
ADDIS ABABA UNIVERSITY

ADDIS ABABA UNIVERSITY

SCHOOL OF GRADUATE STUDIES

INVESTIGATION IN TO SOME DYNAMIC PROPERTIES OF SOILS AROUND ZIWAY

By

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ABBREVIATIONS AND NOTES

AAiT	Addis Ababa university institute of Technology
ASTM	American Society for Testing Materials standard
A_{loop}	Loop area
Cu	Uniformity Coefficient
D	Damping ratio
e	Void ratio
Eq.	Equation
Fig.	Figure
G	Dynamic shear modulus
Gmax	Maximum Dynamic shear modulus
Gs	Specific gravity of soil
I_D	Relative density (Density index)
Ko	Coefficient of lateral earth pressure at rest
LL	Liquid limit
Pc	Pre-consolidation pressure
PI	Plastic index
PL	Plastic Limit
ML	Inorganic silt
OCR	Over consolidation ratio
SM	silty sand
TP	Test pit
W_D	Dissipated energy
W_N	Field moisture content
Ws	Maximum strain energy
v_s	Shear wave velocity
γ	Shear strain
ρ	Density of soil
σ	Normal stress
σ'_o	Effective confining stress
σ'_v	Effective vertical stress
τ	Shear stress

ABSTRACT

The town of Ziway is located in South Easter part of Ethiopia. It has a latitude 08'00 N and longitude 38'43E with the elevation between 1640 and 1670 meter above sea level. The topography of the town is almost flat. The town is located in seismic zone four according to EBCS 8, 1995. Therefore, the objective of the research is to investigate some dynamic properties of soils found in Ziway town. To achieve its objective samples from different parts of the city were collected and laboratory tests were done on the collected samples.

The index property investigation in this study includes; particle size distribution, Atterberg limits and specific gravity. The grain size analysis test result showed that the dominant proportion of soil particle in the research area is silt and silty sand, which have clay content ranging from 1 – 28%, silt fraction 37 - 47%, sand fraction 24 - 57% and gravel content from 0.8 – 2.0%. Liquid limit ranging from 30 – 33%, plastic limit ranging from 26 – 29%, plastic index from 0 – 7% and specific gravity ranging from 2.50 to 2.62.

According to the Unified Soil Classification System, most of soils found in Ziway town are silt and silty sand. A series of cyclic laboratory tests were conducted at field density. The tests were conducted as a function of cyclic strain amplitude of 0.01 % to 5.0 % under an axial stress of 100 kPa, 200 kPa, 300 kPa and 400 kPa. The stress strain responses were recorded, and the shear modulus and damping ratio were obtained for each soil sample. The value of shear modules is in the range of 1.0 to 8MPa for medium strain level (0.01 %< γ <0.1 %) and 8.0 to 25MPa for higher strain level (γ >0.1 %). The damping ratio values range between 2.85 to 10 % for medium strain level (0.01 %< γ <0.1 %) and 10.0 to 27.0 % for higher strain level (γ >0.1 %).

Additionally those parameters are compared with sand and saturated clay soil curves developed by Seed H.B and Idriss (1970), Hawassa silt soil studied by Ayalew G. (2011) and Adama silt and silty sand soil studied by Abu G. (2011).

The results have shown that the obtained normalized shear modulus values are lower than those suggested by Seed H.B and Idriss (1970), especially at lower strains ($\gamma \leq 0.01$ %). For higher strains the obtained normalized shear modulus values agree with those suggested in literature. This shows that testing conditions and sample preparation appear to have significant effect on the shear modulus values, especially at small strain level ($\gamma \leq 0.01$%).

The obtained damping ratio values are almost lower than the sand soil curves developed by Seed, H.B. and Idriss,I.M(1970). But those values are in the range of saturated clay by Seed, H.B. and Idriss,I.M(1970). This shows that the position of damping ratio curves for silt and silty sand soil results are in between the curve for sand and clay. Additionally those values are in good agreement with the curves of local soils of Hawassa and Adama.

Chapter one

1. INTRODUCTION

1.1. Back ground

The behavior of soils when they are subjected to dynamic loading is investigated in this research. In Soil Dynamics and Earthquake Engineering that deformation characteristics of soils, expressed in terms of shear stiffness and damping ratio are the fundamental parameters describing soil behavior. These parameters are required for the estimation of the response of soil and soil-structure systems, when subjected to cyclic and dynamic loadings, i.e., earthquakes, vehicular traffic, machine vibration, pile-driving, blasting, etc. The potential damage caused by Earthquake phenomena includes: loss of bearing capacity, excessive settlement, lateral spreading, flow failure, and ground oscillation.

Vibrations are generated by manmade and natural disasters .The factors affecting the shaking due to an earthquake at a site are soil structure interaction, local soil conditions, path of the wave and location of the source. Soil acts like a dynamic oscillator and affects the ground motion of the structures constructed on top of it to a great extent. The soil structure interaction has two main parts which comprises of kinematic effect and inertial effect, in the former one the flexibility of the soil will influence the response of the soil structure system, and in the latter one the mass of the structure influences the response of the soil structure system.

This article presents results of cyclic simple shear tests, performed for the investigation of the dynamic properties of natural silt and silt sand soils from Ziway. The behavior of soils is described and the implications of the test results for seismic site response are discussed.

1.2. Objective of the Study

1.2.1 General objective

The main objective of this research is determination of dynamic properties of soils in Ziway City for geotechnical design.

1.2.2 Specific objective

- To determine the index properties and classify the soil.
- To determine field density of the soil.
- To determine the dynamic shear modulus and damping ratio of the soil using cyclic simple shear test.

1.3. Scope of the Investigation

The scope of this study is limited to the determination of shear modulus and damping ratio of soils that is collected from Ziway Town. The method used in the determination of these parameters is limited to the cyclic simple shear test.

1.4. Methodology

To meet the above mentioned objectives, soil samples are collected from Ziway Town for the investigation. Cyclic simple shear tests were then performed, to determine the stiffness and damping of the soil samples.

1.5. Organization of the Thesis

This research is organized in five chapters.

The first Chapter gives a brief description of the thesis background, objectives, scope, and the methodology employed.

Chapter 2 of this research gives review on dynamic soil characteristics of soils, and stiffness and damping values of soils.

Chapter 3 presents details about the experimental setup used.

Chapter 4 explains the results obtained from cyclic simple shear.

Chapter 5 presents discussion on test results and Chapter 6 presents the conclusions, recommendations, and possibility of extension of this study for further research.

Chapter two

2. LITERATURE REVIEW

2.1. Introduction

The response of soil deposits under seismic loading conditions is determined mainly by the shear modulus and damping characteristics of the soil under cyclic loading conditions.

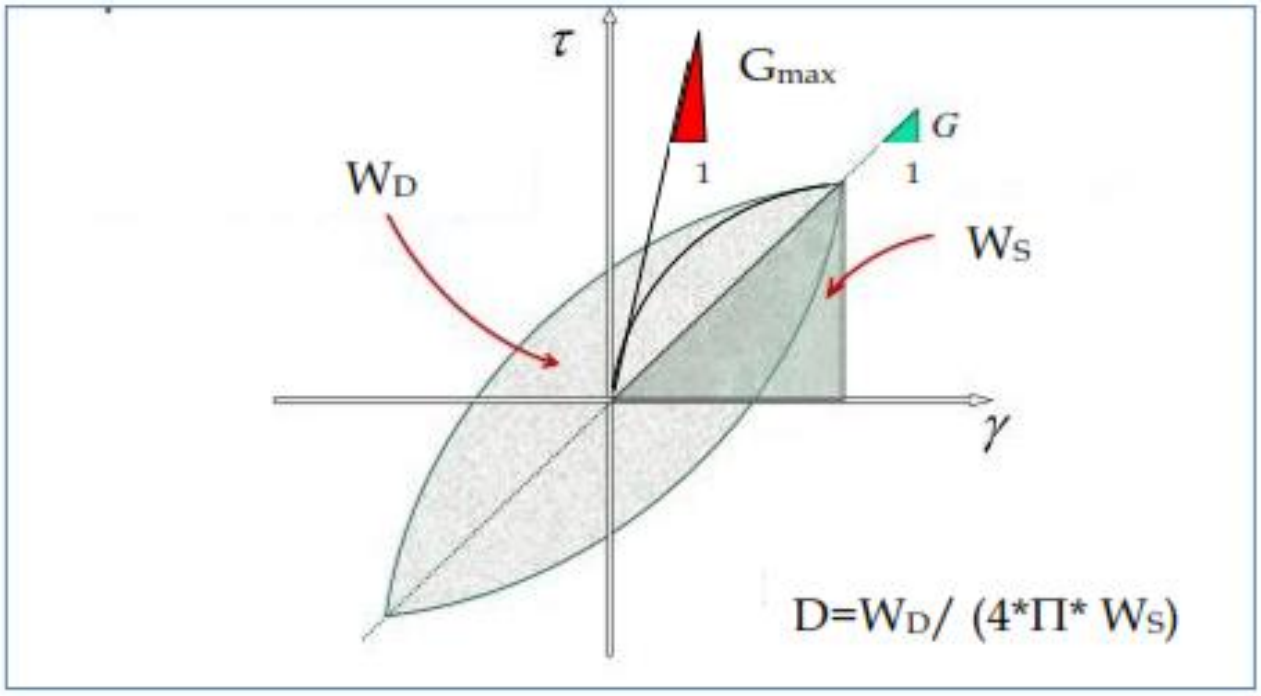
2.2. Dynamic Soil Properties

2.2.1. Damping Ratio

The material Damping represents the dissipation of strain energy during cyclic loading [15]. Referring to Figure 2-1 the damping factor is proportional to the area inside the hysteretic loop. It is readily apparent that each of these properties will depend on the magnitude of the strain for which the hysteresis loop is determined (see Figure 2.1) and thus both shear moduli and damping factors must be determined as functions of the induced strain in a soil specimen or soil deposit.

2.2.2. Shear Modulus

Most soils have curvilinear stress-strain relationships as shown in Figure 2-1 below [9].The shear modulus is expressed as the secant modulus determined by extreme points on the hysteretic loop.



. Hysteres

$\frac{W_D}{\pi * W_S} = \frac{\text{Area of l}}{2\pi}$ is l

2.2.3. Normalized shear modulus

The current state of practice for determining shear modulus (G) and material damping (D) for ground response analysis involves: (1) estimating or measuring shear wave velocity (v_s) in the field and (2) estimating or measuring the variation of G and D with the strain γ, primarily in the laboratory. It is a common practice to normalize G by dividing it by Gmax. A plot of the variation of G/Gmax with γ is called a normalized modulus reduction curve. Since most seismic geophysical tests induce shear strains lower than about $3*10^{-4}$ %, the measured shear wave velocities can be used to compute Gmax as suggested by Luna, R., and Jadi, H. [17]:

$$Gmax=\rho*(v_s)^2 \quad ----------(2.2)[17]$$

Where: ρ is the density of the soil deposit and v_s is shear wave velocity.

The use of measured shear wave velocities is generally the most reliable means of evaluating the in situ value of Gmax for a particular soil deposit. When shear wave velocity measurement are not available Gmax can be estimated in different ways. Hardin and Drnevich [13] developed a particular relationship with Gmax for an isotropic state of stress:

$$Gmax = 3.23 * \frac{((2.97 - e)^2)}{1 + e} * (OCR)^K * (\sigma'_0)^{0.5} \quad -----(2.3)$$

$$\sigma'_0 = \frac{(\sigma'_v + 2K_O\sigma'_v)}{3} \quad ----------(2.4)$$

Where: e = void ratio

OCR = over consolidation ratio

σ'_0= Effective confining stress

σ'_v= Effective vertical stress

K_O =coefficient of lateral earth pressure at rest

K =dimensionless quantity which is a function of PI.

Although developed for cohesive soils, this equation was found to be applicable to cohessionless soils simply by setting k equal to 0 (PI is equal to 0) [8].

Table 2-1 Empirical Values of Exponential Parameter (k) Proposed by Hardin and Drnevich [13]

PI	K
0	0
20	0.18
40	0.3
60	0.41
80	0.48
>100	0.50

2.2.4. Methods of Determining Shear Modules and Damping Characteristics [19]

A wide variety of procedures, including laboratory and field tests have been used to determine both shear modules and damping characteristics. The main procedures can be summarized as follows:

2.2.4.1. Direct Determination of Stress-Strain Relationships

Hysteretic stress-strain relationships of the type is shown in Figure 2-1 can be determined in the laboratory by means of triaxial compression tests, simple shear tests or tensional shear tests conducted under cyclic loading conditions. In general these procedures are useful for measuring shear modules and damping factors under moderate to relatively high strains ($0.01<\gamma<5\%$).

2.2.4.2. Forced vibration tests

Forced vibration tests, involving the determination of resonant frequencies and measurement of response with different frequencies have been used to determine both shear modules and damping factors. Test conditions in the laboratory have included the application of longitudinal vibrations and tensional vibrations to cylindrical samples or shear vibrations to layers of soil placed on a shaking table. In general these procedures are useful for determining properties at relatively low to moderate strain levels ($10^{-4} < \gamma < 10^{-2}$%).

2.2.4.3. Free Vibration Tests

Free vibration tests, in which measurements are made of the decay in response of a soil sample or soil deposit, have been used to measure both shear modules and damping factors for soils. Methods of excitation are essentially similar to those used for forced vibration tests, but the procedures can be used for measurement of soil characteristics at relatively low to moderately high strain levels ($10^{-3} < \gamma < 1$%).

