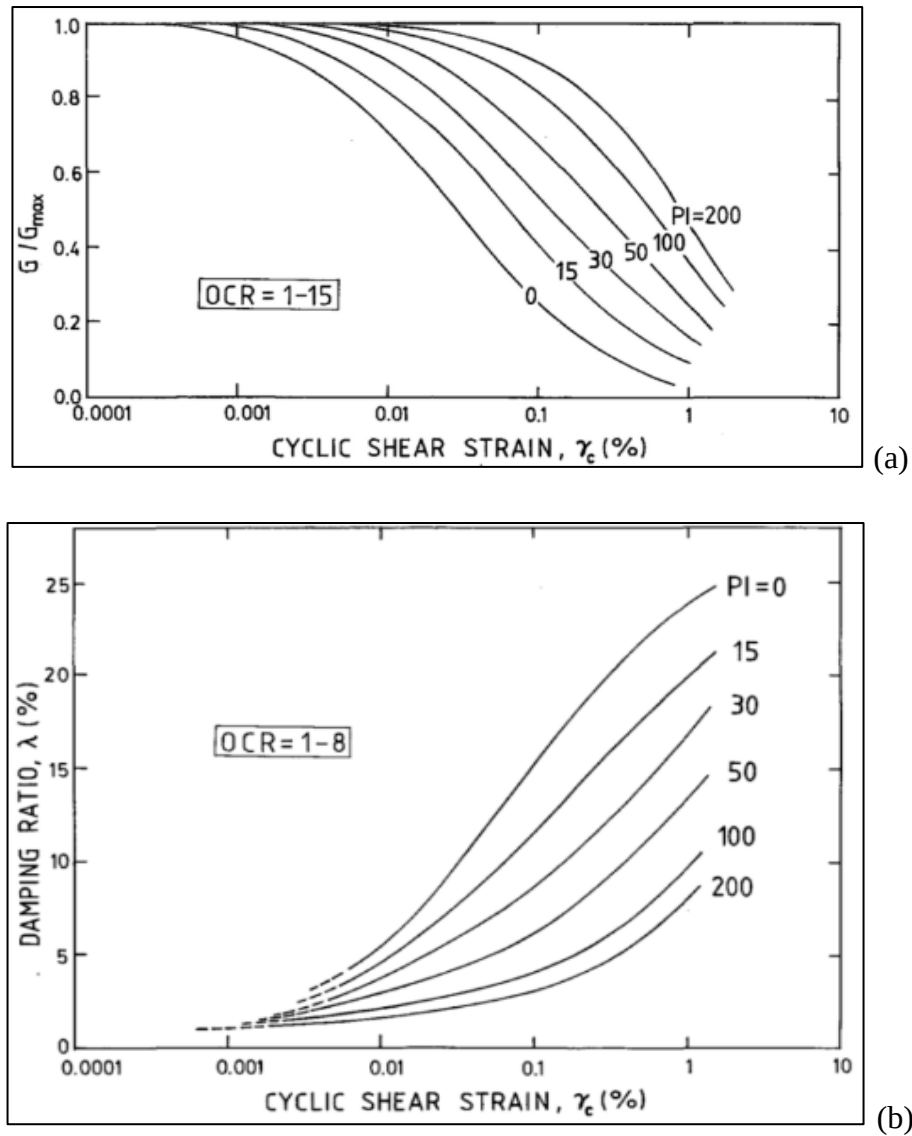


Figure 2.7 Correlations between G/G_{max} (a), damping ratio (b) with Plasticity Index (PI) for normally and over consolidated soils (Vucetic & Dobry, 1991)

2.5.5 Variation of Shear Modulus and Damping Ratio with Soil Type

Several researchers investigated the shear modulus and damping ratio as a function of the shear strain of sand using different laboratory testing procedures under different factors ((Kumar et al., 2017), (Sitharam et al., 2008), (Jafarzadeh & Sadeghi, 2012), (Seed et al., 1986)). All investigation has shown that modulus values for sands are strongly influenced by the confining pressure, the strain amplitude, and the void ratio (or relative density) but not significantly by variations in grain size characteristics. The damping characteristics of sand are affected by shear strain, effective mean principal stress, and number of cycles. Based on these studies, (Seed & Idriss, 1970) presented the range of values of shear modulus and damping ratios shown in Figure 2.8 (a & b).

The Shear modulus and damping ratio of clays are predominantly affected by shear strain amplitude and sample disturbance. Accurate determination of the shear modulus of saturated clays is enormously complicated by the large effects of strain amplitude and sample disturbance on modulus values (Seed & Idriss, 1970). The modulus reduction curves for clay show a much larger scatter and seem to be related to the characteristics of individual clay. However, test data at very low strain levels indicates an approximately linear relationship between the shear modulus and shear strength for many clays. This relationship might be used to assess the influence of strain amplitude on the shear modulus of natural clays, by expressing the ordinate in terms of the ratio of shear modulus at shear strain to shear modulus at a shear strain of 3×10^{-4} percent. This ratio for the average values is plotted as a function of shear strain as shown in Figure 2.9 a. Test data for damping ratios for saturated clays are limited and it is difficult to determine the main factors influencing the damping ratio of these soils (Seed & Idriss, 1970). The results of previous investigations of damping ratios for saturated clays are summarized in Figure 2.9 b below. This average relationship may well provide values of damping ratio with sufficient accuracy for many practical purposes.

Properly established curves for dynamic properties of soils like silts are uncommon compared to sand and clay.

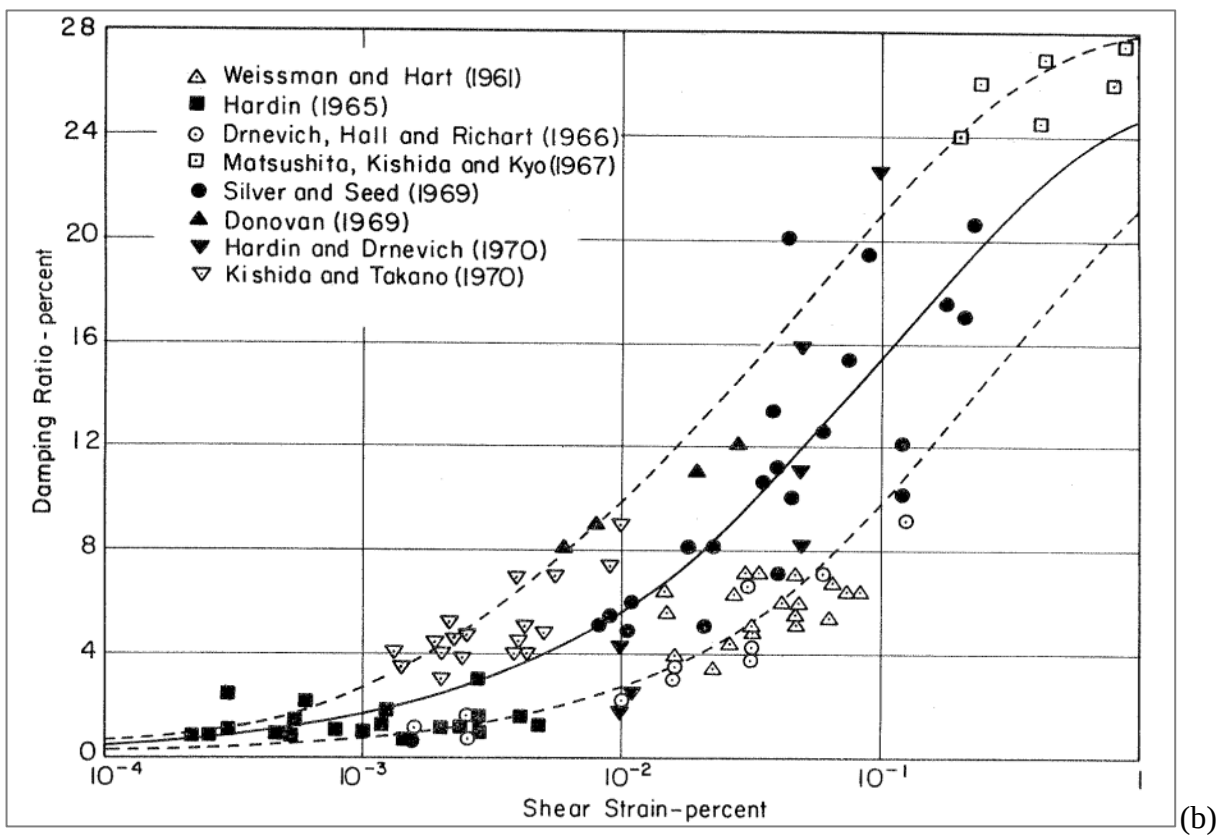
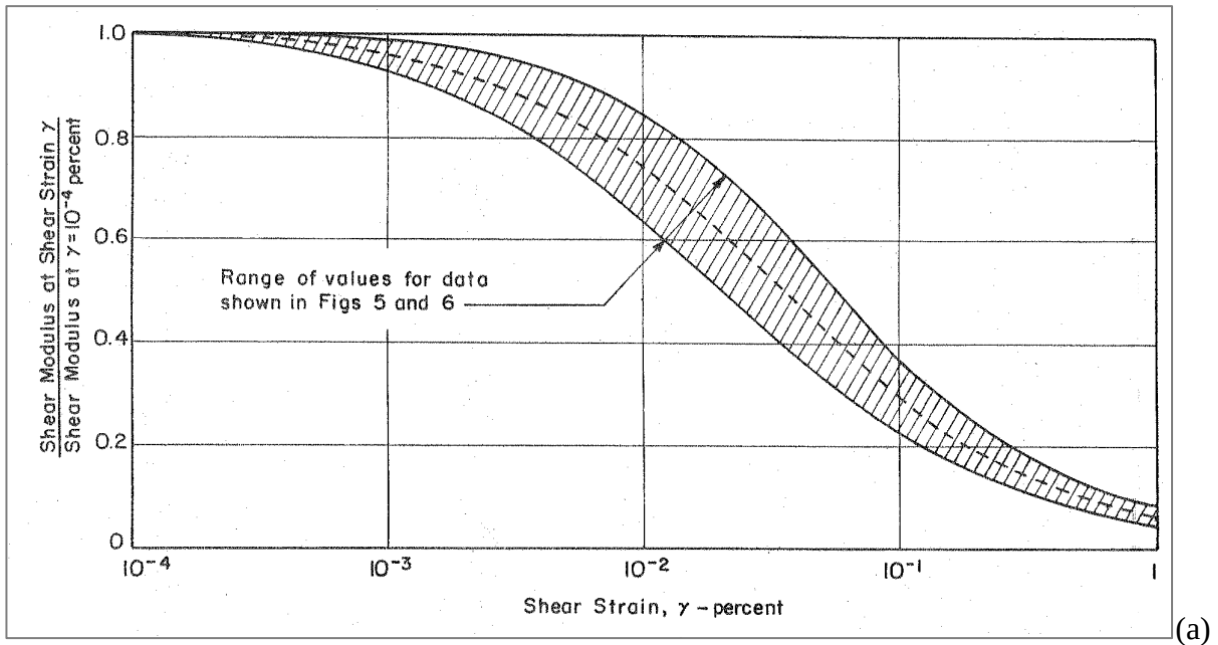


Figure 2.8 Variation of shear modulus (a) and damping ratio (b) with shear strain for sand (Seed & Idriss, 1970)

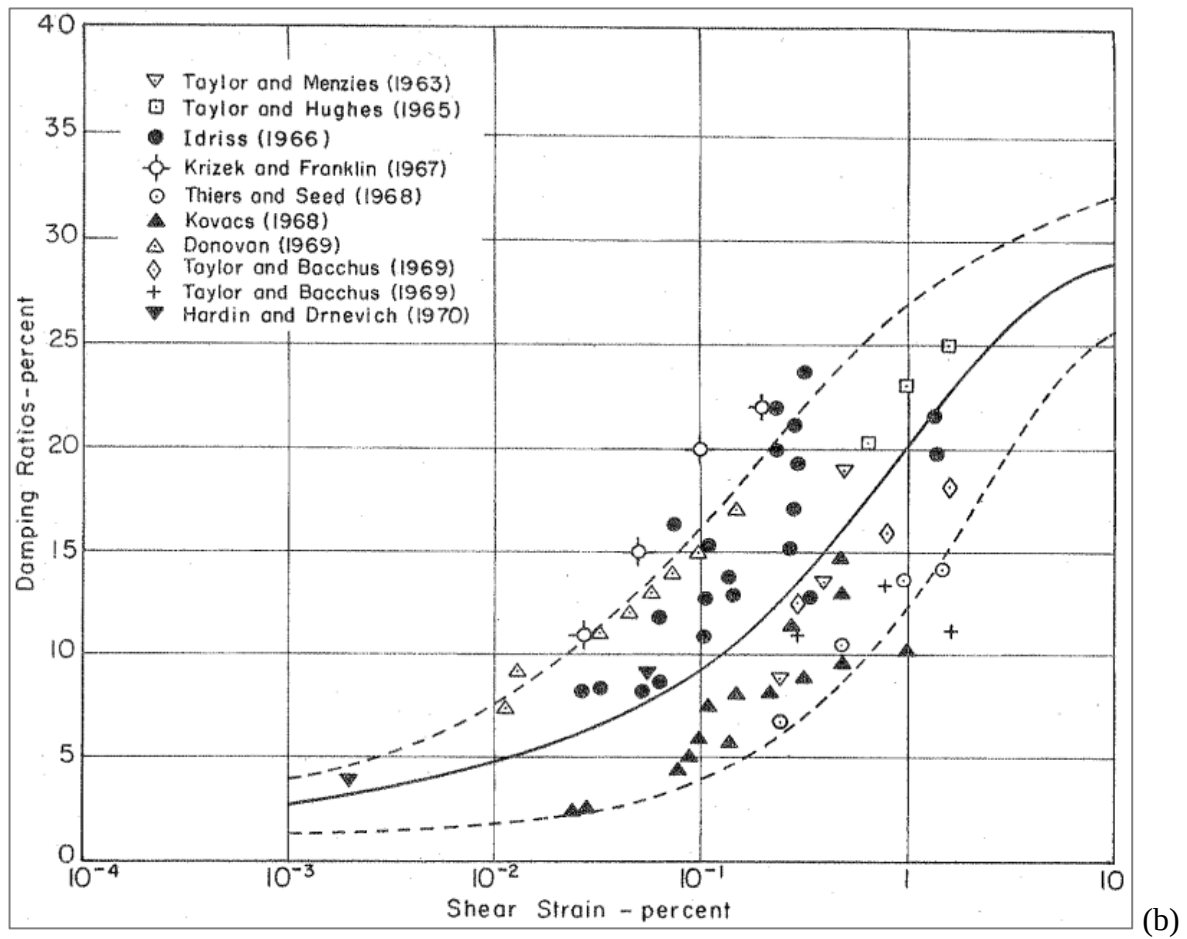
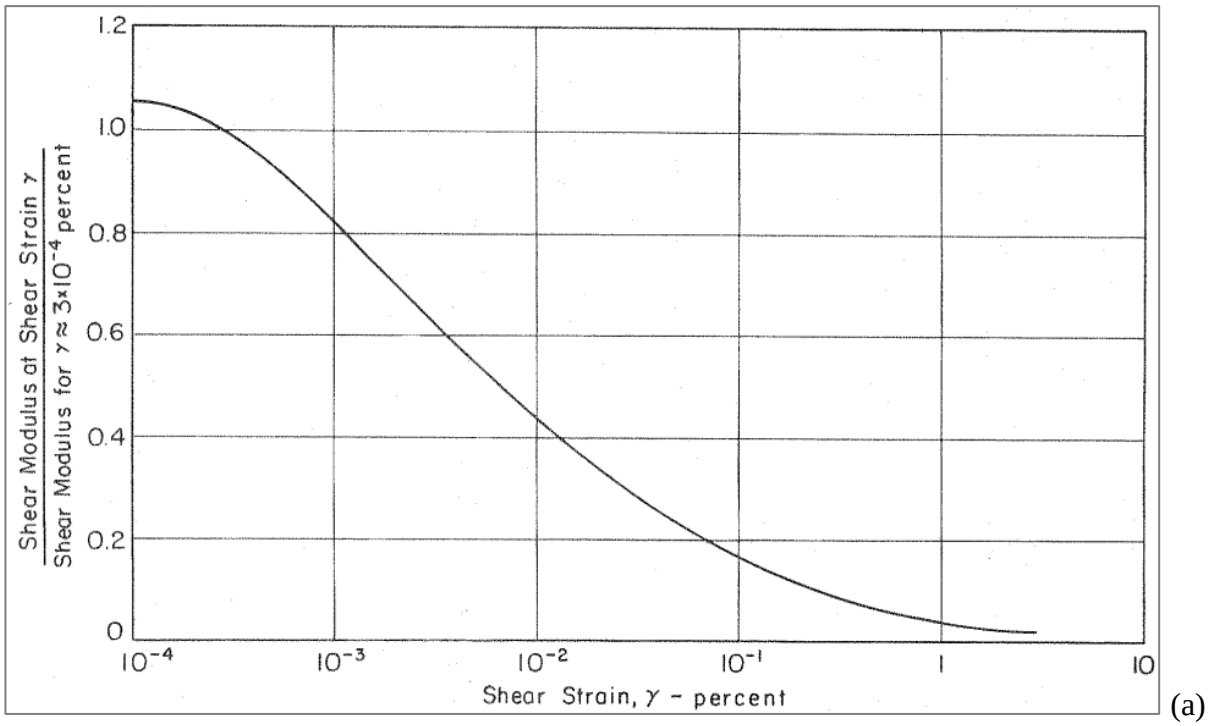
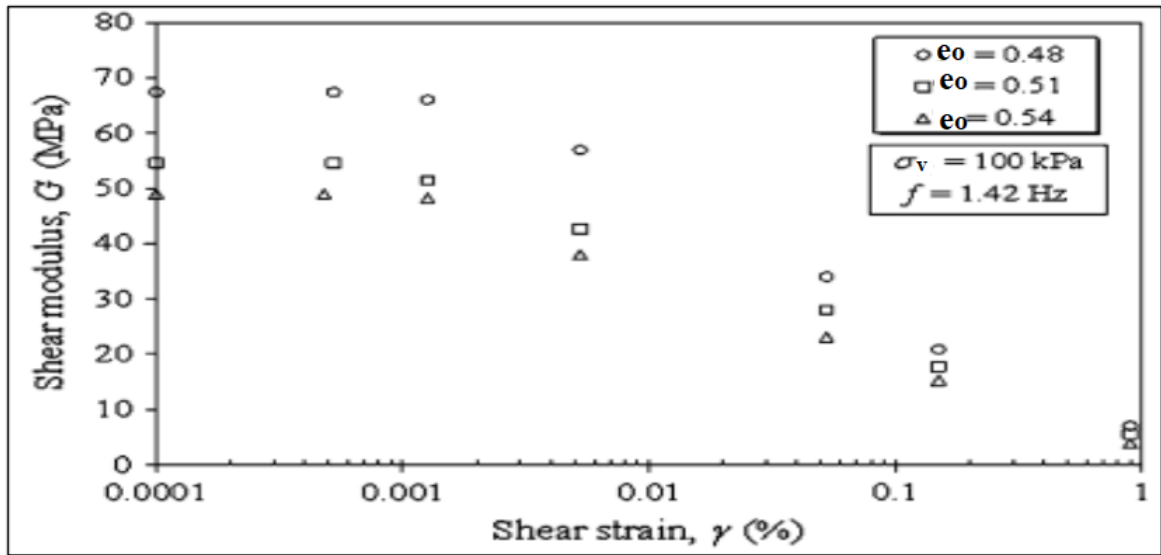


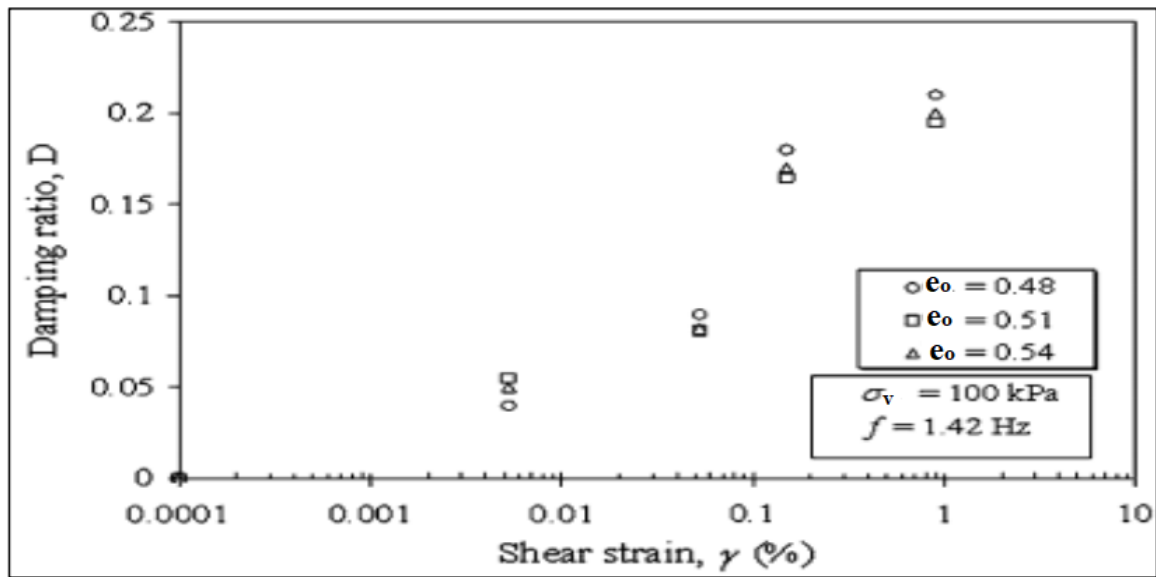
Figure 2.9 Variation of damping ratio with shear strain for saturated clay (Seed & Idriss, 1970)

2.5.6 Variation of Shear Modulus and Damping Ratio with Void Ratio

Void ratio is one of the mechanical properties of soil which can influence the dynamic properties of soil. A larger void ratio means the void in the soil is large, so the presence of a large void may decrease the value of the dynamic shear modulus of the soil. It also reduces the natural frequency of soil that is caused by earthquake load (Munirwansyah et al., 2020). (Sitharam & Vinod, 2010) observed that shear modulus decreases with the increase of void ratio as shown in Figure 2.10 (a) at different confining pressure. And an insignificant influence of initial void ratio on damping ratio values (see Figure 2.10(b)).



(a)



(b)

Figure 2.10 Variation of shear modulus (a) and damping ratio (b) value with void ratio (Sitharam & Vinod, 2010)

2.6 Previous Studies on The Dynamic Property of Soil

Bedr et al. (2019) Discussed the key parameters governing the nonlinear soil behavior under cyclic/dynamic loading and their relative importance in terms of affecting the dynamic properties of soils, which are communally represented by the normalized equivalent shear modulus reduction and damping ratio curves. Equivalent shear modulus (G_{eq}) increases with increasing cyclic shear strain amplitude (γ_c) and mean effective confining stress; this latter increment is reduced with increases in γ_c . The effect of mean effective confining stress decreases as the plasticity index (PI) increases. They also compared the test results and predictive curves from the literature.

Sitharam et al. (2008) Studied the influence of amplitude of cyclic strain, initial confining pressure, and frequency on the dynamic properties of dry sand using a series of strain-controlled undrained cyclic triaxial tests. The shear modulus of dry sands slightly increases with an increase in the number of loading cycles for the first very few cycles and thereafter the shear modulus almost becomes constant with the number of cycles. Whereas, the influence of the number of loading cycles is not significant on damping ratios of the dry sand samples. As confining pressure increases, shear modulus increases but follows a converging trend at very large strains, however, the damping ratio is seen to be decreasing with an increase in the confining pressure for the range tested. The frequency of loading has no significant influence on shear modulus but the damping ratios are influenced to some extent and there is an increasing trend with an increase in the frequency for the range of frequencies and strain amplitudes adopted in this study.

Zhang et al. (2021) Used a dynamic triaxial test system and investigated the effects of the initial shear stress and vibration frequencies on the dynamic shear modulus and damping ratio of saturated sand from Wenchuan. Results showed that when the dynamic shear strain is below the threshold, the dynamic shear modulus significantly increases with the initial shear stress and vibration frequency. Otherwise, the influence of the initial shear stress and vibration frequency gradually decreases and eventually stabilizes. The initial shear stress significantly affects the normalized dynamic shear modulus/strain curves where larger initial shear stress corresponds to a higher curve. Meanwhile, the vibration frequency only exerts a slight influence. The curves under different frequencies are generally within the same band and fall near the Seed upper envelope. The initial shear stress also has a significant influence on the damping ratio where larger initial shear stress corresponds to a smaller damping ratio.

From these previous studies, some influencing factors over shear modulus and damping ratio were discussed. However, they conducted the test with a lower value of shear strains which are not enough for earthquakes (Ishihara, 1996). Therefore, this thesis considered various affecting parameters of G and D over a wider strain.

In Ethiopia, different studies in different places and at different times have been done on the dynamic properties of soils based on the proximity of earthquakes, traffic, and machine vibration. Even if Kombolcha town has the risk of seismic damage (CES, 2015) and highly growth industrialization, the dynamic properties of soils have not been investigated so far. This thesis studied the dynamic properties of soil to provide dynamic information for this town. The dynamic properties of local soil reports for some different places are summarized in Table 2.4 as shown below.

Table 2.4 Summary of some findings on dynamic properties of soils in Ethiopia

Author	Study area	Findings
Birhanu (2019)	Jimma Town	• From a series of cyclic shear test of silty clay and clayey silty soil for shearing strain range of 0.01% to 5%, shear modulus value ranges from 0.33MPa to 6.98MPa, and Damping ratio values obtained in the lab range from 2.03% to 22.98% • With increasing the number of loading cycles both shear modulus and damping ratio decrease, but the rate of decrement is not uniform throughout the loading cycles for silty clay and clayey silt soils
Bekele (2020)	Yeka sub city, Addis Ababa city	• Cyclic simple shear test was performed on undisturbed samples from 6 test pits (silt and clay) for strain values of 0.01 %, 0.1 %, 1 %, 2.5 %, 5 % under axial stress of 100, 200 and 400 kPa. • The normalized shear modulus values of the studied soils agree with curves developed for clay soils of Arbaminch and very close to silty soils of Adama. However, the values show slight scatter with silty soils of Ziway. Also, results were mostly within the curves developed by (Seed & Idriss, 1970).

Author	Study area	Findings
Ayele (2022)	Gelan sub city, Addis Ababa city	• The shear modulus decreases from 2.01Mpa to 0.65Mpa as the shear strain increases for the untreated soil, whereas the shear modulus decreased from 2.31Mpa to 0.75Mpa as the strain increases at the 5th cycle for treated soil. • The damping ratio increased from 19.83 to 23.25% for untreated soil and 22.8 to 26.74% for treated soil as the shear strain increased at the 5th cycle. • With treatment the shear modulus and damping ratio of the soil increases
Asfaw (2015)	Modjo Town	• The values of shear modules range from 0.11MPa to 22.98MPa, the damping ratio is between 0.25% and 25.63%, and maximum shear modulus values from 15.41MPa to 68.71MPa. • The shear modulus increases and the damping ratio decreases with an increasing number of cycles, confining pressure, and soil plasticity • The shear modulus decreases with an increase in shear strain amplitude and void ratio. • The normalized shear modulus values were in good agreement compared with sand and saturated clay soils estimated by (Seed & Idriss, 1970) whereas, damping ratio values were observed with a slight difference. • The shear modulus and damping ratio values of Modjo soil showed similar shape and distribution with the curves of Feyissa, A. G. (Adama) and Mengistu, A. (Ziway) for both silty and silty sand soils.
Arficho (2021)	Awash Melkasa Town	• From cyclic simple shear test determination, the range of shear modulus values of Awash Melkasa lean clay soil is between 1.777 MPa and 15.998 MPa, and the damping ratio is between 0.146 % and 18.913 %, none plastic silt soil is between 0.292

Author	Study area	Findings
		MPa and 10.605 MPa, and the damping ratio is between 0.678 % and 30.851%, and elastic silt soil is between 1.285 MPa and 14.578 MPa, and the damping ratio is between 0.345 % and 21.689% • The normalized shear modulus of the studied soil is consistent with all local curves of high strain values ($\geq 1\%$), but the low strain normalized shear modulus of the studied soil is smaller than the Adama and Modjo curves. The damping ratio values agree with all curves for strains $\leq 1\%$, but it is not consistent with the case of strain $> 1\%$.
Welay (2017)	Dire Dawa Town	• The static properties (shear strength) and dynamic properties (shear modulus(G) and damping ratio(D)) of Dire Dawa typical soils, from laboratory tests on remolded specimens of low plastic silt and poorly graded sand were investigated. • The shear strength parameter (c and ϕ) values of sand from direct shear test results range between 1 kPa to 9 kPa and 26^0 to 28^0 respectively and 28 kPa to 43 kPa and 15^0 to 25^0 respectively for silt were determined. • The values of G and D of the sand range between 1MPa to 38MPa and 3% to 24% respectively and for silt 1MPa to 14MPa and 3% to 29% respectively. • The shear modulus increases with confining pressure and the number of shearing cycles, but it decreases with shear strain amplitude for a given shear strain amplitude • The damping ratio decreases with confining stress and the number of shearing cycles, but it increases with shear strain amplitude, which agrees with those suggested in the literature.

3 MATERIALS AND METHODS

3.1 Description of The Study Area

3.1.1 Location, Topography, and Population size

Kombolcha Town is located in North-Central Ethiopia in the South Wollo Zone of the Amhara Region, it has a latitude and longitude of 11°5'N 39°44'E with an elevation between 1842 and 1915 meters above sea level. The town has an area of 136.98 km² and it is surrounded by magnificent rugged mountains including Ancharo, Yegof, and Tossa (Yayeh, 2022). Kombolcha is located on the Western margin of the MER (see Figure 1.1). Based on the 2007 national census conducted by the Central Statistical Agency of Ethiopia (CSA), Kombolcha has a total population of 85,367 (CSA, 2012) and is estimated to be 125,654 of the total population by 2021 (CSA, 2021). Kombolcha is one of the Amhara regional state towns which have recorded high urban expansion since being recognized and selected as an industrial development center. Kombolcha is a twin town of Dessie which lies some 12 kilometers to the Northwest and is connected through Ethiopian Highway-2 this town shares Kombolcha Airport with neighboring Dessie. The Town is served by a station on the Awash–Weldiya Railway (In progress) the railroad's primary purpose is to connect the north of Ethiopia with the Addis Ababa–Djibouti Railway at the Awash junction and therefore connect it with the world economy through the Port of Djibouti and also with the southern parts of Ethiopia with its capital, Addis Ababa (Lakachew, 2019). The location map of the Town is shown in Figure 3.1 below.

3.1.2 Climatic conditions

Kombolcha has a longer rainy season from June to September and the mean annual rainfall is 1072.15mm with the highest in July and August and the dry season from November to May and the mean minimum and maximum temperature is 12.44 °C and 26.87 °C respectively with a mean annual temperature of 19.66 °C (WorldWeatherOnline, 2022). Figure 3.2 illustrates the climatic condition of the town from 2010 up to 2022.

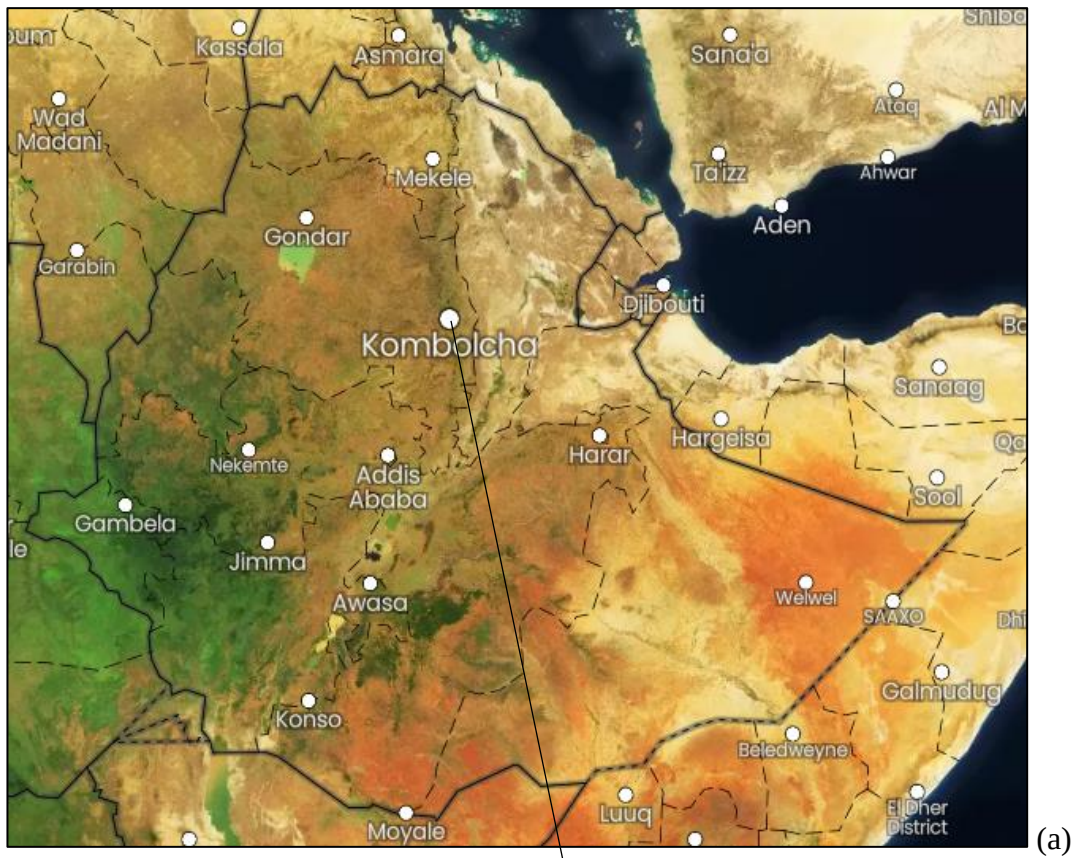


Figure 3.1 Location map of Kombolcha Town (Mapcarta, 2022)

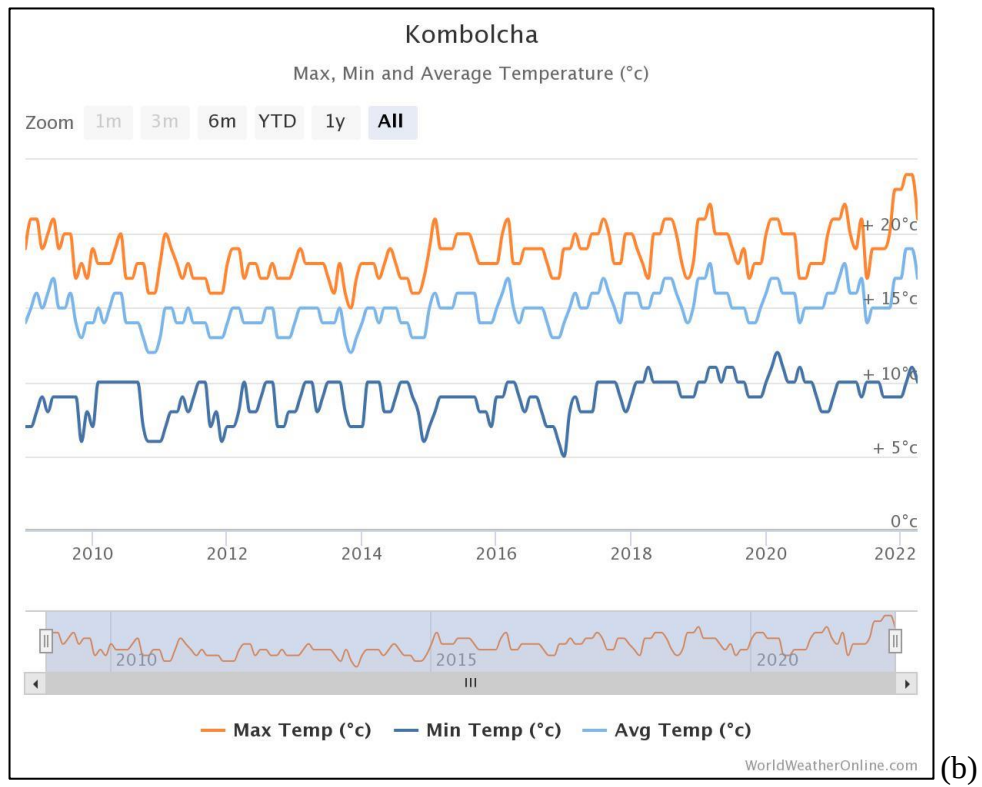
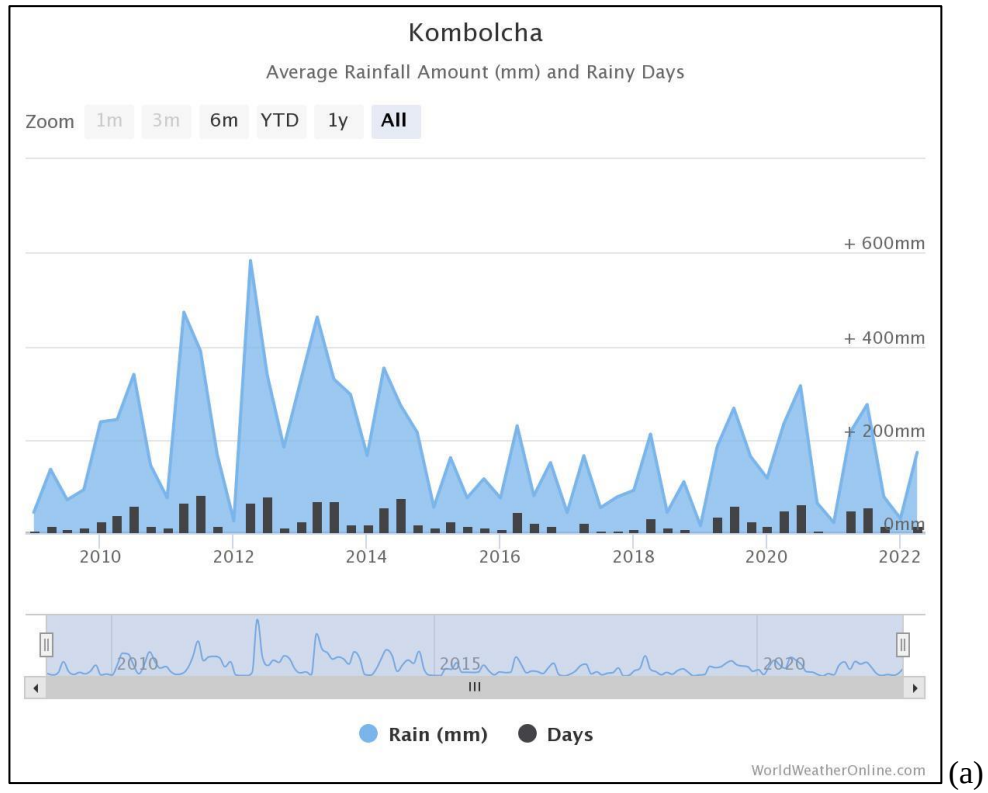


Figure 3.2 (a) Average Rainfall (mm) and (b) Maximum, Minimum, and Average Temperature (°C) (WorldWeatherOnline, 2022)

3.2 Experimental Techniques

3.2.1 Sample Collection and Preparation

In this study, soil samples were collected from selected locations in the study area (see Figure 3.3 (a & b), and Table 3.1). Before sampling, visual site investigations were made to consider different soil types, and to sample evenly in the study area. Six test pits were excavated to the depth of 3m as most of the foundation constructions in the area are founded around this depth. The excavation was done by local laborers. From the test pit, disturbed soil samples were collected with three samples per pit at 1m, 2m, and 3m in depth (i.e., a total of 18 samples). Then, several fields and laboratory tests were conducted on the collected samples. In the field, the in-situ density was done using the sand cone replacement method, natural moisture content was also determined. For the laboratory testing disturbed soil samples were collected in the plastic bag. Then the soil samples were transported to the laboratory. Collected disturbed soil samples from each layer were used to determine index properties for characterizing the soil to select typical soil materials for the cyclic simple shear tests and the 1D-Consolidation test. Hence, three typical soils were selected to conduct these tests. The selected samples were remolded using field density and natural moisture content in the laboratory. The remolded soil samples were used for cyclic simple shear test and for 1D- consolidation test. The laboratory tests were conducted in Addis Ababa Institute of Technology's geotechnical laboratory (AAiT). The following table shows the location of the test pits, the code of the test pits, and their coordinates.

Table 3.1 Location of test pits and their coordinates

No.	Location of Test pits	Code of test pits	Coordinates		Elevation(m)
			Latitude ($^{\circ}$)	Longitude ($^{\circ}$)	
1.	AirPort	AP	11.112318	39.725132	1868
2.	Dry Port	DP	11.084911	39.713451	1875
3.	Industry Park	IP	11.1126	39.714662	1894
4.	Around Amar Factory	Amar	11.082468	39.698336	1902
5.	Around Medhaniallem Church	MD	11.064623	39.736146	1812
6.	Around Mitikolo	MTK	11.090437	39.747397	1914
Remark: AP1 means, Location = Air Port and Depth = 1m; same for others test pits					

The following figure illustrates the location of test pits and a typical test pit when it was excavated.