2.2.4.4. Field Measurement of Wave Velocities

Field tests have been used to measure the velocity of propagation of compression waves, shear waves, and Rayleigh waves from which values of soil modulus can readily be determined for low strain ($\gamma \leq 10^{-4}$ %) conditions. These procedures have not provided values of damping factors.

The different test procedures for measuring shear modules and damping characteristics and the approximate ranges of strain within which they have been used are summarized in Table 2-2.

Table 2-2 Test procedures for measuring moduli and damping characteristics [19]

General Procedure	Test condition	Approximate strain range (γ)	Properties that may 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 vibrations-lab	10^{-4} to 10^{-2}%	Modulus; Damping
	Shear vibrations-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 vibrations-lab	10^{-3} to 1%	Modulus; Damping
	Shear vibrations-field	10^{-3} to 1%	Modulus
Field wave velocity Measurements	Compression waves	~$5x10^{-4}$%	Modulus
	Shear waves	~$5x10^{-4}$%	Modulus

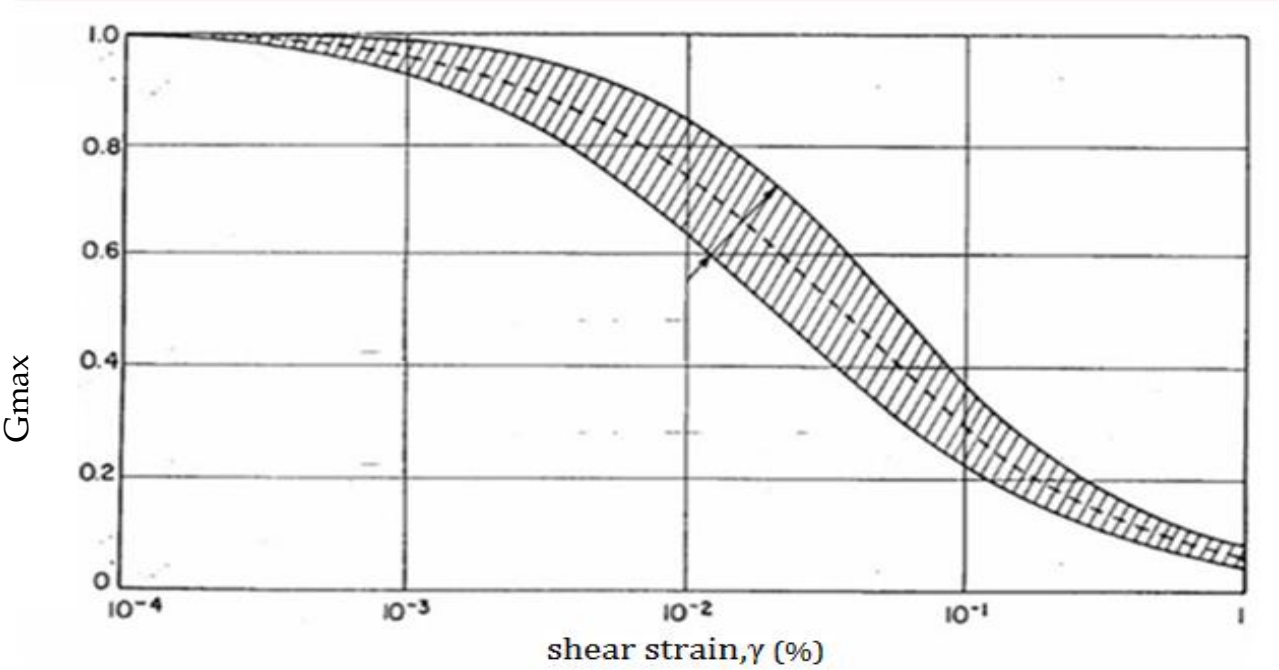
2.3. Factors Affecting Shear Modulus and Damping Ratio

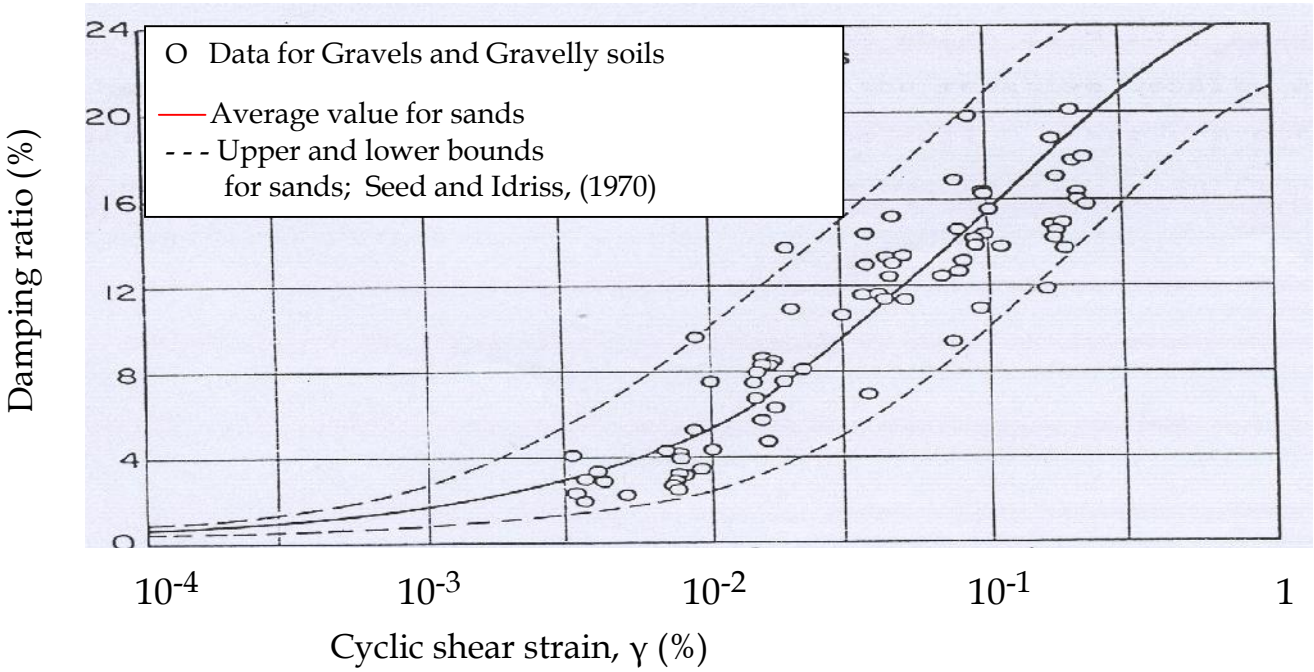
When a soil is subjected to earthquake or cyclic loading, the shear modulus and damping ratio of the soil are influenced by many factors. Those factors affecting the shear modulus and damping ratio of soils have been studied by Hardin and Drnevich [13]. These factors are:

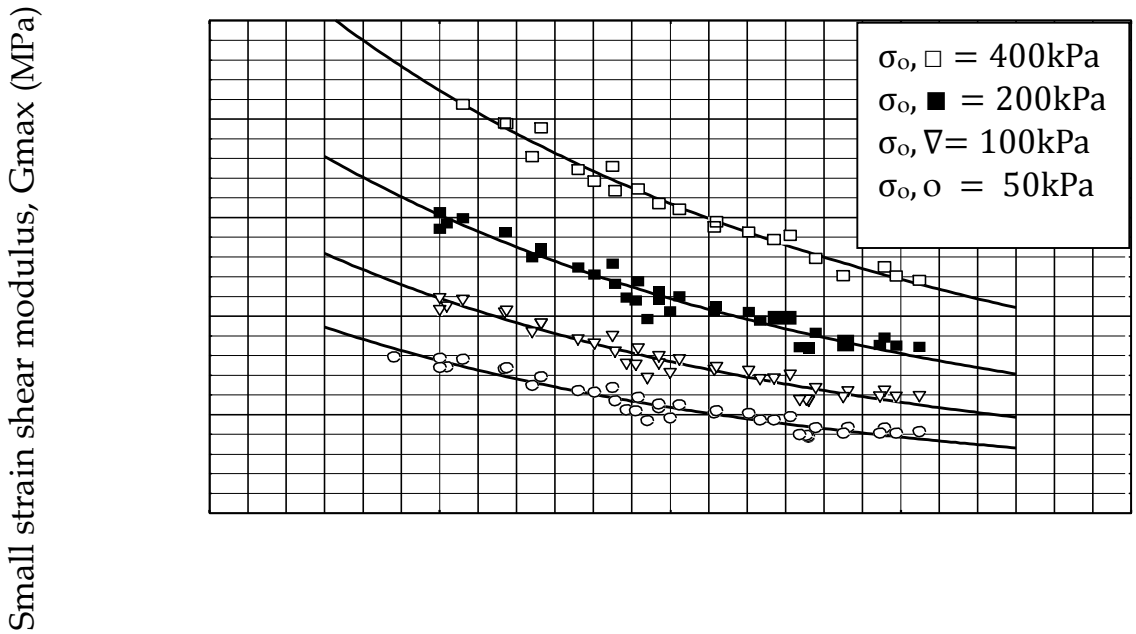
- Strain amplitude, γ
- Void ratio, e
- Effective confining stress, $\sigma'o$
- Frequency of loading
- Effective stress strength parameters, c' and Φ'
- Number of loading cycles, N
- Overconsolidation ratio, OCR
- Degree of saturation, and grain characteristics, time effects

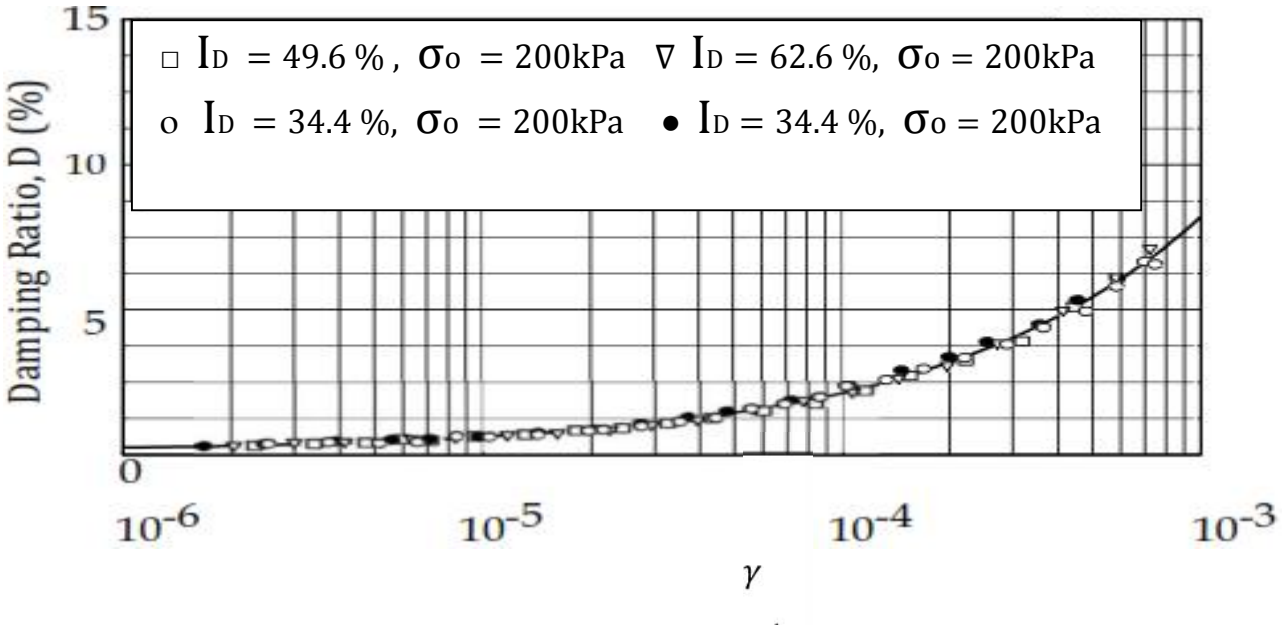
2.3.1. Shearing Strain Amplitude

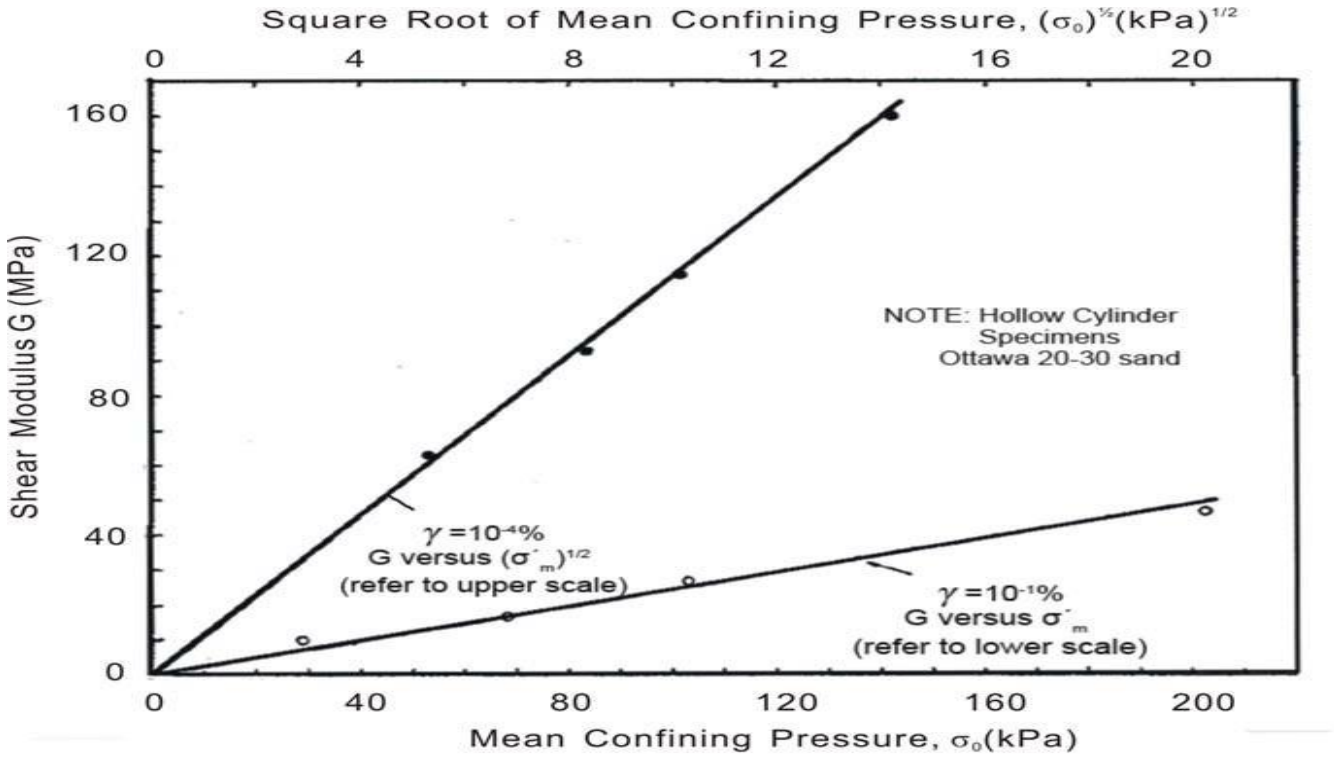
Strain has an extreme influence on dynamic properties of soil; therefore tests should be carried out at definite strain amplitude. For small-strain tests, the shearing strain amplitude is controlled below 0.001% for any test. For the nonlinear dynamic properties tests, the shearing strain amplitude is increased from possible low level to possible high level, ($0.001\ \% < \gamma < 0.1\%$) and for higher strain tests, the shearing strain amplitude is controlled larger than 0.1%. Figure 2-2 show at low strain amplitude, the shear modulus is high, but it decreases as the strain amplitude increases.


G/Gmax
1.0
0.8
0.6
0.4
0.2
0
10⁻⁴
10⁻³
10⁻²
10⁻¹
1
shear strain, γ (%)


O Data for Gravels and Gravelly soils
Average value for sands
- - - Upper and lower bounds for sands; Seed and Idriss, (1970)
Damping ratio (%)
24
20
16
12
8
4
0
10-4
10-3
10-2
10-1
1
Cyclic shear strain, γ (%)


Small strain shear modulus, Gmax (MPa)
σo, □ = 400kPa
σo, ■ = 200kPa
σo, ∇= 100kPa
σo, o = 50kPa


□ ID = 49.6 % , σo = 200kPa ∇ ID = 62.6 %, σo = 200kPa
o ID = 34.4 %, σo = 200kPa • ID = 34.4 %, σo = 200kPa
Damping Ratio, D (%)
15
10
5
0
10-6
10-5
10-4
10-3
γ


Square Root of Mean Confining Pressure, $(\sigma_0)^{1/2}$(kPa)$^{1/2}$
0
4
8
12
16
20
160
120
80
40
0
Shear Modulus G (MPa)
NOTE: Hollow Cylinder
Specimens
Ottawa 20-30 sand
$\gamma = 10^{-4}$%
G versus $(\sigma'_m)^{1/2}$
(refer to upper scale)
$\gamma = 10^{-1}$%
G versus σ'_m
(refer to lower scale)
0
40
80
120
160
200
Mean Confining Pressure, σ_0(kPa)

2.3.5. Frequency of Loading

It is very important to assess the shear modulus and hysteretic damping of soils when predicting or back analyzing the response of ground or soil structures subjected to various types of cyclic loading. The frequency of transient loadings from wave, seismic, traffic and machine loadings may range from 0.01 to 100 Hz. [21]. Several investigations had revealed that loading frequency or strain rate had only small or no influence on small-strain shear modulus for cohesionless soils [11]. It is therefore common practice to carry out laboratory cyclic tests at a frequency range of 0.1 to 2 Hz. Mostly The frequency of 1 Hz preferred [3].

2.3.6. Number of loading cycles

Silver and Seed [22] measured the shear modulus and damping ratio of dry sands at the1st, 10th, and 300th cycles of loading, and indicated that the shear modulus slightly increases and damping ratio significantly decreases with increasing number of loading cycles. Similarly, Li and Cai [14] also reported that in general, the shear modulus moderately increases and the damping ratio decreases with the number of loading cycles as shown in Figure 2-7.

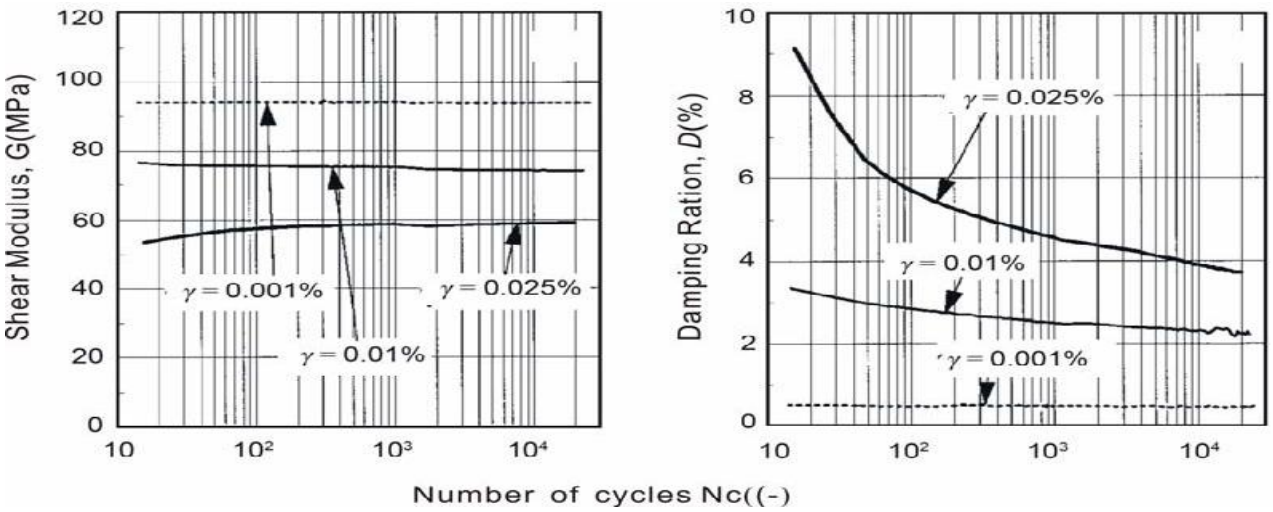
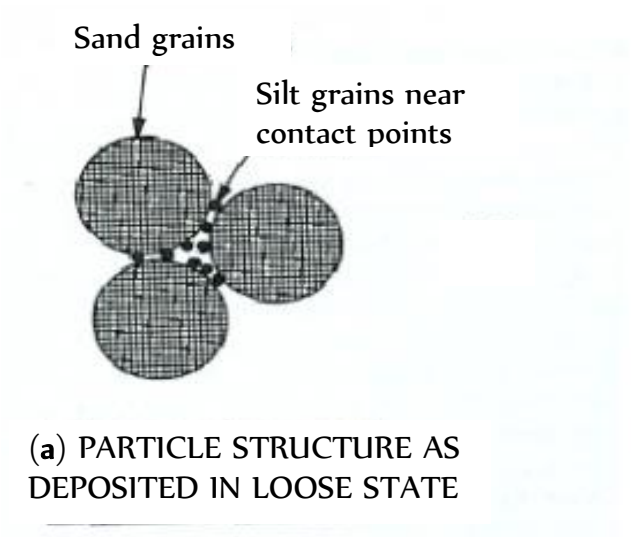
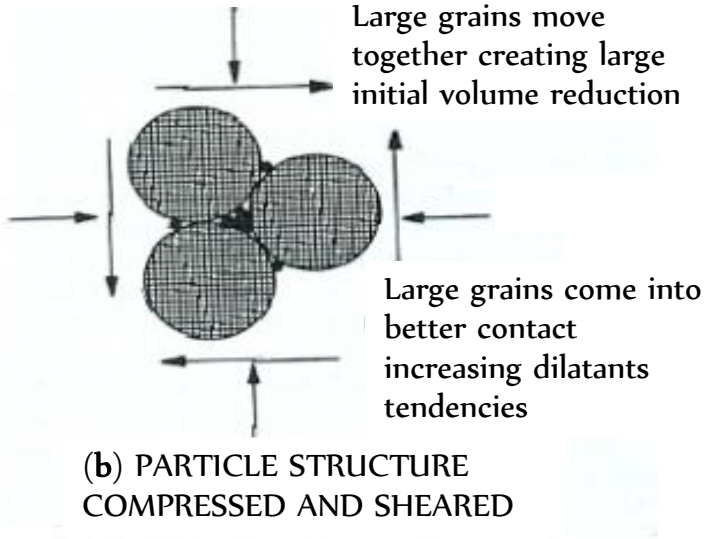


Fig.2-7: Effects of number of cycles on shear modulus and damping ratio for dry sand [14]

In general, the shear modulus increases slightly while damping ratio significantly decreases with increasing number of loading cycles. The primary increase in shear modulus and decrease in damping ratio occurs within the first 10 cycles of loading.



(**a**) PARTICLE STRUCTURE AS DEPOSITED IN LOOSE STATE



(**b**) PARTICLE STRUCTURE COMPRESSED AND SHEARED

Thevanayagam [24] used a similar framework to describe particles of two different diameters in a mixture. At low fine content, the smaller particles fill the voids of the sand skeleton but the behavior of the sand skeleton dominates the mechanical behavior. As more fines are added, the sand skeleton still dominates, but some fine particles begin to separate the coarse particles. This change continues up to some threshold value defined as the threshold fines content at which the voids of the larger particles are completely filled. Above this threshold fines content, the coarse particles become increasingly dispersed in the matrix of the finer particles, and since most inter-particle contacts are now transmitted through the finer particles, the mechanical behavior of the finer material increasingly governs the mechanical behavior of the mixture. An important corollary result of these studies is that relative density may be an insufficient indicator of the liquefaction potential of a silty sand deposit.

The fines in such sand will not contribute to the strength of the soil because only the contacts between the larger particles are carrying the load. The addition of fines, however, increases the relative density of the soil because the fines are filling the voids in the larger particles and reduce the overall void ratio. At higher fines content, the fines may start to fill between the contact points of the larger particles. Even though the addition of fines may increase the relative density of a soil, the stiffness may decrease as a result of fines filling the contact points.

It was also found that non plastic fines can reduce the small-strain shear modulus of a soil and increase the small-strain damping ratio, but this effect decreases with increasing uniformity coefficient (Cu). The reason for this relationship is thought to be because, in uniform soils (low Cu), the fines separate the larger particles of the soil skeleton and act as "rollers, decreasing the stiffness. In well-graded (high Cu) soils, non-plastic fines fill the void between large particles and increase the number of particle contacts. [7]

The primary impact of non-plastic fines is thought to be on the interparticle contacts of the larger particles. At high values of uniformity coefficient, the addition of fines to the soil is thought to be equivalent to the effect of increasing the uniformity coefficient of soil. At lower values of uniformity coefficient, the addition of fines is thought to push apart the larger particles in the soils, increasing the number but reducing the area of particle contacts, resulting in decreasing Gmax. The influence of fines is therefore more pronounced for more uniform soils. [7]

2.4. Summary

The factors that influence shear modulus and damping ratio of soils are addressed in this Chapter, these factors including void ratio, confining pressure, grain characteristics, degree of saturation, frequency of loading and number of loading cycles. Among these factors, void ratio and confining pressure are the primary parameters affecting small strain shear modulus of sandy, silty and clayey soils. Whereas levels of strain and confining pressure have the major effect on the magnitude of the damping ratio.

Chapter three

3. OVERVIEW OF TESTING EQUIPMENT AND METHODS OF TESTING

3.1. Cyclic Simple Shear Testing System

3.1.1. Introduction

In this study, the dynamic properties of soils are investigated using cyclic simple shear equipment. The cyclic simple shear apparatus is generally used for research into the dynamic of soil behavior. Nowadays there are different types of cyclic simple shear apparatuses in use. In this research the type of apparatus used is 31-WF7500 cyclic simple shear machine which is developed by the Controls Group. The complete system is controlled by the UTS004 software application program. In the cyclic simple shear device, the shear strain is induced by horizontal movement at the bottom of the sample relative to the top. The horizontal diameter of the sample remains constant [26]. The system (Figure 3-2) is designed to allow a sample to be consolidated, drained and then sheared.

In this chapter, cyclic simple shear apparatus and the test procedure are described.

3.1.2. Elements of Cyclic Simple Shear Apparatus

The sample is set up in the machine, which has a rigidly fixed top half and a moving bottom half. The top half houses the vertical ram. This is housed in a linear bearing to allow vertical movement and prevent horizontal movement. The bottom half is mounted on roller bearings as in a standard shear box.

The sample is supported by a stack of close fitting-polished stainless steel rings. The rings provide lateral confinement and produce a K_o condition during consolidation and also maintain a constant diameter throughout the test.