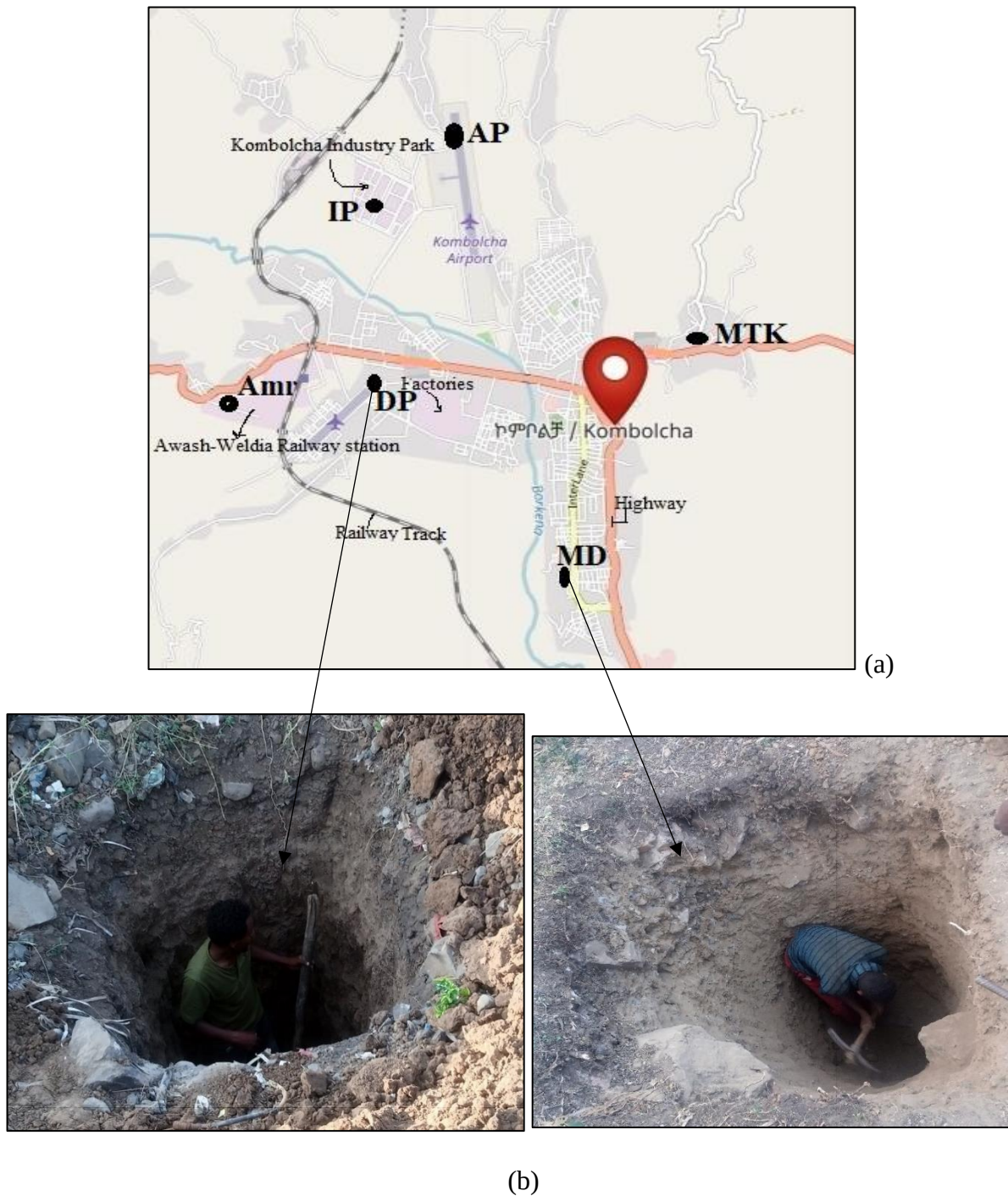


Figure 3.3 (a) Location of test pits (GPS, 2022) and (b) Typical test pits Dry Port (left) and Medhanialalem (right)

3.2.2 Summary of Testing Methods

The procedure used for each test is summarized as shown below:

ASTM D 1556 (2001) Standard Test Method for Density and Unit Weight of Soil in Place by Sand-Cone Method. This test method is used to determine the density and water content of soils in place. The test is performed by hand excavation and the material from the hole is saved and the hole is filled with the sand of known density the volume can then be determined after that the wet density, water content, and dry density of in-place can also be obtained.

ASTM D 422 (2007) Standard Test Method for Particle-Size Analysis of Soils. This test method covers the quantitative determination of the distribution of particle sizes in soils. The distribution of particle sizes larger than 75 μm (retained on the No. 200 sieve) is determined by sieving, while the distribution of particle sizes smaller than 75 μm is determined by a sedimentation process, using a hydrometer to secure the necessary data. For this study, wet sieving and hydrometer test was used.

ASTM D 854-10 (2010) Standard test for specific gravity of soil solids by water pycnometer. The specific gravity of soil solids, G_s , is the ratio of the mass of a unit volume of a soil solids to the mass of the same volume of gas-free distilled water at 20°C. The specific gravity of soil solid is used in calculating the phase relationships of soils, such as void ratio and degree of saturation.

ASTM D 4318 (2005) Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils, the specimen is processed to remove any material retained on a 425- μm (No. 40) sieve. The liquid limit is determined by performing trials in which a portion of the specimen is spread in a brass cup, divided by a grooving tool, and then allowed to flow together from the shocks caused by repeatedly dropping the cup in a standard mechanical device. The Plastic limit is determined by alternately pressing together and rolling into a 3.2-mm diameter thread a small portion of plastic soil until its water content is reduced to a point at which the thread crumbles and can no longer be pressed together and re-rolled. The water content of the soil at this point is reported as the plastic limit. The plasticity index is calculated as the difference between the liquid limit and the plastic limit.

ASTM D2435 (2010) Standard Test Methods for One-Dimensional Consolidation Properties of Soils Using Incremental Loading. In this test method, a soil specimen is restrained laterally and loaded axially with total stress increments. Each stress increment is maintained until excess pore

water pressures are completely dissipated. During the consolidation process, measurements are made of the change in the specimen height and these data are used to determine the relationship between the effective stress and void ratio or strain, and the rate at which consolidation can occur by evaluating the coefficient of consolidation. For this study, the pre-consolidation pressure was determined from the void ratio versus log pressure plot and used for the maximum shear modulus parameter.

ASTM D6528-17 (2017) Standard test method for Consolidated Undrained Direct Simple Shear Testing this is a general cyclic simple shear test procedure and it is explained in the following section (procedures used for cyclic simple shear test).

3.2.3 Cyclic Simple Shear Test Apparatus

The cyclic simple shear test is used to investigate the dynamic behavior of soils. The test is used to study the cyclic response of both the fine-grained and coarse-grained soils. The cyclic behavior can be investigated either by keeping the vertical stress constant or consolidated height constant during the cyclic loading.

Nowadays, there are different types of cyclic simple shear apparatuses in use. In this research, the type of apparatus that was used is the 31-WF7500 developed by Industrial Process Controls (IPC Global) Limited using the Universal Testing System (UTS). UTS is a software application program that incorporates the functionality to perform consolidation, cyclic simple shear, and linear displacement rate shear testing of a mechanically confined unbound material specimen. The system incorporates a two-axis servo-controlled loading apparatus that allows control and measurement of axial and lateral stress and displacement applied to the specimen under test (UTS004, 2003). Specimen testing begins with a consolidation stage which continues until testing is paused by the operator. Loading may then be reinitiated for either a cyclic shear stage. Any of these stages may be reinitiated and paused any number of times and in any sequence. While paused, the test loading control parameters may be altered and will take effect at the commencement of the next loading stage.

The Consolidation Stage

The consolidation stage is simply the application of static axial loading stress to the specimen while the lateral loading (shear) axis is held stationary. Axial stress and specimen displacements (axial and lateral) together with pore pressure data are measured over time and logged by the

system. Logged data is also displayed to the operator in the form of charts and tables as the test stage proceeds.

The consolidation stage is manually terminated by the operator once the consolidation of the specimen is determined to be complete.

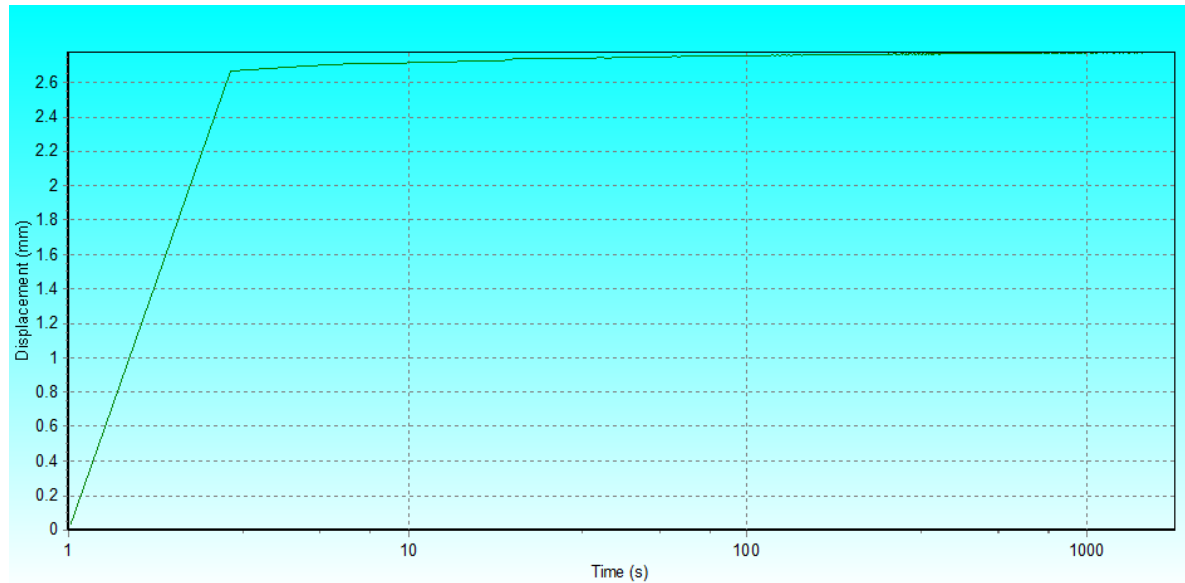


Figure 3.4 Logged data while the consolidation stage proceeds

The Cyclic Simple Shear Stage

The cyclic shear stage of the test applies a lateral cyclic shear force, or optionally a displacement, to the specimen, while the axial axis is either maintained at the specified stress or optionally, the specimen height is maintained. Both axial and lateral force and specimen displacements together with pore pressure are measured for each loading cycle. Measured data were obtained from 50 sample points captured over the cycle period. These data are displayed to the operator in the form of wave shapes, charts, and tables and also logged by the system to an archive data file. The loading cycle shape is operator selectable from predefined functions but may also be a user-generated shape.

Cyclic simple shear tests can be conducted for a wider range of strain amplitude from 10^{-2} % to 5 %). This range is the general range of strain encountered in the ground motion during seismic activities (Das, 2011).

3.2.3.1 Cyclic simple shear testing procedures used in this study

According to ASTM D 6528-17, in this study, 70mm Sample diameter and 20 mm height were used to maintain a height to diameter ratio of less than 0.4. The specimen was remolded when

the soil passes through a 4.75 mm standard sieve size and the sample was prepared by tamping techniques. 1 Hz loading frequency was chosen as recommended by (Ishihara, 1996), (Kramer, 1996) and commonly adopted by several other researchers, ((Vucetic & Dobry, 1991), (Ayele, 2022), (Kumar et al., 2017)). A specimen was subjected to 40 cycles of sinusoidal strain-controlled loading (ASTM D6528-17, 2017). Sinewave was used since it gives approximately 30% higher cyclic strength than rectangular or triangular waveforms (Kumar et al., 2014). In most seismic events, the number of significant cycles is likely to be less than 20. For practical purpose, the 5th cycles are likely to provide reasonable values (Das, 2011). Axial stresses of 100 kPa, 250 kPa, and 400 kPa were used to see the effect of confining pressure on the value of shear modulus and damping ratio similarly, the shear strain of 0.01 %, 0.1 %, 1 %, 2.5 %, and 5 % were also selected to study the effect at a wider strain range. As the cyclic simple shear test gives raw data from 50 data points for each cycle and 40 numbers of cycles were selected for this study so that a total of 2000 data points are recorded for a complete test of any selected pressure and amplitude and in this study, a total of 90,000 data point is found since it is 45 combinations for three test pits, three axial stresses, and five strains.

The main features of cyclic simple shear apparatus:

- 5 kN horizontal and vertical actuators
- 5 kN load cells fitted in-line with actuators, 1 N accuracy
- Constant diameter test performance
- Possibility of constant height shear test
- Operating frequency up to 10 Hz (depending on test conditions)

The following figures illustrate the machine used for this study and its basic elements. And the sample is positioned on a pedestal, with a top cap, and is supported laterally by ring brass (O-rings) it is a rubber membrane that secured a constant diameter throughout the test. During the shearing stage, the rings slide across each other, while keeping the diameter constant. The vertical actuator under closed-loop control with feedback from the vertical LVDT maintains the vertical height of the sample.

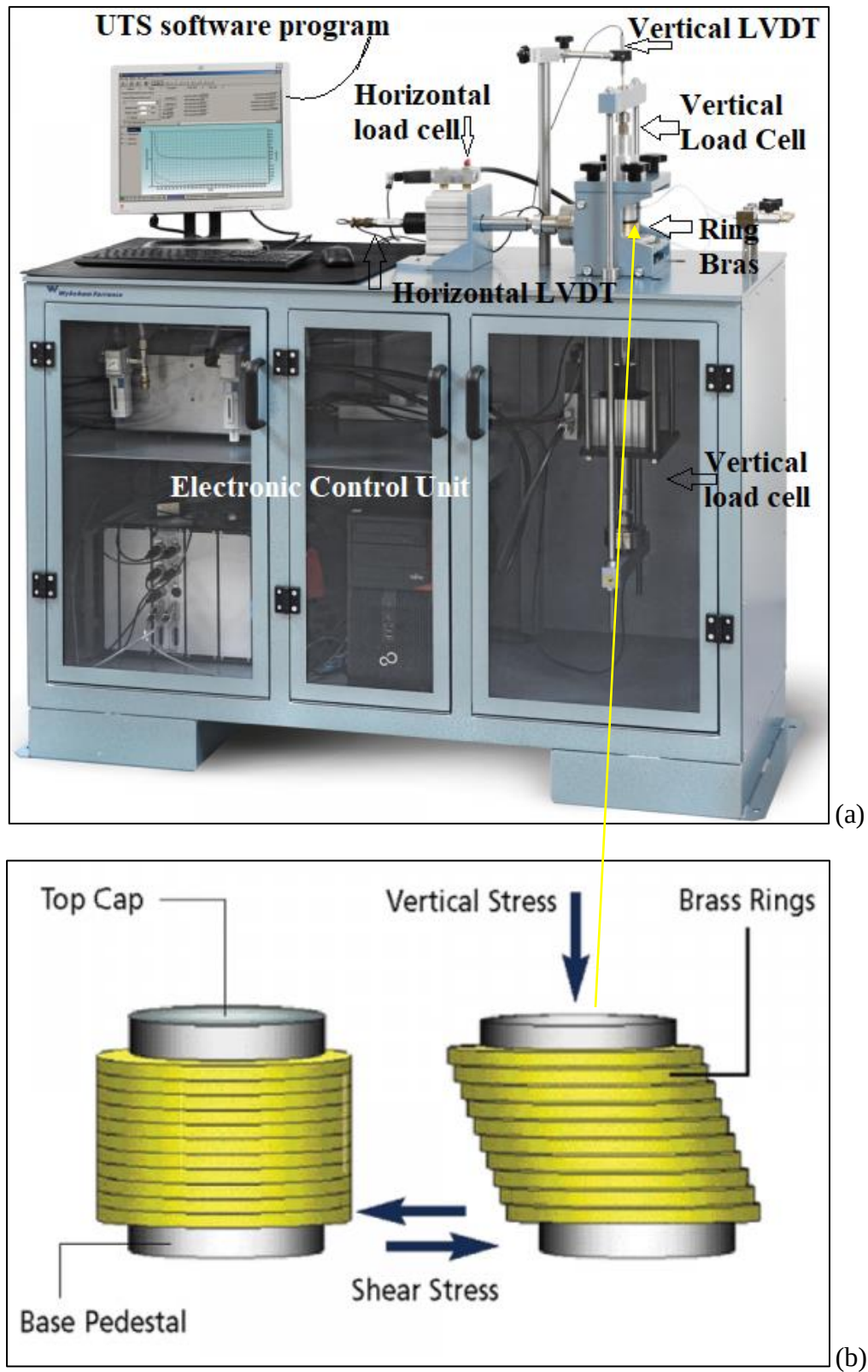


Figure 3.5 (a) Cyclic simple shear machine found in AAiT (photo credit Controls group) and (b) Schematic of shear deformation of O-rings in the simple shear device

4 RESULT AND DISCUSSION

4.1 Index Property Tests

Index properties are commonly used for the identification and classification of soils. Currently, the Unified Soil Classification System (USCS) and the American Association of State Highway and Transportation Officials (AASHTO) systems are in use in civil engineering practice. Both systems classified the soils based on particle size characteristics, liquid limit (LL), and plasticity index (PI) of soils. The subgrouping of fine-grained soils is entirely based on a plasticity chart (i.e., PI versus LL). In addition to classification, field density was done to get natural conditions for the disturbed samples and specific gravity was done for initial void ratio determination and characterization of soils found in Kombolcha town. The important index properties done in this study are listed below and the results are presented and discussed.

- Field density and natural moisture content
- Grain size analysis
- Specific gravity
- Atterberg's limits

To give additional information about the nature of the soil, especially for the clayey soils a very simple testing procedure of the free swell index test was followed and included in the summary table (see Table 4.2) and further in appendix E. The void ratio was also calculated for the primary purpose of determining the maximum shear modulus from the empirical equation (refer to Chapter 2, Equation 2.6) furthermore, it is required for the one-dimensional consolidation test as an initial void ratio (e_o).

4.1.1 Field Density and Natural Moisture Content Test

The test was done in-situ using the sand replacement method. This test method was used for the determination of the in-place density and unit weight of in-situ soils and these results were used to remold the soil for the cyclic simple shear test and one-dimensional consolidation test. The in-situ dry density found from the test ranges from 1.08 g/cc to 1.54 g/cc and natural moisture content ranges from 16.4 % to 33.82 %. The test results are shown in Table 4.1 and the calculation for the determination is shown in appendix A.

4.1.2 Grain Size Distribution Test

For engineering purposes, classification of soils is needed, the grain size distribution is basic for knowing the distribution of the size of particles in a mass of soil. The test was done in the laboratory for both larger than No. 200 Sieve (Wet sieve) and smaller than No. 200 Sieve size (Hydrometer analysis). The percent fraction of soil particles and the grain size distribution curve are shown in Table 4.1 and Figure 4.1 respectively. Refer to Appendix C for all sieve analyses, hydrometer analyses, and the Grain size distribution curve of 18 samples.

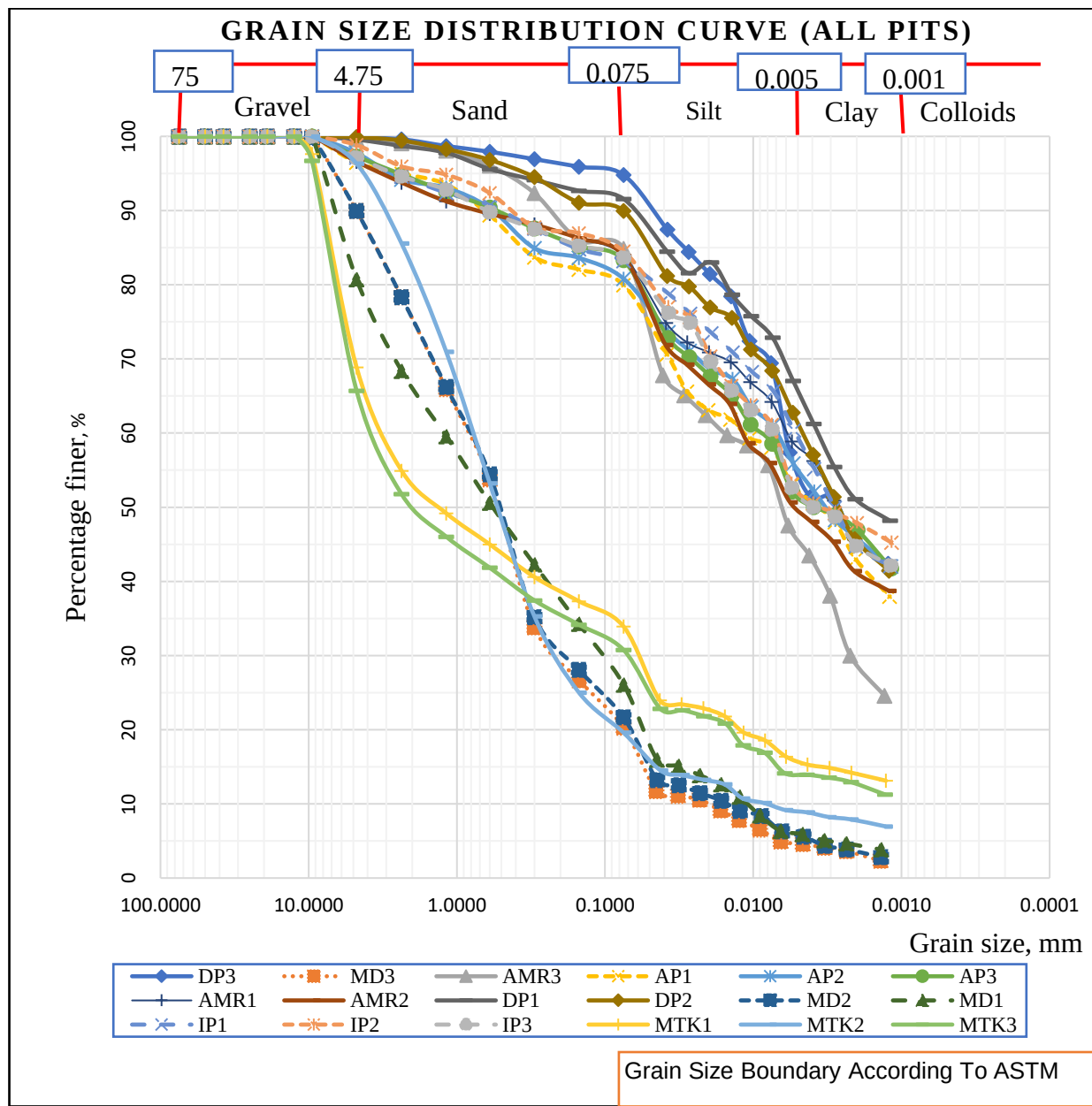


Figure 4.1 Summary of grain size distribution curve

4.1.3 Atterberg Limits Test

Atterberg's limits are limits that depend on the water content of soil: its liquid limit, and plastic limit. In this study, the water content of the liquid limits was determined using the Casagrande apparatus at a 25 number of blows, and the water content of the plastic limit was determined by the hand-rolling method as the thread diameter reaches around 3 mm and starts to crumble condition. The plasticity index was also determined by the difference between the liquid limit and plastic limit. The liquid limit and plastic index are critical parameters for engineering purposes, especially in soil classification. The range of liquid limit is determined from 51% to 77% and the plasticity index ranges from 12 to 47. The result of Atterberg limits is provided in the summary table (Table 4.1). Additionally, for each test pit, analysis of data with results are provided in Appendix D.

4.1.4 Specific Gravity Test

The specific gravity of soil was determined using a 250ml volumetric flask and it is used for the determination of void ratio and to know the ratio of the weight of a given volume of the soil over the weight of an equal volume of distilled water. The value of specific gravity determined in the laboratory ranges from 2.65 to 2.80. The result of specific gravity of soil is shown in Table 4.1. Additional test results and procedures to determine are shown in Appendix B.

4.2 Soil Classification

Soil classification is a systematic method of categorizing soils into various groups and subgroups according to their probable engineering behavior. The soil classification was done based on the USCS (ASTM D 2487 – 06, 2017) and the AASHTO (ASTM D 3282, 2015). Based on USCS the soil from AP, IP, DP, and Amar are highly plastic clay (CH) or fat clay since 50% or more passes through No. 200 (75- μ m) sieve size and the liquid limit is 50 or greater whereas, MTK and MD are silty sand soil (SM) since more than 50% retained on No. 200 (75- μ m) sieve size (i.e., coarse-grained), 50% or more passes through No.4 (4.75mm) (i.e., Sand) and the position of the plasticity index versus liquid limit plot for the fines are below "A" line (i.e., silty) overall the soil classified as Silty sand (SM). Based on the AASHTO classification system AP, IP, DP and Amar have more than 35% of the total sample passing No. 200 and a liquid limit of more than 41% with a plasticity index of more than 11% which results in A-7-5 (Clayey) soil type whereas, MD and MTK, have 35% or less of total sample passing No. 200 and have a liquid

limit of more than 41% with a plasticity index of more than 11% which results in A-2-7 (Silty Sand). In Figure 4.2 (a) and (b) soils are classified using AASHTO and USCS Plasticity charts as shown below.

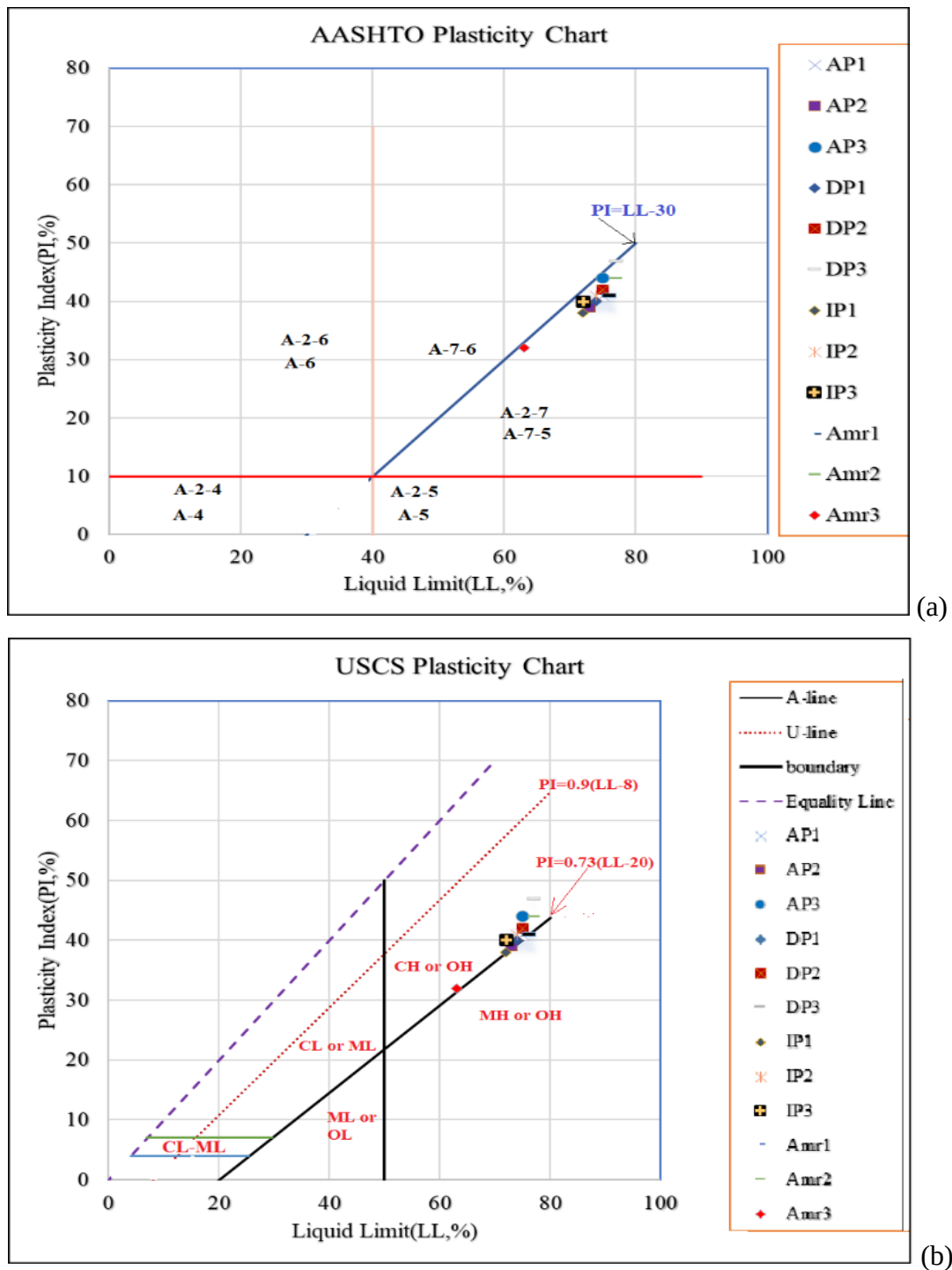


Figure 4.2 USCS(a) and AASHTO (b) plasticity chart

Based on the above sample results all samples are determined and the following table summarizes the basic index properties of soil found in Kombolcha town.

Table 4.1 Summary of index properties test results

Test Pits	Air Port (AP)			Dry Port (DP)			Industry Park (IP)			Around Medhaniallem Church (MD)			Around Amar Factory (Amar)			Around Mitikolo (MTK)		
Depth	1m	2m	3m	1m	2m	3m	1m	2m	3m	1m	2m	3m	1m	2m	3m	1m	2m	3m
Bulk density (g/cc)	1.41	1.43	1.46	1.59	1.66	1.61	1.49	1.49	1.49	1.66	1.64	1.79	1.46	1.53	1.52	1.72	1.76	1.75
Moisture Content (%)	30.15	32.1	30.03	33.8	33.4	32.4	30.4	28.7	27.5	17.7	17.3	16.4	28	28.9	24.9	24.5	23.5	23.4
Dry density (g/cc)	1.08	1.08	1.12	1.19	1.24	1.21	1.14	1.16	1.17	1.41	1.4	1.54	1.14	1.19	1.22	1.38	1.42	1.42
Liquid Limit (%)	75	73	75	74	75	77	72	74	72	54	53	51	75	77	63	68	64	72
Plastic Limit (%)	34	34	31	34	33	30	34	33	32	42	35	39	34	33	31	44	46	49
Plastic index (%)	41	39	44	40	42	47	38	41	40	12	18	12	41	44	32	23	18	23
Gravel fraction (%)	3.5	2.2	2.7	0.4	0.1	0.1	2.8	1.2	2.8	19.3	10.1	10.1	3.4	3.4	0.4	31.1	3.7	34.3
Sand fraction (%)	16.5	17	14	8	9.9	5.1	14	14.3	13.5	54.6	68.2	69.6	12.7	12.7	14.7	35	76.7	34.9
Silt fraction (%)	28	25.8	32.3	25.6	29	40.8	23.2	32	32.7	20	15.58	15.43	26.1	33.7	38.9	18	10.6	16.8
Clay fraction (%)	52	55	51	66	61	54	60	52.5	51	6.11	6.12	4.87	57.8	50.2	46	15.9	9.02	14
Free Swell Index (%)	80	80	85	80	85	95	90	85	95	15	10	15	80	75	55	30	40	30
Specific Gravity (Gs)	2.75	2.77	2.8	2.71	2.73	2.71	2.75	2.77	2.77	2.66	2.68	2.67	2.7	2.72	2.69	2.67	2.66	2.65
AASHTO	A-7-5			A-7-5			A-7-5			A-2-7			A-7-5			A-2-7		
USCS	Highly Plastic Clay (CH)			Highly Plastic Clay (CH)			Highly Plastic Clay (CH)			Silty Sand (SM)			Highly Plastic Clay (CH)			Silty Sand (SM)		

4.3 One Dimensional Consolidation Test

This test was done to know the pre-consolidation pressure which is an important parameter for the determination of maximum shear modulus. It was determined using odometer apparatus for three typical test pits at 3m depth. A sample size of 50mm in diameter by 20mm in height was remolded using field density and natural moisture content and subjected to one-dimensional consolidation. pre-consolidation pressures determined from void ratio against log pressure plot of MD, Amar, and DP were 42, 72, and 98 respectively. In Figure 4.3 and Appendix G has been observed that the pre-consolidation values were low as the tests were done on remolded samples.

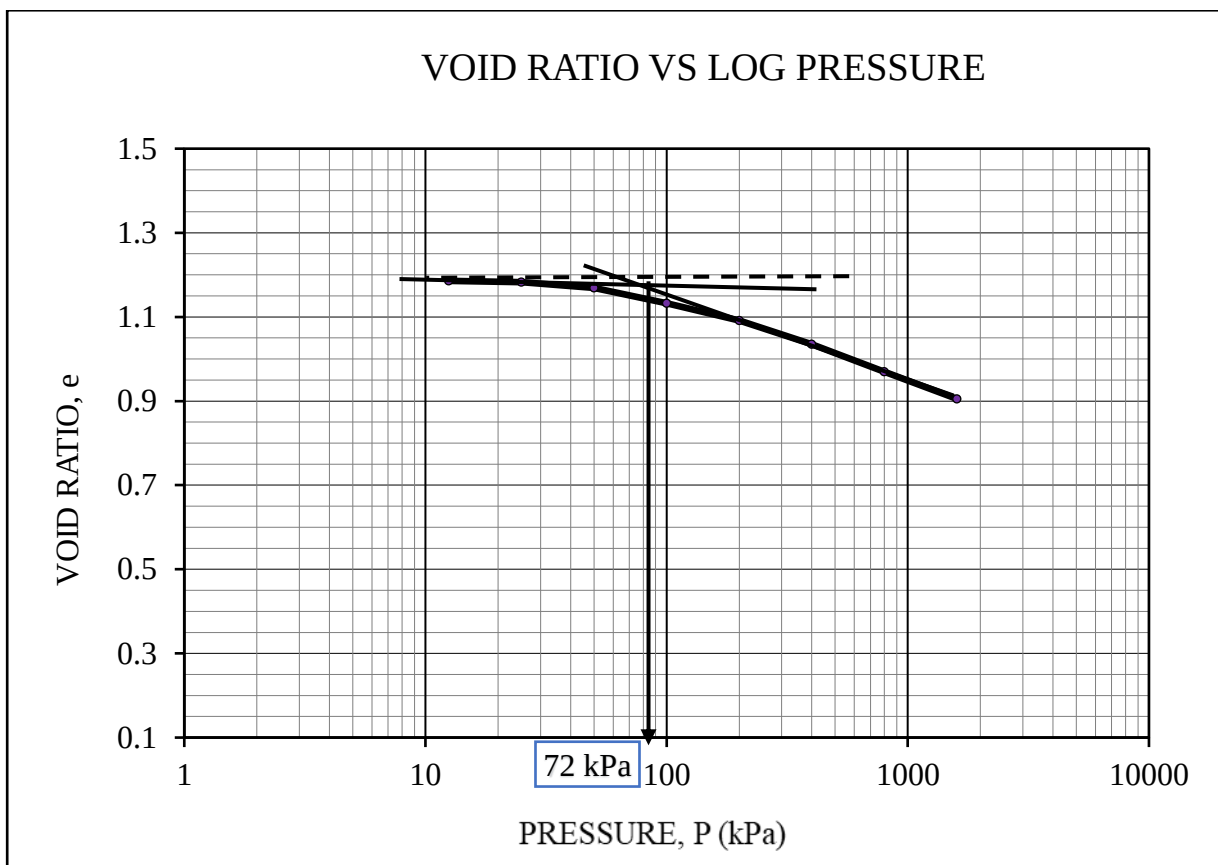


Figure 4.3 Typical Pre-consolidation result of Clay Amar3 soil

4.4 Cyclic Simple Shear Test Results

The remolded soil samples were used under a confining pressure of 100kPa, 250kPa, 400kPa and shear strain values of 0.001%, 0.1%, 1%, 2.5% and 5% with 40 number of loading cycles and 1Hz frequency for all typical test pits. Using these values as an input the output was found from the test through MS-Excel in tabular form.

Table 4.2 shows the output (raw data) of cyclic simple shear test for single cyclic loading (at 5th cycle since it is usual for most practical purposes (Das, 2011)), Axial Lvdt, Axial Force, Lateral Lvdt, and Lateral Force of 50 data points. The shear stress was determined by dividing the Lateral force by the area of the specimen and the shear strain from the ratio of the lateral Lvdt to specimen height after consolidation (smaller than 20mm) where the area of the specimen =3848.45 mm²

Table 4.2 Shear stress and shear strain values of DP3 at 250kPa axial stress, 2.5% axial strain, and 5th cycle

Time (Sec)	Axial Lvdt	Axial Force	Lateral Lvdt	Lateral Force	Shear Stress (MPa)	Shear Strain (%)
0.0000	-4.78008	-0.02753	0.485127	0.241025	0.0626	0.0257
0.0190	-4.81784	-0.02608	0.49647	0.25106	0.0652	0.0263
0.0380	-4.89901	-0.02115	0.50099	0.241631	0.0628	0.0265
0.0570	-4.99772	-0.01034	0.50133	0.23156	0.0602	0.0266
0.0760	-5.08644	-0.00459	0.50062	0.221454	0.0575	0.0265
0.0950	-5.13258	-0.00296	0.47381	0.215635	0.0560	0.0251
0.1140	-5.16051	-0.00251	0.43247	0.141695	0.0368	0.0229
0.1330	-5.17444	-0.00443	0.38269	0.086865	0.0226	0.0203
0.1520	-5.185	-0.00417	0.35905	0.065295	0.0170	0.0190
0.1710	-5.19613	-0.00385	0.30037	0.028705	0.0075	0.0159
0.1900	-5.20731	-0.00661	0.21008	0.015515	0.0040	0.0111
0.2090	-5.21298	-0.01352	0.19409	0.008295	0.0022	0.0103
0.2280	-5.21736	-0.0184	0.1102	-0.01698	-0.0044	0.0058
0.2470	-5.22211	-0.02079	0.06843	-0.03127	-0.0081	0.0036
0.2660	-5.22877	-0.02214	0.01081	-0.05596	-0.0145	0.0006
0.2850	-5.23687	-0.02326	-0.0816	-0.07781	-0.0202	-0.0043
0.3040	-5.24763	-0.024	-0.1021	-0.09014	-0.0234	-0.0054
0.3230	-5.26519	-0.02419	-0.1881	-0.12395	-0.0322	-0.0100
0.3420	-5.29289	-0.02374	-0.2295	-0.1373	-0.0357	-0.0122
0.3610	-5.3304	-0.02215	-0.2705	-0.16269	-0.0423	-0.0143
0.3800	-5.3669	-0.02016	-0.3444	-0.19995	-0.0520	-0.0183
0.3990	-5.39523	-0.01834	-0.362	-0.20753	-0.0539	-0.0192
0.4180	-5.41625	-0.01667	-0.404	-0.24053	-0.0625	-0.0214
0.4370	-5.43396	-0.01543	-0.4475	-0.2645	-0.0687	-0.0237
0.4560	-5.45187	-0.01355	-0.4557	-0.26888	-0.0699	-0.0241

Time (Sec)	Axial Lvdt	Axial Force	Lateral Lvdt	Lateral Force	Shear Stress (MPa)	Shear Strain (%)
0.4750	-5.47359	-0.01129	-0.4812	-0.31198	-0.0811	-0.0255
0.4940	-5.50005	-0.00835	-0.4997	-0.36125	-0.0939	-0.0265
0.5130	-5.53095	-0.0039	-0.5011	-0.29246	-0.0760	-0.0266
0.5320	-5.55902	-0.00358	-0.5013	-0.28944	-0.0752	-0.0266
0.5510	-5.57378	-0.00547	-0.5009	-0.28609	-0.0743	-0.0265
0.5700	-5.58394	-0.00686	-0.4996	-0.28048	-0.0729	-0.0265
0.5890	-5.59424	-0.0075	-0.4872	-0.24655	-0.0641	-0.0258
0.6080	-5.60128	-0.00749	-0.4663	-0.19993	-0.0520	-0.0247
0.6270	-5.60726	-0.00846	-0.4333	-0.13928	-0.0362	-0.0230
0.6460	-5.61478	-0.00932	-0.3891	-0.07746	-0.0201	-0.0206
0.6650	-5.62437	-0.00982	-0.3365	-0.02607	-0.0068	-0.0178
0.6840	-5.63735	-0.01054	-0.2711	0.007975	0.0021	-0.0144
0.7030	-5.65644	-0.01072	-0.2006	0.017695	0.0046	-0.0106
0.7220	-5.67961	-0.0102	0.00472	0.070545	0.0183	0.0003
0.7410	-5.70396	-0.0095	0.00472	0.070545	0.0183	0.0003
0.7600	-5.72427	-0.0088	0.04646	0.084245	0.0219	0.0025
0.7790	-5.74193	-0.00822	0.11283	0.111115	0.0289	0.0060
0.7980	-5.75909	-0.00785	0.16988	0.133925	0.0348	0.0090
0.8170	-5.77629	-0.00743	0.21592	0.151935	0.0395	0.0114
0.8360	-5.79503	-0.00683	0.27317	0.176935	0.0460	0.0145
0.8550	-5.81514	-0.00594	0.32006	0.200765	0.0522	0.0170
0.8740	-5.83608	-0.00453	0.35453	0.219835	0.0571	0.0188
0.8930	-5.85977	-0.00304	0.39184	0.242915	0.0631	0.0208
0.9120	-5.88297	-0.00181	0.43247	0.264115	0.0686	0.0229
0.9310	-5.90374	-0.00098	0.45704	0.275365	0.0716	0.0242

From this data, Lateral Lvdt (specimen displacements) and Lateral force were used to develop the hysteresis loop and to determine the shear modulus and damping ratio of the soil (refer to Section 4.4.1)

The following form of wave shapes (i.e., Sinusoidal form) of DP3 soil at 400kPa axial stress and 2.5% axial strain for three cycles were determined as shown in Figure 4.4 below.