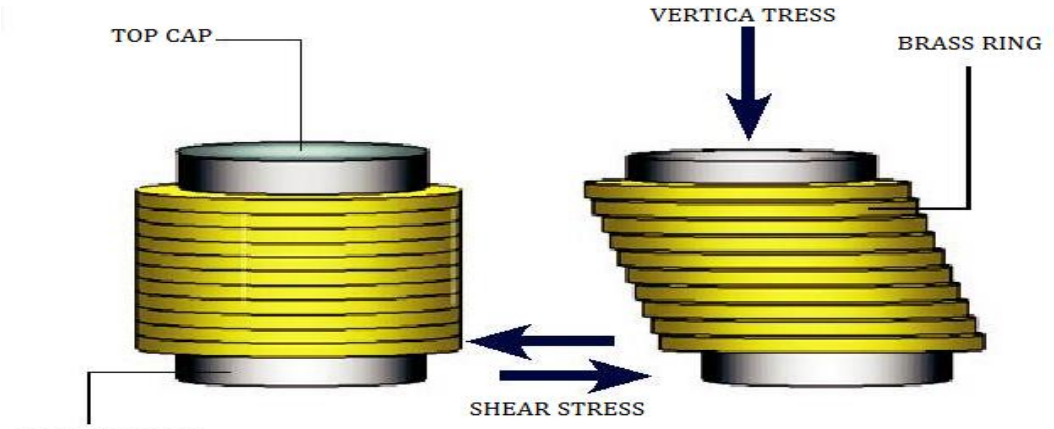


Figure : The Shearing Stage



3.1.3. Sample preparation

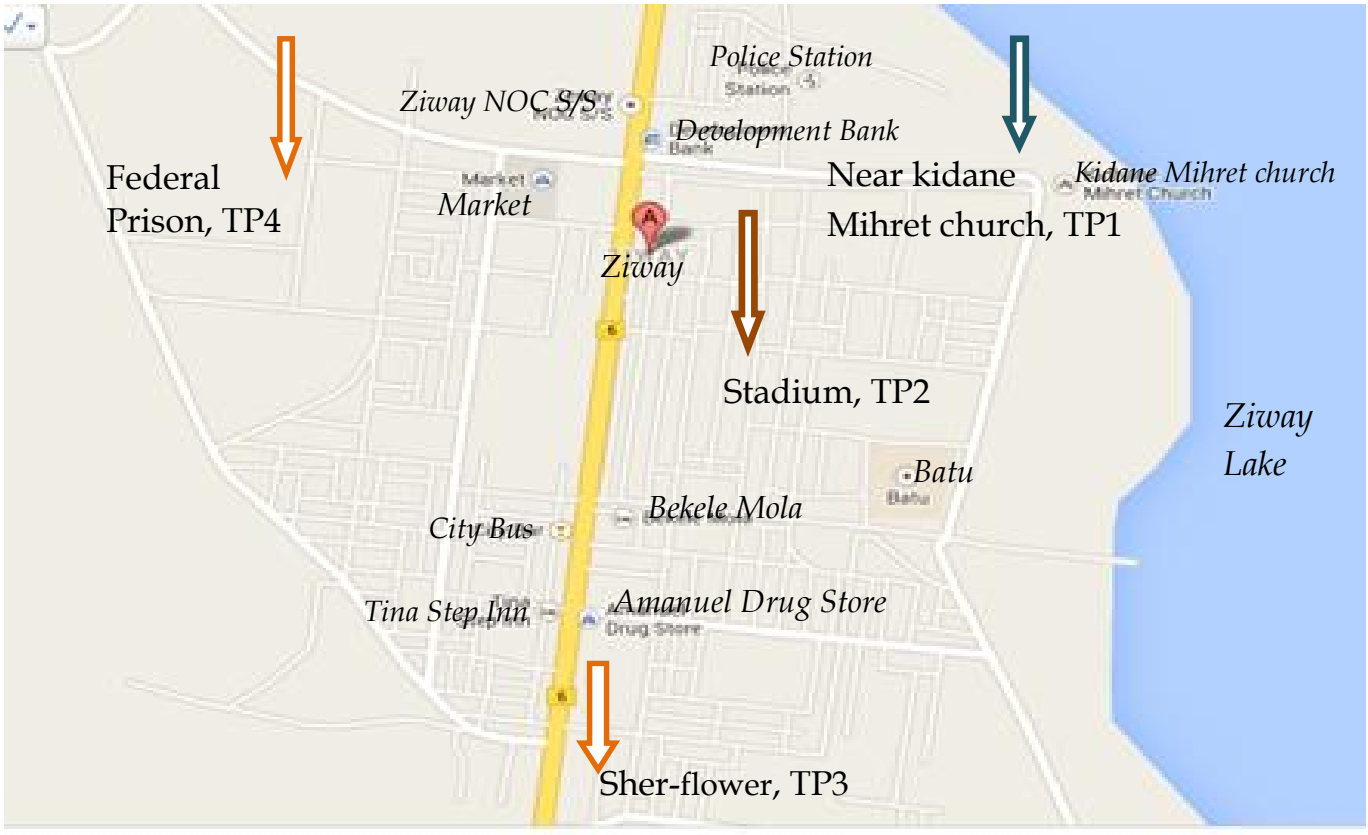
The general procedures of ASTM D6528 were used to prepare and test samples of soil in cyclic simple shear. In this experimental work, the tamping specimen preparation technique was used for the cyclic testing programs. Sample diameter is 70mm and height is varied from 20 mm to maintain height to diameter ratio less than 0.4, in order to fulfill the ASTM D6528-07 criteria.

3.1.4. Consolidation stage

The consolidation stage is simply the application of a static axial loading stress to the specimen while the lateral loading (shear) axis is held stationary. Axial stress and specimen displacements (axial and lateral) 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 rate of vertical strain becomes less than 0.05% per hour [20].

3.1.5. Cyclic simple shear stage

This stage of the test applies a lateral cyclic shear force, or optionally a displacement, to the specimen, while the vertical force is either maintained at the specified stress, or optionally, the specimen height is maintained. Both axial and lateral force and specimen displacements are measured for each loading cycle. Measured data are obtained from 50 sample points captured over the cycle period [25]. This data is 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.


Police Station
Ziway NOC S/St
Development Bank
Federal
Prison, TP4
Market
Near kidane
Mihret church, TP1
Kidane Mihret church
Ziway
Stadium, TP2
Ziway
Lake
Batu
Bekele Mola
City Bus
Tina Step Inn
Amanuel Drug Store
Sher-flower, TP3

4.2. Laboratory Tests for Index Properties

The following laboratory tests are conducted and the results are presented:

- In-situ density and moisture content
- Particle size analysis
- Specific gravity test
- Consolidation tests
- Cyclic shear tests

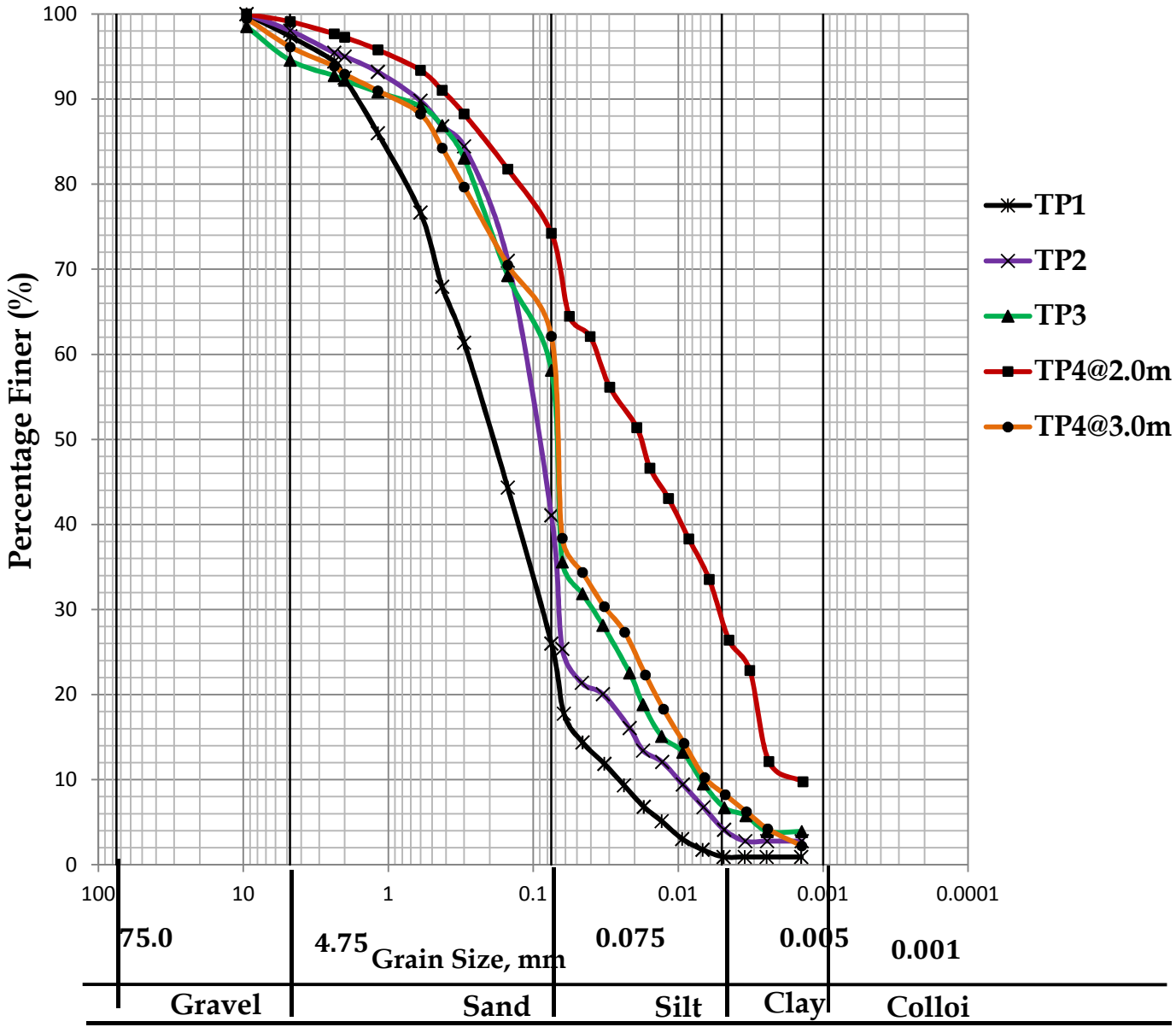
4.2.1. In-situ Density and Moisture Content Tests

The in-situ bulk density test was carried out at field and used to determine bulk densities for all samples. From the test results, it is observed that the bulk density varies from 1.3 to 1.5gm/cc and moisture content varies from 14 to 64% (Appendix–B) see as indicated in Table 4-1.

Table 4.1: In-situ Density and Moisture Content Tests

		Depth (m)	Bulk density (g/cm3)	In situ moisture content (%)	REMARK
TP1	Near Kidane Mihret church	1.0	1.49	64.0	GWT@ 1.0m
TP2	Stadium	2.5	1.30	13.70	
TP3	Share flower farm	2.7	1.41	20.50	
TP4	Federal prison	2.0	1.29	23.00	
TP4	Federal prison	3.0	1.39	24.26	

In this thesis the specific gravities test results are shown in Table 4-2. From this table the values of specific gravities are more reasonable values for silt and silty sand soils. Although the specific gravities are reasonable value, the values of in situ densities are small. This is probably due to; the soil is derived from very light weight parent materials.



Grain Size Boundary According to ASTM

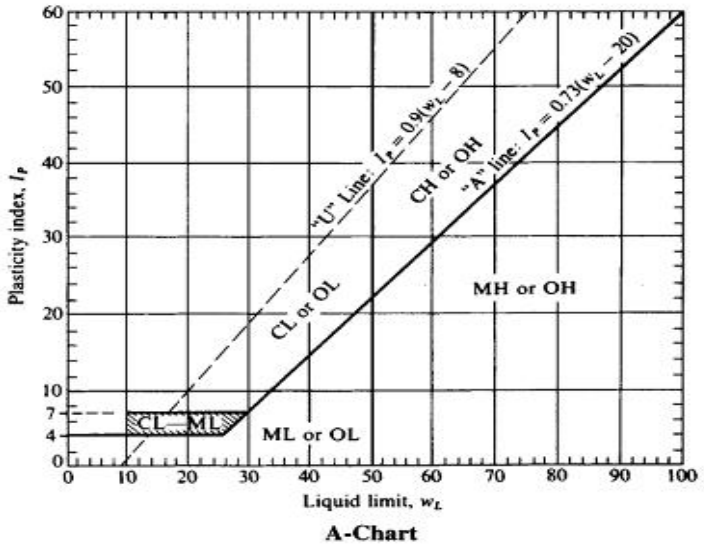
4.2.3. Atterberg Limits Test

Atterberg's Limits tests were carried out on silty soil passing 425 micron sieve. Liquid limit was determined using Casagrande's liquid limit device and plastic limit was determined by rolling wet soil paste in to 3 mm threads and determining the moisture content when thread just started crumbling. The tests were performed as per ASTM code (IS: 2720 (Part-IV)). The Liquid Limit, Plastic Limit and Plasticity Index of the study area are summarized in Table 4-2. From the test results the Liquid Limit varies from 30% to 33%, Plastic Limit varies from 26% to 30% and Plasticity Index varies from 0 to 7.0 for all the specimens tested. [Appendix-D]

4.2.4. Specific Gravity

The specific gravity of solid matter in a soil particle may be defined as the ratio of the unit weight of solid matter to the unit weight of water [23]. The specific gravity was determined in the laboratory according to ASTM D854-92. According to ASTM D854-92, specific gravity of soils is determined by means of a pycnometer. The results of the test are shown in Table 4-2. The specific gravity of the sample is found to vary between 2.50 to 2.65. [Appendix-E]

Major divisions			Group symbols	Typical names	Laboratory classification criteria	
Coarse-grained soils (More than half of material is larger than No. 200 sieve size)	Gravels (More than half of coarse fraction is larger than No. 4 sieve size)	Clean gravels (Little or no fines)	GW	Well-graded gravels, gravel-sand mixtures, little or no fines	Determine percentages of sand and gravel from grain-size curve. Depending on percentages of fines (fraction smaller than No. 200 sieve size), coarse-grained soils are classified as follows: Less than 5% GW, GP, SW, SP; More than 12% GM, GC, SM, SC; 5 to 12 % *Borderline* cases requiring dual symbols†	$C_u = \frac{D_{60}}{D_{10}}$ greater than 4; $C_c = \frac{(D_{30})^2}{D_{10} \times D_{10}}$ between 1 and 3
			GP	Poorly graded gravels, gravel-sand mixtures, little or no fines		Not meeting C_u or C_c requirements for GW
		Gravels with fines (Appreciable amount of fines)	GM* *d* *u*	Silty gravels, gravel-sand-silt mixtures	Atterberg limits below "A" line or I_P less than 4	Limits plotting in hatched zone with I_P between 4 and 7 are *borderline* cases requiring use of dual symbols.
			GC	Clayey gravels, gravel-sand-clay mixtures	Atterberg limits above "A" line with I_P greater than 7	
	Sands (More than half of coarse fraction is smaller than No. 4 sieve size)	Clean sands (Little or no fines)	SW	Well-graded sands, gravelly sands, little or no fines	$C_u = \frac{D_{60}}{D_{10}}$ greater than 6; $C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ between 1 and 3	
			SP	Poorly graded sands, gravelly sands, little or no fines		Not meeting C_u or C_c requirements for SW
		Sands with fines (Appreciable amount of fines)	SM* *d* *u*	Silty sands, sand-silt mixtures	Atterberg limits below "A" line or I_P less than 4	Limits plotting in hatched zone with I_P between 4 and 7 are *borderline* cases requiring use of dual symbols.
			SC	Clayey sands, sand-clay mixtures	Atterberg limits above "A" line with I_P greater than 7	
Fine-grained soils (More than half of material is smaller than No. 200 sieve)	Silts and clays (Liquid limit less than 50%)		ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands, or clayey silts with slight plasticity	For all soils plotting nearly on "A" line use dual symbols, i.e., $I_P = 29.5$, $w_L = 60$ gives CH-OH or CH-MH. When w_L is near 50 use CL/CH, ML/MH. Take "nearly on" as ±2 percent.	
			CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays		
			OL	Organic silts and organic silty clays of low plasticity		
	Silts and clays (Liquid limit greater than 50%)		MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts		
			CH	Inorganic clays of high plasticity, fat clays		
			OH	Organic clays of medium to high plasticity, organic silts		
	Highly organic soils		Pt	Peat and other highly organic soils		



A-Chart

Table 4-2: Engineering properties of tested soils

Sample	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	LL (%)	PL (%)	PI	W_N (%)	Specific gravity	Based on USCS chart
TP1	2.61	71.38	25.01	1	-	-	-	64.0	2.50	SILTY SAND (**SM**)
TP2	1.96	56.97	37.07	4	-	-	-	13.7	2.54	SILTY SAND (**SM**)
TP3	5.43	36.44	51.13	6	30.5	29.1	1.4	20.5	2.57	SILT (**ML**)
TP4 At 2.0m	0.89	24.88	46.23	28	32.7	26	6.7	23.0	2.62	SILT (**ML**)
TP4 At 3.0m	3.88	34	54.12	8	31.7	29	2.68	24.3	2.53	SILT (**ML**)

From the above table, the value of PI increases with clay fraction. This is because of the clay particles have a tendency to absorb moisture compare with silt and sand particles.

4.2.6. Consolidation

The main purpose of consolidation test is to get better understanding on stress history of the soil under study. It also helps to determine pre-consolidation pressure which is used for estimating maximum shear modulus of silt soil in this thesis. Since the stress history has small effect on small strain shear modulus for cohesionless soil, so for silty sand soil the pre-consolidation pressure is not the main parameter for estimating maximum shear modulus in this thesis.

Out of four test pits, two test pits are silt while two test pits are silty sand. The consolidation test is done for TP1 (silty sand) and TP4(silt) in the lab using odometer apparatus, the sample is remolded in field density, and with dimensions of 50mm in diameter and 20mm in height, and the sample is subjected to consolidation. Detailed calculation of test result is shown in Table F-1 and F-2 in the appendix F. The pre-consolidation pressure is obtained from the graph and is found to be 45 to 60 kPa.

4.3. Laboratory Investigation of Dynamic Soil Properties

To meet the objective of the thesis, a series of cyclic simple shear tests were carried out on two different silty sand, (TP1 and TP2), and one silt (TP4) soil samples.

4.3.1. Method of sample Preparation

The general procedures of ASTM D6528 were used to prepare and test samples of soil in cyclic simple shear. In these experimental work, cylindrical soil specimens of size 70 mm diameter and 20mm height were prepared by tamping in three layers. Each layer is compacted by hand tamping to the field density.

4.3.2. Cyclic Simple Shear Test results

4.3.2.1. The Consolidation Stage

These tests were carried out on soil specimens initially packed at required field density. To account the stress history of the soil and to compare with previous study results, the samples are consolidated under an axial stress of 100, 200, 300 and 400 kPa. The specimens were consolidated under different pressures, because the confining pressure is one of the main factors affecting the shear modulus of soils.
The consolidation stage was continued until the rate of vertical strain becomes less than 0.05% per hour [21].

4.3.2.2. The Cyclic Shearing Stage

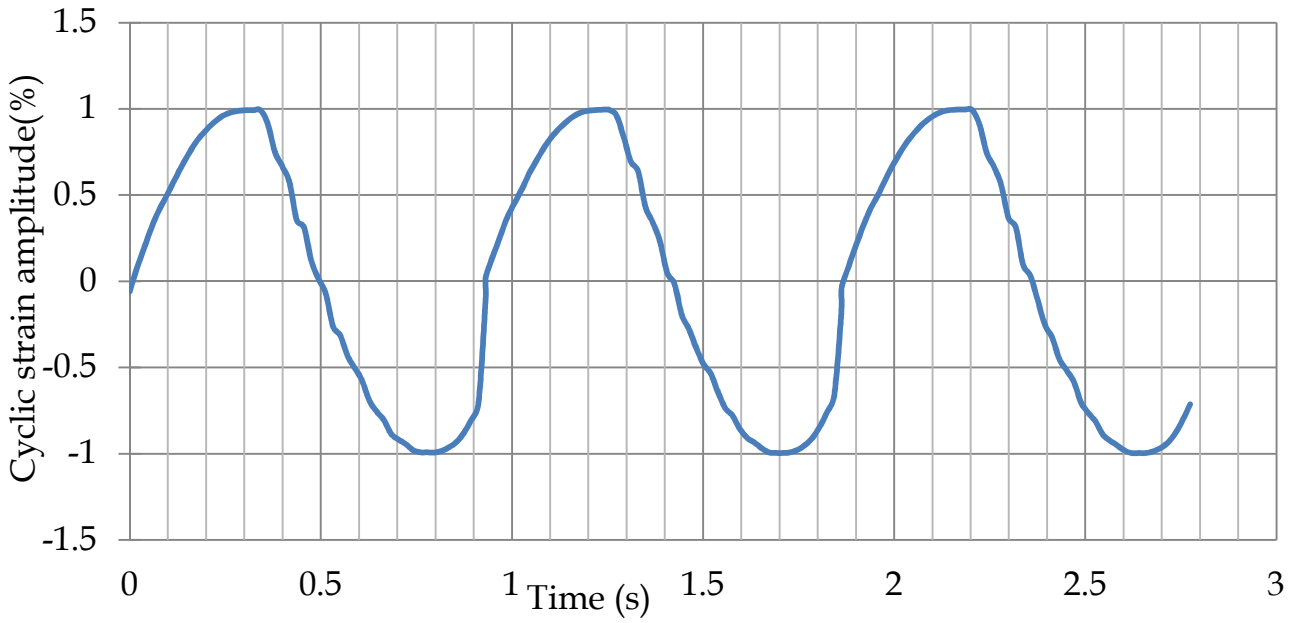
Following consolidations, constant amplitude cyclic stress was applied to the specimen. Each specimen was tested with different cyclic shear stress amplitude. Applied shearing strain values in all series of tests varied from 0.01% up to 5%.
Table 4-3 shows the axial stress and shear strain values used in this thesis. It should be noted here that, preparations of specimens and testing have been done for each strain level and axial load for all representative test pits.

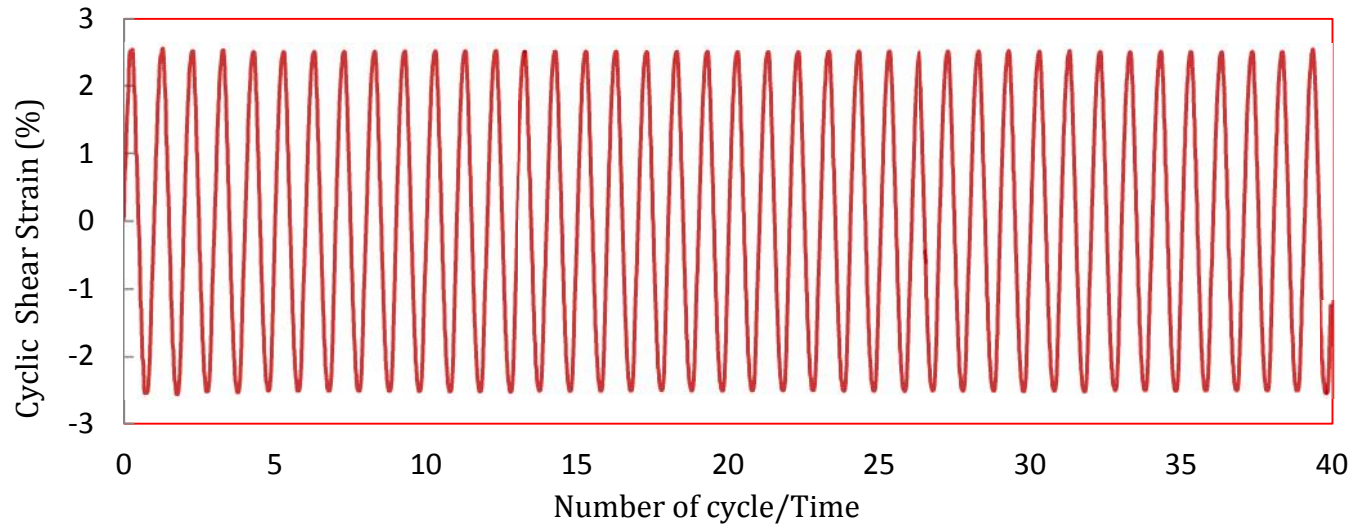
Table 4-3: Axial stress and shear strain values used in this thesis

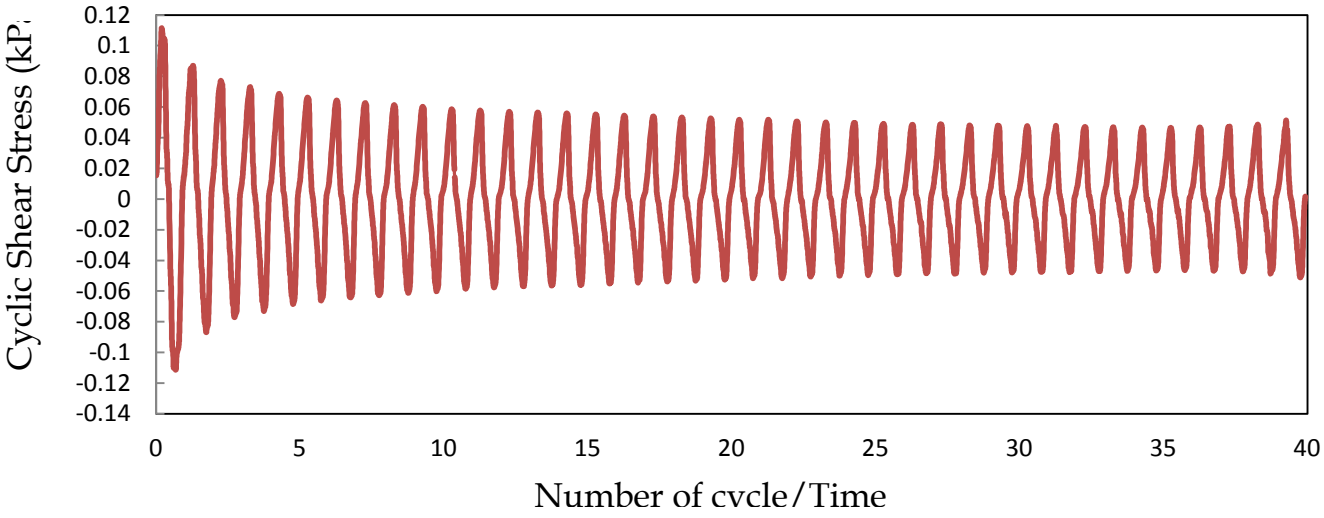
Test pit	Sample type	Axial stress (kPa)	Shear strain (%), γ				
TP1 (SILTY SAND)	Remolded to field condition	100	0.01	0.1	1	2.5	5
		200	0.01	0.1	1	2.5	5
		300	0.01	0.1	1	2.5	5
		400	0.01	0.1	1	2.5	5
TP2 (SILTY SAND)	Remolded to field condition	100	0.01	0.1	1	2.5	5
		200	0.01	0.1	1	2.5	5
		300	0.01	0.1	1	2.5	5
		400	0.01	0.1	1	2.5	5
TP4 (SILT)	Remolded to field condition	100	0.01	0.1	1	2.5	5
		200	0.01	0.1	1	2.5	5
		300	0.01	0.1	1	2.5	5
		400	0.01	0.1	1	2.5	5

In most seismic events, the number of significant cycles is likely to be less than 20, so the specimen were cyclically loaded through 40 cycles [3] using a uniform sinusoidal load at a frequency of 1.0 Hz, which is commonly used in laboratory tests.