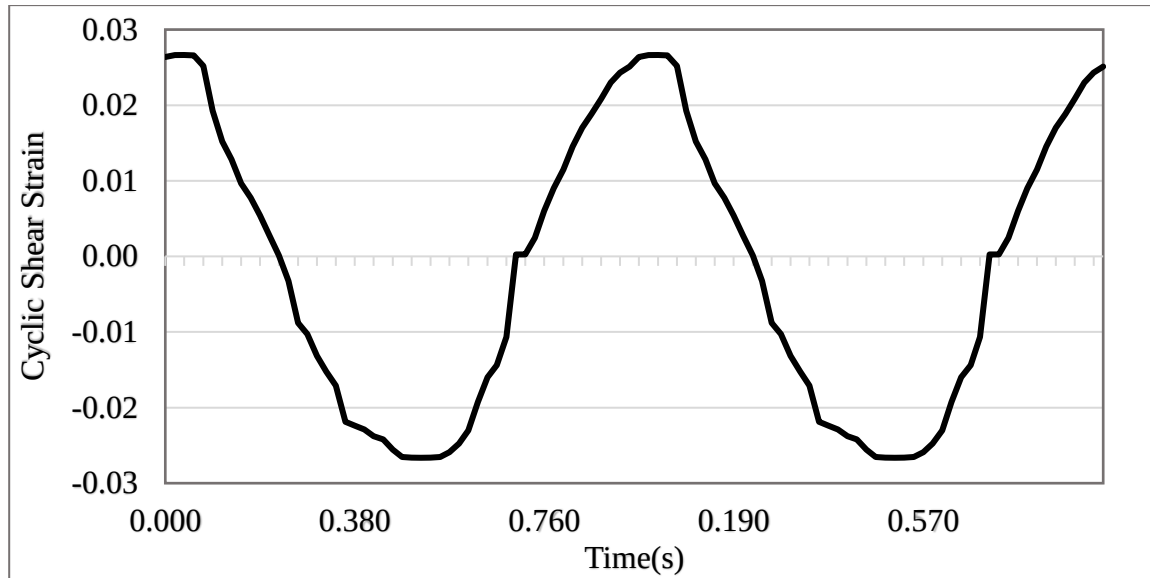
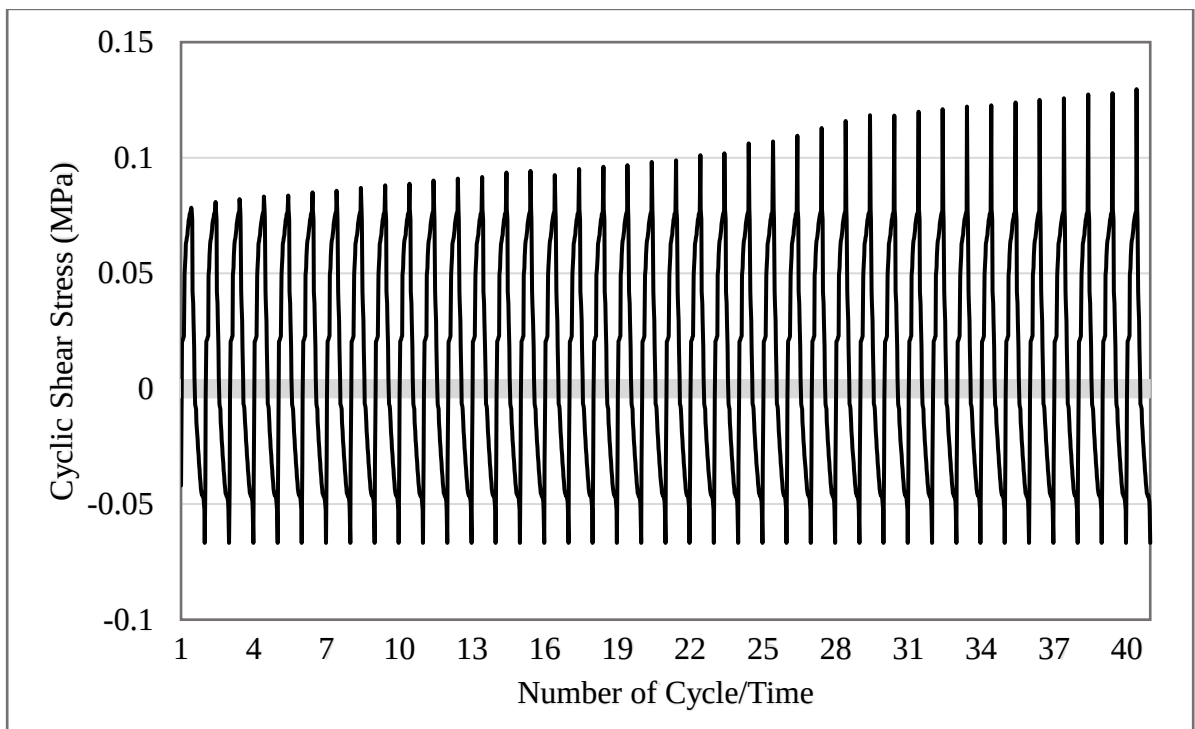


Figure 4.4 Sinusoidal wave shapes of 2.5 % strain of DP3 for three cycles at 400kPa

Charts were also determined for number of cycles per time versus cyclic shear stress and cyclic shear strain at 100kPa axial stress and 2.5% strain of MD3 and a hysteresis loop of Amar3 at 250kPa axial stress and 2.5% axial strain for all 40 cycles were determined (see Figure 4.5 and 4.6).



(a)

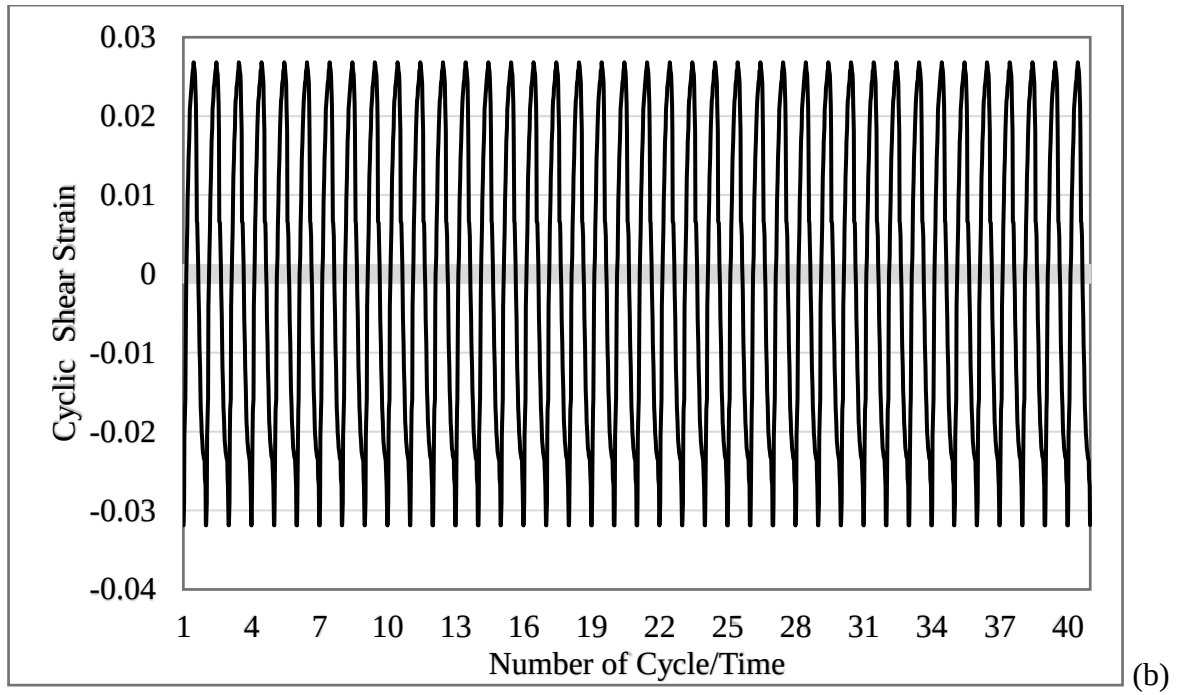


Figure 4.5 Cyclic shear stress (a) and Cyclic shear strain (b) against number of cycles of MD3 at 100kPa axial stress and 2.5 % strain

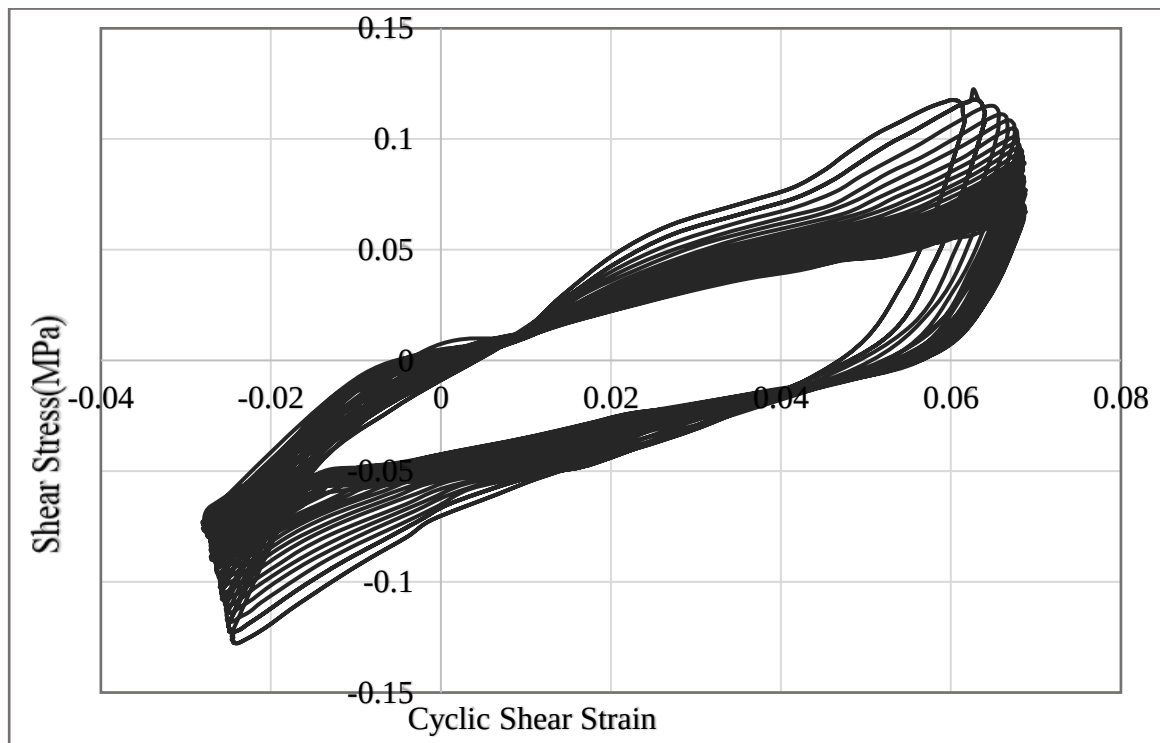


Figure 4.6 The hysteresis loops of Amar3 soil under 250kPa axial pressure and 2.5% cyclic shear strain at the 5th cycle.

4.4.1 Determination of Shear Modulus and Damping Ratio

The values of shear modulus and damping ratio were determined from the hysteresis loop, based on the raw data obtained from the cyclic simple shear test. The calculation of the determination of shear modulus and damping ratio values are shown in the following Figure 4.7 and Table 4.3.

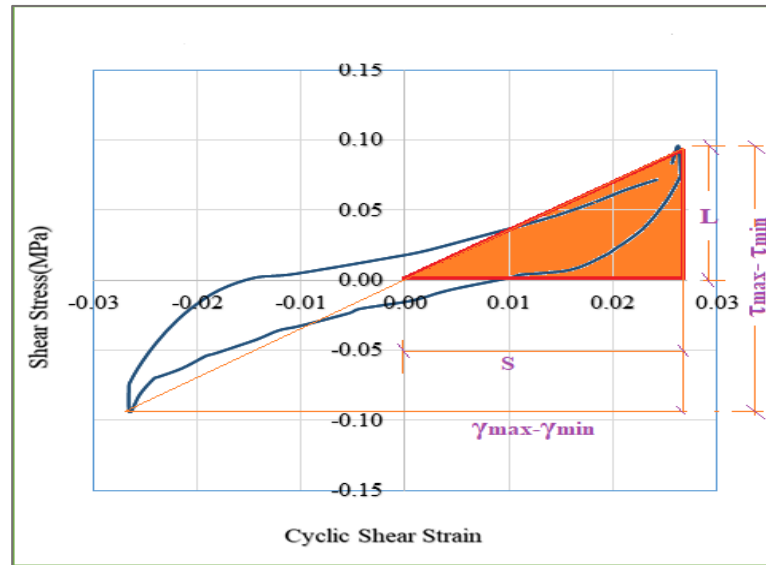


Figure 4.7 Hysteresis loop and triangle using stress-strain values of DP3 of 250kPa axial stress and 2.5% axial strain at 5th cycle

Table 4.3 Calculation of shear modulus and damping ratio of Figure 4.10

Calculation of Shear Modulus (G)		Calculation of Damping Ratio (D)	
Calculation	Value	Calculation	Value
$\tau_{\max} = L$	0.0716	$A_{\text{loop}} = \frac{1}{2} * \sum_{i=1}^n (\tau_i - \tau_{i+1}) \times (\gamma_i + \gamma_{i+1})$	0.0016207
$\tau_{\min}$	-0.0939		
$\tau_{\max} - \tau_{\min}$	0.165419844	$A_{\Delta} = 0.5 \times (L \times S)$	0.0009505
$\gamma_{\max} = S$	0.0266		
$\gamma_{\min}$	-0.0266	$D = \frac{A_{\text{loop}}}{(4\pi A_{\Delta})}$	0.1356897
$\gamma_{\max} - \gamma_{\min}$	0.053133545		
$G[\text{MPa}] = \frac{(\tau_{\max} - \tau_{\min})}{(\gamma_{\max} - \gamma_{\min})}$	3.113284525	D [%]	13.569

Using a similar procedure for all number of cycles at each strain and stresses of each test pit were determined. The following table shows the value of shear modulus and damping ratio for one selected pit (DP3) and confining stress (250kPa) with all 40 cycles and all strains. For the remaining test pits, tables are provided in Appendix H.

Table 4.4 Shear modulus and damping ratio of DP3 at 250kPa of all cycles and all strains

Strain (%)		0.01	0.10	1.00	2.50	5.00	0.01	0.10	1.00	2.50	5.00
Number of Cycles		G (MPa)					D (%)				
	1	7.63	5.58	4.71	3.06	1.07	2.30	3.25	6.65	15.19	16.80
	2	7.64	5.61	4.73	3.07	1.12	2.29	3.22	6.23	13.68	15.29
	3	7.65	5.62	4.77	3.09	1.13	2.29	3.22	6.18	13.62	15.03
	4	7.65	5.64	4.76	3.11	1.14	2.28	3.20	6.09	13.60	14.96
	5	7.66	5.66	4.77	3.11	1.14	2.28	3.19	6.07	13.57	14.94
	6	7.66	5.66	4.78	3.57	1.14	2.28	3.19	6.05	13.54	14.67
	7	7.67	5.67	4.79	3.58	1.14	2.28	3.18	6.02	13.46	14.59
	8	7.68	5.68	4.80	3.59	1.14	2.27	3.17	5.98	12.61	14.46
	9	7.68	5.72	4.81	3.60	1.20	2.27	3.14	5.96	12.54	14.42
	10	7.69	5.73	4.82	3.60	1.20	2.26	3.13	5.94	12.27	14.36
	11	7.70	5.75	4.96	3.61	1.20	2.26	3.12	5.70	12.15	14.33
	12	7.71	5.92	4.97	3.62	1.20	2.25	3.20	5.60	12.07	14.26
	13	7.73	6.16	4.98	3.62	1.19	2.24	3.02	5.57	11.97	14.13
	14	7.83	6.03	5.04	3.62	1.20	2.20	2.92	5.45	11.94	14.02
	15	7.93	6.06	5.14	3.63	1.20	2.12	2.69	5.13	11.54	13.99
	16	8.06	6.08	5.20	3.66	1.22	2.07	2.67	5.02	11.71	13.96
	17	8.14	6.53	5.23	3.67	1.24	2.05	2.81	5.09	11.11	13.74
	18	8.18	6.23	5.25	3.68	1.22	2.03	2.80	5.08	11.05	13.50
	19	8.18	6.27	5.24	3.69	1.24	2.03	2.77	5.00	10.92	13.41
	20	8.20	6.28	5.26	3.70	1.25	2.03	2.77	4.96	10.90	13.35
	21	8.20	6.29	5.34	3.71	1.26	2.02	2.76	4.57	10.89	13.16
	22	8.21	6.32	5.45	3.71	1.26	2.02	2.75	4.48	10.85	13.12
	23	8.22	6.33	5.53	3.71	1.27	2.01	2.74	4.47	10.80	12.99
	24	8.22	6.37	5.55	3.72	1.27	2.01	2.71	4.42	10.76	12.95
	25	8.23	6.46	5.65	3.72	1.28	2.01	2.67	4.38	10.74	12.81
	26	8.23	6.51	5.66	3.72	1.29	2.01	2.64	4.37	10.72	12.68
	27	8.24	6.57	5.65	3.75	1.29	2.01	2.61	4.34	9.40	12.60
	28	8.32	6.60	5.67	3.75	1.30	1.98	2.59	4.30	9.36	12.50
	29	8.36	6.61	5.68	3.76	1.30	1.96	2.59	4.24	9.34	12.43
	30	8.40	6.68	5.69	3.76	1.31	1.94	2.55	4.22	9.30	12.36
	31	8.43	6.75	5.70	3.85	1.31	1.93	2.52	4.19	9.21	12.31
	32	8.47	6.77	5.72	3.93	1.32	1.92	2.51	4.17	9.08	12.14
	33	8.50	6.79	5.72	3.97	1.32	1.91	2.50	4.13	8.98	12.07
	34	8.55	6.84	5.73	4.03	1.33	1.89	2.47	4.07	8.83	12.01
	35	8.56	6.85	5.75	4.05	1.25	1.88	2.47	4.05	8.75	11.99
	36	8.57	6.86	5.75	4.10	1.33	1.88	2.47	4.00	8.58	11.96
	37	8.58	6.86	5.75	4.11	1.34	1.88	2.47	3.93	8.56	11.89
	38	8.63	6.87	5.77	4.21	1.38	1.86	2.46	3.92	8.30	11.19
	39	8.65	6.88	5.78	4.22	1.42	1.85	2.46	3.87	8.13	10.73
	40	8.74	6.89	5.85	4.30	1.43	1.82	2.46	3.74	8.00	10.56

4.4.2 Determination of the Initial Shear Modulus/Maximum Shear modulus (G_{max})

The initial shear modulus/maximum shear modulus was determined from empirical correlations of soil type and index properties that were developed by (Hardin & Drench, 1972). The pre-consolidation pressure determined from the one-dimensional consolidation test was used to determine the OCR value. The calculation used to determine the maximum shear modulus for the above shear modulus value (from Table 4.3, $G=3.11\text{MPa}$) is shown below and tabulated for all typical pits, axial stresses, and cyclic strains at the 5th cycle (see Table 4.5). Using Equation 2.6, the maximum shear modulus can be determined as;

The Void ratio (e) of a typical soil of DP3 is 1.24 and a plasticity index (PI) is 47 using this by interpolation the value of ‘ a ’ was determined equal to 0.34 (see Table 2.2), and the value of OCR was determined by the ratio of pre-consolidation pressure (P_c) to present/normal pressure (P_o).

$$\text{OCR} = \frac{P_c}{P_o} = \frac{98}{250} = 0.392$$

$$\sigma'_o = \frac{(\sigma'_v + 2K_o\sigma'_v)}{3} = \sigma'_o = \frac{(250 + 2 \times 0.5 \times 250)}{3} = 166.67\text{kPa}$$

K_o was taken as 0.5 (HB seed et al, 1986)

$$G_{max} = 3230 \times \frac{(2.97 - 1.24)^2}{(1 + 1.24)} \times (0.392)^{0.34} \times 166.67^{0.5} = 40578.73 \text{ kPa} = \mathbf{40.58\text{MPa}}$$

Using this value, the normalized shear modulus was determined as $\frac{G}{G_{max}} = \frac{3.11}{40.58} = \mathbf{0.08}$

Table 4.5 Maximum shear modulus G_{max} and normalized shear modulus $\frac{G}{G_{max}}$ values

Parameter required for G_{max}		Amar3	DP3	MD3
PI (%)		32	47	12
a		0.25	0.34	0.11
e		1.21	1.24	0.73
P_c (kPa)		72	98	42
K_o		0.50	0.50	0.50
Test pits	Other Parameters to compute G_{max}			
	P_o (kPa)	OCR	σ'_o (kPa)	G_{max} (MPa)
Amar3	100	0.72	66.67	34.30
	250	0.29	166.67	43.05
	400	0.18	266.67	48.37

Test pits		P _o (kPa)	OCR	σ' _o (kPa)		G _{max} (MPa)	
DP3		100	0.98	66.67		35.00	
		250	0.39	166.67		40.58	
		400	0.25	266.67		43.78	
MD3		100	0.42	66.67		69.24	
		250	0.17	166.67		99.16	
		400	0.11	266.67		119.23	
$\frac{G}{G_{max}}$ and D values							
P _o (kPa)	Shear Strain	Amar3(CLAY(PI=32))		DP3(CLAY(PI=47))		MD3(SILTY SAND)	
		$\frac{G}{G_{max}}$	D	$\frac{G}{G_{max}}$	D	$\frac{G}{G_{max}}$	D
100	0.01	0.15	4.55	0.2	3.61	0.13	3.08
	0.1	0.08	5.87	0.1	4.29	0.1	4.7
	1	0.05	8.31	0.05	7.53	0.06	7.03
	2.5	0.02	17.73	0.02	16.79	0.04	16.5
	5	0.02	21.56	0.02	22.4	0.02	19.68
250	0.01	0.15	3.03	0.19	2.28	0.14	1.43
	0.1	0.09	5.14	0.14	3.19	0.08	4.17
	1	0.08	7.42	0.12	6.07	0.06	5.33
	2.5	0.03	10.13	0.08	13.57	0.05	13.31
	5	0.02	17.54	0.03	16.48	0.04	14.17
400	0.01	0.19	2.35	0.23	1.54	0.16	1.06
	0.1	0.16	4.22	0.2	2.84	0.12	2.4
	1	0.13	6.93	0.18	3.74	0.08	3.06
	2.5	0.07	8.71	0.08	11.82	0.06	7.26
	5	0.03	15.8	0.04	12.04	0.04	11.67

4.4.3 Factors Influencing Shear Modulus and Damping Ratio

The dynamic shear modulus and soil damping ratio are affected by many factors. In this study, some of these factors were considered, such as confining pressure, shear strain amplitude, number of loading cycles, soil type, void ratio, and soil plasticity.

4.4.3.1 Variation of Shear Modulus and Damping Ratio with Confining pressure

The influence of confining stress over the values is shown in Figure 4.8 and additional charts were provided in Appendix I-1. From Figure 4.8 (a), the shear modulus increases with increasing confining pressure. The reason is that the compactness of the soil due to confining stress causes an increase in density attributed to the relatively higher stiffness imparted in the specimens which are described as shear modulus. The obtained curves are closer when the shearing strain is increasing, so it indicates that in the condition of larger shear strain, the confining pressure

has little influence. From Figure 4.8 (b) It is observed that specimens subjected to lower confining pressure (100 kPa) depict a higher damping ratio in comparison to that obtained at higher confining pressure (250 kPa and 400 kPa), this is because compactness reduces the deformation of soils, which leads to the reduction of energy loss or damping ratio. The behaviour for shear modulus increases and damping ratio decreases with confining pressure is similar with the results of ((Chattaraj & Sengupta, 2016), (El Mohtar et al., 2013) and (Birhanu, 2019)).

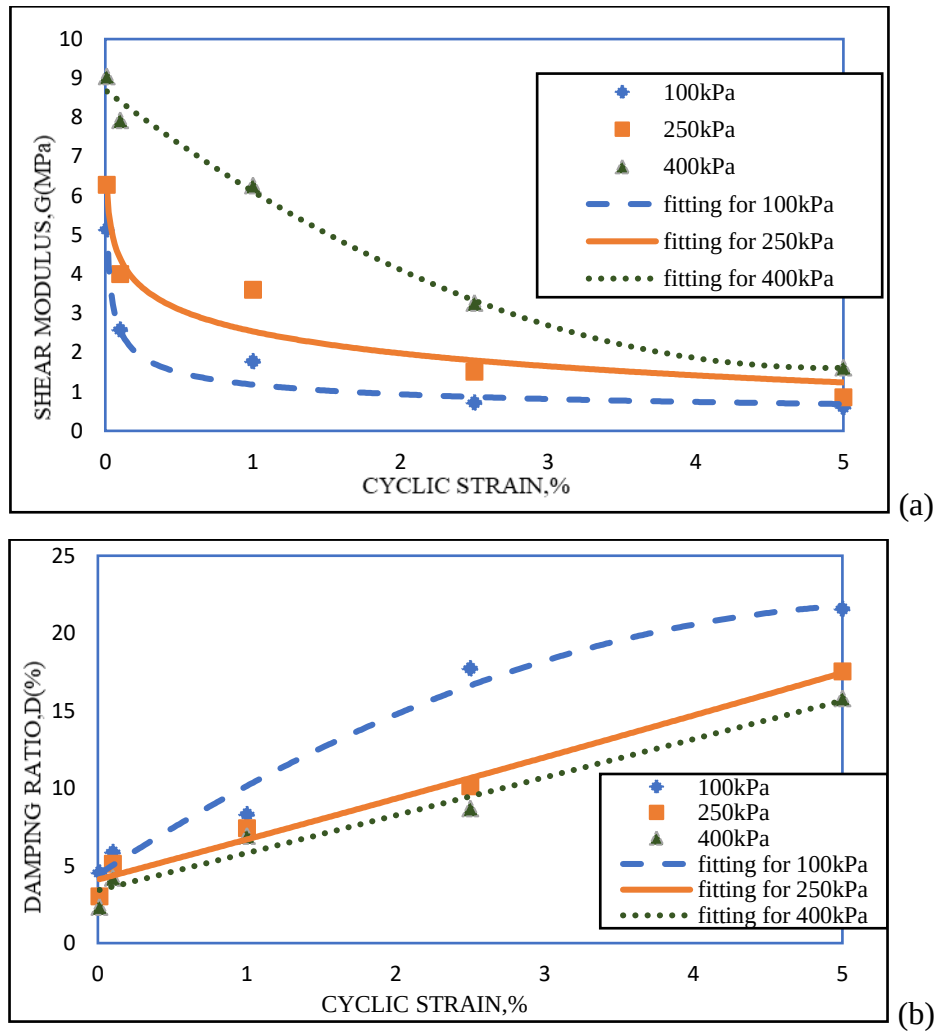


Figure 4.8 Variation of shear modulus (a) and damping ratio (b) of Amar3 clay soil with confining pressure

4.4.3.2 Variation of Shear Modulus and Damping Ratio with cyclic shear strain

Shear modulus and damping ratio of cyclically loaded soils vary significantly with the amplitude of shear strain due to nonlinear deformation characteristics (Hardin & Drnevitch, 1972). Figure 4.9 (a and b) show the variations of shear modulus and damping ratio of MD3 (silty sand soil)

with shear strain for the remaining two pits (Amar3 and DP3) refer to appendix I-2. It was observed that shear modulus decreases, because at higher values of shear strain, the soil strength becomes smaller to resist deformation and more energy released to yield high deformation. and damping ratio increases with increasing cyclic shear strain due to energy dissipation during deformation of soil. Similar observations were reported by many other researchers ((Hardin & Drnevitch, 1972), (Jafarzadeh & Sadeghi, 2012) and (Sezer et al., 2019)). Asfaw (2015) has been observed increasing number of cycles decreases the effect of shear strain on shear modulus and same for damping ratio, and similar trend is observed in Figure 4.9 (a and b).

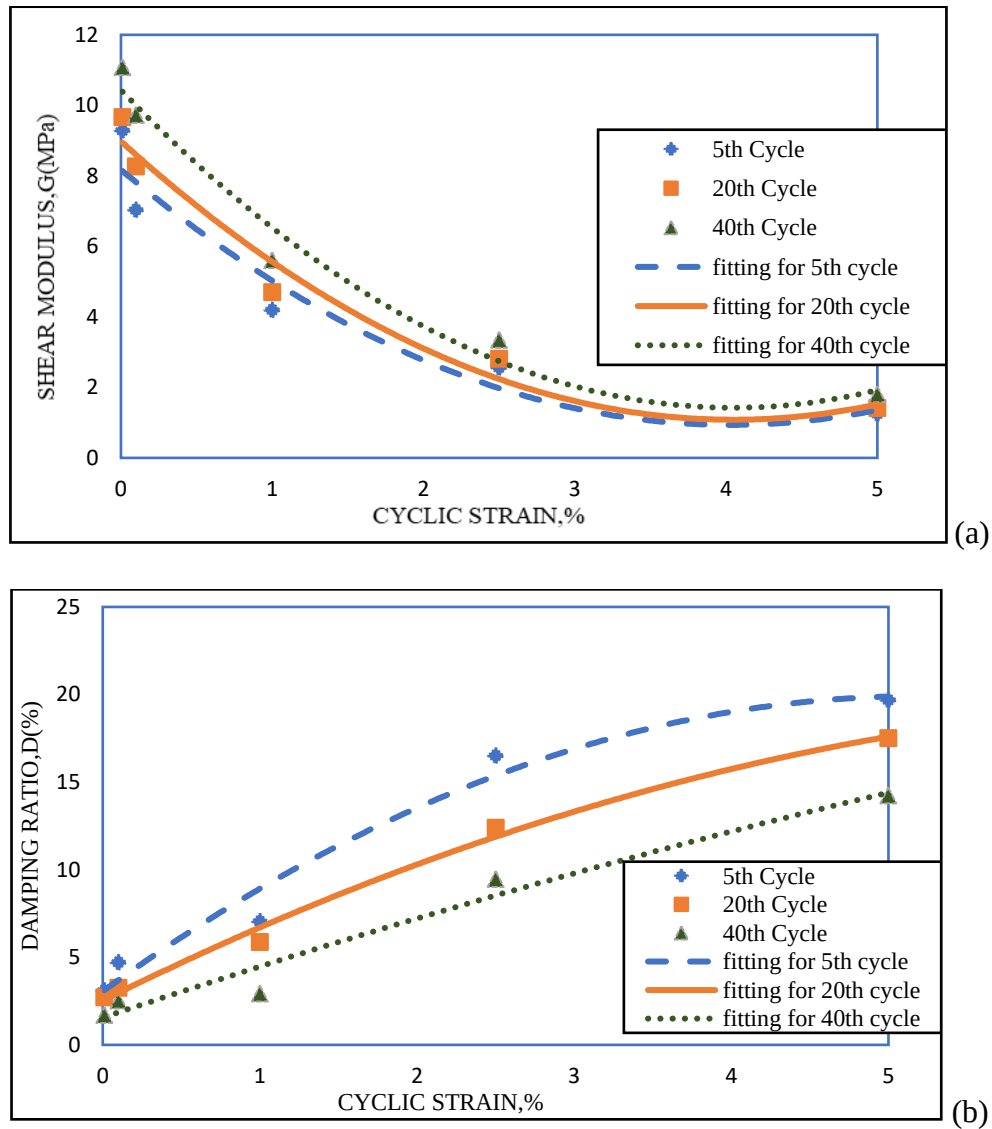


Figure 4.9 Variation of shear modulus (a) and damping ratio (b) of MD3 silty sand soil with cyclic shear strain amplitude

4.4.3.3 Variation of Shear Modulus and Damping Ratio with number of loading cycles

Figures 4.10 (a and b) provided that the shear modulus and damping ratio curves at constant confining pressure (100kPa) with two different cyclic shear strains (i.e., 0.01% and 5%) for all three pits to show the effect of number of loading cycle (i.e., 40 cycles). From these curves, it can be observed that the shear modulus increases as number of cycles are increasing and the damping ratio decreases with an increasing number of cycles. The trend observed is similar to that for the effect of number of cycles reported by ((Seed et al, 1986), (Bekele, 2020)). To show the two remaining confining pressure refer to Appendix I-3. Das (2011) indicates that the values determined at the 5th cycle are likely to provide reasonable values for all practical purposes. Due to this reason, in this research, the values determined at the 5th cycle are considered for most analysis purposes.

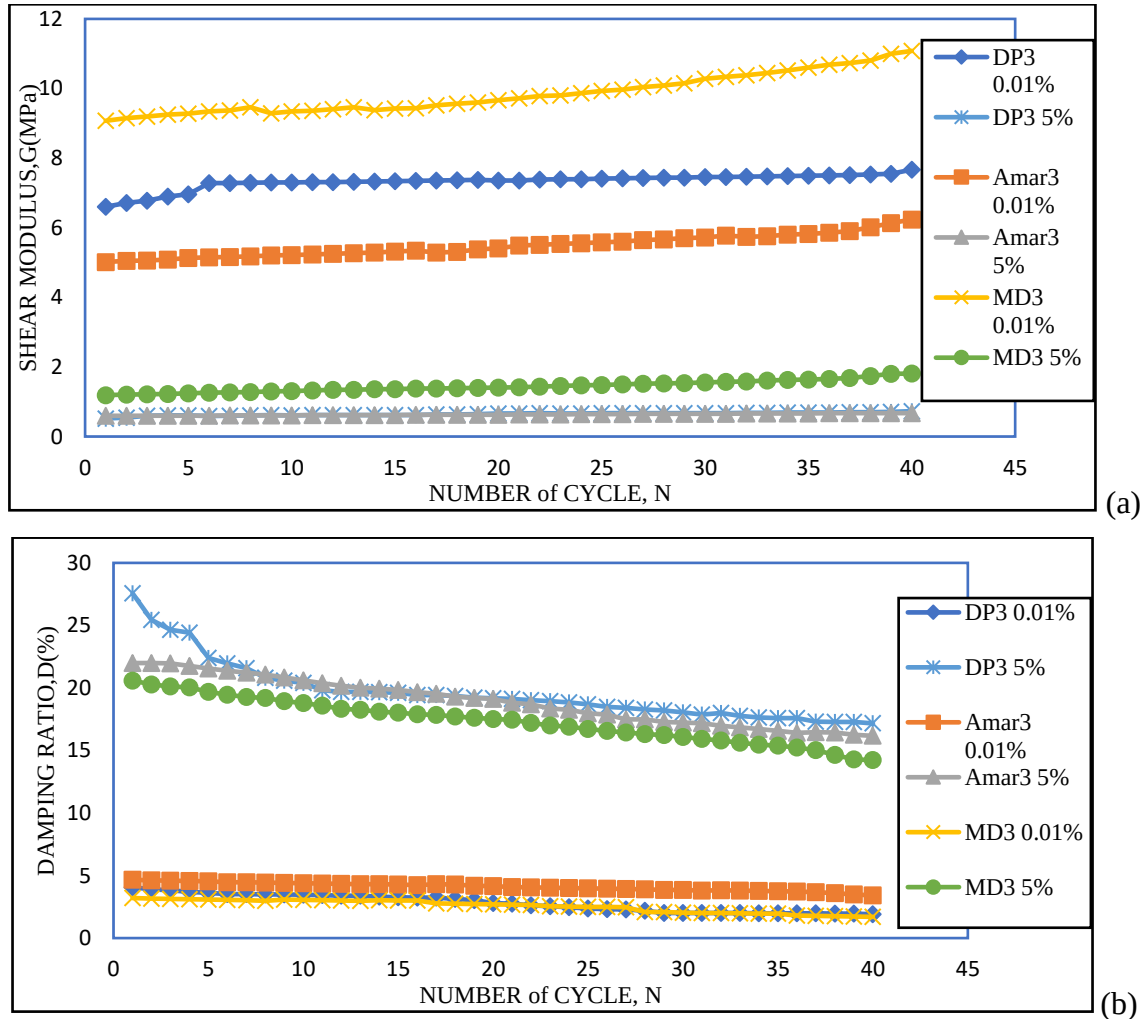


Figure 4.10 Variation of shear modulus (a) and damping ratio (b) with number of loading cycles for 100kPa axial stress and two different strains (0.01% and 5%)

4.4.3.4 Variation of Shear Modulus and Damping Ratio with Soil Plasticity

As shown in the figure 4.11 (a and b), the shear modulus increase, and the damping ratio decrease as the soil plasticity increase with the same axial stress and soil type (Clay). This trend is in good agreement with well established curve given by Vucetic and Dobry (1991) for different values of plasticity index. However, the effect was not significant for larger strains ($\gamma_c \geq 1\%$). This is because highly plastic soils tend to have a more linear cyclic stress-strain response at smaller strains and degrade less at larger shear strain (Vucetic & Dobry, 1991), In this case shear modulus of soil with 32 PI decreases more slowly with the increase in shear strain than that of with 47 PI soil.

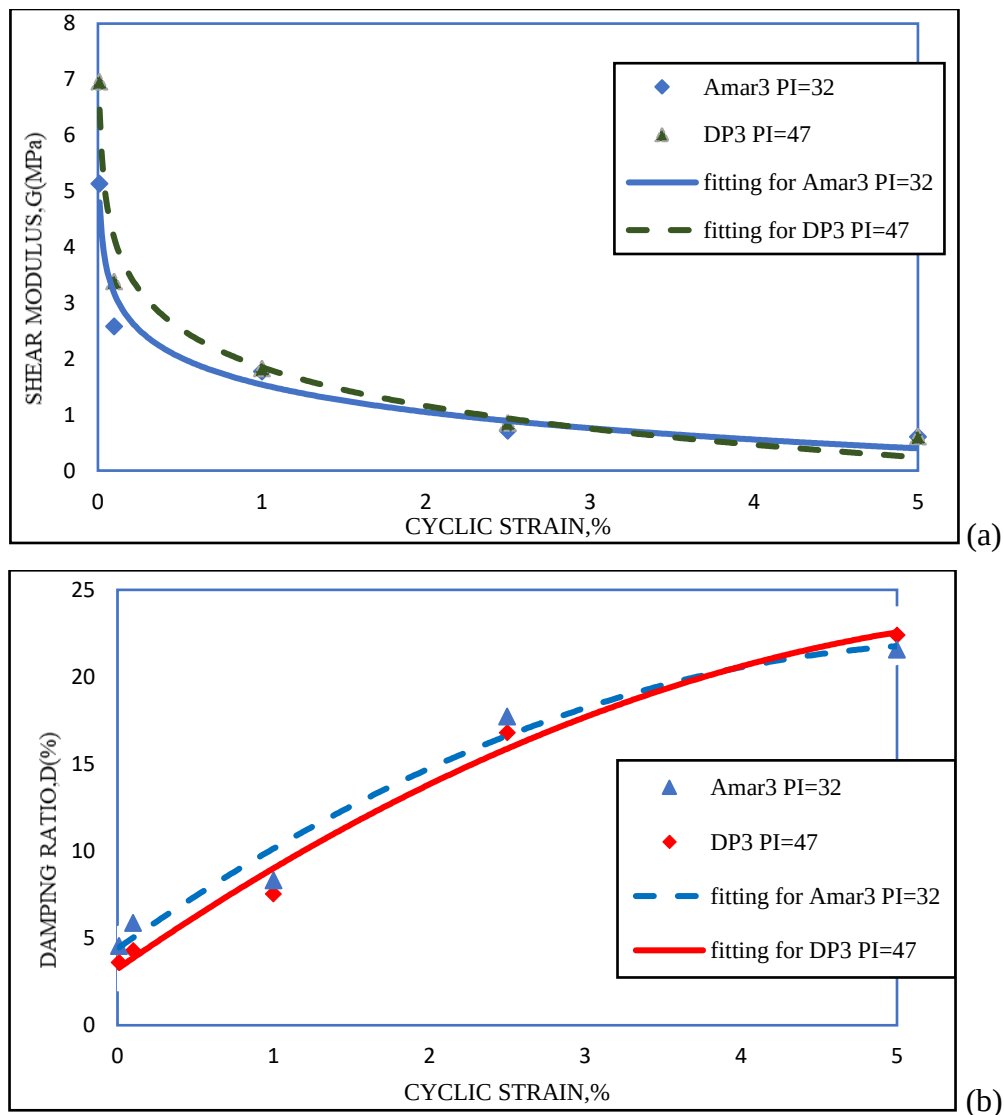


Figure 4.11 Variation of shear modulus (a) of Kombolcha clay soil and damping ratio (b) with soil plasticity at a confining pressure of 100kPa

4.4.3.5 Variation of Shear Modulus and Damping Ratio with Soil Type

From figures 4.12 (a and b) it can be observed that the silty sand (MD3) has higher shear modulus values than the clay soil (Amar3), especially at maximum confining stress (i.e., 400kPa). Because coarser materials show good resistance to cyclic shear under high confining stress (Luna & Jadi, 2000). The effect of soil type becomes decreases at larger shear strain, especially for lower confining stress. However, the effect is not significant for the damping ratio value. Welay (2017) has been observed the same behavior for sand and silt soil.