For all practical purposes the values determined at fifth cycles is likely to provide reasonable values [6]. Sinusoidal wave shapes for 1% strain and 1Hz and for three cycles is shown in Figure: 4-4.


1.5
1
0.5
0
-0.5
-1
-1.5
Cyclic strain amplitude(%)
0
0.5
1
1.5
2
2.5
3
Time (s)


Cyclic Shear Strain (%)
3
2
1
0
-1
-2
-3
0
5
10
15
20
25
30
35
40
Number of cycle/Time


Cyclic Shear Stress (kP
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
-0.12
-0.14
0
5
10
15
20
25
30
35
40
Number of cycle/Time

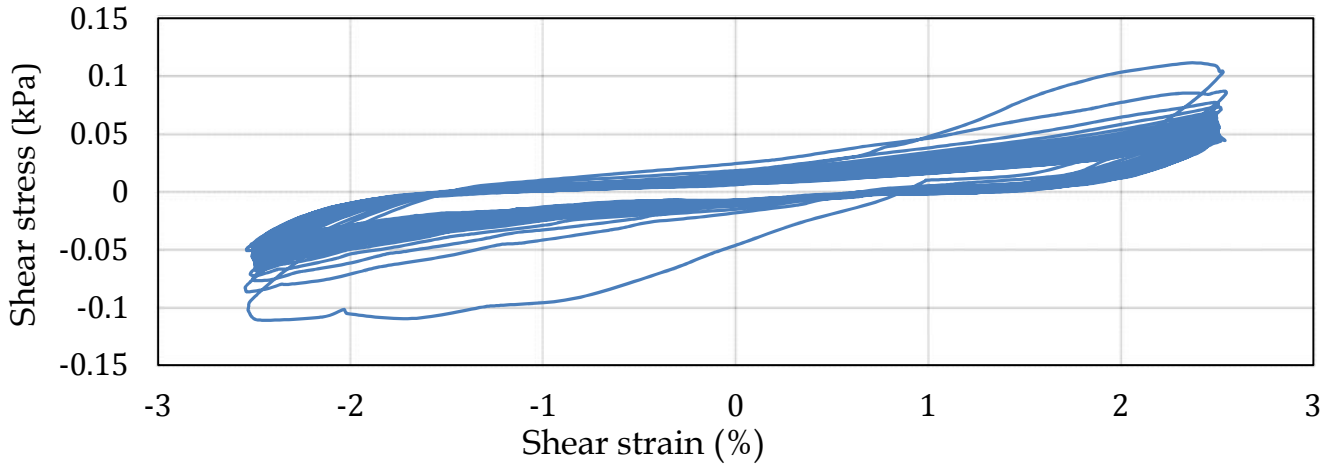

Shear stress (kPa)
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-3
-2
-1
0
1
2
3
Shear strain (%)

Table 4-4: Typical tabulation for shear stress and shear strain values

Cycle No.	Time (sec)	Lateral Lvdt	Lateral force	Area of sample (mm^2)	Shear Stress = $(F/A)*10^3$ (MPa)	Shear strain = (disp./19.6)	$(\tau_i-\tau_{i+1})*(\gamma_i+\gamma_{i+1})$
5	0.0000	0.00472	0.070545	3848.45	0.0183307	0.0002408	-9.3E-06
	0.0190	0.04646	0.084245	3848.45	0.0218906	0.0023704	-5.7E-05
	0.0380	0.11283	0.111115	3848.45	0.0288726	0.0057566	-8.5E-05
	0.0570	0.16988	0.133925	3848.45	0.0347997	0.0086673	-9.2E-05
	0.0760	0.21592	0.151935	3848.45	0.039479	0.0110163	-0.00016
	0.0950	0.27317	0.176935	3848.45	0.0459756	0.0139372	-0.00019
	0.1140	0.32006	0.200765	3848.45	0.0521677	0.0163295	-0.00017
	0.1330	0.35453	0.219835	3848.45	0.0571229	0.0180882	-0.00023
	0.1520	0.39184	0.242915	3848.45	0.0631202	0.0199918	-0.00023
	0.1710	0.43247	0.264115	3848.45	0.0686289	0.0220647	-0.00013
	0.1900	0.45704	0.275365	3848.45	0.0715521	0.0233183	-0.0001
	0.2090	0.47238	0.283525	3848.45	0.0736724	0.024101	-9E-05
	0.2280	0.48471	0.329138	3848.45	0.0855251	0.0247301	-3.17E-04
	0.2470	0.49647	0.353506	3848.45	0.0918567	0.0253301	7.86E-04
	0.2660	0.50099	0.294045	3848.45	0.0764060	0.0255607	5.91E-05
	0.2850	0.50133	0.289595	3848.45	0.0752497	0.0255780	5.86E-05
	0.3040	0.50062	0.285185	3848.45	0.0741038	0.0255418	0.000898
	0.3230	0.47381	0.215635	3848.45	0.0560316	0.0241739	0.000888
	0.3420	0.43247	0.141695	3848.45	0.0368187	0.02206479	0.000593
	0.3610	0.38269	0.086865	3848.45	0.0225714	0.019525	0.000212
	0.3800	0.35905	0.065295	3848.45	0.0169665	0.018318	0.00032
	0.3990	0.30037	0.028705	3848.45	0.0074588	0.0153251	8.93E-05
	0.4180	0.21008	0.015515	3848.45	0.0040314	0.0107183	3.87E-05
	0.4370	0.19409	0.008295	3848.45	0.0021554	0.0099025	0.000102
	0.4560	0.1102	-0.01698	3848.45	-0.004410	0.0056224	3.38E-05
	0.4750	0.06843	-0.03127	3848.45	-0.008124	0.0034913	2.59E-05
	0.4940	0.01081	-0.05596	3848.45	-0.01453	0.0005515	-2.1E-05
	0.5130	-0.0816	-0.07781	3848.45	-0.020217	-0.0041642	-3E-05
	0.5320	-0.1021	-0.09014	3848.45	-0.023421	-0.0052122	-0.00013
	0.5510	-0.1881	-0.12395	3848.45	-0.032206	-0.009597	-7.4E-05
	0.5700	-0.2295	-0.1373	3848.45	-0.035675	-0.0117096	-0.00017
	0.5890	-0.2705	-0.16269	3848.45	-0.042272	-0.0138040	-0.0003
	0.6080	-0.3444	-0.19995	3848.45	-0.051954	-0.0175760	-7.1E-05

	0.6270	-0.3620	-0.20753	3848.45	-0.0539242	-0.018473	-0.00034
	0.6460	-0.4040	-0.24053	3848.451	-0.0624991	-0.020613	-0.00027
	0.6650	-0.4475	-0.2645	3848.451	-0.0687276	-0.022832	-5.2E-05
	0.6840	-0.4557	-0.26888	3848.451	-0.0698657	-0.023252	-0.0003
	0.7030	-0.4812	-0.31198	3848.451	-0.0810682	-0.024552	5.4E-04
	0.7220	-0.4997	-0.35350	3848.451	-0.0918567	-0.025499	8.57E-03
	0.7410	-0.5011	-0.29246	3848.451	-0.0759929	-0.025566	4.01E-05
	0.7600	-0.5013	-0.28944	3848.451	-0.0752081	-0.025578	4.45E-05
	0.7790	-0.5009	-0.28609	3848.451	-0.0743377	-0.025559	7.44E-05
	0.7980	-0.4996	-0.28048	3848.451	-0.0728799	-0.025491	0.000444
	0.8170	-0.4872	-0.24655	3848.451	-0.0640634	-0.024858	0.000589
	0.8360	-0.4663	-0.19993	3848.451	-0.0519494	-0.023791	0.000723
	0.8550	-0.4333	-0.13928	3848.451	-0.0361898	-0.022111	0.000674
	0.8740	-0.3891	-0.07746	3848.451	-0.0201262	-0.019854	0.000494
	0.8930	-0.3365	-0.02607	3848.451	-0.0067728	-0.017168	0.000274
	0.9120	-0.2711	0.007975	3848.451	0.00207226	-0.013834	6.08E-05
	0.9310	-0.2006	0.017695	3848.451	0.00459795	-0.010239	0.000137

Using shear strain and shear strain values of Table 4-4, the hysteresis loop is plotted. The triangle with L and S side dimensions were presented in Figure 4-8.

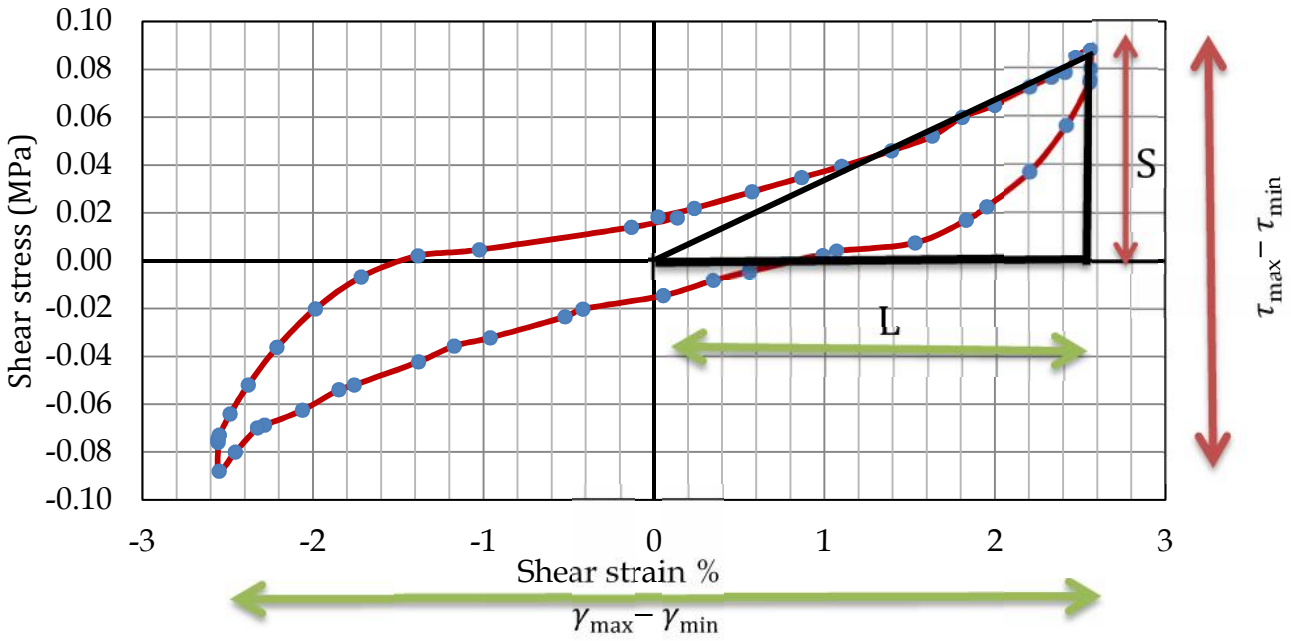


Figure 4-8: Hysteresis loop and triangle using stress strain values at 5th cycle

Shear modulus and damping ratio of hysteresis loop are calculated using the following equations:

$$G=\frac{(\tau_{max}-\tau_{min})}{(\gamma_{max}-\gamma_{min})} \quad \text{and} \quad D=\frac{(\text{Area of loop})}{(4*\prod*\text{Area of Triangle})}$$

with variables as described in Figure 4-8. To obtain these two values from the hysteresis loop the recommendations of standard ASTM D3999 are followed. Since, in most seismic events, the number of significant cycles is likely to be less than 20, the values determined at 5th cycles are likely to provide reasonable values for all practical purposes. [6]