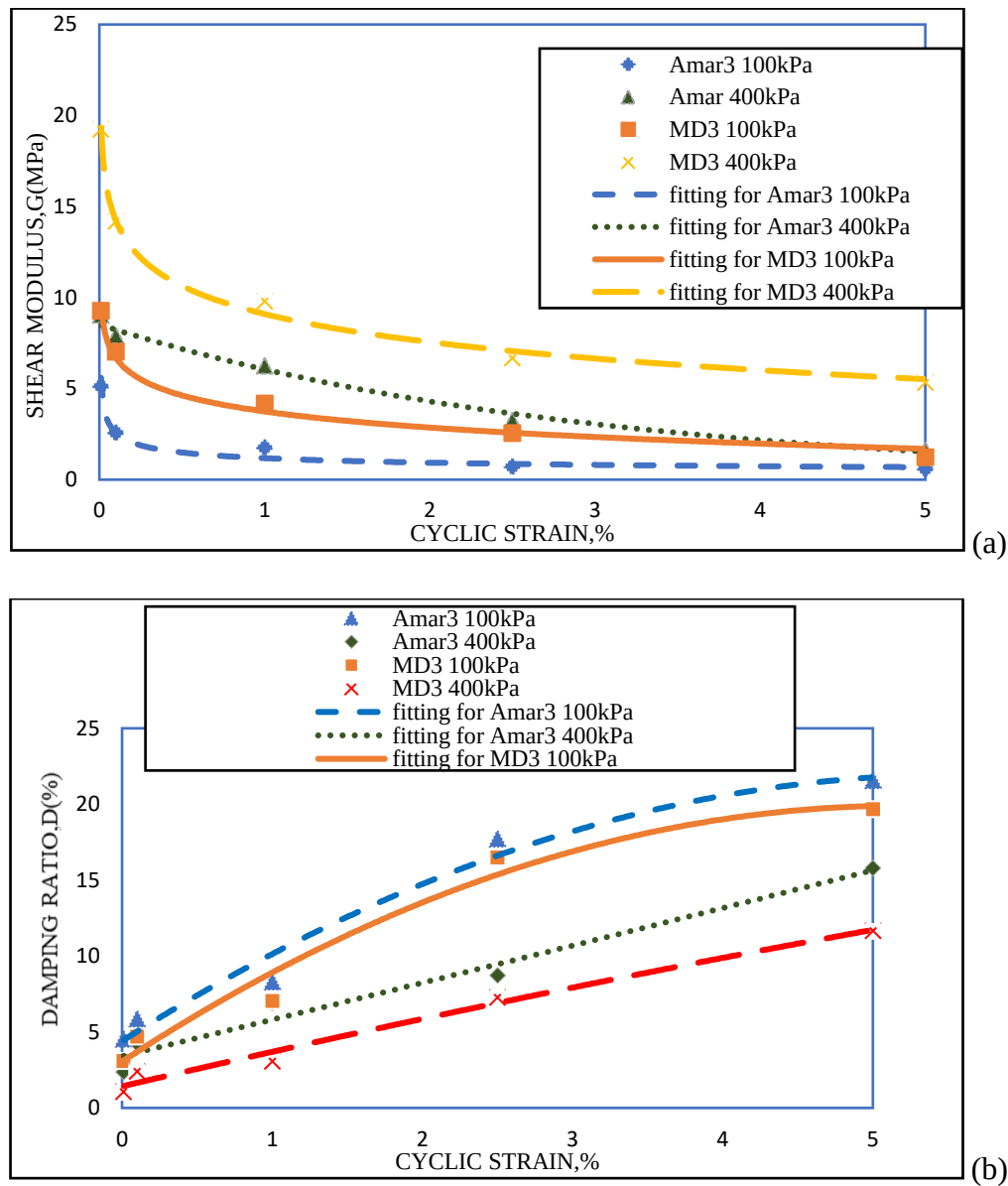


Figure 4.12 Variation of shear modulus (a) and damping ratio (b) with Clay (Amar3) and Silty Sand (MD3) soil type

4.4.3.6 Variation of Shear Modulus and Damping Ratio with Void Ratio

The variation of shear modulus with void ratio was observed by plotting the maximum shear modulus of Kombolcha soil results with confining pressure having different void ratios. It is observed from figure 4.13 that as the void ratio increase, the maximum shear modulus decreases and has no significant influence on the damping ratio at any shearing strain amplitude under all confining pressures and this result is agreed with literatures ((Sitharam & Vinod, 2010), (Asfaw, 2015),(Arficho, 2021)). The reason for this behavior is; when void ratio decreases, the area of contact between soil particles becomes closer and result in increase for shear modulus especially for increament of confining stress and it can also be observed for this figure the effect becomes more significant when the confining pressure is $\geq 250\text{kPa}$ (especially for $e=1.21$ and $e=1.24$) this behavior is similar with Asfaw (2015).

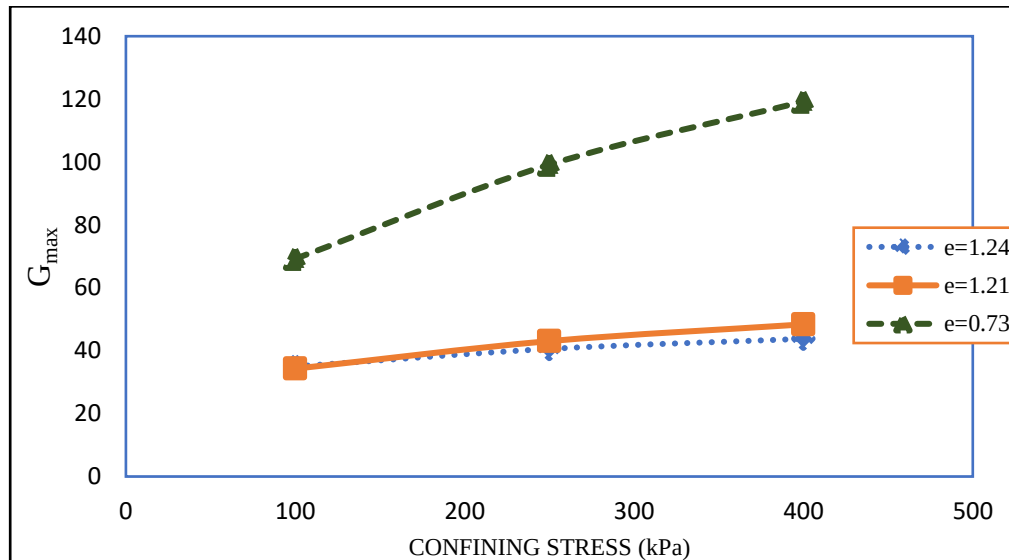


Figure 4.13 Variation of the maximum shear modulus of Kombolcha soil with void ratio

4.4.4 Comparison of Cyclic Test Results with Previous Studies

The result found from soil characterization was Clay and Silty Sand. The value of G/G_{max} and D of these soils results were compared with previous studies that developed a curve by Seed and Idriss (1970) for both sand soil and saturated clay soil by utilizing the value of normalized shear modulus and damping ratio with shear strain as shown in figures 4.14-4.15. On the other hand, the value of normalized shear modulus and damping ratio are compared with different previous local reports (Adama silty sand (Feyissa, 2011), Dire Dawa sand (Welay, 2017), Modjo silty sand (Asfaw, 2015), Ziway silty sand (Mengistu, 2015), Jimma silty clay (Birhanu, 2019),

(Dimer, 2013), Yeka clay (Bekele, 2020) and Gelan clay (Ayele, 2022) soils) by similar soil type considering similar confining pressure (100kPa and 400kPa were common) and shear strain as shown in Figure 4.16-4.19.

Comparison of Kombolcha silty sand soil with the curves developed for sand Seed and Idriss (1970) were done and the relationships are shown in Figure 4.14.

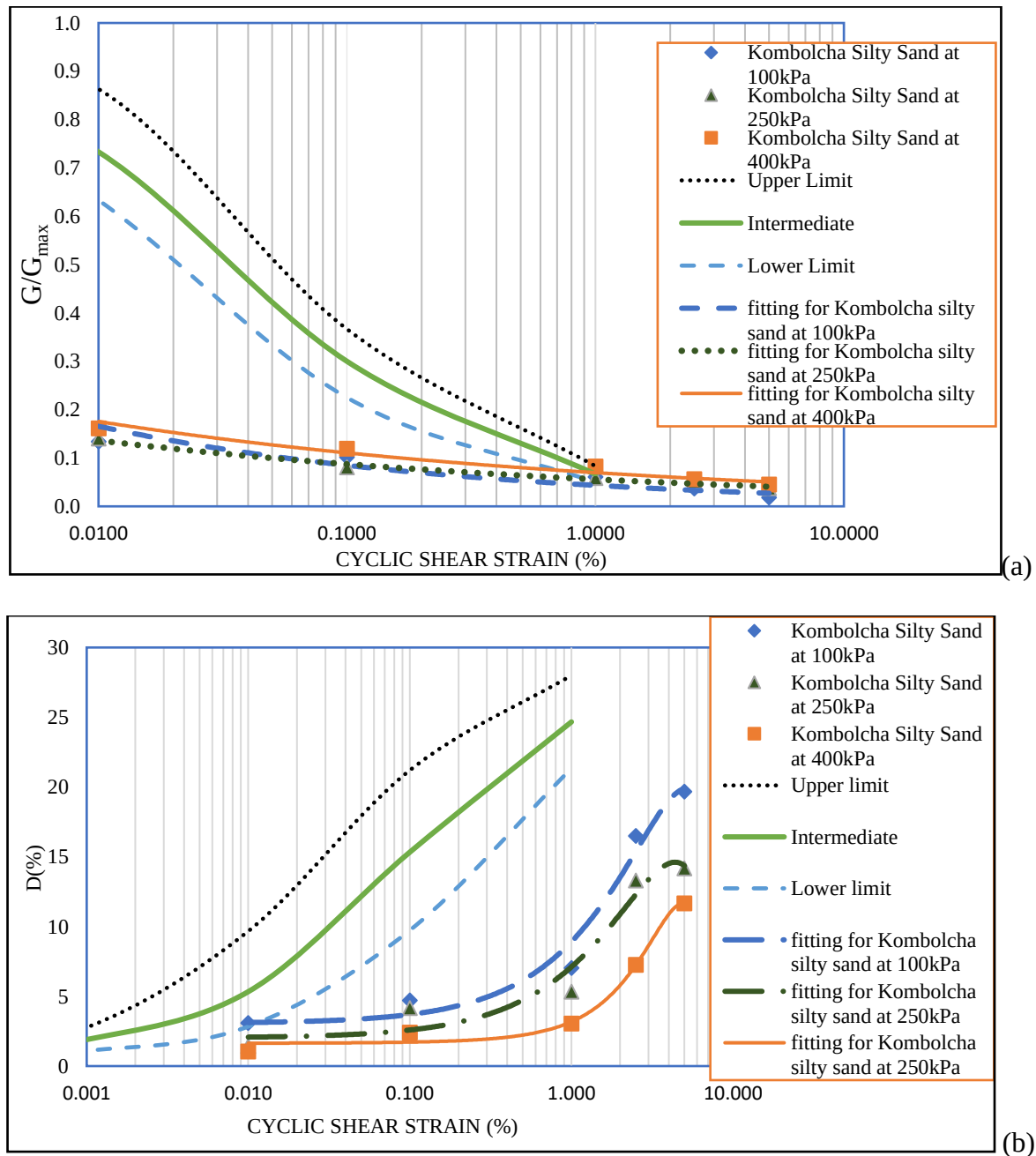
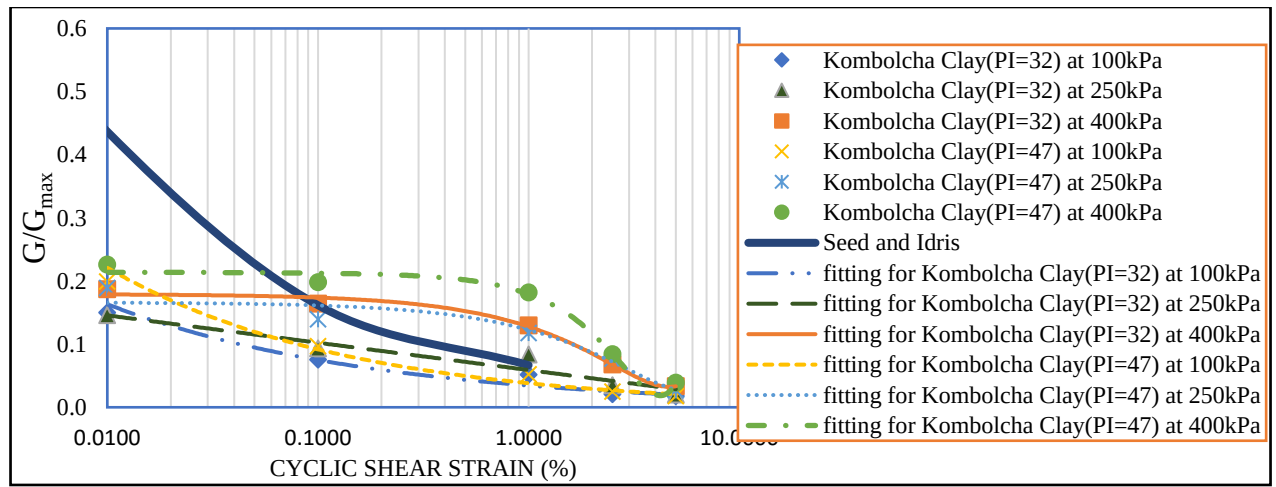


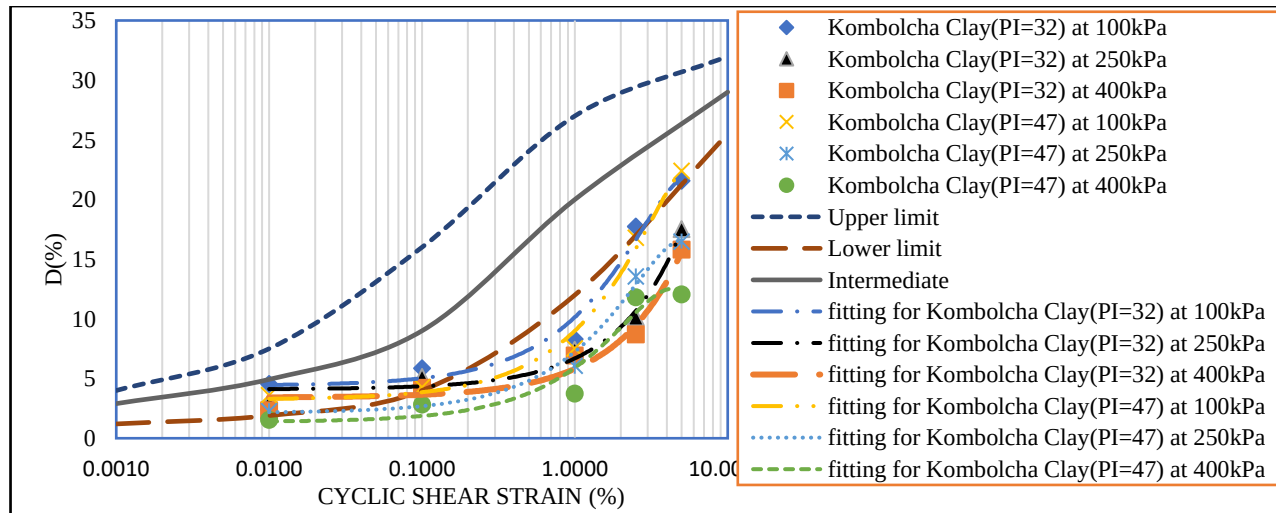
Figure 4.14 Comparison of (a) Normalized shear modulus and (b) damping ratio values of Kombolcha silty sand soil with the curves developed for sands by Seed and Idriss (1970)

In Figure.4.14 (a) the normalized shear modulus (G/G_{max}) values were plotted against shear strain on the curves of Seed and Idriss (1970) given for sand soil. It is observed that the shear modulus reduction values of the Kombolcha silty sand soil were lower than the limit at a smaller strain ($\gamma_c \leq 0.1\%$). However, for higher strains ($\gamma_c > 0.1\%$) the modulus reduction value agrees with the curve. The damping ratio values as shown in Figure 4.14 (b) are below the limit given by Seed and Idriss (1970) for sand with a similar trend. The reason for this reduction in value could be due to sampling preparation and testing conditions.

Comparison of Kombolcha silty sand soil with the curves developed for saturated clay by Seed and Idriss (1970) were done and the relationships are shown in Figure 4.15.



(a)



(b)

Figure 4.15 Comparison of (a) Normalized shear modulus and (b) damping ratio values of Kombolcha clay soil with the curves developed for saturated clay by Seed and Idriss (1970)

The modulus reduction values of Kombolcha Clay soil exhibited similar behavior when it was compared with the curve given for saturated clay (see Figure 4.15 (a)). and from Figure 4.15 (b) it can be seen that; half of the values are within the limit given by Seed and Idriss (1970) for saturated clay and half of them are below the limit.

In general, the reason for values determined for Kombolcha soil is some how lying out of ranges from the limits given by Seed and Idriss (1970) could be due to the type of testing machine for example since cyclic simple shear test was used for this study and Shen et al. (1978) reported that the Norwegian geotechnical institute (NGI) type direct simple shear device may introduce an error of 5 to 15 % in shear modulus and damping ratio determination wheareas, earlier studies were determined by the resonant column and the cyclic triaxial test so that the errors could be lower. Limited experience of the operator in conducting cyclic simple shear test could be also the reason as it is mentioned by Bekele (2020). Method of sample preparation could be also the other reason for this result, in this study, results were obtained using a remolded sample wheare as, the limits were given from undisturbed samples. The cyclic strength of undisturbed specimens was about 15% greater than that of remolded specimens (Kumar, 2014). Finally, use of empirical correlations could be also the reason for this variations since cyclic simple shear test can not be used for lower strain amplitude and due to the limitation of in situ test results maximum shear modulus was obtained from the empirical equation and it causes a reduction of normalized shear modulus values.

Comparison of Kombolcha silty sand soil with Adama silty sand (Feyissa, 2011), Dire Dawa sand (Welay, 2017), Modjo silty sand (Asfaw, 2015), Ziway silty sand (Mengistu, 2015) soils were done and the relationships are shown in the following figures below.

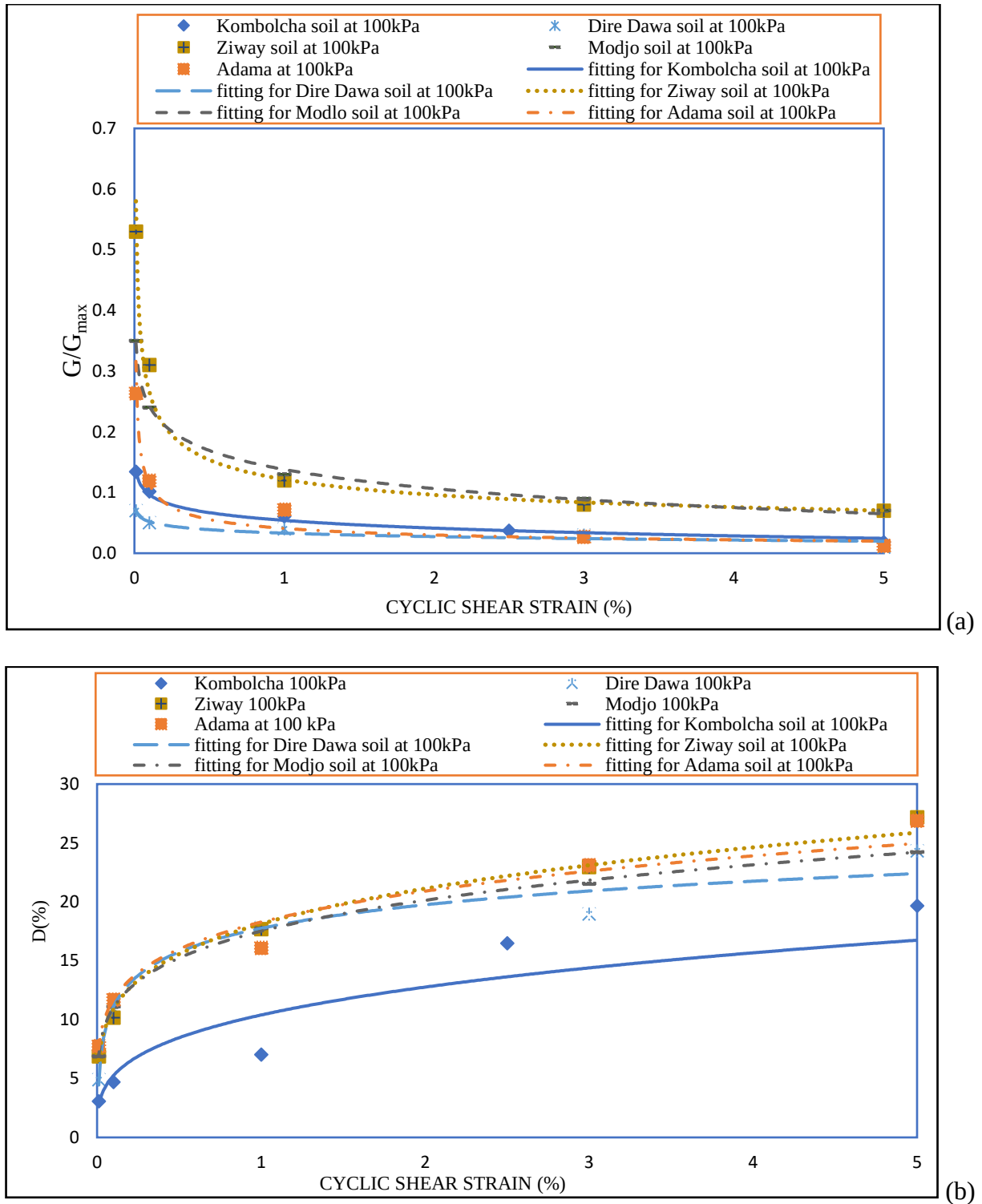


Figure 4.16 Comparison of Normalized shear modulus(a) and damping ratio(b) values of Kombolcha silty sand soil with the curves developed for Dire Dawa sand, Ziway, Modjo, and Adama silty sand soils at 100kPa

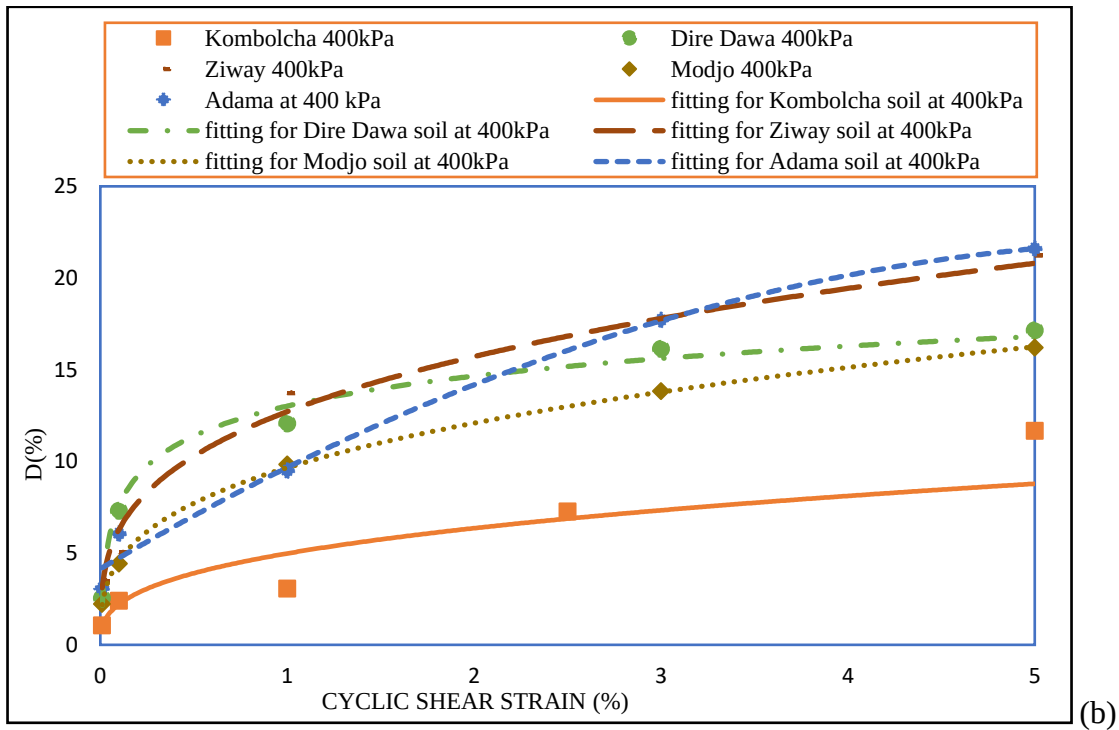
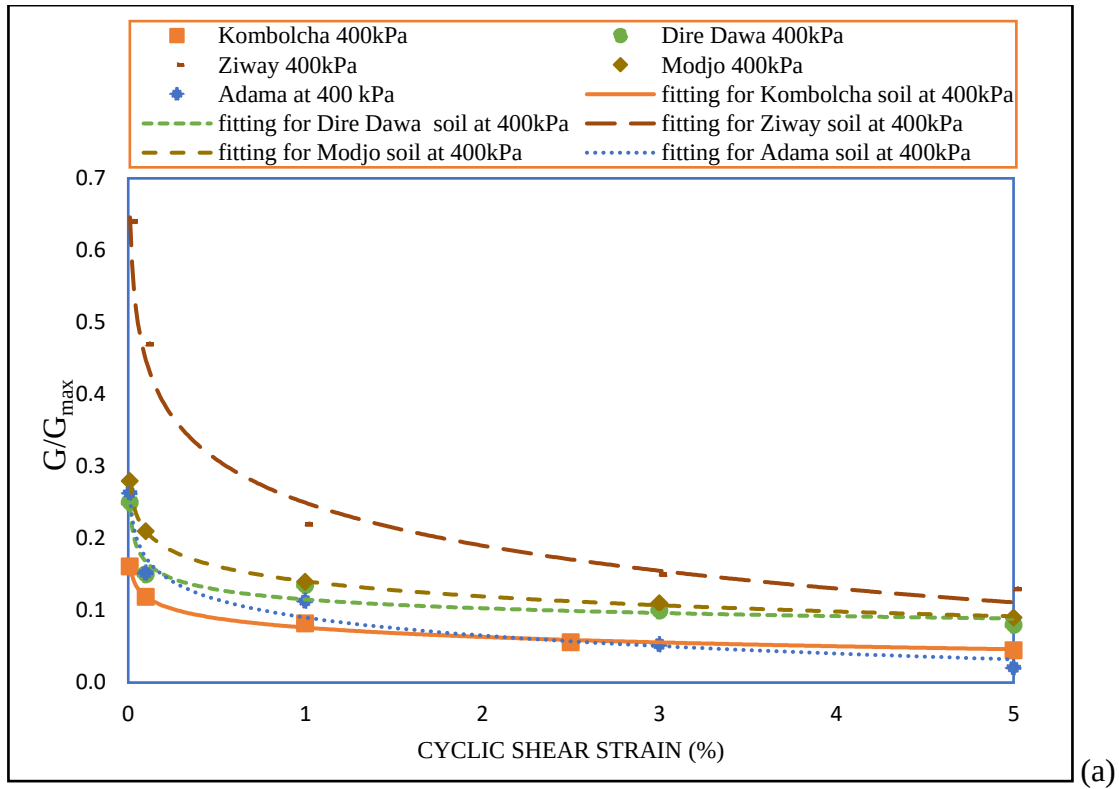
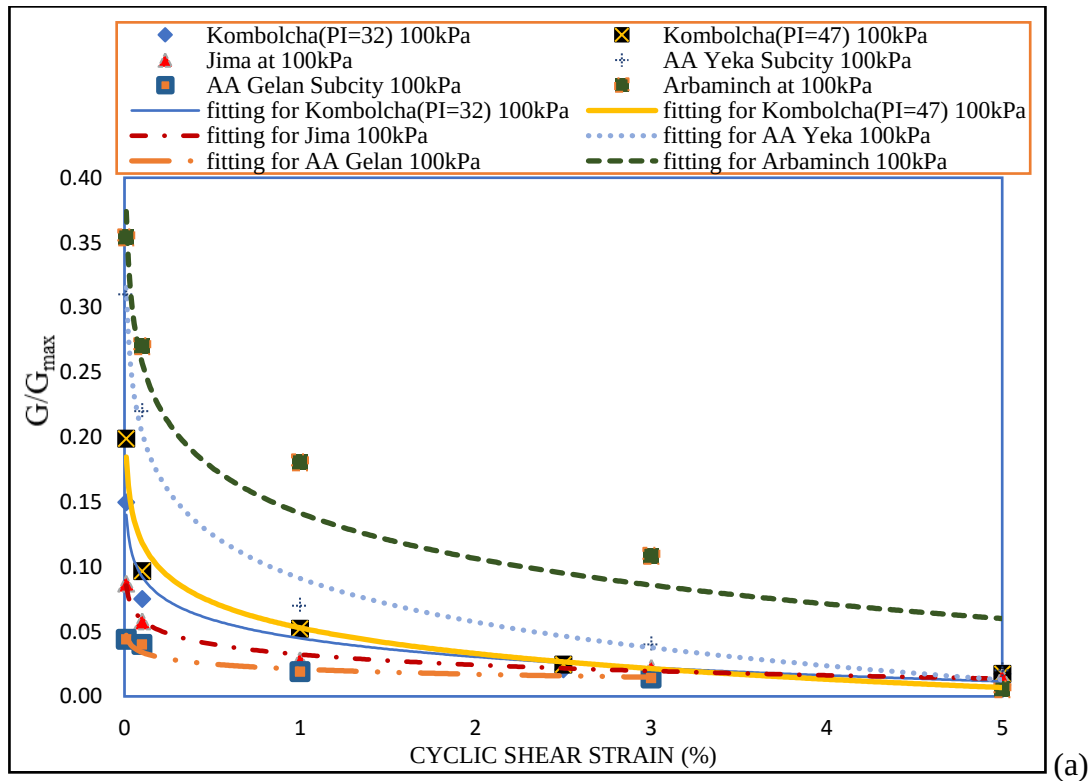


Figure 4.17 Comparison of Normalized shear modulus(a) and damping ratio(b) values of Kombolcha silty sand soil with the curves developed for Dire Dawa sand, Ziway, Modjo, and Adama silty sand soils at 400kPa

From Figure 4.16 (a) it is observed that the normalized shear modulus of silty sand at 100kPa is in good agreement with Adama silty sand when strain $\geq 0.1\%$ and Dire Dawa sand soil for all strain values. However, it is lower than the curves given for Modjo and Ziway Silty sand soils. At confining stress of 400kPa Kombolcha silty sand soil is in good agreement with Adama silty sand soil for larger strain ($\geq 2.5\%$), but slightly lower for ($< 2.5\%$) strain and has a lower value of normalized shear modulus compared with Dire Dawa sand, Ziway, and Modjo silty sand soils (see Figure 4.17 (a)). The value of the damping ratio for silty sand is the least for both 100kPa and 400kPa (see Figures 4.16(b) and 4.17(b)). From this result, it can be said that Kombolcha Silty sand has less value of both G/G_{max} and damping ratio as compared with Dire Dawa, Ziway, and Modjo results but is compatible with Adama silty sand soil of normalized shear modulus.

Comparison of Kombolcha clay soil with Jimma silty clay (Birhanu, 2019), Arbaminch clay (Dimer, 2013), Yeka clay (Bekele, 2020), and Gelan clay (Ayele, 2022) soils were done and the relationships are shown in the following figures below.



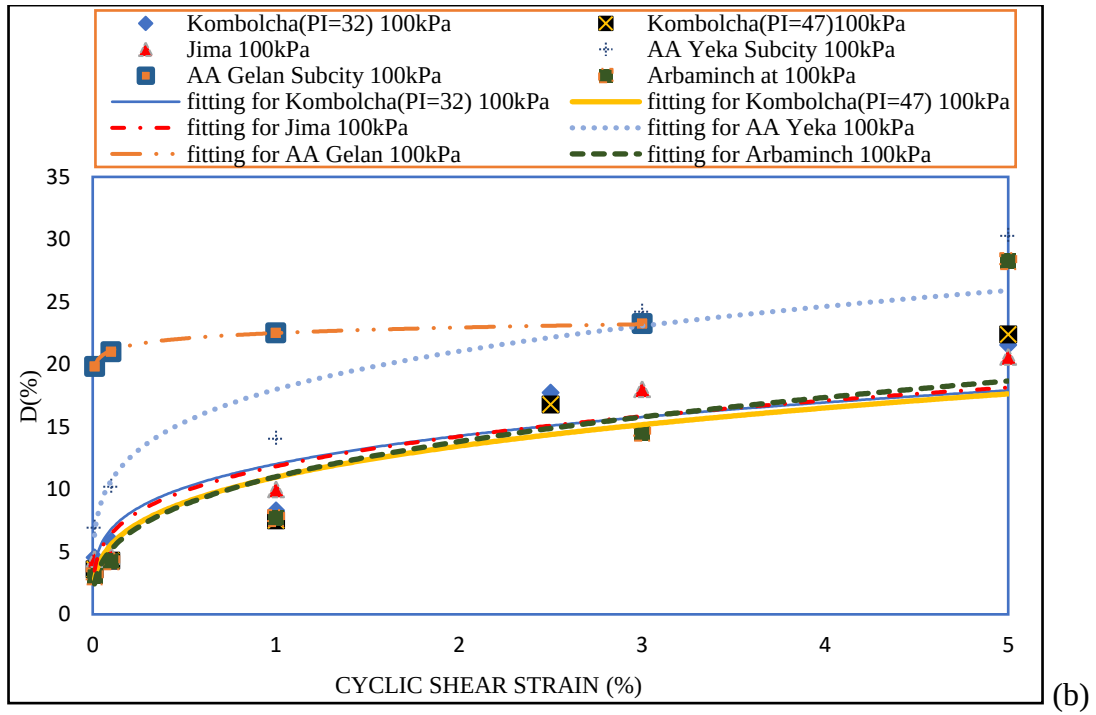
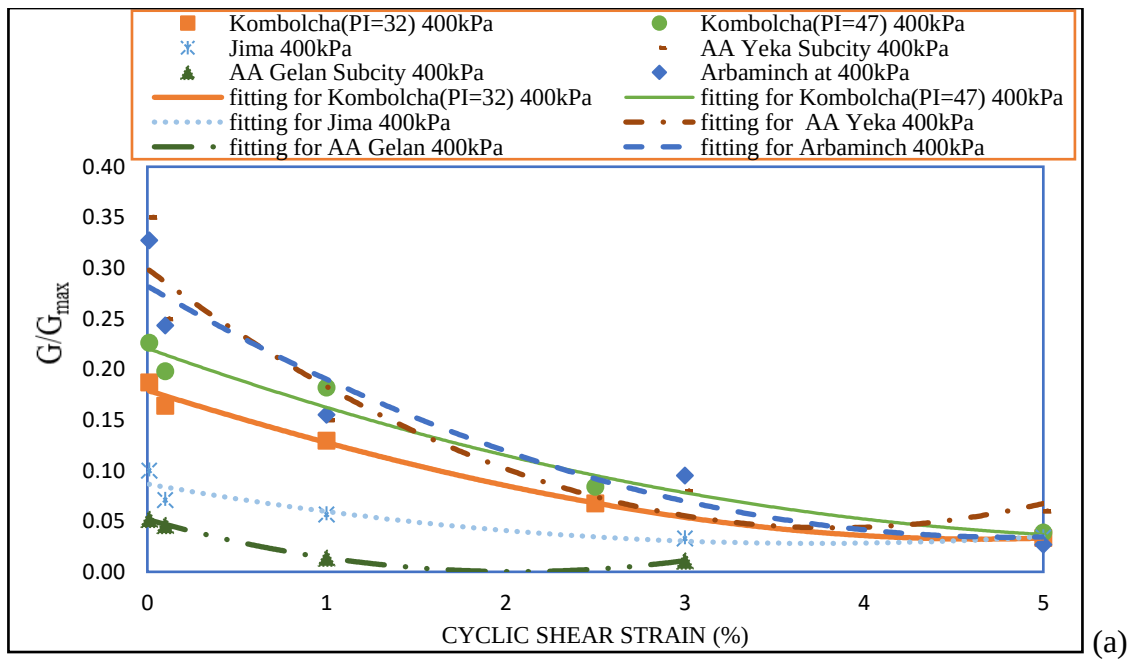


Figure 4.18 Comparison of Normalized shear modulus(a) and damping ratio(b) values of Kombolcha clay soil with the curves developed for Jima, Arbaminch, Addis Ababa Yeka sub-city, and Addis Ababa Gelan sub-city clay soils at 100kPa



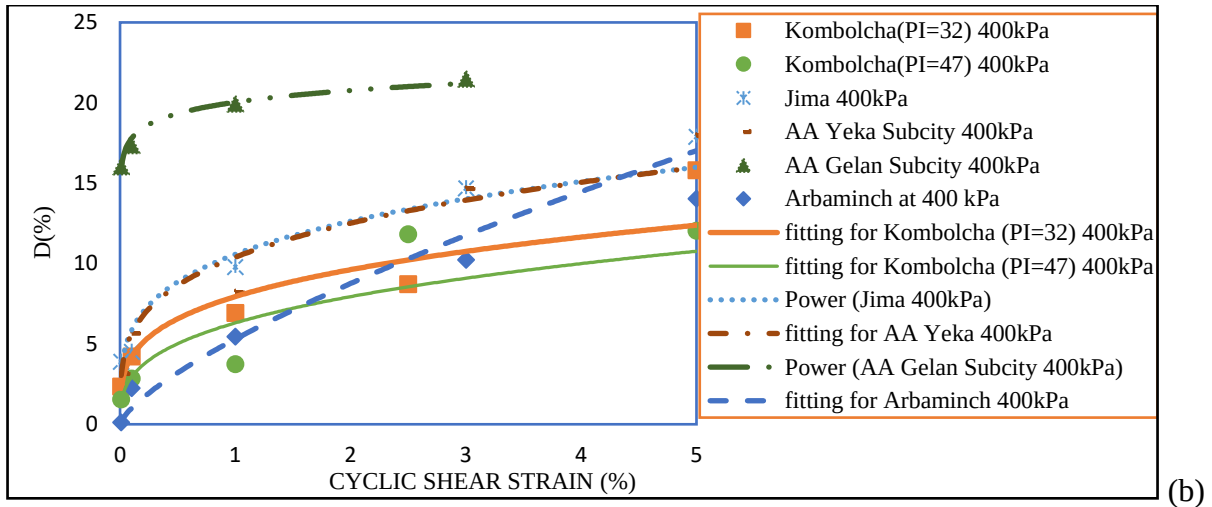


Figure 4.19 Comparison of Normalized shear modulus (a) and damping ratio(b) values of Kombolcha clay soil with the curves developed for Jima, Arbaminch, Addis Ababa Yeka sub-city, and Addis Ababa Gelan sub-city clay soils at 400kPa.

From figure 4.18 (a) and 4.19 (a) it is illustrated that the G/G_{max} of Kombolcha clay soil is in a good agreement with Jima and Gelan, but lower than Yeka and Arbaminch clay soils for both plasticity index (PI=32 and PI=47) and confining pressure (100kPa and 400kPa) variations for all strain. For strain values, ($\geq 1\%$) Kombolcha clay soil is compatible with all local soils. In the case of damping ratio, Kombolcha clay soil (PI=32 and PI=47) has a good agreement with Jima and Arbaminch clay soil at 100kPa confining stress and lower than Yeka and Gelan clay soils. For 400 kPa confining pressure, Kombolcha clay soil has a good agreement with Arbaminch clay soil, but a lower damping ratio as compared with Yeka, Gelan, and Jima clay soils (see Figures 4.18 (b) and 4.19 (b)).

Generally, Kombolcha's values were a bit lower than compared local towns, the reason for this could be due to the difference in preparation of sample, disturbance caused by sampling and sample preparation alters soil properties such as fabric and structures, stress history, strain history, density and degree of saturation. All of these adversely affect the ability of laboratory tests to accurately measure dynamic soil properties. As PI, OCR, void ratio of soil, and empirical equation used for the determination of maximum shear modulus is different, the value of normalized shear modulus also different. From this reason, higher value of maximum shear modulus results lower value of normalized shear modulus. Duration of consolidation stage during operation of cyclic simple shear test could be also the reason for this variation of results as compared with previous studies for local towns.

5 CONCLUSION AND RECOMMENDATION

5.1 Conclusion

This study has investigated the dynamic properties (shear modulus(G) and Damping ratio(D) values) of Kombolcha soil using cyclic simple shear test apparatus. The soil samples collected were clay (CH) and silty sand (SM) soils. The soil was remolded in the field condition from field density and natural moisture content results determined from the sand cone apparatus. Strain-controlled cyclic simple test at strain values of 0.01%, 0.1%, 1% 2.5%, and 5% and under axial stress of 100kPa, 250kPa and 400kPa. The following conclusion are drawn based on analysis and interpretation of the laboratory test results:

- The shear modules value for clay-type samples ranges from 0.52 MPa to 10.79 MPa, the damping ratios are between 1.36% and 27.57%, and maximum shear modulus values range from 34.3MPa to 48.57MPa. These range values for Kombolcha clay soils are somewhat similar to values from previous studies on similar type of soils.
- The shear modules value for silty sand-type samples ranges from 1.19 MPa to 24.9 MPa, the damping ratios are between 0.83% and 20.60%, and maximum shear modulus values range from 69.24 MPa to 119.23 MPa These range values for Kombolcha silty sand soils are somewhat similar to values from previous studies on similar type of soils.
- The influence of different parameters on dynamic properties of Kombolcha soils was investigated. It was observed that the value of shear modulus increased as confining pressure, number of cycles, and plasticity increased, but it decreased with cyclic strain amplitude and void ratio (for $G_{\max}$). Similar trends were observed by other researchers.
- The damping ratio values increased as cyclic shear strain amplitude increased, but it decreased as confining pressure, number of cycles, and plasticity increased. Similar trends were observed by other researchers.

5.2 Recommendation

In this study, the values of shear modulus and damping ratio of Kombolcha town soil using cyclic simple shear apparatus were determined. The following points are recommended based on these findings:

- The shear modulus and damping value of Kombolcha soil determined from this study could be used as an input parameter for the design of dynamic loading resistant buildings, retaining walls and embankments, analysis of soil-structure interactions, and machine foundations.
- The test could be investigated using the cyclic triaxial machine for better understanding.
- To observe the effect of other factors on the damping and shear modulus values it is recommended to conduct the test by considering additional factors.
- To have an accurate initial modulus (G_{max}) value it is recommended to conduct a small strain field (Geophysical) or laboratory test (Resonant column test).

REFERENCE

- Abdellaziz, M., Karray, M., & Chekired, M. (2019). Shear modulus and damping ratio curves of sensitive Eastern Canadian clays in cyclic simple shear triaxial test. *in 12th Canadian conference on earthquake engineering*, pp. 1–8.
- Arficho, T. A. (2021). Experimental study of soil under static and cyclic shear loading: a case of awash melkasa town. *Adama Science and Technology University*
- Asfaw, Y. H. (2015). Investigation of Shear Modulus and Damping Ratio of Modjo Silt and Silty Sand Soil Using Cyclic Simple Shear Test. *Adama Science and Technology University*
- ASTM D1556 (2001). Standard Test Method for Density and Unit Weight of Soil in Place. *ASTM International, West Conshohocken, PA. Significance, 04 (Reapproved)*, 1–6.
- ASTM D2435 (2010). Standard Test Methods for One-Dimensional Consolidation Properties of Soils. *Annual Book of ASTM Standards, i*, pp. 1–10.
- ASTM D2487-06 (2017). Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System). *ASTM International, West Conshohocken, PA.*
- ASTM D3282-15. (1993). Standard Practice for Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes (AASHTO). *ASTM International*, pp. 1–6.
- ASTM D422-63. (2007). Standard Test Method for Particle-Size Analysis of Soils. *ASTM International, D422-63 (Reapproved)*, pp. 1–8.
- ASTM D4318-17 (2005). Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils. *Report, 04(March 2010)*, 1–14.
- ASTM D6528-17. (2017). Standard Test Method for Consolidated Undrained Direct Simple Shear Testing of Cohesive Soils. *Astm International, 04.09(August 2017)*, 1–10.
- ASTM D854-10 (2010). Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer, *ASTM International, West Conshohocken, PA.*
- Ayele, A. B. (2022). A Study on the Dynamic Property of Expansive Soil Treated With Sugarcane Bagasse Ash. *Adama Science and Technology University*
- Bedr, S., Mezouar, N., Verrucci, L., & Lanzo, G. (2019). Investigation on shear modulus and damping ratio of Algiers marls under cyclic and dynamic loading conditions. *Bulletin of Engineering Geology and the Environment*, 78(4), pp. 2473–2493.
- Bekele, N. (2020). A Study of Dynamic Properties of Soils Found in Yeka subcity Area of Addis Ababa. *Addis Ababa Institute of Technology*

- Birhanu, K. T. (2019). *Cyclic Behaviour and Dynamic Properties of Soils: A Case of Jimma Town. Addis Ababa Science and Technology University*
- CES. (2015). *Design of Structures for Earthquake Resistance-Part 1: General rules-seismic actions and rules for buildings*. Ethiopian Standards Agency
- Chattaraj, R., & Sengupta, A. (2016). Liquefaction potential and strain dependent dynamic properties of Kasai River sand. *Soil Dynamics and Earthquake Engineering*, pp. 467–475.
- CSA. (2012). *2007 Population and housing census of Ethiopia administrative report* Central Statistical Authority Addis Ababa, Ethiopia.
- CSA. (2021). *Population Size of Towns by Sex, Region, Zone and Weredas as of July 2021*. National Statistical Press, pp. 1–118.
- Das, B. M. (2011). *Principles of Soil Dynamics*, Second Edition., Stanford, USA: Cengage Learning, 96-185 pp.
- Dimer, M. (2013). Investigation of Dynamic property of soil found in Arba Minch Town. *Addis Ababa University*
- El Mohtar, C. S., Drnevich, V. P., Santagata, M., & Bobet, A. (2013). Combined resonant column and cyclic triaxial tests for measuring undrained shear modulus reduction of sand with plastic fines. *Geotechnical Testing Journal*, 36(4).
- Fakharian, K., Shirkavand, D., & Hejazi, M. (2019). A comparison between simple shear and triaxial tests for evaluating the variations of g and d with matric suction. *E3S Web of Conferences*, 92, pp. 1–6.
- Feyissa, A. G. (2011). Shear Modulus and Damping Ratio values of Soils found in Adama. pp. 1–104. *Addis Ababa Institute of Technology*
- Gabrys, K., Soból, E., Sas, W., Šadzevičius, R., & Skominas, R. (2021). Warsaw glacial quartz sand with different grain-size characteristics and its shear wave velocity from various interpretation methods of bet. *In Materials* (Vol. 14, Issue 3, pp. 1–26).
- GPS. (2022). *GPS coordinates of Kombolcha, Ethiopia. Latitude: 11.0667 Longitude: 39.7333*. retrived from <https://latitude.to/articles-by-country/et/ethiopia/29315/kombolcha>
- Haileslassie, W. (2017). Study on Some Static and Dynamic Properties of Soils Commonly Found In Dire Dawa Town. *Adama Science and Technology University*
- Hardin, B. O, & Drnevich, V. P. (1972) Shear modulus and damping in soils: measurement and parameter effects. *Journal of Soil Mechanics and Foundations Division*; 6: pp. 603–624.
- Hsiao, DH., & Phan V.T. (2016). Evaluation of static and dynamic properties of sand–fines mixtures through the state and equivalent state parameters. *Elsevier*.

- Hussien, M. N., & Karray, M. (2016). Shear wave velocity as a geotechnical parameter: An overview. *In Canadian Geotechnical Journal* (Vol. 53, Issue 2, pp. 252–272).
- Ishihara K. (1996). *Soil Behaviour in Earthquake Geotechnics*. Oxford science publications.
- Jafarzadeh, F., & Sadeghi, H. (2012). Experimental study on dynamic properties of sand with emphasis on the degree of saturation. *Soil Dynamics and Earthquake Engineering*, 32(1), pp. 26–41.
- Jia, J. (2018). Soil Dynamics and Foundation Modeling. *In Soil Dynamics and Foundation Modeling*.
- Karray, M., & Chekired, M. (2019). Triaxial simple shear test: TxSS. *E3S Web of Conferences*, 92, pp. 1–6.
- Kinde, S., Engeda, S., Kebede, A., & Tessema, E. (2011). Technical notes and proposed guidelines on updated seismic codes in ethiopia implication for large-scale infrastructures. *In Journal of EEA* (Vol. 28).
- Kramer, S. L. (1996). *Geotechnical earthquake engineering*. Prentice Hall; New Jersey (NJ).
- Kumar, S. S., Krishna, A. M., & Dey, A. (2017). Evaluation of dynamic properties of sandy soil at high cyclic strains. *Soil Dynamics and Earthquake Engineering*, 99, pp. 157–167.
- Lakachew Atinafu (2019). *ERC finalizing Awash-Kombolcha Railway project*. Retrieved May 24, 2022, from <https://en.wikipedia.org/wiki/Kombolcha>
- Luna, R., & Jadi, H. (2000). Determination of dynamic soil properties using geophysical methods. *First International Conference on the Application of Geophysical and NDT Methodologies to Transportation Facilities and Infrastructure, December*, pp. 1–15.
- Mapcarta. (2022). *Kombolcha-Map-Ethiopia*. Retrieved from <https://mapcarta.com/13012424>
- Mengistu, A. (2015). Investigation Into Some Dynamic Properties of Soils Around Ziway. *Addis Ababa University*
- Munirwansyah, M., Munirwan, R. P., Listia, V., Munirwan, H., & Melinda, Z. (2020). Void ratio effect on dynamic shear modulus and shear wave velocity for soil stiffness in Banda Aceh and Aceh Besar. *(ICTAP) Journal of Physics: Conference Series*, 1572, pp. 12090.
- Okur, D. V., & Ansal, A. (2007). Stiffness degradation of natural fine grained soils during cyclic loading. *Soil Dynamics and Earthquake Engineering*, 27(9), pp. 843–854.
- Qiao, F., Bo, J., Qi, W., Wang, L., Chang, C., Zhang, Z., & Wang, J. (2020). Study on the dynamic characteristics of soft soil. *RSC Advances*, 10(8), pp. 4630–4639.
- Sas, W., Gabryś, K., & Szymański, A. (2017). Experimental studies of dynamic properties of Quaternary clayey soils. *Soil Dynamics and Earthquake Engineering*, 95, pp. 29–39.

- Seed, H. B., & Idriss, I. M. (1970) Soil moduli and damping factors for dynamic response analyses. Report No. EERC 70–10, *Earthquake Engineering Research Centre*, University of California, Berkeley, California.
- Seed, H. B., Wong, R. T., Idriss, I. M., & Tokimatsu, K. (1986). Moduli and damping factors for dynamic analyses of cohesionless soils. *Journal of Geotechnical Engineering*, 112(11), pp. 1016–1032.
- Sezer, A., Karakan, E., & Tanrinian, N. (2019). Shear modulus and damping ratio of a nonplastic silt at large shear strains. *E3S Web of Conferences*, 92, pp. 1–6.
- Shankar Kumar, S., Murali Krishna, A., & Dey, A. (2014). Parameters Influencing Dynamic Soil Properties: A Review Treatise. *International Journal of Innovative Research in Science*, 3(4), pp. 47–60.
- Shen, C.K., Hermann, L. R. and Sadigh, K. (1978), "Analysis of Cyclic Simple shear test data." ASCE, *Earthquake Engineering and Soil Dynamics*, Speciality Conference, Pasadena, pp 864-874.
- Sitharam, T. G., Ravishankar, B. V, & Vinod, J. S. (2008). Dynamic Properties of Dry Sands. *In Indian Geotechnical Journal* (Vol. 38, Issue 3).
- Sitharam, T. G., & Vinod, J. S. (2010). Evaluation of Shear Modulus and Damping Ratio of Granular Materials Using Discrete Element Approach. *Geotechnical and Geological Engineering* 28:5, 28(5), pp. 591–601.
- UTS004. (2003). *Simple shear test software reference*, Universal testing system, IPC Global
- Vucetic, M., & Dobry, R. (1991). Effect of soil plasticity on cyclic response. *Journal of Geotechnical Engineering*, ASCE 117(1), pp. 89–107.
- Wilks, M., Ayele, A., Kendall, J. M., & Wookey, J. (2017). The 24th January 2016 Hawassa earthquake: Implications for seismic hazard in the Main Ethiopian Rift. *JAfES*, 125, pp. 118–125.
- WorldWeatherOnline (2022). *What is weather like in Kombolcha, Ethiopia* Retrieved May 24, 2022, from <https://www.worldweatheronline.com/kombolcha-weather-averages/et.aspx>
- Yayeh, A. (2022). Assessments of The Impact of Industrial Effluents and Urbanization on Groundwater and Surface Water Quality in Kombolcha Town. *Bahir Dar University*
- Zhang, J., Cao, J., Huang, S., & Shi, B. (2021). Experimental Study on the Dynamic Shear Modulus and Damping Ratio of Saturated Sand Under Cyclic Loading. *Materiali in Tehnologije*, 55(5), pp. 741–749. <https://doi.org/10.17222/MIT.2021.230>

Research Fund Acknowledgement

This research project is funded by Adama Science and Technology University under the grant number ASTU/SM-R/526/22, Adama, Ethiopia.

APPENDICES

Appendix A Natural Moisture Content and Field Density Determination

A-1 Natural Moisture Content Determination																		
Test Pit Code	AP									Amar								
Depth, m	1.00			2.00			3.00			1.00			2.00			3.00		
Container No	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Mass of container, g	15.56	14.41	15.72	15.40	15.19	15.89	15.40	15.19	15.89	15.98	15.84	14.26	15.25	14.28	15.92	15.61	15.41	13.72
Mass of container + Wet soil, g	61.22	55.26	57.52	52.11	53.01	56.24	51.71	57.01	52.82	61.12	62.12	59.21	62.87	65.57	60.17	58.65	65.64	55.74
Mass of container + Dry soil, g	50.50	45.89	47.87	43.32	43.63	46.51	43.53	47.11	44.30	51.21	52.13	49.32	52.48	54.21	49.89	50.61	55.72	46.80
Water content, %	30.68	29.76	30.02	31.48	32.98	31.78	29.08	31.02	29.99	28.13	27.53	28.21	27.91	28.45	30.26	22.97	24.61	27.03
Average water content, % (%)	30.15			32.08			30.03			27.96			28.87			24.87		
Test Pit Code	DP									IP								
Depth, m	1.00			2.00			3.00			1.00			2.00			3.00		
Container No	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Mass of container, g	15.54	15.40	15.78	15.74	15.48	13.75	15.42	15.40	15.81	15.72	15.31	15.42	15.72	15.31	15.42	15.72	15.31	15.42
Mass of container + Wet soil, g	61.89	55.59	60.85	60.05	54.48	56.65	60.59	53.32	58.18	61.22	55.26	57.52	51.12	51.89	55.45	54.17	51.17	57.14
Mass of container + Dry soil, g	50.25	45.36	49.47	48.85	44.62	46.12	49.68	44.01	47.68	50.50	45.89	47.87	43.32	43.63	46.51	45.80	43.28	48.38

Water content, %	33.54	34.15	33.78	33.83	33.84	32.53	31.84	32.54	32.95	30.82	30.64	29.74	28.26	29.17	28.76	27.83	28.21	26.58
Average water content, % (%)	33.82			33.40			32.44			30.40			28.73			27.54		
Test Pit Code	MD									MTK								
Depth, m	1.00			2.00			3.00			1.00			2.00			3.00		
Container No	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Mass of container, g	15.63	15.80	15.93	15.91	15.49	15.11	15.91	15.49	15.11	15.45	15.79	15.81	15.41	15.82	15.32	15.41	15.82	15.32
Mass of container + Wet soil, g	73.84	83.23	78.74	84.25	77.38	84.47	82.89	77.21	81.10	65.61	59.81	64.75	69.25	71.02	72.87	51.84	56.47	63.23
Mass of container + Dry soil, g	65.35	73.26	68.92	74.51	67.90	74.29	73.09	68.61	72.11	55.84	50.75	55.45	59.18	60.55	61.75	44.98	49.10	53.70
Water content, %	17.08	17.35	18.53	16.62	18.09	17.20	17.14	16.19	15.77	24.19	25.92	23.46	23.01	23.41	23.95	23.20	22.15	24.83
Average water content, % (%)	17.65			17.30			16.37			24.52			23.45			23.39		

A-2 Field Density Determination										
Test Pits		Air Port (AP)			Amar Factory (Amar)			Dry Port (DP)		
Calculation	Symbols	AP1	AP2	AP3	Amar1	Amar2	Amar3	DP1	DP2	DP3
Weight of wet soil from hole(g)	A	1653	2356	1285	2565	2412	2370	2546	2360	3790
Initial weight of sand cone bottle (g)	B	5487	5458	2785	6586	5200	4256	4521	4050	7024
Final weight of sand cone bottle (g)	C	2712	2012	422	2987	1854	934	1132	921	2567
Weight of sand in hole and cone (g)	D=B-C	2775	3446	2363	3599	3346	3322	3389	3129	4457
Weight of sand in cone(g)	E	1110	1110	1110	1110	1110	1110	1110	1110	1110
Weight of sand in Hole(g)	F=D-E	1665	2336	1253	2489	2236	2212	2279	2019	3347
Unit weight of sand(g/cc)	G	1.42	1.42	1.42	1.42	1.42	1.42	1.42	1.42	1.42
Volume of Hole(cc)	H=F/G	1172.54	1645.07	882.39	1752.82	1574.65	1557.75	1604.93	1421.83	2357.04
Wet density of soil(g/cc)	I=A/H	1.41	1.43	1.46	1.46	1.53	1.52	1.59	1.66	1.61
Moisture content (%)	J	30.15	32.08	30.03	27.96	28.87	24.87	33.82	33.40	32.44
Dry density of soil(g/cc)	K= [I/(1+J)] *100	1.08	1.08	1.12	1.14	1.19	1.22	1.19	1.24	1.21
Test Pits		Industry Park (IP)			Medhanialem (MD)			Mitikolo (MTK)		

Calculation	Symbols	IP1	IP2	IP3	MD1	MD2	MD3	MTK1	MTK2	MTK3
Weight of wet soil from hole(g)	A	2335	2430	2742	2250	1800	2025	2370	2370	4256
Initial weight of sand cone bottle (g)	B	7589	6754	5254	7310	7250	6898	5252	5210	7158
Final weight of sand cone bottle (g)	C	4258	3331	1524	4272	4581	4185	2184	2187	2604
Weight of sand in hole and cone (g)	D=B-C	3331	3423	3730	3038	2669	2713	3068	3023	4554
Weight of sand in cone(g)	E	1110	1110	1110	1110	1110	1110	1110	1110	1110
Weight of sand in Hole(g)	F=D-E	2221	2313	2620	1928	1559	1603	1958	1913	3444
Unit weight of sand(g/cc)	G	1.42	1.42	1.42	1.42	1.42	1.42	1.42	1.42	1.42
Volume of Hole(cc)	H=F/G	1564.08	1628.87	1845.07	1357.75	1097.89	1128.87	1378.87	1347.18	2425.35
Wet density of soil(g/cc)	I=A/H	1.49	1.49	1.49	1.66	1.64	1.79	1.72	1.76	1.75
Moisture content (%)	J	30.40	28.73	27.54	17.65	17.30	16.37	24.52	23.45	23.39
Dry density of soil(g/cc)	K= [I/(1+J)] *100	1.14	1.16	1.17	1.41	1.40	1.54	1.38	1.43	1.42

Appendix B Specific Gravity Determination

Sample Location	AP						DP					
Sample Depth(m)	1		2		3		1		2		3	
[A] Calibration of pycnometer												
Pycnometer No.	P1	P2	P1	P2	P1	P2	P1	P2	P1	P2	P1	P2
Weight of dry, clean pycnometer, w_p (g)	107.2	108.7	107.2	108.7	107.2	108.7	107.2	108.7	107.2	108.7	107.2	108.7
Weight of pycnometer + water, w_{pw} (g)	355.9	357.3	355.9	357.3	355.9	357.3	355.9	357.3	355.9	357.3	355.9	357.3
Observed temperature of water, T_i (°C)	20.1	20.6	20	20.6	20.3	20.6	20.3	20.7	20.4	20.4	20.3	20.7
[B] Specific Gravity Determination												
Pycnometer No.	P1	P2	P1	P2	P1	P2	P1	P2	P1	P2	P1	P2
Weight of pycnometer + soil + water, W_{pws} (g)	381.3	382.7	381.4	382.8	381.5	383	381.1	382.5	381.2	382.5	381.2	382.7
Temperature, T_x (°C)	21.8	21.8	22.1	21.6	21.5	21.5	21	20.5	21.2	21.7	22.4	22.9
Weight of pycnometer + water at T_x , W_{pw} (at T_x) (g)	355.79	357.24	355.79	357.24	355.79	357.24	355.85	357.3	355.85	357.19	356.01	357.41
Weight of dry soil, W_s (gm)	40	40	40	40	40	40	40	40	40	40	40	40
Conversion factor, K	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9998	0.9998	0.9998	0.9996	0.9996	0.9993
Specific gravity of soil (Gs) at 20°C. $G_s=K W_s/(W_s+W_{pw} \text{ (at } T_x)-W_{pws})$	2.76	2.75	2.78	2.77	2.8	2.81	2.71	2.7	2.73	2.72	2.7	2.72
Average specific gravity of soil.	2.75		2.77		2.8		2.71		2.73		2.71	
Sample Location	Amar						IP					
Sample Depth(m)	1		2		3		1		2			
[A] Calibration of pycnometer												

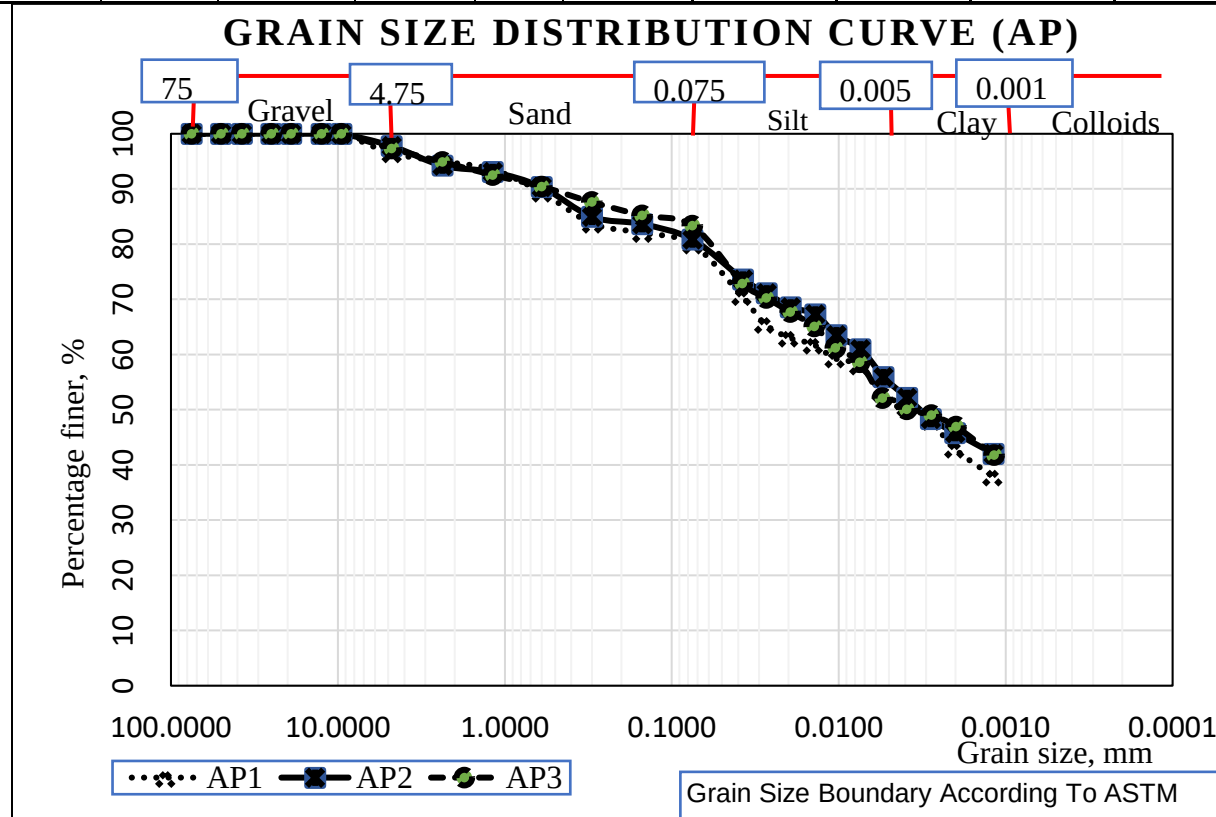
Pycnometer No.	P1	P2	P1	P2	P1	P2	P1	P2	P1	P2	P1	P2
Weight of dry, clean pycnometer, w_p (g)	107.2	108.7	107.2	108.7	107.2	108.7	107.2	108.7	107.2	108.7	107.2	108.7
Weight of pycnometer + water, w_{pw} (g)	355.9	357.3	355.9	357.3	355.9	357.3	355.9	357.3	355.9	357.3	355.9	357.3
Observed temperature of water, T_i (°C)	20.5	20.2	20.1	20.6	20.3	20.7	21.8	20.4	20.5	20.2	20.3	20.2
[B] Specific Gravity Determination												
Pycnometer No.	P1	P2	P1	P2	P1	P2	P1	P2	P1	P2	P1	P2
Weight of pycnometer + soil + water, W_{pws} (g)	381.1	382.4	381	382.6	380.9	382.5	381.4	382.7	381.4	382.7	381.5	382.7
Temperature, T_x (°C)	22	21.2	21.8	21.8	21	20.5	21.3	21.2	21.6	22.5	21.9	21.1
Weight of pycnometer + water at T_x , W_{pw} (at T_x) (g)	355.84	357.25	355.79	357.24	355.85	357.3	355.96	357.25	355.84	357.13	355.79	357.25
Weight of dry soil, W_s (gm)	40	40	40	40	40	40	40	40	40	40	40	40
Conversion factor, K	0.9996	0.9998	0.9996	0.9996	0.9998	0.9998	0.9998	0.9998	0.9996	0.9993	0.9998	0.9998
Specific gravity of soil (G_s) at 20°C. $G_s=K W_s/$ $(W_s+W_{pw}$ (at T_x)- $W_{pws})$	2.71	2.69	2.7	2.73	2.68	2.7	2.75	2.75	2.77	2.77	2.8	2.75
Average specific gravity of soil.	2.7		2.72		2.69		2.75		2.77		2.77	
Sample Location	MD						MTK					
Sample Depth (m)	1		2		3		1		2		3	
[A] Calibration of pycnometer												
Pycnometer No.	P1	P2	P1	P2	P1	P2	P1	P2	P1	P2	P1	P2
Weight of dry, clean pycnometer, w_p (g)	107.2	108.7	107.2	108.7	107.2	108.7	107.2	108.7	107.2	108.7	107.2	108.7
Weight of pycnometer + water, w_{pw} (g)	355.9	357.3	355.9	357.3	355.9	357.3	355.9	357.3	355.9	357.3	355.9	357.3
Observed temperature of water, T_i (°C)	20.3	20.6	20.4	20	20.3	20.7	20	20.6	20.3	20.2	20.5	
[B] Specific Gravity Determination												
Pycnometer No.	P1	P2	P1	P2	P1	P2	P1	P2	P1	P2	P1	P2
Weight of pycnometer + soil + water, W_{pws} (g)	380.8	382.2	380.9	382.2	380.8	382.4	380.8	382.3	380.8	382.2	380.7	382.4
Temperature, T_x (°C)	21.5	21.5	22.4	22.9	21	20.5	22.1	21.6	21.9	21.1	21.6	22.5
Weight of pycnometer + water at T_x , W_{pw} (at T_x) (g)	355.79	357.24	355.79	357.13	355.85	357.3	355.79	357.24	355.79	357.25	355.84	357.13
Weight of dry soil, W_s (gm)	40	40	40	40	40	40	40	40	40	40	40	40
Conversion factor, K	0.9996	0.9996	0.9996	0.9993	0.9998	0.9998	0.9996	0.9996	0.9998	0.9998	0.9996	0.9993
Specific gravity of soil (G_s) at 20°C. $G_s=K W_s/$ $(W_s+W_{pw}$ (at T_x)- $W_{pws})$	2.67	2.66	2.66	2.68	2.66	2.68	2.67	2.68	2.67	2.66	2.64	2.66
Average specific gravity of soil	2.66		2.68		2.67		2.67		2.66		2.65	

Appendix C Grain Size Analysis

Sieve Analysis Mass of sample(g)=1000			AP at 1m					AP at 2m					AP at 3m				
Sieve No.	Sieve Opening (mm)	Mass of Sieve (g)	Mass of sieve +Retained soi (g)	Mass of Retained soi(g)	Percentage Retained (%)	Cum. Percentage Retained (%)	Perc. Passing (%)	Mass of sieve +Retained soi (g)	Mass of Retained soi(g)	Percentage Retained (%)	Cum. Percentage Retained (%)	Perc. Passing (%)	Mass of sieve +Retained soi (g)	Mass of Retained soi(g)	Percentage Retained (%)	Cum. Percentage Retained (%)	Perc. Passing (%)
3"	75	1057	1057	0	0	0	100	1057.0	0.0	0.0	0.0	100.0	1057.0	0.0	0.0	0.0	100.0
2"	50	1199	1199	0	0	0	100	1199.0	0.0	0.0	0.0	100.0	1199.0	0.0	0.0	0.0	100.0
1.5"	37.5	1084	1084	0	0	0	100	1084.0	0.0	0.0	0.0	100.0	1084.0	0.0	0.0	0.0	100.0
1"	25	1187	1187	0	0	0	100	1187.0	0.0	0.0	0.0	100.0	1187.0	0.0	0.0	0.0	100.0
3/4"	19	716	716	0	0	0	100	716.0	0.0	0.0	0.0	100.0	716.0	0.0	0.0	0.0	100.0
1/2"	12.5	584	584	0	0	0	100	584.0	0.0	0.0	0.0	100.0	584.0	0.0	0.0	0.0	100.0
3.8"	9.5	445.1	445.1	0	0	0	100	445.1	0.0	0.0	0.0	100.0	445.1	0.0	0.0	0.0	100.0
No 4	4.75	566.6	601.8	35.2	3.5	3.5	96.5	589.0	22.4	2.2	2.2	97.8	593.7	27.1	2.7	2.7	97.3
No 8	2.36	396.5	411.5	15	1.5	5	95	432.0	35.5	3.6	5.8	94.2	420.6	24.1	2.4	5.1	94.9
No 16	1.18	354	368.5	14.5	1.5	6.5	93.5	365.4	11.4	1.1	6.9	93.1	377.6	23.6	2.4	7.5	92.5
No 30	0.6	323.9	365.4	41.5	4.2	10.6	89.4	351.2	27.3	2.7	9.7	90.3	345.0	21.1	2.1	9.6	90.4
No40	0.425	447.8	479.5	31.7	3.2	13.8	86.2	474.2	26.4	2.6	12.3	87.7	459.5	11.7	1.2	10.8	89.2
No 50	0.3	308.6	333.5	24.9	2.5	16.3	83.7	336.2	27.6	2.8	15.1	84.9	325.0	16.4	1.6	12.4	87.6
No 100	0.15	423.2	439.8	16.6	1.7	17.9	82.1	436.3	13.1	1.3	16.4	83.6	447.2	24.0	2.4	14.8	85.2
No 200	0.075	417.1	437.9	20.8	2.1	20	80	445.2	28.1	2.8	19.2	80.8	435.9	18.8	1.9	16.7	83.3
Pan	-----	240.3	240.3	799.8	80	100	-----	240.3	808.2	80.8	100.0	-----	240.3	833.2	83.3	100.0	-----

Hydrometer Analysis Specific gravity=2.75					AP at 1m Temperature (°C)=19				AP at 2m Specific gravity=2.77 Temperature (°C)=19							
Elapsed Time (min)	Actual Hydrometer Reading	Composite Correction	Corrected Hydrometer Reading	Effective Depth (cm)	Coefficient K	Grain Size (mm)	Perc. Finer (%)	Perc. Finer Combined (%)	Actual Hydrometer Reading	Composite Correction	Corrected Hydrometer Reading	Effective Depth (cm)	Coefficient K	Grain Size (mm)	Perc. Finer (%)	Perc. Finer Combined (%)
3/4	1.0310	-0.0029	1.0281	8.10	0.01342	0.0382	88.31	70.63	1.0320	-0.0029	1.0291	7.84	0.013372	0.0374	91.08	73.61
1	1.0290	-0.0029	1.0261	8.63	0.01342	0.0279	82.03	65.61	1.0310	-0.0029	1.0281	8.10	0.013372	0.0269	87.95	71.08
2	1.0280	-0.0029	1.0251	8.89	0.01342	0.0200	78.89	63.09	1.0300	-0.0029	1.0271	8.36	0.013372	0.0193	84.82	68.55
4	1.0275	-0.0029	1.0246	9.03	0.01342	0.0143	77.31	61.84	1.0295	-0.0029	1.0266	8.50	0.013372	0.0138	83.26	67.29
8	1.0265	-0.0029	1.0236	9.29	0.01342	0.0106	74.17	59.32	1.0280	-0.0029	1.0251	8.89	0.013372	0.0103	78.56	63.49
15	1.0260	-0.0029	1.0231	9.42	0.01342	0.0075	72.60	58.07	1.0270	-0.0029	1.0241	9.16	0.013372	0.0074	75.43	60.96
30	1.0250	-0.0029	1.0221	9.69	0.01342	0.0054	69.46	55.55	1.0260	-0.0029	1.0231	9.42	0.013372	0.0053	72.30	58.43
60	1.0240	-0.0029	1.0211	9.95	0.01342	0.0055	66.31	53.04	1.0250	-0.0029	1.0221	9.69	0.013372	0.0054	69.17	55.90
120	1.0230	-0.0029	1.0201	10.22	0.01342	0.0039	63.17	50.52	1.0235	-0.0029	1.0206	10.08	0.013372	0.0039	64.48	52.11

240	1.0220	-0.0029	1.0191	10.48	0.01342	0.0028	60.03	48.01	1.0220	-0.0029	1.0191	10.48	0.013372	0.0028	59.78	48.32
480	1.0200	-0.0029	1.0171	11.01	0.01342	0.0020	53.74	42.98	1.0210	-0.0029	1.0181	10.75	0.013372	0.0020	56.65	45.79
1440	1.0180	-0.0029	1.0151	11.54	0.01342	0.0012	47.46	37.96	1.0195	-0.0029	1.0166	11.14	0.013372	0.0012	51.96	41.99



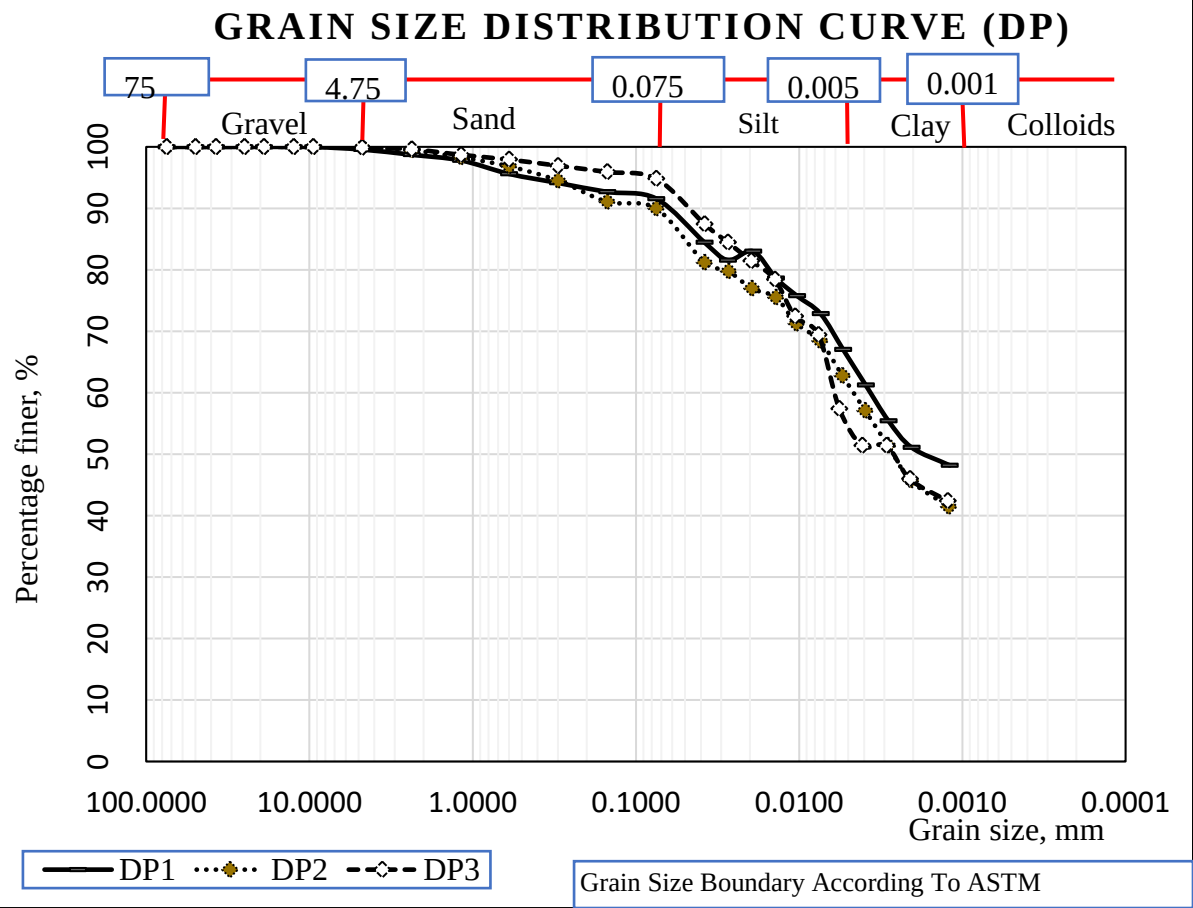
AP at 3m								
Specific gravity=2.8			Temperature (°C)=19					
Elapsed Time (min)	Actual Hydrometer Reading	Composite Correction	Corrected Hydrometer Reading	Effective Depth (cm)	Coefficient K	Grain Size (mm)	Perc. Finer (%)	Perc. Finer Combined (%)
3/4	1.0310	-0.0029	1.0281	8.10	0.01323	0.0377	87.42	72.84
1	1.0300	-0.0029	1.0271	8.36	0.01323	0.0271	84.31	70.25
2	1.0290	-0.0029	1.0261	8.63	0.01323	0.0194	81.20	67.66
4	1.0280	-0.0029	1.0251	8.89	0.01323	0.0139	78.09	65.06
8	1.0265	-0.0029	1.0236	9.29	0.01323	0.0104	73.42	61.18

15	1.0255	-0.0029	1.0226	9.55	0.01323	0.0075	70.31	58.58
30	1.0245	-0.0029	1.0216	9.82	0.01323	0.0054	67.20	55.99
60	1.0230	-0.0029	1.0201	10.22	0.01323	0.0055	62.53	52.10
120	1.0222	-0.0029	1.0193	10.43	0.01323	0.0039	60.04	50.03
240	1.0218	-0.0029	1.0189	10.53	0.01323	0.0028	58.80	48.99
480	1.0210	-0.0029	1.0181	10.75	0.01323	0.0020	56.31	46.92
1440	1.0190	-0.0029	1.0161	11.27	0.01323	0.0012	50.09	41.73

Sieve Analysis Mass of sample(g)=1000			DP at 1m					DP at 2m					DP at 3m				
Sieve No.	Sieve Opening (mm)	Mass of Sieve (g)	Mass of sieve +Retained soi (g)	Mass of Retained soi(g)	Percentage Retained (%)	Cum. Percentage Retained (%)	Perc. Passing (%)	Mass of sieve +Retained soi (g)	Mass of Retained soi(g)	Percentage Retained (%)	Cum. Percentage Retained (%)	Perc. Passing (%)	Mass of sieve +Retained soi (g)	Mass of Retained soi(g)	Percentage Retained (%)	Cum. Percentage Retained (%)	Perc. Passing (%)
3"	75	1057	1057.0	0.0	0.0	0.0	100.0	1057.0	0.0	0.0	0.0	100.0	1057.0	0.0	0.0	0.0	100.0
2"	50	1199	1199.0	0.0	0.0	0.0	100.0	1199.0	0.0	0.0	0.0	100.0	1199.0	0.0	0.0	0.0	100.0
1.5"	37.5	1084	1084.0	0.0	0.0	0.0	100.0	1084.0	0.0	0.0	0.0	100.0	1084.0	0.0	0.0	0.0	100.0
1"	25	1187	1187.0	0.0	0.0	0.0	100.0	1187.0	0.0	0.0	0.0	100.0	1187.0	0.0	0.0	0.0	100.0
3/4"	19	716	716.0	0.0	0.0	0.0	100.0	716.0	0.0	0.0	0.0	100.0	716.0	0.0	0.0	0.0	100.0
1/2"	12.5	584	584.0	0.0	0.0	0.0	100.0	584.0	0.0	0.0	0.0	100.0	584.0	0.0	0.0	0.0	100.0
3.8"	9.5	445.1	445.1	0.0	0.0	0.0	100.0	445.1	0.0	0.0	0.0	100.0	445.1	0.0	0.0	0.0	100.0
No 4	4.75	566.6	571.0	4.4	0.4	0.4	99.6	567.6	1.0	0.1	0.1	99.9	568.0	1.4	0.1	0.1	99.9
No 8	2.36	396.5	405.0	8.5	0.9	1.3	98.7	401.1	4.6	0.5	0.6	99.4	399.0	2.5	0.3	0.4	99.6
No 16	1.18	354	363.2	9.2	0.9	2.2	97.8	365.5	11.5	1.2	1.7	98.3	363.1	9.1	0.9	1.3	98.7
No 30	0.6	323.9	345.7	21.8	2.2	4.4	95.6	338.5	14.6	1.5	3.2	96.8	331.6	7.7	0.8	2.1	97.9
No40	0.425	447.8	452.8	5.0	0.5	4.9	95.1	457.9	10.1	1.0	4.2	95.8	451.7	3.9	0.4	2.5	97.5
No 50	0.3	308.6	318.4	9.8	1.0	5.9	94.1	321.6	13.0	1.3	5.5	94.5	314.7	6.1	0.6	3.1	96.9
No 100	0.15	423.2	437.8	14.6	1.5	7.3	92.7	457.8	34.6	3.5	8.9	91.1	433.4	10.2	1.0	4.1	95.9
No 200	0.075	417.1	432.5	11.0	1.1	8.4	91.6	438.9	11.0	1.1	10.0	90.0	427.7	11.0	1.1	5.2	94.8
Pan	-----	240.3	240.3	915.7	91.6	100.0	-----	240.3	899.6	90.0	100.0	-----	240.3	948.1	94.8	100.0	-----

Hydrometer Analysis									DP at 2m							
Specific gravity=2.71				DP at 1m					Specific gravity=2.73				DP at 2m			
				Temperature (°C)=19									Temperature (°C)=19			
Elapsed Time (min)	Actual Hydrometer Reading	Composite Correction	Corrected Hydrometer Reading	Effective Depth (cm)	Coefficient K	Grain Size (mm)	Perc. Finer (%)	Perc. Finer Combined (%)	Actual Hydrometer Reading	Composite Correction	Corrected Hydrometer Reading	Effective Depth (cm)	Coefficient K	Grain Size (mm)	Perc. Finer (%)	Perc. Finer Combined (%)
3/4	1.0320	-0.0029	1.0291	7.84	0.01358	0.0380	92.24	84.46	1.0315	-0.0029	1.0286	7.97	0.013484	0.0381	90.26	81.20
1	1.0310	-0.0029	1.0281	8.10	0.01358	0.0273	89.07	81.56	1.0310	-0.0029	1.0281	8.10	0.013484	0.0271	88.69	79.78
2	1.0315	-0.0029	1.0286	7.97	0.01358	0.0192	90.65	83.01	1.0300	-0.0029	1.0271	8.36	0.013484	0.0195	85.53	76.94
4	1.0300	-0.0029	1.0271	8.36	0.01358	0.0139	85.90	78.65	1.0295	-0.0029	1.0266	8.50	0.013484	0.0139	83.95	75.52
8	1.0290	-0.0029	1.0261	8.63	0.01358	0.0103	82.73	75.75	1.0280	-0.0029	1.0251	8.89	0.013484	0.0104	79.22	71.26

15	1.0280	-0.0029	1.0251	8.89	0.01358	0.0074	79.56	72.85	1.0270	-0.0029	1.0241	9.16	0.013484	0.0075	76.06	68.42
30	1.0270	-0.0029	1.0241	9.16	0.01358	0.0053	76.39	69.95	1.0260	-0.0029	1.0231	9.42	0.013484	0.0053	72.91	65.59
60	1.0260	-0.0029	1.0231	9.42	0.01358	0.0054	73.22	67.05	1.0250	-0.0029	1.0221	9.69	0.013484	0.0054	69.75	62.75
120	1.0240	-0.0029	1.0211	9.95	0.01358	0.0039	66.88	61.24	1.0230	-0.0029	1.0201	10.22	0.013484	0.0039	63.44	57.07
240	1.0220	-0.0029	1.0191	10.48	0.01358	0.0028	60.54	55.44	1.0210	-0.0029	1.0181	10.75	0.013484	0.0029	57.12	51.39
480	1.0205	-0.0029	1.0176	10.88	0.01358	0.0020	55.78	51.08	1.0190	-0.0029	1.0161	11.27	0.013484	0.0021	50.81	45.71
1440	1.0195	-0.0029	1.0166	11.14	0.01358	0.0012	52.62	48.18	1.0175	-0.0029	1.0146	11.67	0.013484	0.0012	46.08	41.45