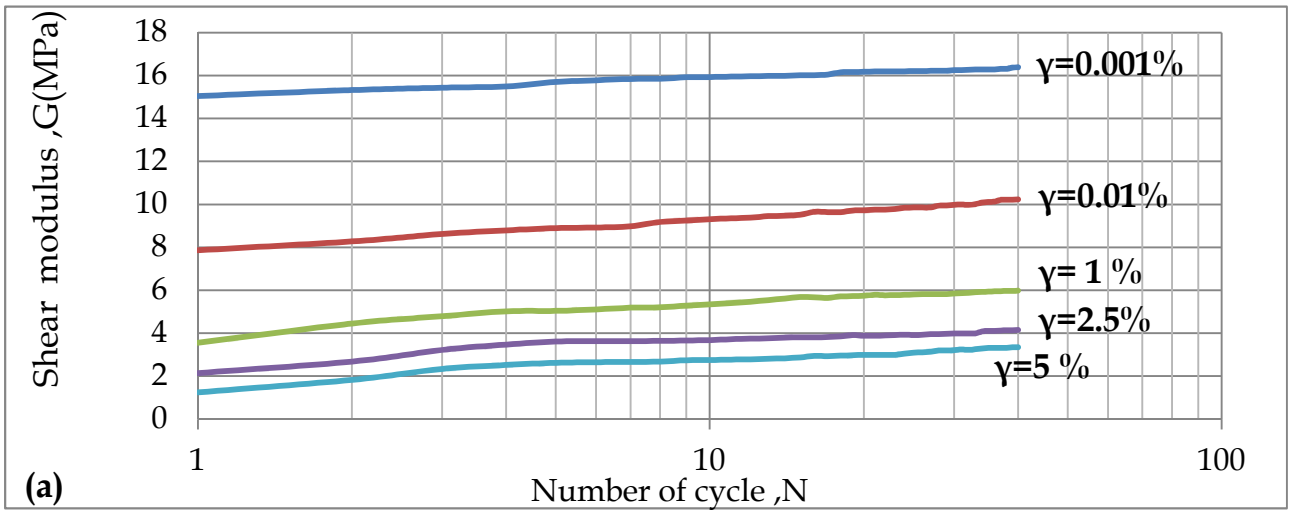
Table 4-5: Typical calculation for shear modulus and damping ratio using Table 4-4 and Figure 4-8

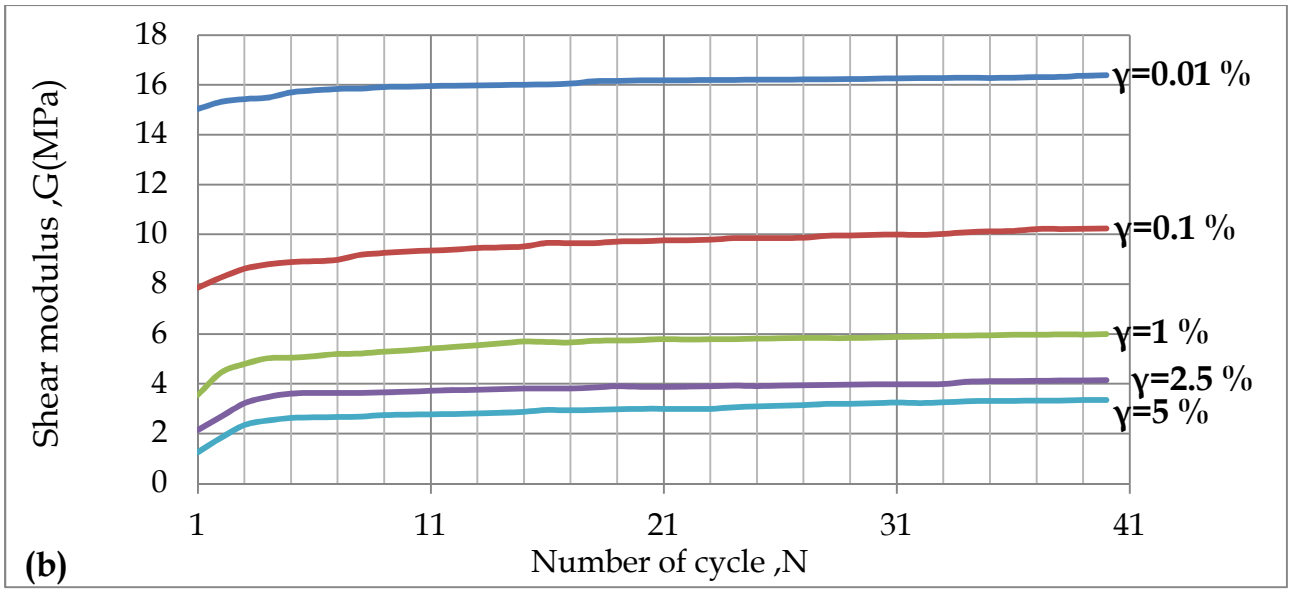
<table>
<tr><th colspan="2">Calculation of Shear</th><th colspan="2">Calculation of Damping Ratio</th></tr>
<tr><td>τ_{max}</td><td>0.0920</td><td>Area of the hysteresis loop= $0.5*\sum(\tau_i-\tau_{i+1})*(\gamma_i+\gamma_{i+1})$</td><td>$2.75*10^{-3}$</td></tr>
<tr><td>τ_{min}</td><td>-0.0920</td><td rowspan="2">Area of the triangle=0.5*S*L</td><td rowspan="2">$1.17*10^{-3}$</td></tr>
<tr><td>$\tau_{max}-\tau_{min}=2S$</td><td>0.1841</td></tr>
<tr><td>γ_{max}</td><td>0.0255</td><td rowspan="4">$D=\frac{(\text{Area of loop})}{(4*\Pi*\text{Area of Triangle})}*100\%$</td><td rowspan="4">18.65</td></tr>
<tr><td>γ_{min}</td><td>-0.0255</td></tr>
<tr><td>$\gamma_{max}-\gamma_{min}=2L$</td><td>0.051</td></tr>
<tr><td>$G=\frac{(\tau_{max}-\tau_{min})}{(\gamma_{max}-\gamma_{min})}$ in MPa.</td><td>3.61</td></tr>
</table>

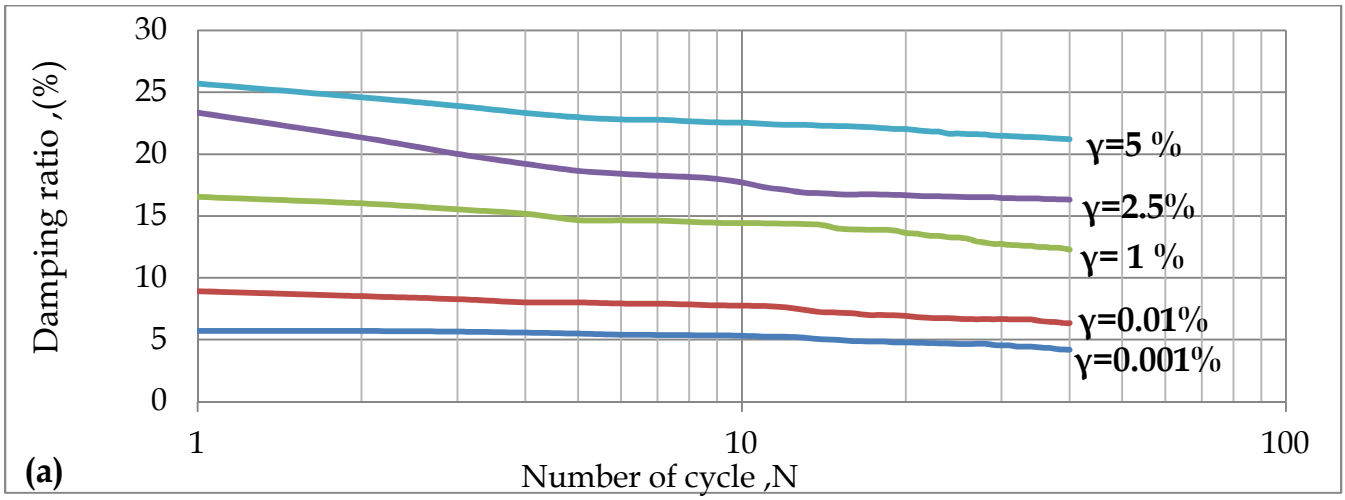
In similar manner with Table 4.4, the value of shear modulus and damping ratio of each cycle in a test can be determined. In this study, a single specimen was tested up to 40 cycles and Table 4-5 shows shear modulus and damping ratio values of each cycle for TP4 under an axial stress of 200kPa. Additional test results are shown in appendix G.

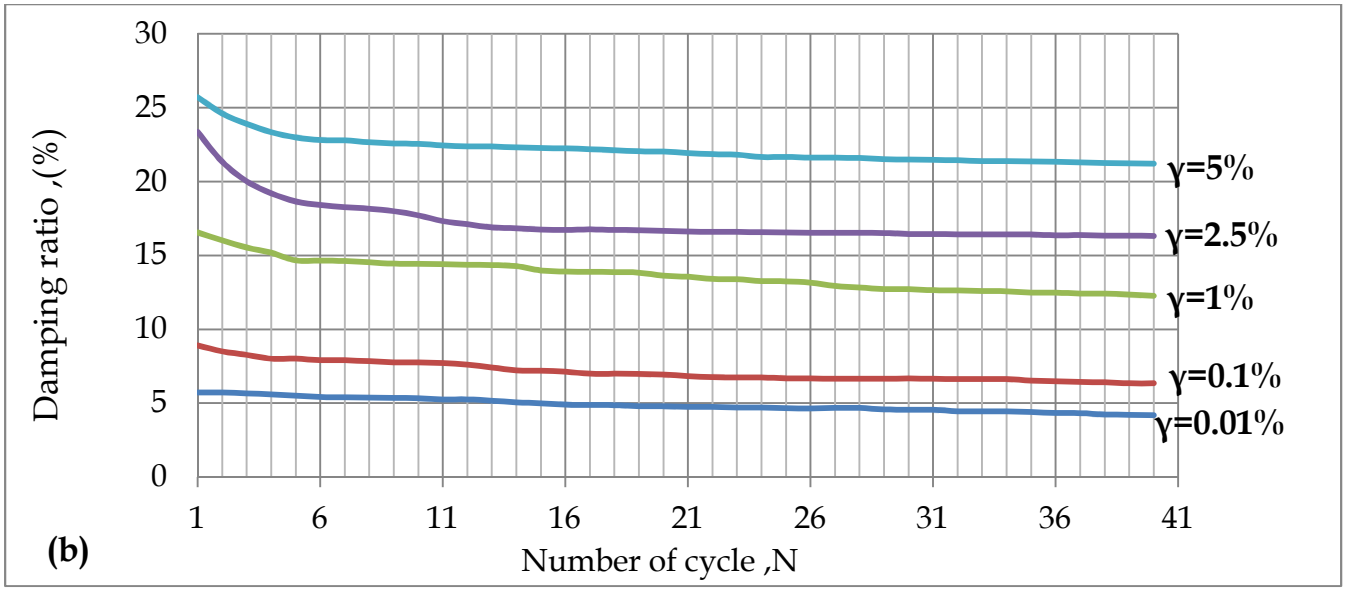
Table 4-6: Shear modulus and damping ratio values for TP4 under an axial stress of 200kPa.