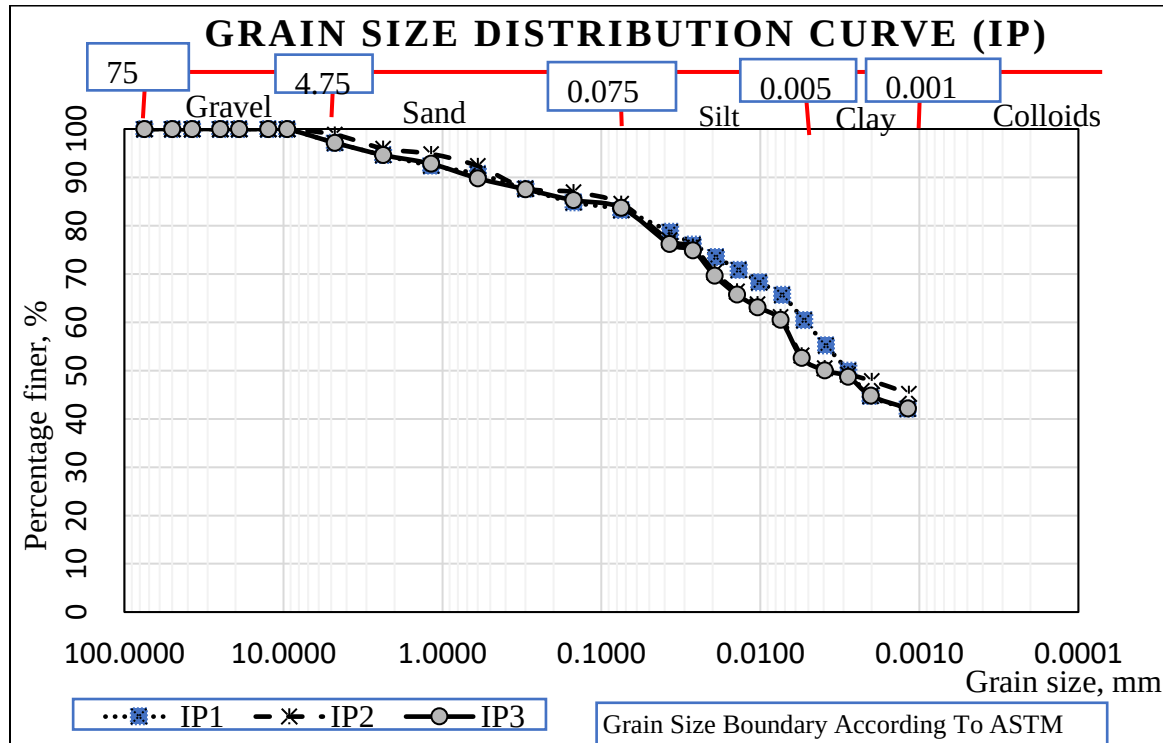


DP at 3m								
Specific gravity=2.71					Temperature (°C)=19			
Elapsed Time (min)	Actual Hydrometer Reading	Composite Correction	Corrected Hydrometer Reading	Effective Depth (cm)	Coefficient K	Grain Size (mm)	Perc. Finer (%)	Perc. Finer Combined (%)
3/4	1.0320	-0.0029	1.0291	7.84	0.013568	0.0380	92.24	87.45
1	1.0310	-0.0029	1.0281	8.10	0.013568	0.0273	89.07	84.44
2	1.0300	-0.0029	1.0271	8.36	0.013568	0.0196	85.90	81.44
4	1.0290	-0.0029	1.0261	8.63	0.013568	0.0141	82.73	78.43
8	1.0270	-0.0029	1.0241	9.16	0.013568	0.0106	76.39	72.42
15	1.0260	-0.0029	1.0231	9.42	0.013568	0.0076	73.22	69.42
30	1.0250	-0.0029	1.0221	9.69	0.013568	0.0055	70.05	66.41
60	1.0220	-0.0029	1.0191	10.48	0.013568	0.0057	60.54	57.40
120	1.0200	-0.0029	1.0171	11.01	0.013568	0.0041	54.20	51.39
240	1.0200	-0.0029	1.0171	11.01	0.013568	0.0029	54.20	51.39
480	1.0182	-0.0029	1.0153	11.49	0.013568	0.0021	48.49	45.98
1440	1.0170	-0.0029	1.0141	11.80	0.013568	0.0012	44.69	42.37

Sieve Analysis Mass of sample(g)=1000			IP at 1m					IP at 2m					IP at 3m				
Sieve No.	Sieve Opening (mm)	Mass of Sieve (g)	Mass of sieve +Retained soi (g)	Mass of Retained soi(g)	Percentage Retained (%)	Cum. Percentage Retained (%)	Perc. Passing (%)	Mass of sieve +Retained soi (g)	Mass of Retained soi(g)	Percentage Retained (%)	Cum. Percentage Retained (%)	Perc. Passing (%)	Mass of sieve +Retained soi (g)	Mass of Retained soi(g)	Percentage Retained (%)	Cum. Percentage Retained (%)	Perc. Passing (%)
3"	75	1057	1057.0	0.0	0.0	0.0	100.0	1057.0	0.0	0.0	0.0	100.0	1057.0	0.0	0.0	0.0	100.0
2"	50	1199	1199.0	0.0	0.0	0.0	100.0	1199.0	0.0	0.0	0.0	100.0	1199.0	0.0	0.0	0.0	100.0
1.5"	37.5	1084	1084.0	0.0	0.0	0.0	100.0	1084.0	0.0	0.0	0.0	100.0	1084.0	0.0	0.0	0.0	100.0
1"	25	1187	1187.0	0.0	0.0	0.0	100.0	1187.0	0.0	0.0	0.0	100.0	1187.0	0.0	0.0	0.0	100.0
3/4"	19	716	716.0	0.0	0.0	0.0	100.0	716.0	0.0	0.0	0.0	100.0	716.0	0.0	0.0	0.0	100.0
1/2"	12.5	584	584.0	0.0	0.0	0.0	100.0	584.0	0.0	0.0	0.0	100.0	584.0	0.0	0.0	0.0	100.0
3.8"	9.5	445.1	445.1	0.0	0.0	0.0	100.0	445.1	0.0	0.0	0.0	100.0	445.1	0.0	0.0	0.0	100.0
No 4	4.75	566.6	595.0	28.4	2.8	2.8	97.2	578.2	11.6	1.2	1.2	98.8	595.0	28.4	2.8	2.8	97.2
No 8	2.36	396.5	422.0	25.5	2.6	5.4	94.6	425.3	28.8	2.9	4.0	96.0	422.0	25.5	2.6	5.4	94.6
No 16	1.18	354	376.0	22.0	2.2	7.6	92.4	365.2	11.2	1.1	5.2	94.8	372.0	18.0	1.8	7.2	92.8
No 30	0.6	323.9	341.0	17.1	1.7	9.3	90.7	348.7	24.8	2.5	7.6	92.4	354.0	30.1	3.0	10.2	89.8
No 40	0.425	447.8	462.3	14.5	1.5	10.8	89.3	468.8	21.0	2.1	9.7	90.3	455.0	7.2	0.7	10.9	89.1
No 50	0.3	308.6	325.1	16.5	1.7	12.4	87.6	333.6	25.0	2.5	12.2	87.8	324.2	15.6	1.6	12.5	87.5
No 100	0.15	423.2	451.2	28.0	2.8	15.2	84.8	431.2	8.0	0.8	13.0	87.0	445.7	22.5	2.3	14.7	85.3
No 200	0.075	417.1	433.0	15.9	1.6	16.8	83.2	441.5	24.4	2.4	15.5	84.5	433.0	15.9	1.6	16.3	83.7
Pan	-----	240.3	240.3	832.1	83.2	100.0	-----	240.3	845.2	84.5	100.0	-----	240.3	836.8	83.7	100.0	-----

Hydrometer Analysis									IP at 2m							
Specific gravity=2.75									Specific gravity=2.77							
IP at 1m									Temperature (°C)=19							
Elapsed Time (min)	Actual Hydrometer Reading	Composite Correction	Corrected Hydrometer Reading	Effective Depth (cm)	Coefficient K	Grain Size (mm)	Perc. Finer (%)	Perc. Finer Combined (%)	Actual Hydrometer Reading	Composite Correction	Corrected Hydrometer Reading	Effective Depth (cm)	Coefficient K	Grain Size (mm)	Perc. Finer (%)	Perc. Finer Combined (%)
3/4	1.0330	-0.0029	1.0301	7.57	0.01342	0.0369	94.60	78.72	1.0320	-0.0029	1.0291	7.84	0.013344	0.0374	91.08	76.98
1	1.0320	-0.0029	1.0291	7.84	0.01342	0.0266	91.46	76.10	1.0315	-0.0029	1.0286	7.97	0.013344	0.0266	89.52	75.66
2	1.0310	-0.0029	1.0281	8.10	0.01342	0.0191	88.31	73.49	1.0295	-0.0029	1.0266	8.50	0.013344	0.0194	83.26	70.37
4	1.0300	-0.0029	1.0271	8.36	0.01342	0.0137	85.17	70.87	1.0280	-0.0029	1.0251	8.89	0.013344	0.0141	78.56	66.40
8	1.0290	-0.0029	1.0261	8.63	0.01342	0.0102	82.03	68.26	1.0270	-0.0029	1.0241	9.16	0.013344	0.0104	75.43	63.75
15	1.0280	-0.0029	1.0251	8.89	0.01342	0.0073	78.89	65.64	1.0260	-0.0029	1.0231	9.42	0.013344	0.0075	72.30	61.11
30	1.0270	-0.0029	1.0241	9.16	0.01342	0.0052	75.74	63.03	1.0245	-0.0029	1.0216	9.82	0.013344	0.0054	67.61	57.14
60	1.0260	-0.0029	1.0231	9.42	0.01342	0.0053	72.60	60.41	1.0230	-0.0029	1.0201	10.22	0.013344	0.0055	62.91	53.17
120	1.0240	-0.0029	1.0211	9.95	0.01342	0.0039	66.31	55.18	1.0220	-0.0029	1.0191	10.48	0.013344	0.0039	59.78	50.53
240	1.0220	-0.0029	1.0191	10.48	0.01342	0.0028	60.03	49.95	1.0215	-0.0029	1.0186	10.61	0.013344	0.0028	58.22	49.20
480	1.0200	-0.0029	1.0171	11.01	0.01342	0.0020	53.74	44.72	1.0210	-0.0029	1.0181	10.75	0.013344	0.0020	56.65	47.88
1440	1.0190	-0.0029	1.0161	11.27	0.01342	0.0012	50.60	42.10	1.0200	-0.0029	1.0171	11.01	0.013344	0.0012	53.52	45.24

IP at 3m								
Specific gravity=2.77								
Temperature (°C)=19								
Elapsed Time (min)	Actual Hydrometer Reading	Composite Correction	Corrected Hydrometer Reading	Effective Depth (cm)	Coefficient K	Grain Size (mm)	Perc. Finer (%)	Perc. Finer Combined (%)
3/4	1.0320	-0.0029	1.0291	7.84	0.013344	0.0374	91.08	76.22
1	1.0315	-0.0029	1.0286	7.97	0.013344	0.0266	89.52	74.91
2	1.0295	-0.0029	1.0266	8.50	0.013344	0.0194	83.26	69.67
4	1.0280	-0.0029	1.0251	8.89	0.013344	0.0141	78.56	65.74
8	1.0270	-0.0029	1.0241	9.16	0.013344	0.0104	75.43	63.12
15	1.0260	-0.0029	1.0231	9.42	0.013344	0.0075	72.30	60.50
30	1.0250	-0.0029	1.0221	9.69	0.013344	0.0054	69.17	57.88
60	1.0230	-0.0029	1.0201	10.22	0.013344	0.0055	62.91	52.64
120	1.0220	-0.0029	1.0191	10.48	0.013344	0.0039	59.78	50.03
240	1.0215	-0.0029	1.0186	10.61	0.013344	0.0028	58.22	48.72
480	1.0200	-0.0029	1.0171	11.01	0.013344	0.0020	53.52	44.79
1440	1.0190	-0.0029	1.0161	11.27	0.013344	0.0012	50.39	42.17



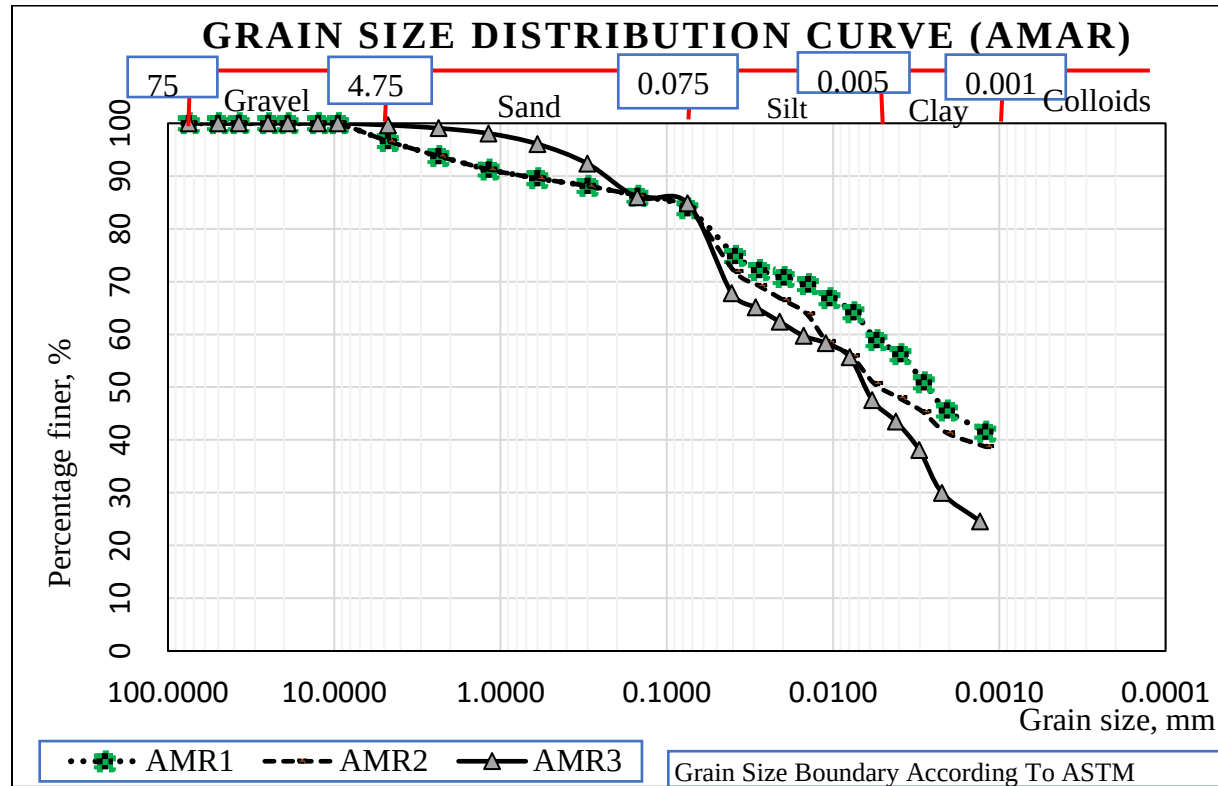
Sieve Analysis Mass of sample(g)=1000			Amar at 1m					Amar at 2m					Amar at 3m				
Sieve No.	Sieve Opening (mm)	Mass of Sieve (g)	Mass of sieve +Retained soi (g)	Mass of Retained soi(g)	Percentage Retained (%)	Cum. Percentage Retained (%)	Perc. Passing (%)	Mass of sieve +Retained soi (g)	Mass of Retained soi(g)	Percentage Retained (%)	Cum. Percentage Retained (%)	Perc. Passing (%)	Mass of sieve +Retained soi (g)	Mass of Retained soi(g)	Percentage Retained (%)	Cum. Percentage Retained (%)	Perc. Passing (%)
3"	75	1057	1057.0	0.0	0.0	0.0	100.0	1057.0	0.0	0.0	0.0	100.0	1057.0	0.0	0.0	0.0	100.0
2"	50	1199	1199.0	0.0	0.0	0.0	100.0	1199.0	0.0	0.0	0.0	100.0	1199.0	0.0	0.0	0.0	100.0
1.5"	37.5	1084	1084.0	0.0	0.0	0.0	100.0	1084.0	0.0	0.0	0.0	100.0	1084.0	0.0	0.0	0.0	100.0
1"	25	1187	1187.0	0.0	0.0	0.0	100.0	1187.0	0.0	0.0	0.0	100.0	1187.0	0.0	0.0	0.0	100.0
3/4"	19	716	716.0	0.0	0.0	0.0	100.0	716.0	0.0	0.0	0.0	100.0	716.0	0.0	0.0	0.0	100.0
1/2"	12.5	584	584.0	0.0	0.0	0.0	100.0	584.0	0.0	0.0	0.0	100.0	584.0	0.0	0.0	0.0	100.0
3.8"	9.5	445.1	445.1	0.0	0.0	0.0	100.0	445.1	0.0	0.0	0.0	100.0	445.1	0.0	0.0	0.0	100.0
No 4	4.75	566.6	600.5	33.9	3.4	3.4	96.6	600.5	33.9	3.4	3.4	96.6	570.2	3.6	0.4	0.4	99.6
No 8	2.36	396.5	424.8	28.3	2.8	6.2	93.8	424.8	28.3	2.8	6.2	93.8	402.3	5.8	0.6	0.9	99.1
No 16	1.18	354	379.3	25.3	2.5	8.8	91.3	379.3	25.3	2.5	8.8	91.3	363.9	9.9	1.0	1.9	98.1

No 30	0.6	323.9	340.7	16.8	1.7	10.4	89.6	340.7	16.8	1.7	10.4	89.6	343.8	19.9	2.0	3.9	96.1
No40	0.425	447.8	453.3	5.5	0.6	11.0	89.0	453.3	5.5	0.6	11.0	89.0	462.6	14.8	1.5	5.4	94.6
No 50	0.3	308.6	317.7	9.1	0.9	11.9	88.1	317.7	9.1	0.9	11.9	88.1	331.1	22.5	2.3	7.7	92.4
No 100	0.15	423.2	441.7	18.5	1.9	13.7	86.3	441.7	18.5	1.9	13.7	86.3	487.1	63.9	6.4	14.0	86.0
No 200	0.075	417.1	440.9	23.8	2.4	16.1	83.9	440.9	23.8	2.4	16.1	83.9	498.6	11.0	1.1	15.1	84.9
Pan	-----	240.3	240.3	838.8	83.9	100.0	-----	240.3	838.8	83.9	100.0	-----	240.3	848.6	84.9	100.0	-----

Hydrometer Analysis									Amar at 2m							
Specific gravity=2.70									Specific gravity=2.72							
Temperature (°C)=19									Temperature (°C)=19							
Elapsed Time (min)	Actual Hydrometer Reading	Composite Correction	Corrected Hydrometer Reading	Effective Depth (cm)	Coefficient K	Grain Size (mm)	Perc. Finer (%)	Perc. Finer Combined (%)	Actual Hydrometer Reading	Composite Correction	Corrected Hydrometer Reading	Effective Depth (cm)	Coefficient K	Grain Size (mm)	Perc. Finer (%)	Perc. Finer Combined (%)
3/4	1.0310	-0.0029	1.0281	8.10	0.01361	0.0387	89.26	74.87	1.0300	-0.0029	1.0271	8.36	0.013526	0.0391	85.71	71.89
1	1.0300	-0.0029	1.0271	8.36	0.01361	0.0278	86.08	72.21	1.0290	-0.0029	1.0261	8.63	0.013526	0.0281	82.55	69.24
2	1.0295	-0.0029	1.0266	8.50	0.01361	0.0198	84.49	70.87	1.0280	-0.0029	1.0251	8.89	0.013526	0.0202	79.39	66.59
4	1.0290	-0.0029	1.0261	8.63	0.01361	0.0141	82.91	69.54	1.0270	-0.0029	1.0241	9.16	0.013526	0.0145	76.22	63.94
8	1.0280	-0.0029	1.0251	8.89	0.01361	0.0105	79.73	66.88	1.0250	-0.0029	1.0221	9.69	0.013526	0.0109	69.90	58.63
15	1.0270	-0.0029	1.0241	9.16	0.01361	0.0075	76.55	64.21	1.0240	-0.0029	1.0211	9.95	0.013526	0.0078	66.73	55.98
30	1.0260	-0.0029	1.0231	9.42	0.01361	0.0054	73.38	61.55	1.0230	-0.0029	1.0201	10.22	0.013526	0.0056	63.57	53.32
60	1.0250	-0.0029	1.0221	9.69	0.01361	0.0055	70.20	58.88	1.0220	-0.0029	1.0191	10.48	0.013526	0.0057	60.41	50.67
120	1.0240	-0.0029	1.0211	9.95	0.01361	0.0039	67.02	56.22	1.0210	-0.0029	1.0181	10.75	0.013526	0.0040	57.25	48.02
240	1.0220	-0.0029	1.0191	10.48	0.01361	0.0028	60.67	50.89	1.0200	-0.0029	1.0171	11.01	0.013526	0.0029	54.08	45.37
480	1.0200	-0.0029	1.0171	11.01	0.01361	0.0021	54.32	45.56	1.0185	-0.0029	1.0156	11.41	0.013526	0.0021	49.34	41.39
1440	1.0185	-0.0029	1.0156	11.41	0.01361	0.0012	49.55	41.57	1.0175	-0.0029	1.0146	11.67	0.013526	0.0012	46.18	38.73

Amar at 3m								
Specific gravity=2.69								
Temperature (°C)=19								
Elapsed Time (min)	Actual Hydrometer Reading	Composite Correction	Corrected Hydrometer Reading	Effective Depth (cm)	Coefficient K	Grain Size (mm)	Perc. Finer (%)	Perc. Finer Combined (%)
3/4	1.0280	-0.0029	1.0251	8.89	0.013652	0.0407	79.90	67.81
1	1.0270	-0.0029	1.0241	9.16	0.013652	0.0292	76.72	65.11
2	1.0260	-0.0029	1.0231	9.42	0.013652	0.0210	73.54	62.40
4	1.0250	-0.0029	1.0221	9.69	0.013652	0.0150	70.35	59.70
8	1.0245	-0.0029	1.0216	9.82	0.013652	0.0110	68.76	58.35
15	1.0235	-0.0029	1.0206	10.08	0.013652	0.0079	65.58	55.65
30	1.0220	-0.0029	1.0191	10.48	0.013652	0.0057	60.80	51.60
60	1.0205	-0.0029	1.0176	10.88	0.013652	0.0058	56.03	47.55
120	1.0190	-0.0029	1.0161	11.27	0.013652	0.0042	51.25	43.49

240	1.0170	-0.0029	1.0141	11.80	0.013652	0.0030	44.89	38.09
480	1.0140	-0.0029	1.0111	12.60	0.013652	0.0022	35.34	29.99
1440	1.0120	-0.0029	1.0091	13.13	0.013652	0.0013	28.97	24.58

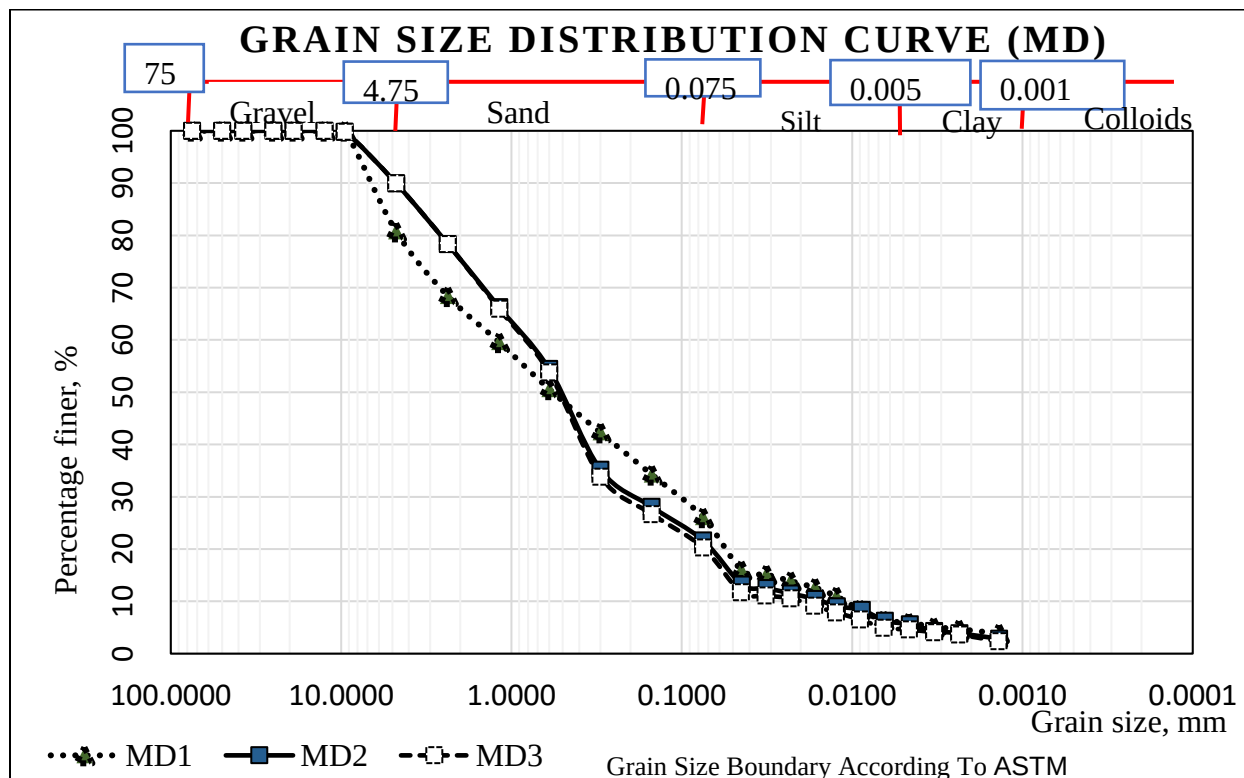


Sieve Analysis Mass of sample(g)=1000			MD at 1m					MD at 2m					MD at 3m				
Sieve No.	Sieve Opening (mm)	Mass of Sieve (g)	Mass of sieve +Retained soi (g)	Mass of Retained soi(g)	Percentage Retained (%)	Cum. Percentage Retained (%)	Perc. Passing (%)	Mass of sieve +Retained soi (g)	Mass of Retained soi(g)	Percentage Retained (%)	Cum. Percentage Retained (%)	Perc. Passing (%)	Mass of sieve +Retained soi (g)	Mass of Retained soi(g)	Percentage Retained (%)	Cum. Percentage Retained (%)	Perc. Passing (%)
3"	75	1057	1057.0	0.0	0.0	0.0	100.0	1057.0	0.0	0.0	0.0	100.0	1057.0	0.0	0.0	0.0	100.0
2"	50	1199	1199.0	0.0	0.0	0.0	100.0	1199.0	0.0	0.0	0.0	100.0	1199.0	0.0	0.0	0.0	100.0
1.5"	37.5	1084	1084.0	0.0	0.0	0.0	100.0	1084.0	0.0	0.0	0.0	100.0	1084.0	0.0	0.0	0.0	100.0
1"	25	1187	1187.0	0.0	0.0	0.0	100.0	1187.0	0.0	0.0	0.0	100.0	1187.0	0.0	0.0	0.0	100.0

3/4"	19	716	716.0	0.0	0.0	0.0	100.0	716.0	0.0	0.0	0.0	100.0	716.0	0.0	0.0	0.0	100.0
1/2"	12.5	584	584.0	0.0	0.0	0.0	100.0	584.0	0.0	0.0	0.0	100.0	584.0	0.0	0.0	0.0	100.0
3.8"	9.5	445.1	445.1	0.0	0.0	0.0	100.0	447.0	1.9	0.2	0.2	99.8	447.0	1.9	0.2	0.2	99.8
No 4	4.75	566.6	759.4	192.8	19.3	19.3	80.7	665.2	98.6	9.9	10.1	90.0	665.2	98.6	9.9	10.1	90.0
No 8	2.36	396.5	520.0	123.5	12.4	31.6	68.4	512.6	116.1	11.6	21.7	78.3	512.6	116.1	11.6	21.7	78.3
No 16	1.18	354	442.0	88.0	8.8	40.4	59.6	475.0	121.0	12.1	33.8	66.2	478.0	124.0	12.4	34.1	65.9
No 30	0.6	323.9	413.8	89.9	9.0	49.4	50.6	442.0	118.1	11.8	45.6	54.4	445.7	121.8	12.2	46.2	53.8
No40	0.425	447.8	485.6	37.8	3.8	53.2	46.8	489.0	41.2	4.1	49.7	50.3	496.1	48.3	4.8	51.1	48.9
No 50	0.3	308.6	353.8	45.2	4.5	57.7	42.3	459.7	151.1	15.1	64.8	35.2	459.7	151.1	15.1	66.2	33.8
No 100	0.15	423.2	503.5	80.3	8.0	65.8	34.3	494.5	71.3	7.1	71.9	28.1	494.5	71.3	7.1	73.3	26.7
No 200	0.075	417.1	498.8	81.7	8.2	73.9	26.1	481.2	64.1	6.4	78.3	21.7	481.2	64.1	6.4	79.7	20.3
Pan	-----	240.3	240.3	260.8	26.1	100.0	-----	240.3	216.6	21.7	100.0	-----	240.3	202.8	20.3	100.0	-----

Hydrometer Analysis									MD at 2m								
Specific gravity=2.66									Specific gravity=2.68								
Temperature (°C)=19									Temperature (°C)=19								
Elapsed Time (min)	Actual Hydrometer Reading	Composite Correction	Corrected Hydrometer Reading	Effective Depth (cm)	Coefficient K	Grain Size (mm)	Perc. Finer (%)	Perc. Finer Combined (%)	Actual Hydrometer Reading	Composite Correction	Corrected Hydrometer Reading	Effective Depth (cm)	Coefficient K	Grain Size (mm)	Perc. Finer (%)	Perc. Finer Combined (%)	
3/4	1.0220	-0.0029	1.0191	10.48	0.013778	0.0446	61.21	15.96	1.0220	-0.0029	1.0191	10.48	0.013694	0.0443	60.94	13.20	
1	1.0210	-0.0029	1.0181	10.75	0.013778	0.0319	58.01	15.13	1.0210	-0.0029	1.0181	10.75	0.013694	0.0317	57.75	12.51	
2	1.0195	-0.0029	1.0166	11.14	0.013778	0.0230	53.20	13.87	1.0195	-0.0029	1.0166	11.14	0.013694	0.0229	52.96	11.47	
4	1.0180	-0.0029	1.0151	11.54	0.013778	0.0165	48.39	12.62	1.0180	-0.0029	1.0151	11.54	0.013694	0.0164	48.18	10.43	
8	1.0160	-0.0029	1.0131	12.07	0.013778	0.0124	41.98	10.95	1.0160	-0.0029	1.0131	12.07	0.013694	0.0123	41.80	9.05	
15	1.0130	-0.0029	1.0101	12.86	0.013778	0.0090	32.37	8.44	1.0150	-0.0029	1.0121	12.33	0.013694	0.0088	38.60	8.36	
30	1.0115	-0.0029	1.0086	13.26	0.013778	0.0065	27.56	7.19	1.0140	-0.0029	1.0111	12.60	0.013694	0.0063	35.41	7.67	
60	1.0105	-0.0029	1.0076	13.52	0.013778	0.0065	24.36	6.35	1.0120	-0.0029	1.0091	13.13	0.013694	0.0064	29.03	6.29	
120	1.0100	-0.0029	1.0071	13.65	0.013778	0.0046	22.75	5.93	1.0110	-0.0029	1.0081	13.39	0.013694	0.0046	25.84	5.60	
240	1.0090	-0.0029	1.0061	13.92	0.013778	0.0033	19.55	5.10	1.0092	-0.0029	1.0063	13.87	0.013694	0.0033	20.10	4.35	
480	1.0085	-0.0029	1.0056	14.05	0.013778	0.0024	17.95	4.68	1.0085	-0.0029	1.0056	14.05	0.013694	0.0023	17.87	3.87	
1440	1.0075	-0.0029	1.0046	14.32	0.013778	0.0014	14.74	3.84	1.0070	-0.0029	1.0041	14.45	0.013694	0.0014	13.08	2.83	
MD at 3m																	
Specific gravity=2.67									Temperature (°C)=19								
Elapsed Time (min)	Actual Hydrometer Reading	Composite Correction	Corrected Hydrometer Reading	Effective Depth (cm)	Coefficient K	Grain Size (mm)	Perc. Finer (%)	Perc. Finer Combined (%)									

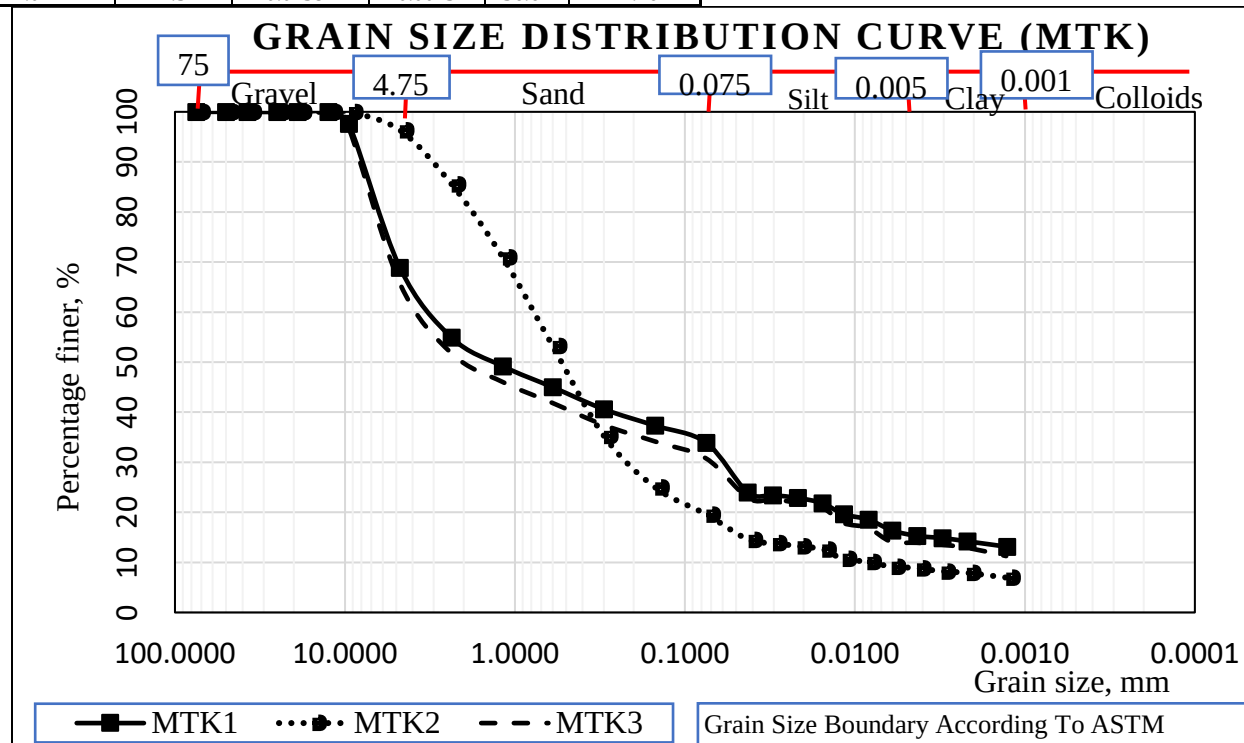
3/4	1.0210	-0.0029	1.0181	10.75	0.013736	0.0450	57.88	11.74
1	1.0200	-0.0029	1.0171	11.01	0.013736	0.0322	54.68	11.09
2	1.0192	-0.0029	1.0163	11.22	0.013736	0.0230	52.12	10.57
4	1.0170	-0.0029	1.0141	11.80	0.013736	0.0167	45.09	9.14
8	1.0150	-0.0029	1.0121	12.33	0.013736	0.0125	38.69	7.85
15	1.0130	-0.0029	1.0101	12.86	0.013736	0.0090	32.30	6.55
30	1.0115	-0.0029	1.0086	13.26	0.013736	0.0065	27.50	5.58
60	1.0105	-0.0029	1.0076	13.52	0.013736	0.0065	24.30	4.93
120	1.0100	-0.0029	1.0071	13.65	0.013736	0.0046	22.70	4.60
240	1.0092	-0.0029	1.0063	13.87	0.013736	0.0033	20.14	4.09
480	1.0085	-0.0029	1.0056	14.05	0.013736	0.0024	17.91	3.63
1440	1.0065	-0.0029	1.0036	14.58	0.013736	0.0014	11.51	2.33



Sieve Analysis Mass of sample(g)=1000			MTK at 1m					MTK at 2m					MTK at 3m				
Sieve No.	Sieve Opening (mm)	Mass of Sieve (g)	Mass of sieve +Retained soi (g)	Mass of Retained soi(g)	Percentage Retained (%)	Cum. Percentage Retained (%)	Perc. Passing (%)	Mass of sieve +Retained soi (g)	Mass of Retained soi(g)	Percentage Retained (%)	Cum. Percentage Retained (%)	Perc. Passing (%)	Mass of sieve +Retained soi (g)	Mass of Retained soi(g)	Percentage Retained (%)	Cum. Percentage Retained (%)	Perc. Passing (%)
3"	75	1057	1057.0	0.0	0.0	0.0	100.0	1057.0	0.0	0.0	0.0	100.0	1057.0	0.0	0.0	0.0	100.0
2"	50	1199	1199.0	0.0	0.0	0.0	100.0	1199.0	0.0	0.0	0.0	100.0	1199.0	0.0	0.0	0.0	100.0
1.5"	37.5	1084	1084.0	0.0	0.0	0.0	100.0	1084.0	0.0	0.0	0.0	100.0	1084.0	0.0	0.0	0.0	100.0
1"	25	1187	1187.0	0.0	0.0	0.0	100.0	1187.0	0.0	0.0	0.0	100.0	1187.0	0.0	0.0	0.0	100.0
3/4"	19	716	716.0	0.0	0.0	0.0	100.0	716.0	0.0	0.0	0.0	100.0	716.0	0.0	0.0	0.0	100.0
1/2"	12.5	584	584.0	0.0	0.0	0.0	100.0	584.0	0.0	0.0	0.0	100.0	584.0	0.0	0.0	0.0	100.0
3.8"	9.5	445.1	469.0	23.9	2.4	2.4	97.6	445.1	0.0	0.0	0.0	100.0	478.0	32.9	3.3	3.3	96.7
No 4	4.75	566.6	854.0	287.4	28.7	31.1	68.9	603.3	36.7	3.7	3.7	96.3	876.6	310.0	31.0	34.3	65.7
No 8	2.36	396.5	536.0	139.5	14.0	45.1	54.9	504.2	107.7	10.8	14.4	85.6	536.0	139.5	14.0	48.2	51.8
No 16	1.18	354	411.3	57.3	5.7	50.8	49.2	500.0	146.0	14.6	29.0	71.0	411.3	57.3	5.7	54.0	46.0
No 30	0.6	323.9	365.8	41.9	4.2	55.0	45.0	501.1	177.2	17.7	46.8	53.2	365.8	41.9	4.2	58.2	41.8
No40	0.425	447.8	467.7	19.9	2.0	57.0	43.0	539.2	91.4	9.1	55.9	44.1	467.7	19.9	2.0	60.2	39.9
No 50	0.3	308.6	332.7	24.1	2.4	59.4	40.6	396.6	88.0	8.8	64.7	35.3	332.7	24.1	2.4	62.6	37.4
No 100	0.15	423.2	456.0	32.8	3.3	62.7	37.3	526.1	102.9	10.3	75.0	25.0	456.0	32.8	3.3	65.8	34.2
No 200	0.075	417.1	451.1	34.0	3.4	66.1	33.9	471.2	54.1	5.4	80.4	19.6	451.1	34.0	3.4	69.2	30.8
Pan	-----	240.3	240.3	339.2	33.9	100.0	-----	240.3	196.0	19.6	100.0	-----	240.3	307.6	30.8	100.0	-----

Hydrometer Analysis							MTK at 1m		MTK at 2m							
Specific gravity=2.67							Temperature (°C)=19		Specific gravity=2.75				Temperature (°C)=19			
Elapsed Time (min)	Actual Hydrometer Reading	Composite Correction	Corrected Hydrometer Reading	Effective Depth (cm)	Coefficient K	Grain Size (mm)	Perc. Finer (%)	Perc. Finer Combined (%)	Actual Hydrometer Reading	Composite Correction	Corrected Hydrometer Reading	Effective Depth (cm)	Coefficient K	Grain Size (mm)	Perc. Finer (%)	Perc. Finer Combined (%)
3/4	1.0250	-0.0029	1.0221	9.69	0.013736	0.0428	70.67	23.97	1.0260	-0.0029	1.0231	9.42	0.013778	0.0423	74.03	14.51
1	1.0245	-0.0029	1.0216	9.82	0.013736	0.0304	69.07	23.43	1.0250	-0.0029	1.0221	9.69	0.013778	0.0303	70.83	13.88
2	1.0240	-0.0029	1.0211	9.95	0.013736	0.0217	67.47	22.89	1.0240	-0.0029	1.0211	9.95	0.013778	0.0217	67.62	13.25
4	1.0230	-0.0029	1.0201	10.22	0.013736	0.0155	64.27	21.80	1.0230	-0.0029	1.0201	10.22	0.013778	0.0156	64.42	12.63
8	1.0210	-0.0029	1.0181	10.75	0.013736	0.0116	57.88	19.63	1.0200	-0.0029	1.0171	11.01	0.013778	0.0118	54.80	10.74
15	1.0200	-0.0029	1.0171	11.01	0.013736	0.0083	54.68	18.55	1.0190	-0.0029	1.0161	11.27	0.013778	0.0084	51.60	10.11
30	1.0190	-0.0029	1.0161	11.27	0.013736	0.0060	51.48	17.46	1.0180	-0.0029	1.0151	11.54	0.013778	0.0060	48.39	9.48
60	1.0180	-0.0029	1.0151	11.54	0.013736	0.0060	48.28	16.38	1.0175	-0.0029	1.0146	11.67	0.013778	0.0061	46.79	9.17
120	1.0170	-0.0029	1.0141	11.80	0.013736	0.0043	45.09	15.29	1.0170	-0.0029	1.0141	11.80	0.013778	0.0043	45.19	8.86
240	1.0166	-0.0029	1.0137	11.91	0.013736	0.0031	43.81	14.86	1.0160	-0.0029	1.0131	12.07	0.013778	0.0031	41.98	8.23
480	1.0160	-0.0029	1.0131	12.07	0.013736	0.0022	41.89	14.21	1.0155	-0.0029	1.0126	12.20	0.013778	0.0022	40.38	7.91
1440	1.0150	-0.0029	1.0121	12.33	0.013736	0.0013	38.69	13.12	1.0140	-0.0029	1.0111	12.60	0.013778	0.0013	35.57	6.97
MTK at 3m																
Specific gravity=2.75									Temperature (°C)=19							

Elapsed Time (min)	Actual Hydrometer Reading	Composite Correction	Corrected Hydrometer Reading	Effective Depth (cm)	Coefficient K	Grain Size (mm)	Perc. Finer (%)	Perc. Finer Combined (%)
3/4	1.0260	-0.0029	1.0231	9.42	0.01382	0.0424	74.20	22.82
1	1.0258	-0.0029	1.0229	9.48	0.01382	0.0301	73.56	22.63
2	1.0250	-0.0029	1.0221	9.69	0.01382	0.0215	70.99	21.84
4	1.0240	-0.0029	1.0211	9.95	0.01382	0.0154	67.78	20.85
8	1.0210	-0.0029	1.0181	10.75	0.01382	0.0117	58.14	17.88
15	1.0200	-0.0029	1.0171	11.01	0.01382	0.0084	54.93	16.90
30	1.0190	-0.0029	1.0161	11.27	0.01382	0.0060	51.72	15.91
60	1.0172	-0.0029	1.0143	11.75	0.01382	0.0061	45.93	14.13
120	1.0170	-0.0029	1.0141	11.80	0.01382	0.0043	45.29	13.93
240	1.0166	-0.0029	1.0137	11.91	0.01382	0.0031	44.01	13.54
480	1.0160	-0.0029	1.0131	12.07	0.01382	0.0022	42.08	12.94
1440	1.0143	-0.0029	1.0114	12.52	0.01382	0.0013	36.62	11.26



Appendix D Atterberg Limit Tests

Location	DP @1m						DP @2m						DP @3m					
DP	Liquid Limit			Plastic Limit			Liquid Limit			Plastic Limit			Liquid Limit			Plastic Limit		
Trial No	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Container No	p22	p12	p11	p13	p23	p21	AG4	DA4	MS6	AG4	DA4	AP3	AG4	DA4	MS6	AG4	DA4	AP3
Mass of container, g	14.74	15.96	15.94	15.25	14.39	15.52	14.42	15.64	15.72	15.92	15.54	15.94	14.42	15.64	15.72	15.92	15.54	15.94
Mass of container + Wet soil, g	28.92	38.82	41.12	19.75	18.58	19.59	29.02	37.67	41.21	20.12	18.78	19.51	32.12	37.27	40.88	19.55	18.12	19.39
Mass of container + Dry soil, g	23.00	29.12	30.13	18.61	17.51	18.56	22.87	28.26	30.05	19.06	17.97	18.64	24.69	27.89	29.51	18.71	17.55	18.59
Mass of water, g	5.92	9.70	10.99	1.14	1.07	1.03	6.15	9.41	11.16	1.06	0.81	0.87	7.43	9.38	11.37	0.84	0.57	0.80
Mass of dry soil, g	8.26	13.16	14.19	3.36	3.12	3.04	8.45	12.62	14.33	3.14	2.43	2.70	10.27	12.25	13.79	2.79	2.01	2.65
Water content, %	71.67	73.71	77.45	33.93	34.29	33.88	72.78	74.56	77.88	33.76	33.33	32.22	72.35	76.57	82.45	30.11	28.36	30.19
No of blows	33	26	14	-----	-----	-----	35	24	18	-----	-----	-----	34	26	16	-----	-----	-----
LL, % @ 25 blows= 74	Plastic Limit, % = 34			PI, %= 40			LL= 75	Plastic Limit, % = 33			PI, %= 42			LL= 77	Plastic Limit, % = 30			PI, %= 47

Location	AP@1m						AP@2m						AP@3m					
AP	Liquid Limit			Plastic Limit			Liquid Limit			Plastic Limit			Liquid Limit			Plastic Limit		
Trial No	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Container No	C11	E16	N23	M21	R32	L12	D22	DA4	MS2	AG4	Ap2	NH1	AG4	DA4	MS6	MS2	AP3	MS4
Mass of container, g	14.93	14.98	15.21	15.41	15.25	15.11	15.83	15.55	15.85	15.43	14.89	15.25	15.93	15.55	15.93	15.72	15.78	15.63
Mass of container + Wet soil, g	39.11	37.15	40.41	21.08	21.25	20.62	38.13	36.30	40.11	21.01	20.82	20.12	38.13	37.71	40.41	20.67	20.78	20.25
Mass of container + Dry soil, g	28.92	27.55	29.31	19.64	19.75	19.2	28.97	27.50	29.19	19.60	19.25	18.9	28.97	28.21	29.19	19.50	19.58	19.15
Mass of water, g	10.19	9.60	11.10	1.44	1.50	1.42	9.16	8.80	10.92	1.41	1.57	1.22	9.16	9.50	11.22	1.17	1.20	1.10
Mass of dry soil, g	13.99	12.57	14.10	4.23	4.50	4.09	13.14	11.95	13.34	4.17	4.36	3.65	13.04	12.66	13.26	3.78	3.80	3.52
Water content, %	72.84	76.37	78.72	34.04	33.33	34.72	69.71	73.64	81.86	33.81	36.01	33.42	72.00	77.00	79.00	30.95	31.58	31.25
No of blows	31	23	13	-----	-----	-----	33	22	14	-----	-----	-----	35	24	15	-----	-----	-----
LL, % @ 25 blows =	LL=75			Plastic Limit, % = 34			LL=73			Plastic Limit, % = 34			LL=75			Plastic Limit, % = 31		
				PI, %= 41						PI, %= 39						PI, %= 44		

Location	Amar@1m						Amar@2m						Amar@3m					
Amar	Liquid Limit			Plastic Limit			Liquid Limit			Plastic Limit			Liquid Limit			Plastic Limit		
Trial No	1	2	3	1	2	3	1	2	3	1	2	1	2	3	1	2	3	
Container No	p22	p12	p11	p13	p23	p21	p11	p12	p13	p21	p22	AG4	DA4	MS6	HA2	MTK	AG2	
Mass of container, g	14.74	15.96	15.94	15.25	14.39	15.52	15.49	15.14	15.97	15.90	15.63	15.50	15.98	15.41	15.81	15.39	15.81	
Mass of container + Wet soil, g	28.92	38.82	41.12	19.75	18.58	19.59	39.25	39.03	39.30	21.95	22.33	34.49	36.98	39.54	20.98	20.11	19.61	
Mass of container + Dry soil, g	23.00	29.12	30.13	18.61	17.51	18.56	29.07	28.69	28.97	20.45	20.67	27.32	28.91	30.10	19.78	18.97	18.72	
Mass of water, g	5.92	9.70	10.99	1.14	1.07	1.03	10.18	10.34	10.33	1.50	1.66	7.17	8.07	9.44	1.20	1.14	0.89	
Mass of dry soil, g	8.26	13.16	14.19	3.36	3.12	3.04	13.58	13.55	13.00	4.55	5.04	11.82	12.93	14.69	3.97	3.58	2.91	
Water content, %	71.67	73.71	77.45	33.93	34.29	33.88	74.96	76.31	79.46	32.97	32.94	60.66	62.41	64.26	30.23	31.84	30.58	
No of blows	33	26	14	-----	-----	-----	35	24	15	-----	-----	34	27	18	-----	-----	-----	
LL, % @ 25 blows =	LL= 75	Plastic Limit, % =		34	PI, %=	41	LL= 77	Plastic Limit, % =		33	PI, %= 44	LL= 63	Plastic Limit, % =		31	PI, %=	32	

Location	MTK@1m						MTK@2m						MTK@3m					
MTK	Liquid Limit			Plastic Limit			Liquid Limit			Plastic Limit		Liquid Limit			Plastic Limit			
Trial No	1	2	3	1	2	3	1	2	3	1	2	1	2	3	1	2	3	
Container No	n11	n12	n13	n21	n22	n23	p11	p12	p13	p21	p22	DA2	HA2	AP12	H2SO4	AMR33	AG2	
Mass of container, g	15.25	15.89	15.91	14.92	15.50	15.86	15.97	15.16	15.47	15.92	15.65	15.39	15.79	15.46	14.92	15.50	15.86	
Mass of container + Wet soil, g	40.86	39.31	36.86	21.01	21.15	22.02	38.06	35.43	36.48	24.19	20.62	40.86	39.31	36.86	20.98	21.70	22.52	
Mass of container + Dry soil, g	30.87	29.85	28.12	19.16	19.41	20.12	29.51	27.50	28.13	21.57	19.05	30.56	29.58	27.75	19.06	19.62	20.31	
Mass of water, g	9.99	9.46	8.74	1.85	1.74	1.90	8.55	7.93	8.35	2.62	1.57	10.30	9.73	9.11	1.92	2.08	2.21	
Mass of dry soil, g	15.62	13.96	12.21	4.24	3.91	4.26	13.54	12.34	12.66	5.65	3.40	15.17	13.79	12.29	4.14	4.12	4.45	
Water content, %	63.96	67.77	71.58	43.63	44.50	44.60	63.15	64.26	65.96	46.37	46.18	67.90	70.56	74.13	46.38	50.49	49.66	
No of blows	33	24	19	-----	-----	-----	33	23	15	-----	-----	35	27	20	-----	-----	-----	
LL, % @ 25 blows =	LL= 68	Plastic Limit, % =		45	PI, %=	23	LL= 64	Plastic Limit, % =		46	PI, %=	LL= 72	Plastic Limit, % =		49	PI, %=	23	

Location	MD@1m						MD @2m						MD @3m							
MD	Liquid Limit			Plastic Limit			Liquid Limit			Plastic Limit			Liquid Limit			Plastic Limit				
Trial No	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3		
Container No	AG2	DA2	H2SO4	HA2	AMR33	AP12	p11	p12	p13	p21	p22	p23	AG2	DA2	H2SO4	HA2	AMR33	AP12		
Mass of container, g	15.86	15.39	14.91	15.80	15.51	15.47	14.86	15.25	15.41	14.89	14.97	15.25	15.86	15.39	14.91	15.80	15.51	15.47		
Mass of container + Wet soil, g	37.85	48.56	41.41	23.11	21.21	22.07	37.25	48.02	40.89	23.11	21.01	21.91	37.41	48.02	40.89	23.11	21.01	21.91		
Mass of container + Dry soil, g	30.24	36.86	31.90	20.98	19.52	20.12	30.24	36.42	31.21	21.06	19.45	20.12	30.24	36.86	31.90	21.06	19.48	20.12		
Mass of water, g	7.61	11.70	9.51	2.13	1.69	1.95	7.01	11.60	9.68	2.05	1.56	1.79	7.17	11.16	8.99	2.05	1.53	1.79		
Mass of dry soil, g	14.38	21.47	16.99	5.18	4.01	4.65	15.38	21.17	15.80	6.17	4.48	4.87	14.38	21.47	16.99	5.26	3.97	4.65		
Water content, %	52.92	54.49	55.97	41.12	42.14	41.94	45.58	54.79	61.27	33.23	34.82	36.76	49.86	51.98	52.91	38.97	38.54	38.49		
No of blows	34	22	15	-----	-----	-----	35	24	16	-----	-----	-----	34	22	15	-----	-----	-----		
LL, % @ 25 blows =	LL= 54	Plastic Limit, % =		42	PI, %=		LL= 53	Plastic Limit, % =		35	PI, %=		18	LL= 51	Plastic Limit, % =		39	PI, %=		12

Location	IP @1m						IP @2m						IP @3m					
IP	Liquid Limit			Plastic Limit			Liquid Limit			Plastic Limit			Liquid Limit			Plastic Limit		
Trial No	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Container No	a1	a4	c12	d88	c14	a3	s42	s66	n22	g32	ng1	pp2	AG4	DA4	MS6	MS2	AP3	MS4
Mass of container, g	14.28	14.56	14.97	14.98	15.41	15.23	15.93	15.55	15.93	15.66	15.74	15.57	15.93	15.55	15.93	15.72	15.78	15.63
Mass of container + Wet soil, g	39.41	39.54	39.57	21.70	21.01	21.01	37.65	37.54	39.20	20.89	20.84	20.87	38.20	37.40	39.20	21.02	20.84	20.87
Mass of container + Dry soil, g	29.12	29.05	29.01	19.99	19.58	19.63	28.68	28.15	28.88	19.59	19.59	19.57	29.01	28.20	29.28	19.75	19.63	19.56
Mass of water, g	10.29	10.49	10.56	1.71	1.43	1.38	8.97	9.39	10.32	1.30	1.25	1.30	9.19	9.20	9.92	1.27	1.21	1.31
Mass of dry soil, g	14.84	14.49	14.04	5.01	4.17	4.40	12.75	12.60	12.95	3.93	3.85	4.00	13.08	12.65	13.35	4.03	3.85	3.93
Water content, %	69.34	72.39	75.21	34.13	34.29	31.36	70.35	74.52	79.69	33.08	32.47	32.50	70.26	72.73	74.31	31.51	31.43	33.33
No of blows	32	24	16	-----	-----	-----	33	24	15	-----	-----	-----	35	21	15	-----	-----	-----
	LL=	Plastic Limit, %			Plastic Limit, %		LL=	Plastic Limit, %			Plastic Limit, %		LL=	Plastic Limit, %			Plastic Limit, %	
LL, % @ 25 blows =	72	=		34	PI, %=	38	74	=		33	PI, %=	41	72	=		32	PI, %=	40

Appendix E Free Swell Test

Sample Location	Depth(m)	Initial Volume (cc)	Final Volume	Average	Free Final Volume (cc)	Swell Index (%)
			Sample No.1 (cc)	Sample No.2 (cc)		
AP	1	10.0	18.0	18.0	18.0	80
	2	10.0	18.0	18.0	18.0	80
	3	10.0	19.0	18.0	18.5	85
MD	1	10.0	12.0	11.0	11.5	15
	2	10.0	11.0	11.0	11.0	10
	3	10.0	11.0	12.0	11.5	15
IP	1	10.0	19.0	19.0	19.0	90
	2	10.0	19.0	18.0	18.5	85
	3	10.0	18	18	18	80
Amr	1	10.0	18.0	18.0	18.0	80
	2	10.0	17.0	18.0	17.5	75
	3	10.0	15.0	16.0	15.5	55
MTK	1	10.0	13.0	13.0	13.0	30
	2	10.0	14.0	14.0	14.0	40
	3	10.0	12.0	14.0	13.0	30
DP	1	10.0	18.0	18.0	18.0	80
	2	10.0	19.0	18.0	18.5	85
	3	10.0	19.0	20.0	19.5	95

Appendix F Void Ratio Determination

Void ratio(e)= (Specific Gravity*Density of Water/Dry Density of Soil)-1

Location	AP			DP			IP			MD			Amr			MTK		
Depth	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Void ratio(e)	1.55	1.56	1.50	1.28	1.20	1.24	1.41	1.39	1.37	0.89	0.91	0.73	1.36	1.29	1.20	0.93	0.87	0.87

Appendix G One-Dimensional Consolidation Test

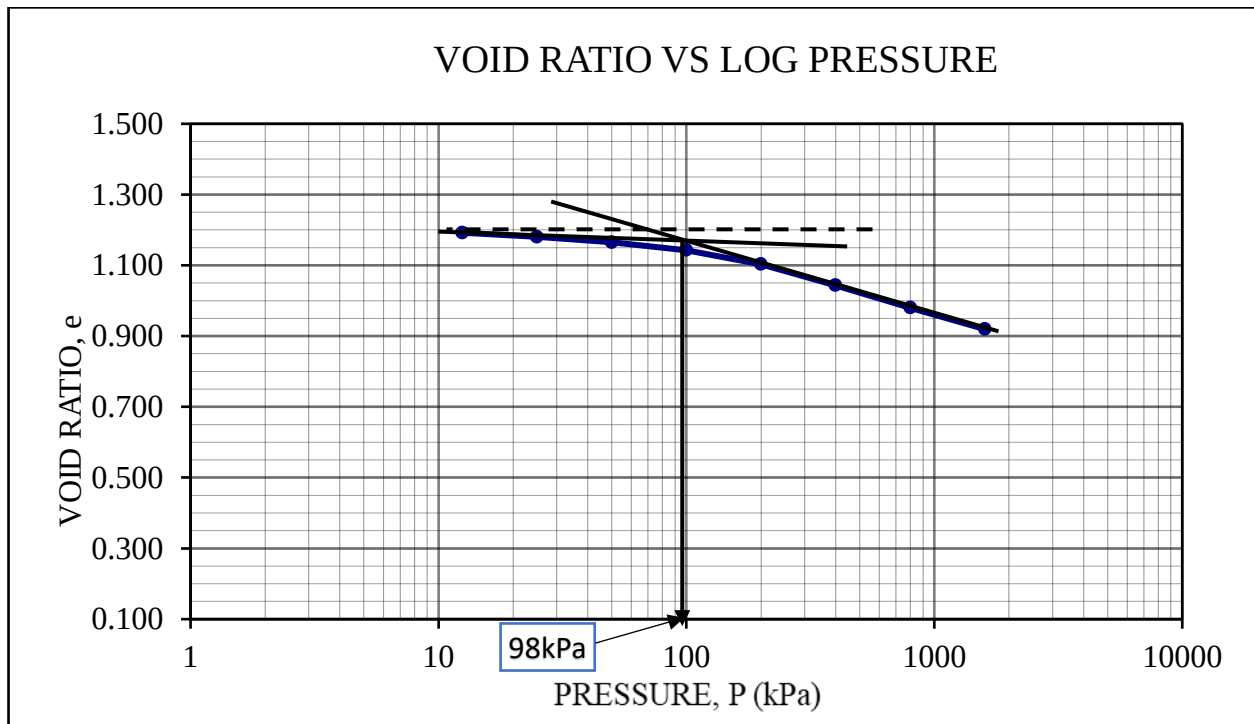
Determination of pre-consolidation Pressure For Clay Soil (DP3)

Specimen data

Before test	
Specific Gravity (G_s)	2.71
Sample Diameter (D) (mm)	50.00
Sample Thickness (H_o) (mm)	20.00
Area (A) (cm ²)	19.63
Volume (V) (cm ³)	39.26
Dry Density (γ_d) (g/cm ³)	1.210
Initial Moisture content (M_o) (%)	32.44
Initial Void Ratio: $e_o = (G_s/\gamma_d)-1$	1.24
Height of Solids: $H_s = H_o/(1+e_o)$ (mm)	8.930

After test	
Final Moisture Content (M_f) (%)	42.58
Dry Density (γ_d) (g/cm ³)	1.412
Final Void ratio(e_f)	0.919
Final Height (H_f)	17.140

Increment N°	Pressure, P (kPa)	Cumulative compression, DH (mm)	Consolidated height H = $H_o - DH$ (mm)	Voids Ratio $e = e_o - DH/H_s$
0	0	0.000	20.000	1.240
1	12.5	0.425	19.575	1.192
2	25	0.532	19.468	1.180
3	50	0.667	19.333	1.165
4	100	0.864	19.136	1.143
5	200	1.221	18.779	1.103
6	400	1.754	18.246	1.043
7	800	2.321	17.679	0.980
8	1600	2.860	17.140	0.919



Determination of Pre-consolidation pressure for Silty Sand soil (MD3)

Specimen data

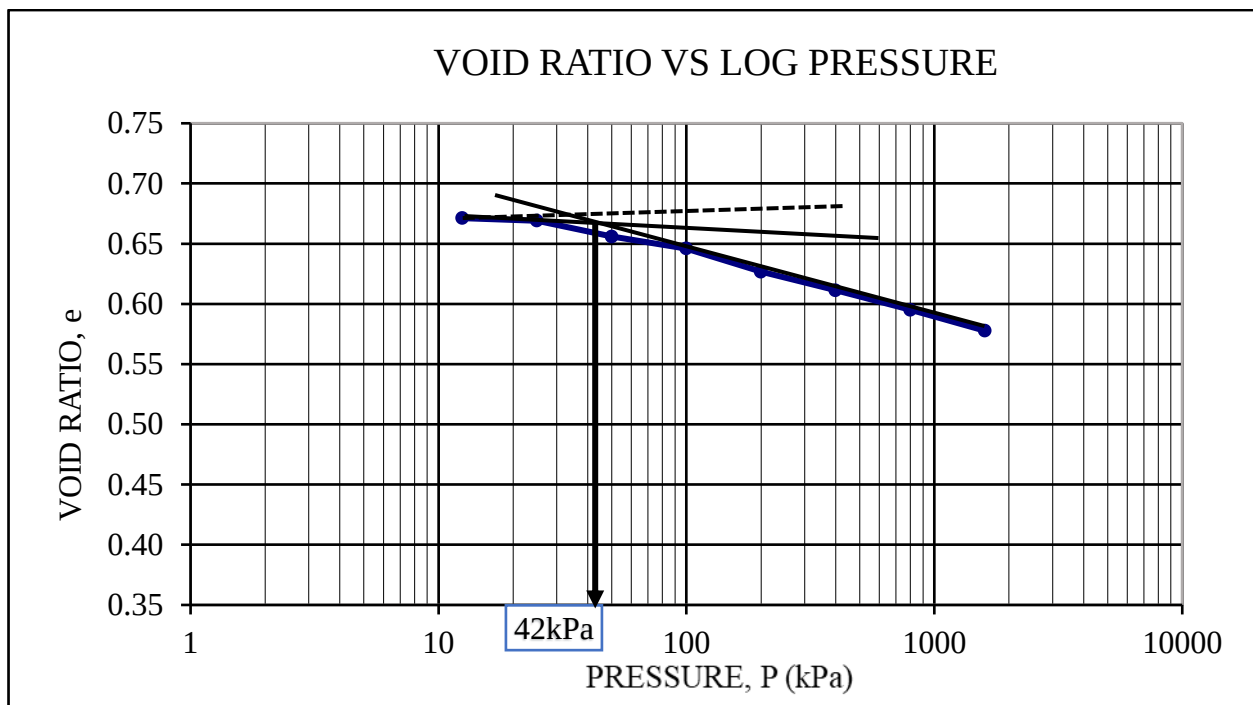
Before test

Specific Gravity (G_s)	2.67
Sample Diameter (D) (mm)	50.00
Sample Thickness (H_o) (mm)	20.00
Area (A) (cm^2)	19.63
Volume (V) (cm^3)	39.26
Dry Density (γ_d) (g/cm^3)	1.540
Initial Moisture content (M_o) (%)	16.40
Initial Void Ratio: $e_o = (G_s/\gamma_d) - 1$	0.73
Height of Solids: $H_s = H_o/(1+e_o)$ (mm)	11.536

After test

Final Moisture Content (M_f) (%)	17.62
Dry Density (γ_d) (g/cm^3)	1.693
Final Void ratio(e_f)	0.578
Final Height (H_f) (mm)	18.2

Increment N°	Pressure, P (kPa)	Cumulative compression, DH (mm)	Consolidated height H = $H_o - DH$ (mm)	Voids Ratio $e = e_o - DH/H_s$
0	0	0.000	20.000	0.734
1	12.5	0.721	19.279	0.671
2	25	0.746	19.254	0.699
3	50	0.898	19.103	0.656
4	100	1.013	18.987	0.646
5	200	1.235	18.765	0.627
6	400	1.412	18.588	0.611
7	800	1.600	18.400	0.595
8	1600	1.800	18.200	0.578



Appendix H Cyclic Simple Shear Test



Sample Preparation



Soil Sample



Cyclic simple shear test operation

Soil Sample after test



Determination of Shear modulus and Damping ratio

DP3 at 100kPa

Strain	0.01	0.1	1	2.5	5	0.01	0.1	1	2.5	5
No of Cycle	G (MPa)					D %				
1	6.603	3.358	1.704	0.841	0.520	4.063	4.631	7.463	19.019	27.573
2	6.717	3.374	1.740	0.854	0.540	3.906	4.373	7.399	17.583	25.450
3	6.773	3.374	1.773	0.884	0.600	3.833	4.315	7.593	17.188	24.653
4	6.896	3.380	1.797	0.873	0.609	3.684	4.302	7.581	17.491	24.419
5	6.962	3.386	1.830	0.857	0.609	3.609	4.286	7.526	16.792	22.396
6	7.279	3.390	1.842	0.785	0.593	3.516	3.671	7.360	13.924	21.957
7	7.285	3.392	1.859	0.798	0.598	3.511	3.664	7.168	13.745	21.579
8	7.289	3.391	1.877	0.812	0.607	3.495	3.659	6.985	13.406	20.803
9	7.303	3.398	1.877	0.800	0.618	3.482	3.655	6.570	13.311	20.594
10	7.305	3.398	1.889	0.808	0.611	3.468	3.647	6.777	13.031	20.398
11	7.309	3.403	1.875	0.804	0.619	3.431	3.634	6.582	12.929	19.824
12	7.315	3.406	1.891	0.797	0.621	3.398	3.611	6.671	12.849	19.699
13	7.318	3.409	1.932	0.800	0.618	3.388	3.605	6.840	12.804	19.678
14	7.330	3.420	1.946	0.800	0.621	3.325	3.582	6.434	12.792	19.659
15	7.337	3.427	1.974	0.813	0.619	3.257	3.555	7.044	12.676	19.605
16	7.344	3.442	1.914	0.814	0.621	3.241	3.550	6.979	12.608	19.431
17	7.357	3.443	1.948	0.807	0.634	3.239	3.531	6.194	12.599	19.429
18	7.368	3.449	1.951	0.823	0.635	3.141	3.514	6.161	12.474	19.349
19	7.372	3.458	1.966	0.802	0.640	3.024	3.496	6.102	12.414	19.227
20	7.353	3.465	2.008	0.836	0.664	2.794	3.463	5.952	12.248	19.179
21	7.360	3.469	1.979	0.811	0.659	2.746	3.444	5.823	12.198	19.124
22	7.381	3.477	2.021	0.818	0.671	2.623	3.429	5.273	12.091	19.017
23	7.389	3.484	2.066	0.829	0.663	2.532	3.416	5.106	12.018	18.945
24	7.393	3.489	2.100	0.818	0.664	2.461	3.410	5.288	11.971	18.836
25	7.407	3.488	2.119	0.822	0.669	2.377	3.408	4.928	11.790	18.696
26	7.425	3.493	2.161	0.815	0.669	2.317	3.399	4.793	11.737	18.497
27	7.433	3.501	2.183	0.818	0.670	2.289	3.385	4.726	11.598	18.401
28	7.441	3.505	2.187	0.828	0.670	2.196	3.379	4.712	11.493	18.276
29	7.444	3.516	2.132	0.822	0.671	2.013	3.359	4.675	11.391	18.205
30	7.455	3.518	2.205	0.829	0.673	2.007	3.234	4.381	11.303	18.056
31	7.459	3.523	2.216	0.831	0.672	2.005	3.226	4.327	11.273	17.875
32	7.466	3.523	2.254	0.835	0.679	2.001	3.226	4.220	11.137	17.987
33	7.474	3.523	2.259	0.831	0.684	1.997	3.200	4.151	11.094	17.779
34	7.481	3.544	2.313	0.819	0.688	1.994	3.199	4.062	11.068	17.645
35	7.493	3.557	2.361	0.843	0.692	1.988	3.154	3.945	11.039	17.587
36	7.502	3.562	2.381	0.843	0.695	1.983	3.096	3.896	11.013	17.588
37	7.516	3.570	2.502	0.848	0.697	1.976	3.078	3.735	10.961	17.318
38	7.531	3.591	2.613	0.854	0.696	1.969	3.057	3.593	10.850	17.271
39	7.547	3.637	2.695	0.863	0.706	1.961	3.019	3.777	10.714	17.269
40	7.670	3.653	2.787	0.860	0.730	1.903	2.966	3.746	10.660	17.168

DP3 at 250kPa

Strain	0.01	0.1	1	2.5	5	0.01	0.1	1	2.5	5
No of Cycle	G (MPa)					D (%)				
1	7.625	5.578	4.705	3.495	1.044	2.286	3.250	6.647	15.191	17.621
2	7.639	5.613	4.734	3.552	1.046	2.291	3.223	6.235	13.682	17.532
3	7.646	5.619	4.773	3.561	1.047	2.287	3.218	6.181	13.620	17.515
4	7.653	5.643	4.760	3.563	1.047	2.284	3.198	6.089	13.598	17.498
5	7.660	5.656	4.769	3.113	1.081	2.280	3.188	6.066	13.569	16.484
6	7.664	5.657	4.777	3.571	1.141	2.278	3.188	6.046	13.544	14.674
7	7.668	5.666	4.787	3.582	1.144	2.275	3.180	6.021	13.460	14.587
8	7.678	5.676	4.803	3.588	1.144	2.270	3.173	5.982	12.608	14.463
9	7.684	5.725	4.812	3.598	1.199	2.267	3.135	5.960	12.538	14.421
10	7.691	5.732	4.818	3.602	1.201	2.263	3.129	5.945	12.275	14.365
11	7.700	5.750	4.959	3.613	1.203	2.259	3.116	5.696	12.154	14.326
12	7.712	5.922	4.971	3.616	1.196	2.252	3.201	5.600	12.066	14.263
13	7.727	6.159	4.984	3.618	1.194	2.245	3.016	5.575	11.968	14.134
14	7.833	6.026	5.040	3.620	1.195	2.200	2.922	5.455	11.941	14.016
15	7.933	6.060	5.139	3.626	1.204	2.121	2.685	5.132	11.542	13.992
16	8.062	6.083	5.202	3.662	1.220	2.069	2.672	5.018	11.714	13.960
17	8.139	6.526	5.234	3.674	1.242	2.050	2.808	5.095	11.108	13.740
18	8.180	6.230	5.246	3.680	1.223	2.032	2.796	5.077	11.047	13.503
19	8.183	6.274	5.245	3.694	1.242	2.031	2.769	5.002	10.924	13.414
20	8.196	6.282	5.256	3.704	1.252	2.026	2.765	4.956	10.903	13.354
21	8.199	6.291	5.345	3.707	1.262	2.024	2.760	4.565	10.886	13.160
22	8.213	6.315	5.446	3.709	1.264	2.019	2.745	4.480	10.851	13.118
23	8.223	6.330	5.525	3.714	1.270	2.015	2.737	4.466	10.798	12.993
24	8.223	6.371	5.546	3.719	1.273	2.015	2.714	4.417	10.763	12.947
25	8.230	6.458	5.647	3.722	1.280	2.012	2.666	4.379	10.739	12.809
26	8.234	6.509	5.656	3.723	1.287	2.010	2.639	4.372	10.719	12.682
27	8.242	6.571	5.647	3.746	1.292	2.007	2.607	4.342	9.397	12.595
28	8.316	6.599	5.671	3.753	1.298	1.977	2.593	4.299	9.362	12.495
29	8.355	6.613	5.684	3.758	1.302	1.961	2.586	4.243	9.335	12.432
30	8.405	6.683	5.691	3.764	1.306	1.942	2.551	4.215	9.304	12.363
31	8.434	6.750	5.704	3.848	1.309	1.931	2.519	4.189	9.210	12.308
32	8.470	6.766	5.715	3.926	1.319	1.917	2.511	4.169	9.077	12.145
33	8.503	6.785	5.725	3.974	1.324	1.905	2.502	4.131	8.985	12.066
34	8.550	6.845	5.735	4.030	1.327	1.888	2.475	4.066	8.829	12.014
35	8.565	6.851	5.747	4.049	1.252	1.883	2.472	4.050	8.749	11.991
36	8.569	6.856	5.754	4.102	1.330	1.881	2.470	4.001	8.576	11.965
37	8.578	6.860	5.752	4.114	1.335	1.878	2.468	3.932	8.556	11.887
38	8.627	6.871	5.770	4.211	1.383	1.861	2.463	3.917	8.304	11.185
39	8.653	6.878	5.778	4.221	1.417	1.852	2.460	3.875	8.134	10.732
40	8.743	6.887	5.848	4.305	1.431	1.821	2.456	3.743	8.000	10.559

DP3 at 400 kPa

Strain	0.01	0.10	1.00	2.50	5.00	0.01	0.10	1.00	2.50	5.00
No of Cycle	G (MPa)					D (%)				
1.0	9.817	7.892	7.735	3.486	1.590	1.563	3.632	3.994	12.046	13.637
2.0	9.839	8.038	7.786	3.500	1.603	1.557	3.505	3.934	11.882	13.437
3.0	9.869	8.054	7.842	3.510	1.604	1.550	3.492	3.871	11.824	13.414
4.0	9.881	8.061	7.889	3.520	1.608	1.547	3.486	3.818	11.640	13.364
5.0	9.896	8.672	7.962	3.675	1.704	1.543	2.837	3.740	11.825	13.124
6.0	9.903	8.094	8.034	3.551	1.628	1.542	3.458	3.666	11.356	13.059
7.0	9.917	8.122	8.064	3.562	1.637	1.538	3.436	3.636	11.141	12.923
8.0	9.928	8.147	8.101	3.574	1.647	1.536	3.416	3.600	10.970	12.790
9.0	9.945	8.168	8.152	3.584	1.656	1.532	3.399	3.551	10.715	12.660
10.0	9.966	8.193	8.201	3.593	1.671	1.527	3.380	3.506	10.564	12.470
11.0	9.970	8.205	8.255	3.605	1.685	1.526	3.371	3.456	10.416	12.286
12.0	10.114	8.231	8.328	3.610	1.694	1.492	3.351	3.392	10.342	12.167
13.0	10.219	8.261	8.345	3.627	1.704	1.469	3.328	3.378	10.261	12.051
14.0	10.294	8.269	8.356	3.639	1.713	1.453	3.322	3.369	10.173	11.936
15.0	10.394	8.285	8.366	3.657	1.718	1.432	3.310	3.361	10.060	11.880
16.0	10.495	8.301	8.377	3.668	1.727	1.411	3.299	3.352	9.893	11.769
17.0	10.535	8.313	8.398	3.674	1.737	1.403	3.290	3.334	9.788	11.661
18.0	10.554	8.331	8.409	3.679	1.745	1.400	3.277	3.325	9.771	11.565
19.0	10.588	8.354	8.430	3.686	1.754	1.393	3.260	3.308	9.692	11.472
20.0	10.597	8.383	8.439	3.736	1.761	1.391	3.239	3.301	9.610	11.389
21.0	10.605	8.411	8.443	3.746	1.770	1.390	3.219	3.297	9.556	11.298
22.0	10.620	8.437	8.460	3.757	1.785	1.387	3.201	3.283	9.508	11.144
23.0	10.634	8.458	8.483	3.765	1.799	1.384	3.187	3.265	9.452	11.003
24.0	10.642	8.465	8.499	3.776	1.813	1.382	3.182	3.252	9.397	10.861
25.0	10.648	8.474	8.522	3.785	1.822	1.381	3.176	3.234	9.382	10.776
26.0	10.654	8.596	8.541	3.795	1.832	1.380	3.095	3.220	9.357	10.686
27.0	10.658	8.671	8.554	3.806	1.836	1.379	3.047	3.209	9.336	10.642
28.0	10.668	8.740	8.563	3.816	1.846	1.378	3.004	3.203	9.266	10.556
29.0	10.675	8.756	8.574	3.822	1.851	1.376	2.995	3.195	9.253	10.513
30.0	10.681	8.907	8.585	3.834	1.856	1.375	2.907	3.186	9.202	10.460
31.0	10.688	8.970	8.594	4.083	1.862	1.374	2.871	3.179	8.104	10.409
32.0	10.695	9.115	8.597	4.185	1.863	1.372	2.793	3.177	7.819	10.403
33.0	10.702	9.268	8.652	4.265	1.867	1.371	2.716	3.136	7.587	10.365
34.0	10.710	9.379	8.666	4.324	1.868	1.370	2.662	3.126	7.403	10.354
35.0	10.718	9.593	8.782	4.357	1.877	1.368	2.565	3.044	7.333	10.284
36.0	10.725	9.668	8.887	4.420	1.880	1.367	2.532	2.974	7.184	10.254
37.0	10.754	9.742	8.911	4.470	1.899	1.361	2.501	2.959	7.080	10.096
38.0	10.767	9.903	9.023	4.729	1.940	1.359	2.436	2.888	6.453	9.767
39.0	10.775	10.078	9.180	4.762	1.991	1.358	2.369	2.795	6.428	9.402
40.0	10.788	10.258	9.407	5.015	1.991	1.355	2.305	2.670	4.983	9.402

MD3 at 100kPa

Strain	0.01	0.10	1.00	2.50	5.00	0.01	0.10	1.00	2.50	5.00
No of Cycle	G (MPa)					D (%)				
1.00	9.073	7.023	4.107	2.472	1.191	3.203	4.732	7.304	17.570	20.595
2.00	9.146	7.026	4.142	2.515	1.209	3.160	4.744	7.194	17.031	20.286
3.00	9.200	7.029	4.155	2.535	1.218	3.129	4.741	7.159	16.796	20.130
4.00	9.249	7.030	4.195	2.553	1.224	3.101	4.727	7.050	16.581	20.036
5.00	9.283	7.031	4.196	2.561	1.246	3.083	4.702	7.032	16.495	19.676
6.00	9.345	7.852	4.239	2.584	1.260	3.049	3.797	6.920	14.267	19.467
7.00	9.369	7.867	4.251	2.598	1.273	3.036	3.733	6.882	14.134	19.273
8.00	9.458	7.917	4.294	2.618	1.277	2.989	3.509	6.773	13.775	19.207
9.00	9.287	7.931	4.308	2.636	1.296	3.080	3.498	6.734	13.729	18.939
10.00	9.345	7.957	4.346	2.649	1.307	3.049	3.479	6.642	13.461	18.781
11.00	9.361	7.981	4.377	2.672	1.322	3.040	3.461	6.564	13.254	18.580
12.00	9.407	7.997	4.417	2.686	1.342	3.016	3.449	6.470	13.120	18.328
13.00	9.465	8.046	4.452	2.698	1.348	2.986	3.413	6.388	13.002	18.251
14.00	9.376	8.064	4.495	2.730	1.359	3.032	3.399	6.294	12.833	18.110
15.00	9.425	8.106	4.508	2.742	1.366	3.007	3.369	6.266	12.743	18.028
16.00	9.433	8.139	4.546	2.712	1.377	3.002	3.346	6.191	12.927	17.894
17.00	9.514	8.187	4.562	2.758	1.381	2.773	3.313	6.147	12.557	17.841
18.00	9.564	8.199	4.611	2.774	1.392	2.750	3.305	6.049	12.490	17.711
19.00	9.602	8.251	4.661	2.786	1.400	2.732	3.269	5.937	12.445	17.620
20.00	9.666	8.271	4.697	2.810	1.411	2.704	3.256	5.866	12.390	17.501
21.00	9.721	8.317	4.722	2.820	1.415	2.679	3.226	5.820	12.284	17.454
22.00	9.786	8.326	4.775	2.859	1.438	2.651	3.220	5.724	12.141	17.195
23.00	9.805	8.448	4.806	2.874	1.456	2.556	3.143	5.667	11.360	17.006
24.00	9.866	8.464	4.850	2.946	1.468	2.531	3.133	5.590	11.353	16.886
25.00	9.931	8.515	4.894	2.961	1.484	2.505	3.102	5.519	11.359	16.726
26.00	9.965	8.562	4.906	3.003	1.501	2.492	3.074	5.498	11.002	16.564
27.00	10.043	8.600	4.979	3.058	1.514	2.462	3.052	5.370	10.956	16.437
28.00	10.084	8.661	5.014	3.111	1.529	2.096	3.017	5.192	10.749	16.302
29.00	10.155	8.712	5.087	3.154	1.536	2.074	2.989	5.069	10.591	16.238
30.00	10.282	8.725	5.116	3.152	1.553	2.035	2.981	5.003	10.502	16.085
31.00	10.340	8.788	5.165	3.179	1.572	2.018	2.947	4.887	10.511	15.918
32.00	10.377	8.863	5.221	3.199	1.587	2.007	2.907	4.750	10.243	15.795
33.00	10.449	8.955	5.277	3.218	1.610	1.986	2.860	4.648	10.075	15.608
34.00	10.519	8.993	5.337	3.227	1.629	1.966	2.840	4.532	9.939	15.461
35.00	10.599	9.081	5.387	3.247	1.639	1.944	2.797	4.463	9.835	15.383
36.00	10.685	9.147	5.413	3.267	1.660	1.791	2.766	3.806	9.736	15.224
37.00	10.735	9.216	5.497	3.278	1.685	1.779	2.733	3.300	9.754	15.037
38.00	10.808	9.290	5.550	3.306	1.742	1.761	2.700	3.184	9.609	14.648
39.00	10.998	9.521	5.587	3.317	1.799	1.717	2.600	2.978	9.568	14.291
40.00	11.081	9.729	5.612	3.346	1.809	1.699	2.517	2.933	9.459	14.229

MD3 at 250kPa

Strain	0.01	0.1	1	2.5	5	0.01	0.1	1	2.5	5
No of Cycle	G (MPa)					D (%)				
1	13.35	7.89	5.34	4.92	3.61	1.44	4.89	5.81	14.87	15.26
2	13.68	7.95	5.45	4.99	3.89	1.43	4.86	5.69	14.67	13.86
3	13.76	7.95	5.64	5.02	3.70	1.43	4.86	5.49	14.57	14.28
4	13.90	7.98	5.77	5.06	3.72	1.43	4.85	5.36	14.45	14.19
5	13.93	7.98	5.80	5.09	3.72	1.43	4.17	5.33	13.31	14.17
6	14.03	7.98	5.82	5.14	3.78	1.43	4.84	5.31	14.21	13.86
7	14.18	7.98	5.86	5.20	3.81	1.42	4.84	5.28	14.03	13.71
8	14.30	7.99	5.95	5.26	3.82	1.42	4.84	5.20	13.85	13.66
9	14.40	8.01	5.98	5.32	3.82	1.42	4.83	5.17	13.68	13.68
10	14.44	8.21	6.08	5.37	3.83	1.42	4.73	5.08	13.54	13.63
11	14.46	8.26	6.19	5.43	3.84	1.42	4.70	4.99	13.38	13.57
12	14.50	8.28	6.27	5.47	3.86	1.42	4.70	4.93	13.28	13.47
13	14.55	8.29	5.64	5.54	3.87	1.42	4.69	5.49	13.10	13.43
14	14.79	8.34	5.72	5.56	3.88	1.38	4.67	5.41	13.05	13.26
15	14.89	8.39	5.79	5.65	3.89	1.35	4.90	5.62	12.43	12.77
16	15.00	8.43	6.00	5.71	3.90	1.28	4.88	5.42	12.30	12.70
17	15.05	8.46	6.45	5.79	3.92	1.25	4.61	4.79	12.51	12.57
18	15.14	8.49	6.64	5.85	3.93	1.23	4.59	4.65	12.37	12.49
19	15.28	8.51	6.70	5.87	3.96	1.23	4.59	4.61	12.33	12.40
20	15.42	8.53	7.09	5.88	3.98	1.23	4.58	4.36	12.31	12.31
21	15.53	8.56	7.17	5.90	4.02	1.22	4.56	4.32	12.28	12.16
22	15.56	8.69	7.30	5.90	4.04	1.22	4.51	4.25	12.26	12.06
23	16.03	8.85	7.53	5.97	4.07	1.20	4.44	4.12	12.13	11.97
24	16.17	8.95	7.54	6.02	4.08	1.20	4.40	4.12	12.03	11.90
25	16.23	8.98	7.55	6.08	4.13	1.20	4.38	4.11	11.89	11.74
26	16.28	9.04	7.55	6.13	4.14	1.19	4.36	4.11	11.81	11.71
27	16.35	9.07	7.57	6.19	4.15	1.19	4.35	4.10	11.69	11.66
28	16.64	9.16	7.59	6.21	4.16	1.19	4.31	4.09	11.65	11.63
29	16.79	5.19	7.70	6.24	4.19	1.20	6.97	4.03	11.58	11.54
30	16.88	9.33	7.80	6.26	4.22	1.18	4.25	3.99	11.55	11.44
31	17.03	9.41	7.89	6.30	4.25	1.18	4.22	3.94	11.48	11.32
32	17.26	9.44	7.90	6.33	4.28	1.16	4.21	3.94	11.42	11.23
33	17.44	9.91	7.93	6.35	4.32	1.16	4.05	3.93	11.39	11.12
34	17.57	10.23	7.95	6.38	4.33	1.15	3.95	3.92	11.33	11.06
35	17.75	10.32	7.96	6.46	4.40	1.15	3.93	3.91	11.19	10.86
36	18.00	10.60	7.98	6.60	4.45	1.15	3.85	3.90	10.96	10.73
37	18.09	10.81	8.01	6.71	4.65	1.15	3.79	3.89	10.78	10.18
38	18.18	10.96	8.16	6.81	4.92	1.14	3.75	3.83	10.62	9.58
39	18.49	12.27	8.33	6.91	5.21	1.13	3.45	3.75	10.47	9.00
40	18.70	13.51	8.50	7.02	5.22	1.125	3.22	3.68	10.30	8.98

MD3 at 400kPa

Strain	0.01	0.10	1.00	2.50	5.00	0.01	0.10	1.00	2.50	5.00
No of Cycle	G (MPa)					D (%)				
1	18.389	13.999	9.412	6.487	5.267	1.103	2.424	3.145	10.046	11.960
2	18.605	14.057	9.531	6.544	5.291	1.091	2.415	3.117	9.937	11.867
3	18.816	14.128	9.611	6.606	5.315	1.079	2.404	3.099	9.818	11.781
4	18.999	14.153	9.763	6.667	5.329	1.069	2.400	3.066	9.707	11.731
5	19.238	14.182	9.801	6.688	5.346	1.056	2.396	3.058	7.264	11.668
6	19.346	14.215	9.900	6.801	5.361	1.050	2.390	3.037	9.471	11.616
7	19.610	14.264	9.830	6.857	5.419	1.037	2.383	3.051	9.377	11.413
8	19.771	14.330	9.939	6.903	5.433	1.029	2.373	3.029	9.300	11.364
9	19.933	14.354	10.018	6.962	5.448	1.021	2.369	3.012	9.205	11.313
10	20.342	14.395	10.132	6.989	5.472	1.001	2.363	2.989	9.161	11.232
11	20.507	14.533	10.198	7.044	5.507	0.994	2.342	2.976	9.075	11.119
12	20.728	14.558	10.299	7.097	5.542	0.984	2.338	2.957	8.994	11.008
13	20.892	14.565	10.420	7.185	5.569	0.976	2.337	2.934	8.863	10.921
14	21.079	14.574	10.497	7.223	5.575	0.968	2.336	2.920	8.808	10.902
15	21.298	14.760	10.644	7.284	5.603	0.963	2.308	4.802	6.177	10.852
16	21.521	15.002	10.747	7.318	5.623	0.959	2.274	4.764	6.146	10.743
17	21.653	15.181	10.840	7.402	5.653	0.944	2.251	2.859	8.559	10.665
18	21.943	15.271	10.956	7.448	5.669	0.932	2.239	2.839	8.497	10.620
19	22.060	15.367	10.890	7.526	5.702	0.927	2.226	2.850	8.396	10.525
20	22.276	15.395	11.068	7.534	5.723	0.919	2.222	2.821	8.386	10.465
21	22.418	15.422	11.860	7.656	5.765	0.913	2.219	2.701	8.232	10.345
22	22.591	15.427	12.226	7.729	5.789	0.907	2.218	2.652	8.144	10.280
23	22.803	15.436	12.362	7.782	5.806	0.899	2.217	2.634	8.081	10.233
24	23.049	15.445	12.470	7.820	5.830	0.890	2.216	2.620	8.037	10.169
25	23.206	15.455	12.528	7.877	5.842	0.884	2.215	2.613	7.972	10.138
26	23.376	15.510	12.637	7.959	5.873	0.878	2.207	2.600	7.880	10.056
27	23.571	15.559	12.692	8.000	5.885	0.872	2.201	2.593	7.835	10.023
28	23.740	15.650	12.793	8.059	5.917	0.866	2.190	2.581	7.771	9.943
29	23.765	15.798	12.653	8.112	5.929	0.865	2.171	2.598	7.715	9.911
30	23.781	15.882	12.745	8.154	5.953	0.864	2.161	2.587	7.672	9.852
31	23.923	16.021	12.751	8.207	5.966	0.860	2.144	2.586	7.617	9.819
32	24.089	16.150	12.763	8.278	5.973	0.854	2.129	2.585	7.546	9.803
33	24.164	16.241	12.823	8.334	5.991	0.852	2.119	2.577	7.490	9.757
34	24.366	16.344	12.934	8.389	6.009	0.845	2.107	2.564	7.437	9.714
35	24.519	16.417	12.995	8.427	6.012	0.840	2.098	2.557	7.402	9.706
36	24.681	16.524	13.127	8.480	6.023	0.835	2.086	2.542	7.352	9.681
37	24.730	16.627	13.169	8.526	6.040	0.834	2.075	2.538	7.309	9.639
38	24.872	16.891	13.323	8.603	6.054	0.829	2.047	2.521	7.239	9.606
39	24.884	17.004	13.419	8.746	6.061	0.829	2.035	2.511	7.114	9.590
40	24.904	17.207	13.467	8.883	6.076	0.828	2.014	2.505	6.999	9.555

Amar3 at 100kPa

Strain	0.01	0.1	1	2.5	5	0.01	0.1	1	2.5	5
No of Cycle	G (MPa)					D (%)				
1	5.015	2.532	1.528	0.701	0.596	4.659	5.981	9.360	18.543	21.996
2	5.046	2.543	1.558	0.706	0.596	4.616	5.949	9.037	18.207	21.997
3	5.057	2.559	1.611	0.710	0.597	4.601	5.902	8.590	17.964	21.955
4	5.085	2.564	1.658	0.712	0.598	4.562	5.887	8.300	17.876	21.763
5	5.133	2.579	1.770	0.714	0.600	4.552	5.873	8.310	17.727	21.563
6	5.151	2.583	1.779	0.715	0.602	4.474	5.835	8.215	17.638	21.378
7	5.163	2.593	1.817	0.717	0.604	4.459	5.807	8.110	17.557	21.210
8	5.178	2.631	1.821	0.719	0.605	4.439	5.702	8.046	17.398	21.080
9	5.202	2.650	1.825	0.721	0.608	4.409	5.650	8.023	17.297	20.843
10	5.213	2.660	1.839	0.722	0.611	4.394	5.624	7.973	17.255	20.604
11	5.235	2.667	1.857	0.726	0.613	4.367	5.607	7.886	17.024	20.387
12	5.254	2.680	1.858	0.728	0.616	4.343	5.572	7.854	16.883	20.168
13	5.274	2.685	1.862	0.733	0.617	4.319	5.559	7.767	16.637	20.018
14	5.287	2.698	1.873	0.737	0.618	4.303	5.527	7.746	16.432	19.938
15	5.312	2.708	1.898	0.739	0.620	4.273	5.501	7.617	17.569	19.833
16	5.344	2.716	1.911	0.743	0.622	4.235	5.481	7.560	17.381	19.670
17	5.284	2.730	1.930	0.742	0.623	4.307	5.448	7.478	16.161	19.525
18	5.303	2.735	1.940	0.749	0.626	4.284	5.436	7.441	15.832	19.302
19	5.384	2.761	1.980	0.751	0.627	4.190	5.374	7.437	15.718	19.206
20	5.411	2.789	1.981	0.754	0.629	4.159	5.306	7.170	15.564	19.120
21	5.494	2.834	1.998	0.759	0.633	4.068	5.204	7.104	15.368	18.808
22	5.513	2.863	2.021	0.763	0.634	4.048	5.140	7.057	15.187	18.692
23	5.533	2.882	2.063	0.764	0.639	4.027	5.099	7.032	15.133	18.366
24	5.552	2.915	2.107	0.767	0.640	4.007	5.030	6.977	15.004	18.257
25	5.585	2.940	2.136	0.769	0.644	3.973	4.979	6.849	14.886	17.974
26	5.604	2.960	2.158	0.773	0.646	3.955	4.939	6.937	14.740	17.865
27	5.643	2.979	2.172	0.774	0.652	3.916	4.900	6.669	14.684	17.480
28	5.667	2.989	2.206	0.778	0.652	3.892	4.881	6.664	14.524	17.480
29	5.703	3.009	2.252	0.780	0.655	3.859	4.843	6.456	14.464	17.294
30	5.716	3.039	2.283	0.782	0.656	3.846	4.786	6.324	14.385	17.236
31	5.775	3.049	2.413	0.785	0.657	3.790	4.767	6.235	14.243	17.185
32	5.739	3.064	2.448	0.790	0.660	3.826	4.741	6.098	14.059	16.967
33	5.761	3.080	2.472	0.792	0.662	3.805	4.710	6.010	13.970	16.837
34	5.799	3.095	2.514	0.794	0.664	3.770	4.684	5.859	13.903	16.726
35	5.817	3.116	2.522	0.800	0.667	3.752	4.646	5.832	13.700	16.577
36	5.860	3.144	2.562	0.806	0.669	3.721	4.598	5.697	13.482	16.418
37	5.902	3.164	2.576	0.806	0.669	3.680	4.564	5.654	13.453	16.463
38	6.011	3.209	2.604	0.811	0.669	3.586	4.489	7.322	13.291	16.426
39	6.132	3.250	2.654	0.815	0.672	3.490	4.423	5.413	13.172	16.266
40	6.236	3.309	2.688	0.816	0.674	3.413	4.333	4.984	13.132	16.170

Amar3 at 250kPa

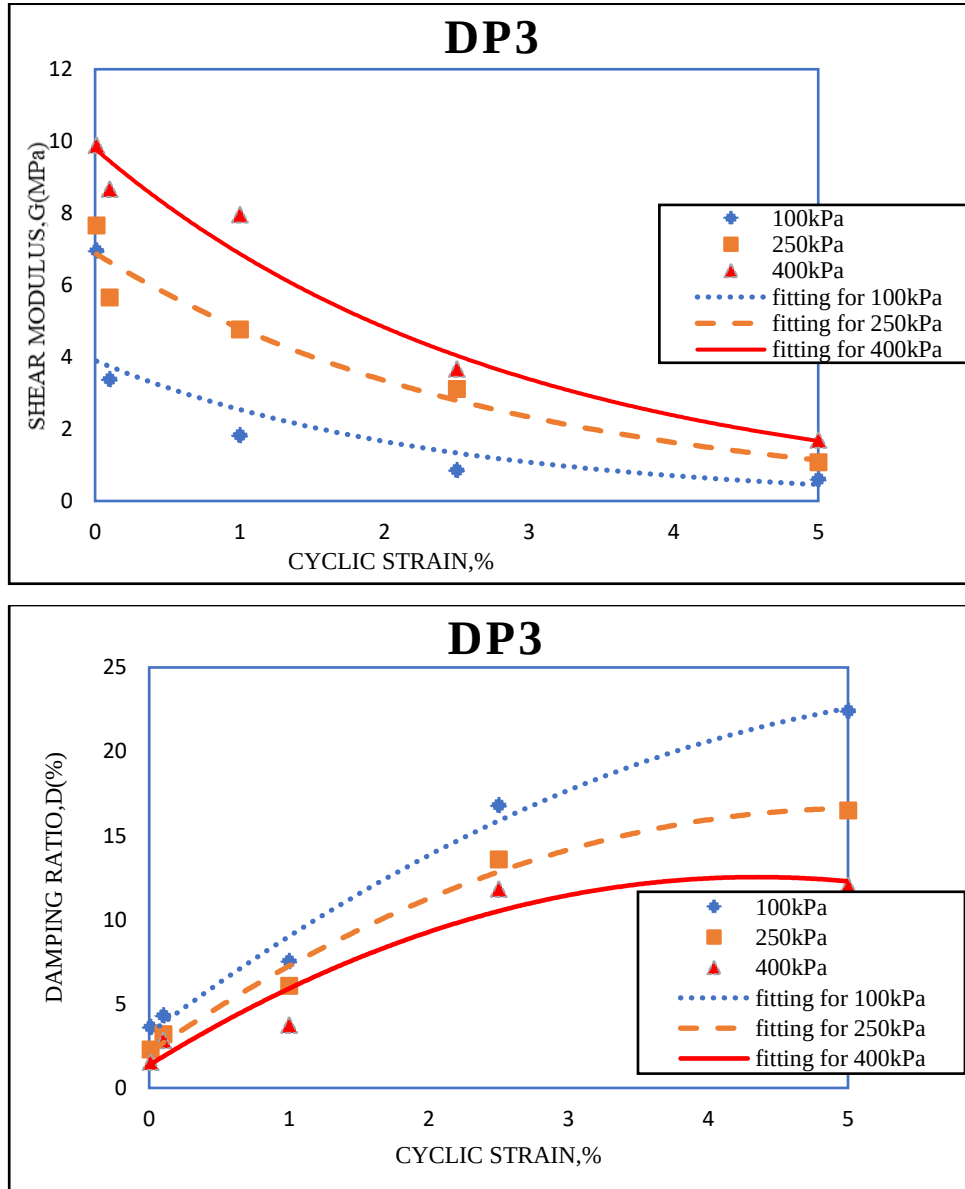
Strain	0.01	0.1	1	2.5	5	0.01	0.1	1	2.5	5
No of Cycle	G(MPa)					D (%)				
1	6.175	3.899	3.531	1.461	0.840	3.091	5.308	9.170	13.557	18.194
2	6.199	3.931	3.540	1.471	0.847	3.100	5.254	9.118	13.483	17.935
3	6.216	3.969	3.567	1.482	0.852	3.086	5.189	8.968	12.671	17.738
4	6.251	3.980	3.581	1.493	0.855	3.055	5.170	8.890	10.356	17.629
5	6.276	4.001	3.600	1.506	0.858	3.035	5.136	7.415	10.134	17.537
6	6.303	4.019	3.638	1.510	0.862	3.013	5.090	8.592	13.360	17.387
7	6.349	4.030	3.654	1.530	0.864	2.976	5.090	8.514	12.652	17.315
8	6.365	4.055	3.697	1.538	0.868	2.963	5.050	8.308	13.690	17.180
9	6.397	4.091	3.745	1.545	0.870	2.938	4.994	8.089	12.846	17.096
10	6.429	4.118	3.770	1.554	0.869	2.914	4.952	7.978	13.647	17.140
11	6.451	4.140	3.793	1.568	0.873	2.897	4.919	7.880	13.109	17.000
12	6.459	4.162	3.807	1.584	0.875	2.891	4.887	7.819	13.286	16.926
13	6.500	4.202	3.851	1.598	0.879	2.861	4.830	7.640	13.190	16.804
14	6.520	4.234	3.865	1.605	0.880	2.847	4.784	7.585	12.596	16.764
15	6.550	4.273	3.883	1.623	0.883	2.825	4.782	7.518	12.473	16.687
16	6.580	4.298	3.899	1.641	0.885	2.804	4.748	7.455	12.408	16.613
17	6.631	4.317	3.914	1.656	0.887	2.769	4.670	7.401	12.094	16.541
18	6.662	4.327	3.932	1.680	0.890	2.748	4.657	7.336	11.997	16.453
19	6.707	4.350	3.955	1.701	0.893	2.719	4.627	7.252	11.819	16.378
20	6.753	4.366	3.980	1.732	0.896	2.690	4.605	7.166	11.918	16.275
21	6.809	4.376	4.008	1.754	0.898	2.655	4.593	7.067	11.770	16.204
22	6.845	4.399	4.026	1.779	0.902	2.632	4.564	7.010	11.481	16.085
23	6.879	4.415	4.062	1.807	0.904	2.612	4.543	6.892	11.365	16.030
24	6.930	4.432	4.074	1.832	0.907	2.582	4.521	6.853	11.379	15.929
25	6.955	4.465	4.117	1.873	0.908	2.568	4.482	6.721	11.074	15.913
26	7.018	4.483	4.167	1.912	0.910	2.532	4.459	6.574	10.813	15.862
27	7.049	4.518	4.188	1.959	0.913	2.515	4.418	6.513	10.693	15.761
28	7.081	4.551	4.218	2.007	0.920	2.498	4.378	6.429	10.653	15.580
29	7.107	4.580	4.240	2.060	0.922	2.484	4.345	6.367	10.502	15.510
30	7.148	4.611	4.288	2.119	0.928	2.462	4.310	6.241	10.301	15.354
31	7.155	4.619	4.333	2.196	0.936	2.459	4.301	6.126	10.426	15.140
32	7.195	4.641	4.370	2.270	0.938	2.438	4.276	6.036	10.158	15.093
33	7.245	4.684	4.432	2.350	0.942	2.413	4.229	5.889	10.031	14.982
34	7.265	4.723	4.485	2.445	0.990	2.403	4.187	5.770	10.228	13.843
35	7.304	4.780	4.507	2.564	1.014	2.384	4.128	5.720	10.118	13.321
36	7.347	4.816	4.578	2.695	1.051	2.363	4.091	5.571	9.908	12.615
37	7.394	4.823	4.614	2.700	1.077	2.341	4.084	5.498	9.898	12.153
38	7.460	4.859	4.662	2.754	1.113	2.311	4.048	5.405	9.517	11.575
39	7.515	4.872	4.720	2.834	1.132	2.286	4.036	5.296	9.455	11.287
40	7.603	4.891	4.763	2.845	1.170	2.248	4.017	5.217	9.490	10.763

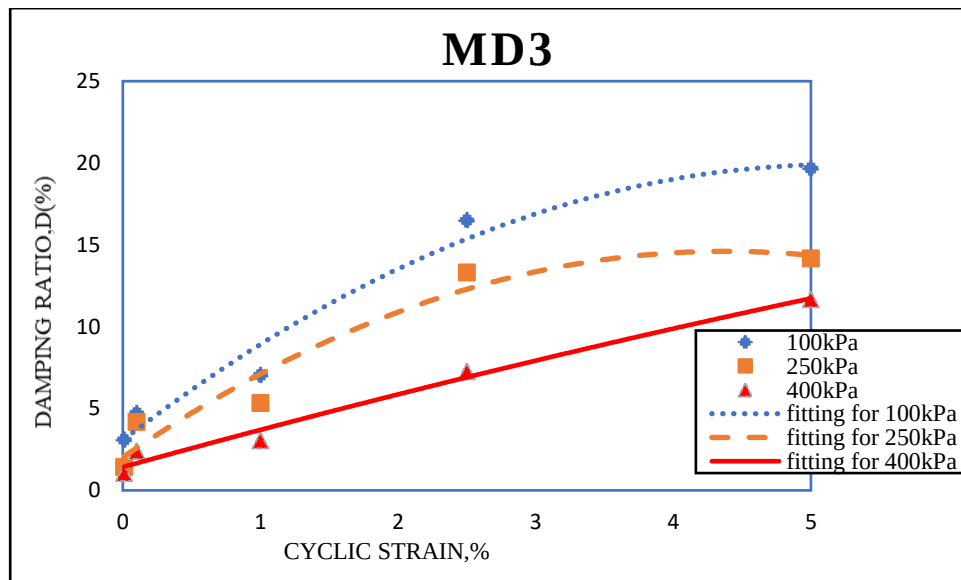
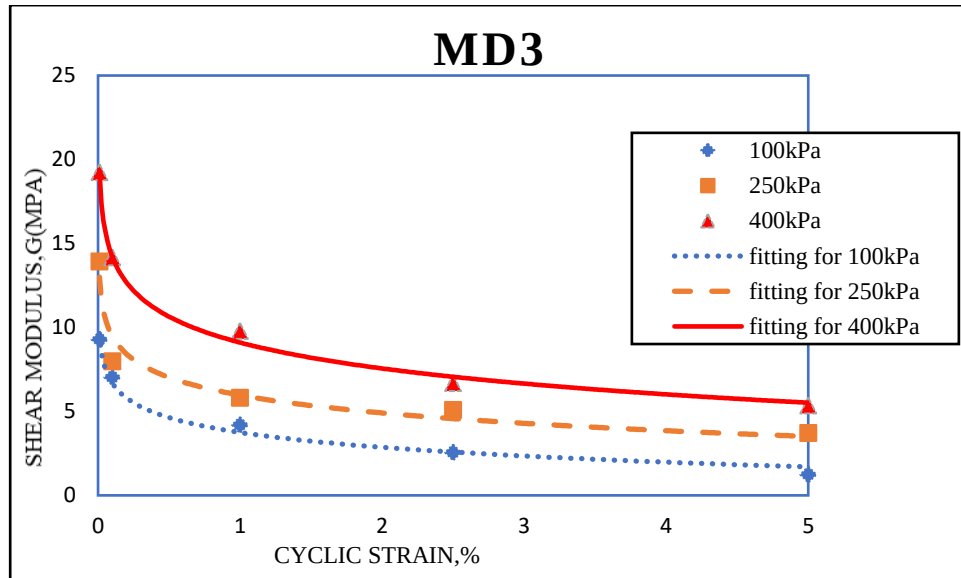
Amar3 at 400kPa

Strain	0.01	0.1	1	2.5	5	0.01	0.1	1	2.5	5
No of Cycle	G (MPa)					D (%)				
1	8.855	7.839	6.074	3.077	1.592	2.403	4.949	8.984	12.133	17.556
2	8.874	7.855	6.111	3.122	1.598	2.398	4.929	8.870	11.715	17.445
3	8.948	7.880	6.168	3.167	1.600	2.378	4.899	8.700	11.324	17.402
4	8.981	7.910	6.216	3.186	1.609	2.370	4.864	8.564	11.163	17.249
5	9.049	7.928	6.261	3.267	1.617	2.352	4.217	6.928	8.714	17.155
6	9.114	7.976	6.284	3.297	1.625	2.336	4.786	8.375	10.325	16.954
7	9.143	8.011	6.310	3.311	1.636	2.329	4.747	8.306	10.230	16.779
8	9.222	8.042	6.330	3.359	1.648	2.310	4.712	8.253	9.913	16.572
9	9.342	8.055	6.360	3.376	1.658	2.283	4.697	8.177	9.806	16.415
10	9.393	8.110	6.379	3.423	1.669	2.272	4.637	8.129	9.518	16.245
11	9.465	8.139	6.418	3.439	1.679	2.256	4.606	8.031	9.427	16.097
12	9.561	8.186	6.464	3.476	1.706	2.236	4.557	7.918	9.219	15.704
13	9.657	8.202	6.507	3.504	1.598	2.217	4.541	7.817	9.066	15.589
14	9.707	8.260	6.528	3.538	1.718	2.207	4.482	7.768	8.884	15.529
15	9.742	8.272	6.573	3.571	1.727	2.201	4.470	7.666	8.721	15.415
16	9.784	8.346	6.594	3.618	1.741	2.193	4.397	7.619	8.495	15.221
17	9.800	8.403	6.634	3.651	1.746	2.190	4.343	7.533	8.340	15.166
18	9.873	8.415	6.687	3.697	1.760	2.176	4.332	7.421	8.140	14.988
19	9.884	8.461	6.728	3.745	1.763	2.174	4.290	7.336	7.937	14.947
20	9.929	8.529	6.738	3.763	1.769	2.166	4.228	7.314	7.866	14.868
21	9.958	8.570	6.781	3.810	1.780	2.161	4.192	7.229	7.680	14.731
22	9.988	8.585	6.813	3.833	1.789	2.156	4.179	7.165	7.595	14.628
23	10.032	8.606	6.865	3.876	1.797	2.148	4.161	7.066	7.438	14.534
24	10.042	8.624	6.896	3.897	1.805	2.147	4.146	7.008	7.360	14.441
25	10.070	8.635	6.943	3.936	1.812	2.142	4.136	6.922	7.227	14.358
26	10.112	8.669	7.009	3.969	1.830	2.135	4.107	6.805	7.117	14.157
27	10.124	8.694	7.063	4.017	1.845	2.133	4.086	6.712	6.963	13.997
28	10.143	8.716	7.108	4.058	1.853	2.130	4.069	6.636	6.838	13.915
29	10.177	8.753	7.178	4.081	1.870	2.124	4.038	6.522	6.770	13.740
30	10.204	8.764	7.210	4.131	1.879	2.120	4.029	6.471	6.625	13.647
31	10.209	8.788	7.264	4.154	1.886	2.119	4.010	6.388	6.561	13.587
32	10.246	8.821	7.326	4.212	1.889	2.113	3.984	6.294	6.404	13.557
33	10.265	8.847	7.412	4.267	1.895	2.110	3.964	6.170	6.262	13.492
34	10.279	8.859	7.447	4.323	1.904	2.108	3.954	6.120	6.123	13.413
35	10.283	8.892	7.475	4.352	1.914	2.107	3.929	6.081	6.053	13.311
36	10.293	8.918	7.532	4.402	1.919	2.106	3.909	6.003	5.938	13.272
37	10.302	8.939	7.606	4.453	1.923	2.104	3.893	5.906	5.826	13.230
38	10.366	8.964	7.676	4.500	1.931	2.095	3.874	5.816	5.724	13.158
39	10.383	9.007	7.750	4.530	1.938	2.092	3.843	5.724	5.661	13.094
40	10.419	9.061	7.813	4.586	1.940	2.087	3.804	5.649	5.548	13.074

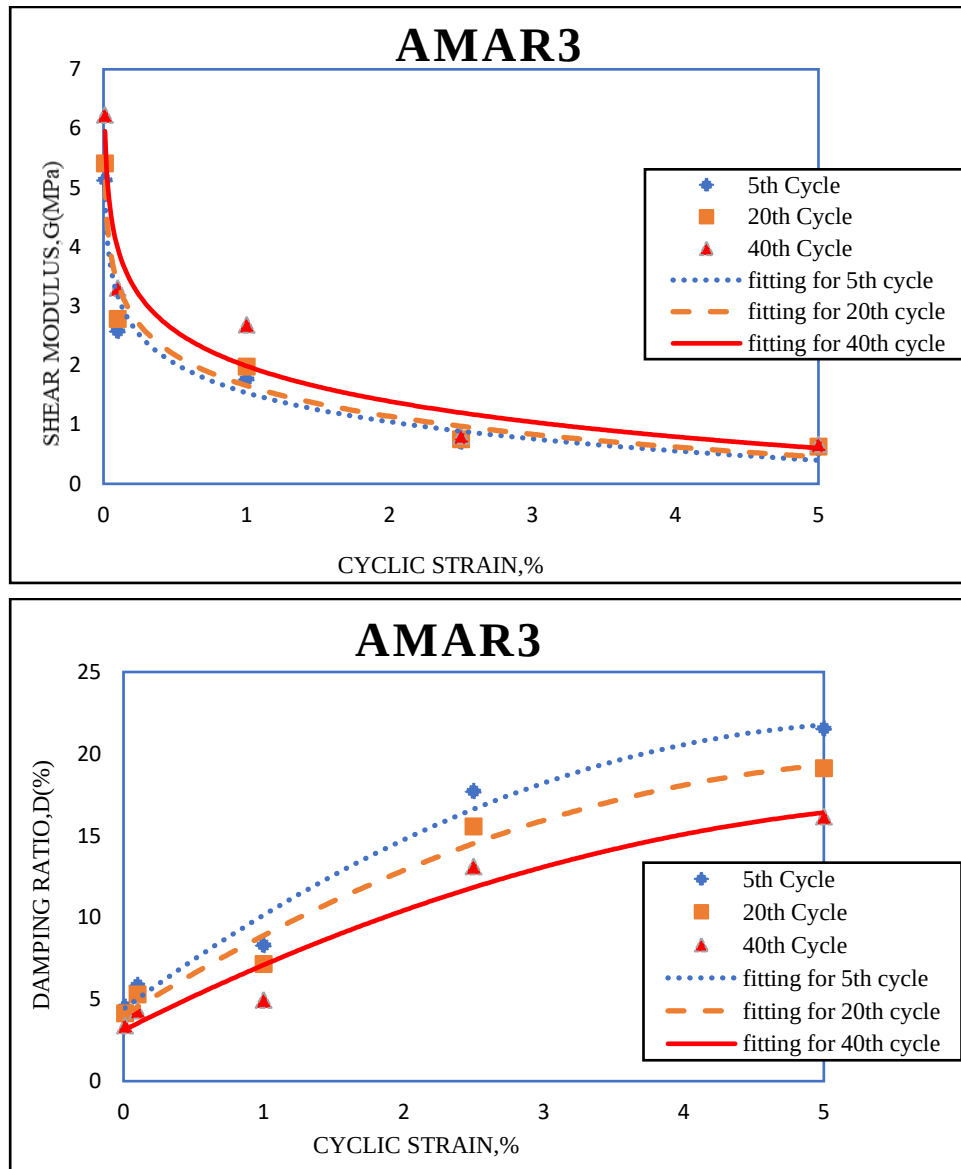
Appendix I Parameters that affect shear modulus and damping ratio values

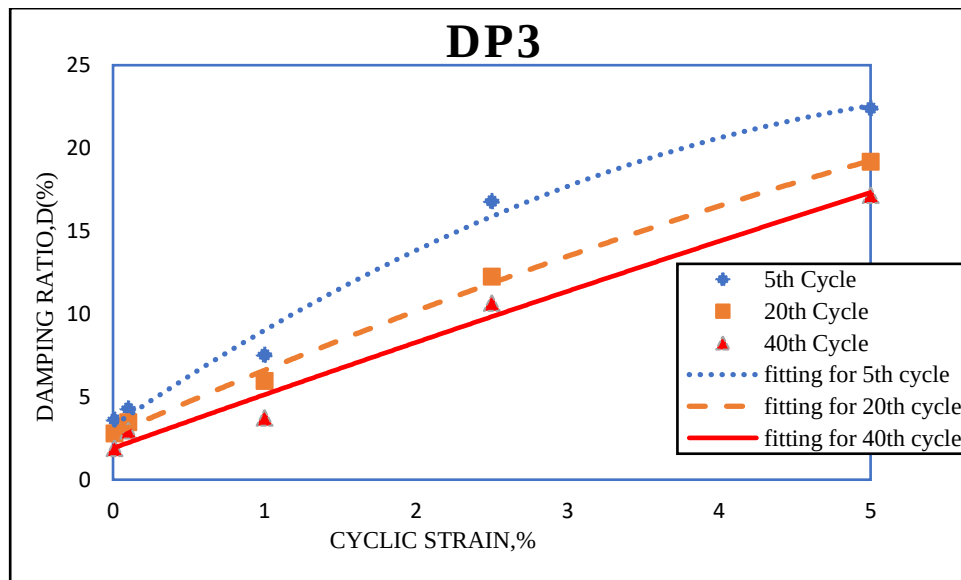
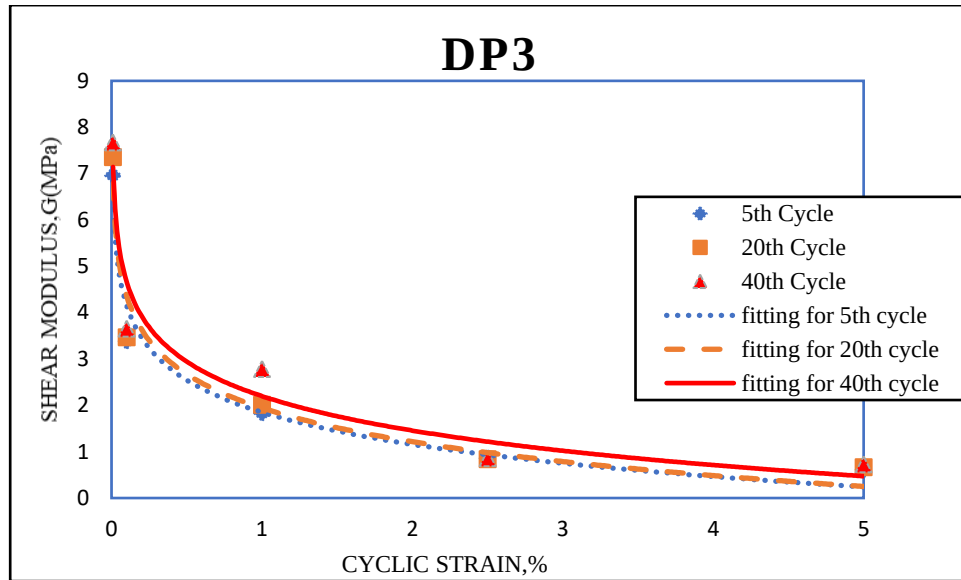
I-1 The influence of Confining Pressure over shear modulus and damping ratio values



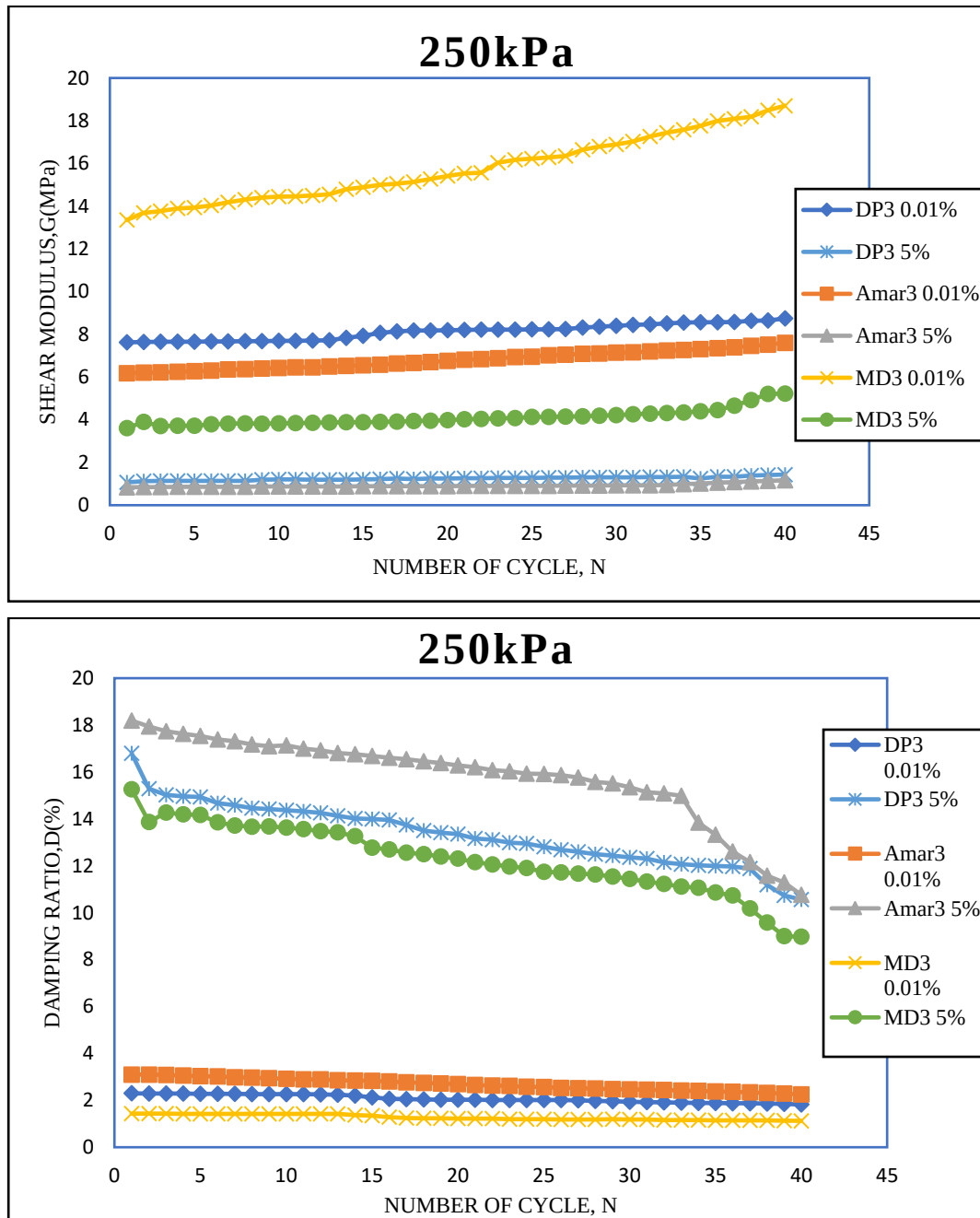


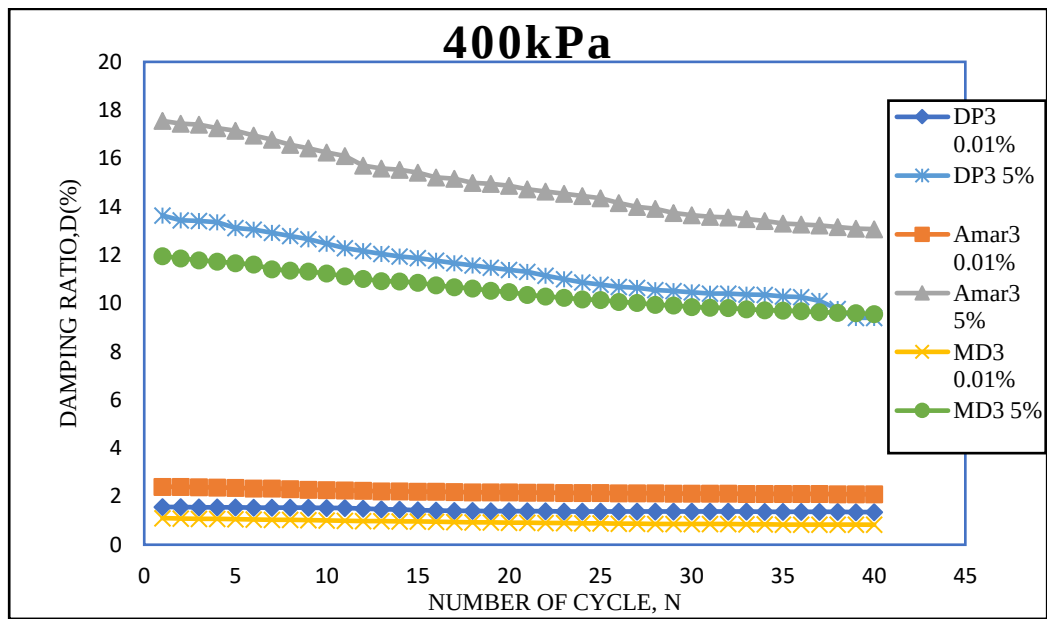
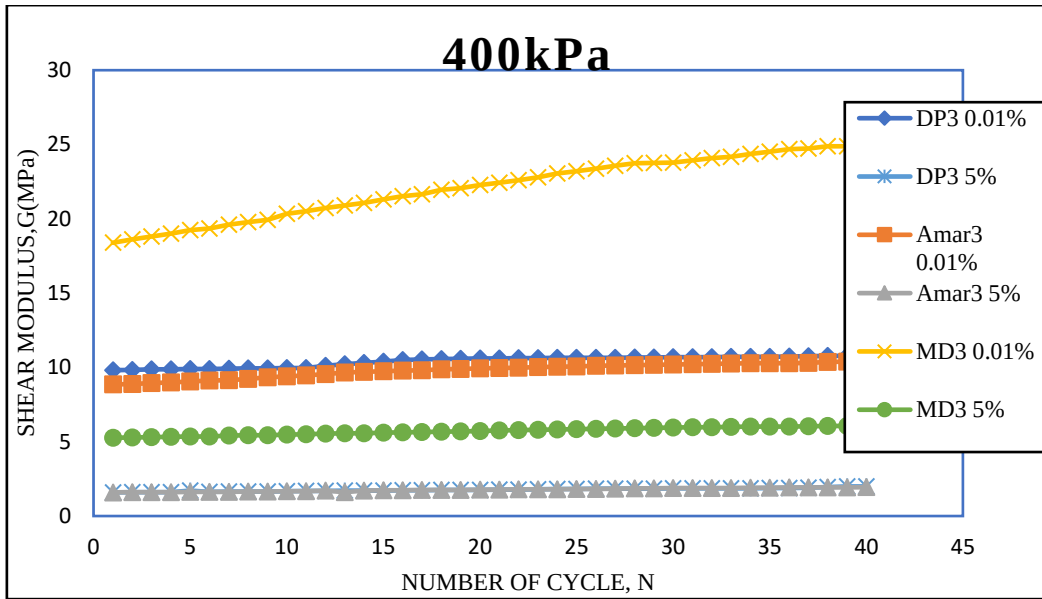
I-2 The influence of Cyclic strain over shear modulus and damping ratio values





I-3 The influence of Number of loading cycles over shear modulus and damping ratio values





I-4 The influence of plasticity over shear modulus and damping ratio values