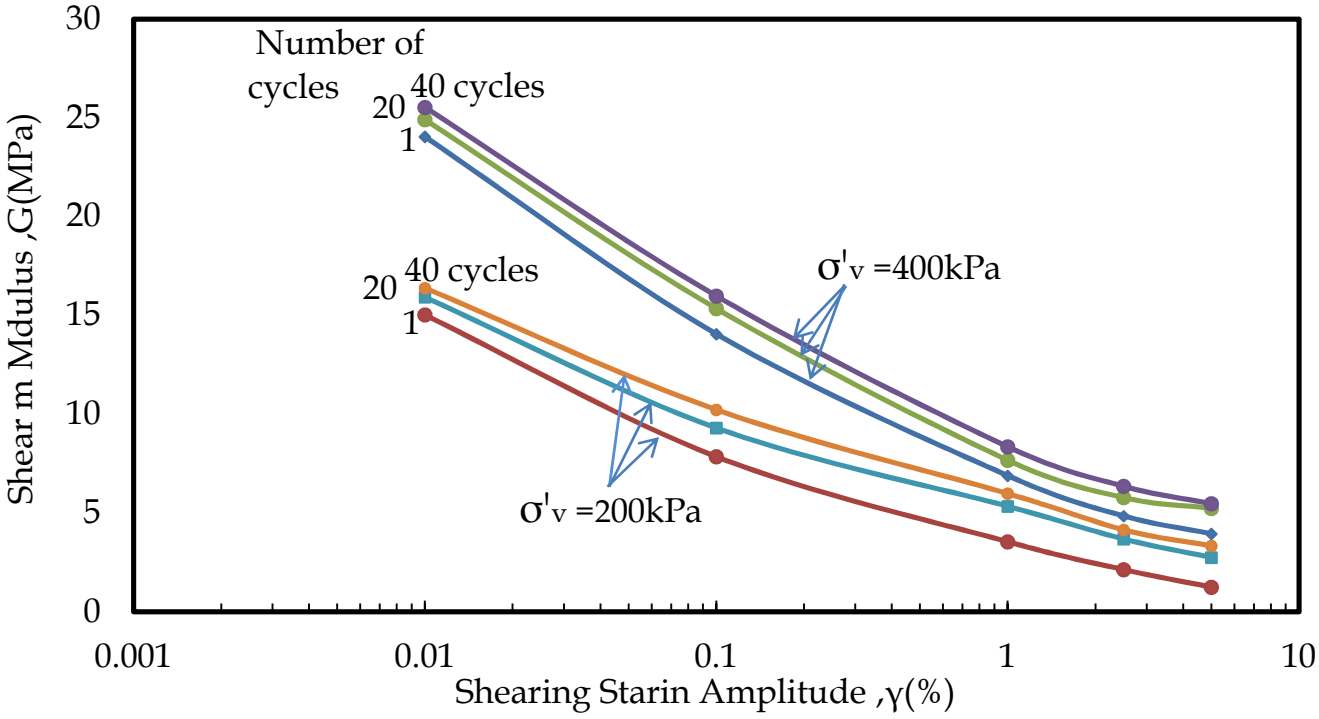
Strain level	0.01%	0.10%	1%	2.50%	5%	0.01%	0.10%	1%	2.50%	5%
Cycles No.	G (MPa)					D (%)				
1	15.04	8.36	4.05	3.03	1.85	5.71	8.91	16.56	23.36	25.72
2	15.32	8.67	4.55	3.28	2.23	5.71	8.51	16.03	21.35	24.61
3	15.43	8.72	4.89	3.42	2.34	5.66	8.27	15.54	20.02	23.91
4	15.49	8.79	5.02	3.57	2.52	5.58	8.01	15.19	19.21	23.34
5	15.70	8.89	5.04	3.61	2.62	5.50	8.01	14.67	18.65	22.99
6	15.78	8.92	5.11	3.63	2.65	5.41	7.92	14.65	18.41	22.81
7	15.84	8.98	5.19	3.63	2.66	5.39	7.91	14.63	18.26	22.79
8	15.85	8.98	5.21	3.64	2.68	5.37	7.84	14.54	18.16	22.66
9	15.92	9.09	5.29	3.66	2.74	5.35	7.77	14.45	17.99	22.58
10	15.93	9.11	5.34	3.68	2.75	5.33	7.75	14.43	17.71	22.55
11	15.95	9.15	5.41	3.72	2.77	5.25	7.71	14.41	17.32	22.45
12	15.97	9.23	5.47	3.75	2.78	5.25	7.61	14.38	17.11	22.38
13	15.98	9.35	5.54	3.76	2.81	5.16	7.42	14.35	16.89	22.37
14	15.99	9.37	5.62	3.79	2.83	5.05	7.22	14.28	16.74	22.31
15	16.01	9.51	5.69	3.81	2.87	4.99	7.19	13.99	16.65	22.27
16	16.02	9.65	5.67	3.81	2.94	4.89	7.13	13.91	16.62	22.25
17	16.05	9.64	5.65	3.82	2.93	4.87	6.99	13.89	16.56	22.19
18	16.15	9.64	5.72	3.85	2.95	4.86	6.99	13.88	16.52	22.13
19	16.16	9.71	5.73	3.91	2.97	4.79	6.97	13.84	16.51	22.05
20	16.18	9.72	5.75	3.88	2.99	4.79	6.93	13.63	16.46	22.03
21	16.19	9.75	5.79	3.88	2.99	4.75	6.83	13.56	16.22	21.93
22	16.19	9.76	5.77	3.89	2.98	4.74	6.76	13.41	16.19	21.85
23	16.2	9.78	5.78	3.91	2.99	4.71	6.74	13.39	16.19	21.82
24	16.2	9.84	5.79	3.93	3.05	4.69	6.74	13.27	16.16	21.66
25	16.21	9.85	5.81	3.91	3.09	4.65	6.68	13.25	16.14	21.67
26	16.21	9.85	5.82	3.93	3.11	4.64	6.67	13.16	16.13	21.62
27	16.22	9.86	5.83	3.95	3.14	4.67	6.65	12.94	16.13	21.62
28	16.22	9.94	5.83	3.96	3.19	4.67	6.66	12.84	16.12	21.59
29	16.23	9.95	5.83	3.97	3.19	4.57	6.65	12.73	16.11	21.51
30	16.25	9.98	5.85	3.98	3.21	4.55	6.67	12.73	15.95	21.49
31	16.26	9.99	5.87	3.98	3.24	4.54	6.65	12.65	15.85	21.46
32	16.27	9.97	5.89	3.98	3.22	4.45	6.63	12.63	15.82	21.44
33	16.28	10.01	5.91	3.99	3.25	4.44	6.63	12.59	15.76	21.39
34	16.29	10.08	5.93	4.08	3.29	4.43	6.63	12.58	15.71	21.38
35	16.28	10.11	5.94	4.11	3.31	4.39	6.53	12.49	15.71	21.36
36	16.29	10.13	5.96	4.11	3.31	4.34	6.47	12.49	15.64	21.33
37	16.31	10.21	5.96	4.12	3.32	4.32	6.43	12.42	15.57	21.29
38	16.32	10.21	5.98	4.14	3.32	4.23	6.41	12.42	15.54	21.26
39	16.37	10.22	5.97	4.14	3.34	4.21	6.34	12.36	15.54	21.24
40	16.39	10.23	5.99	4.15	3.34	4.18	6.34	12.27	15.51	21.21

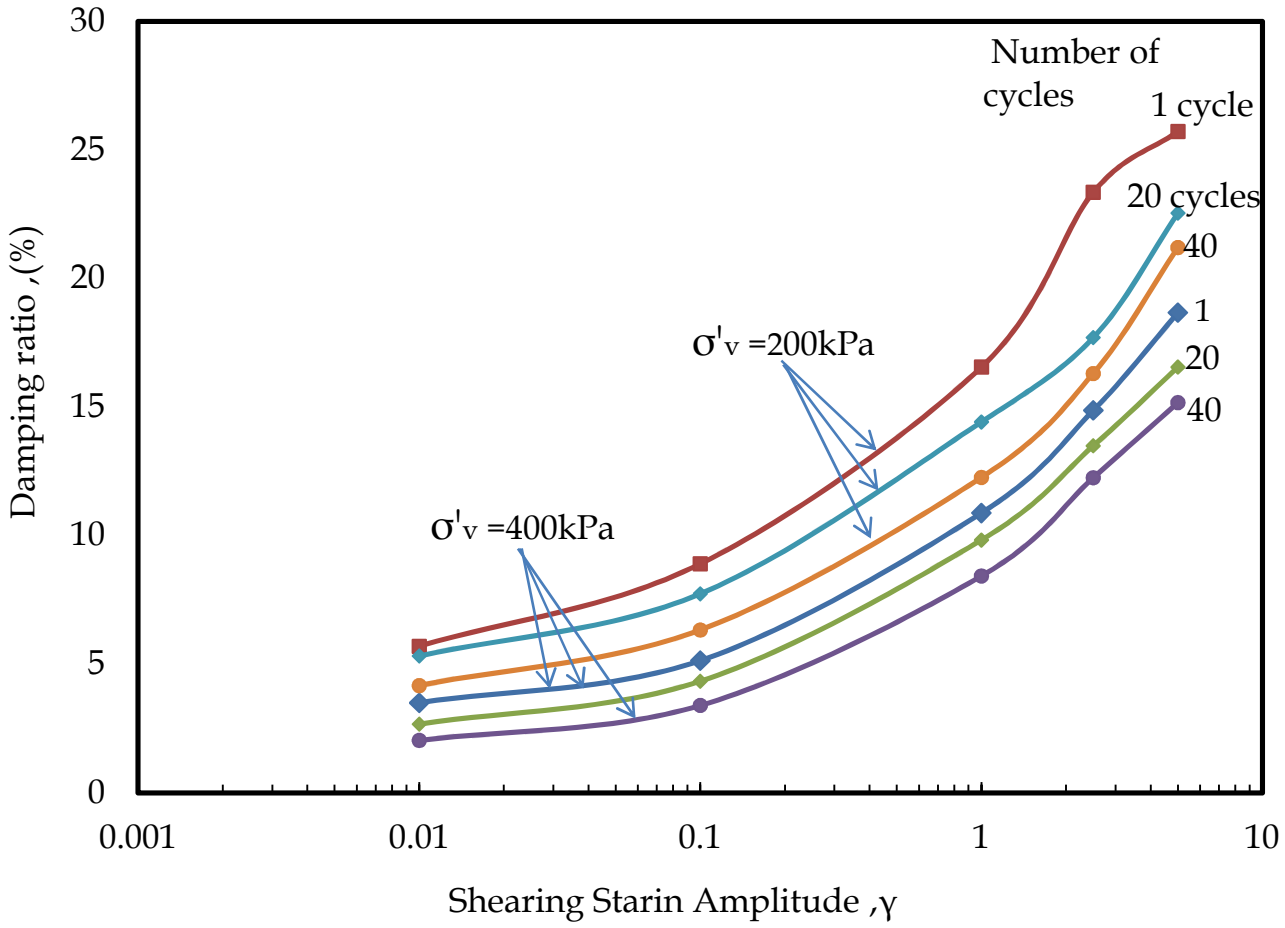

Shear modulus ,G(MPa)
18
16
14
12
10
8
6
4
2
0
1
10
100
Number of cycle ,N
γ=0.001%
γ=0.01%
γ= 1 %
γ=2.5%
γ=5 %
(a)

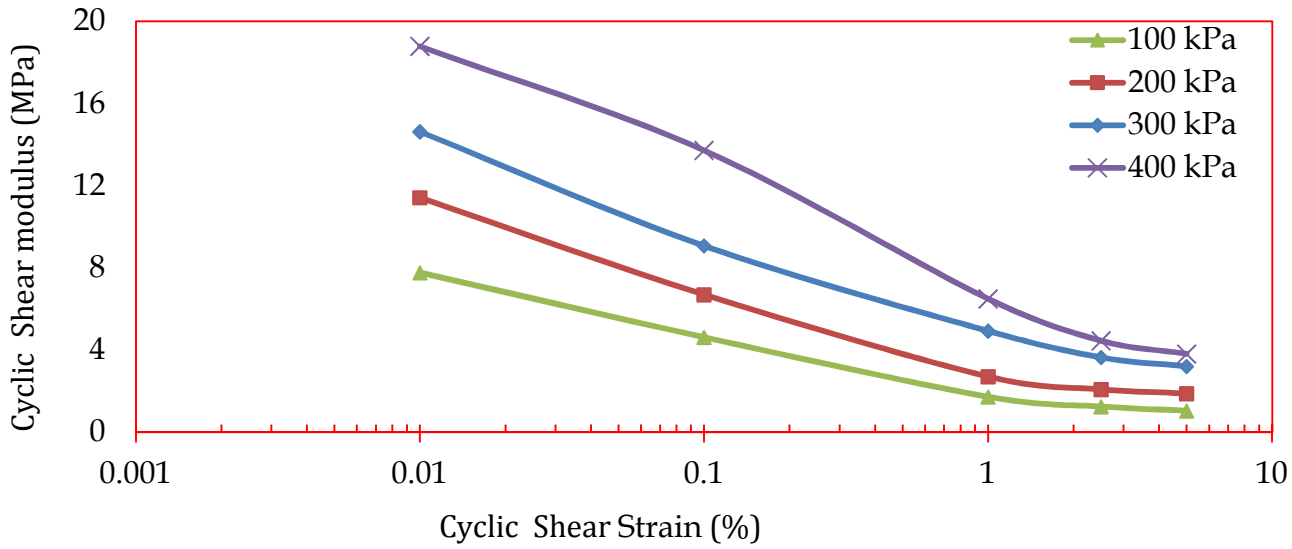

Shear modulus ,G(MPa)
18
16
14
12
10
8
6
4
2
0
1
11
21
31
41
Number of cycle ,N
γ=0.01 %
γ=0.1 %
γ=1 %
γ=2.5 %
γ=5 %
(b)

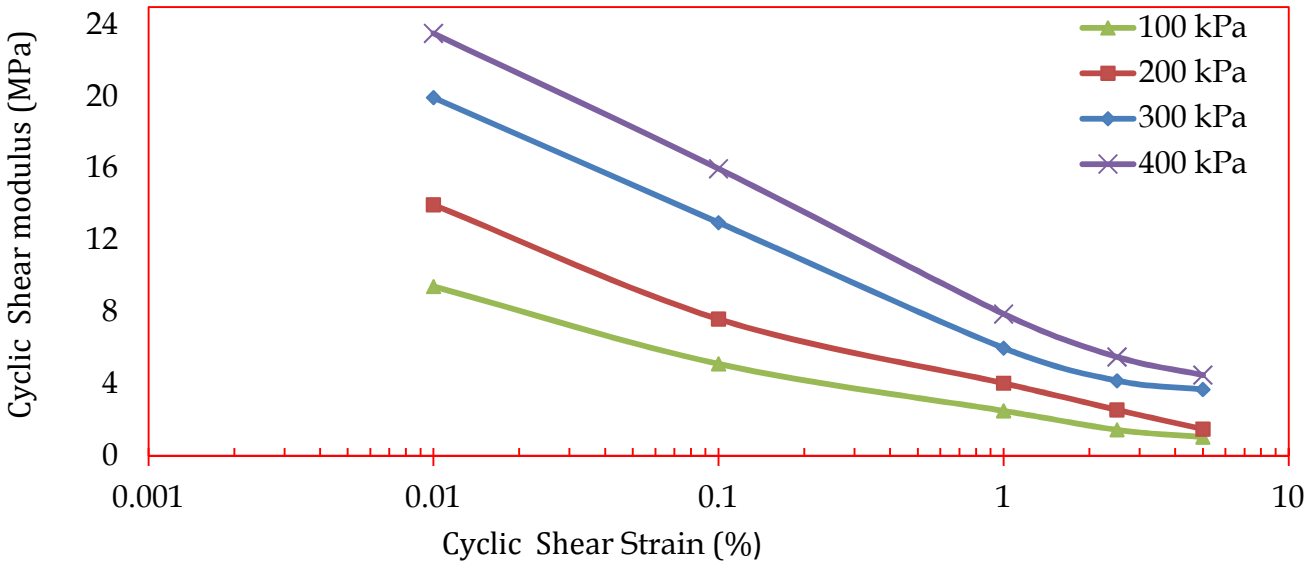

Damping ratio ,(%)
30
25
20
15
10
5
0
1
10
100
Number of cycle ,N
γ=5 %
γ=2.5%
γ= 1 %
γ=0.01%
γ=0.001%
(a)

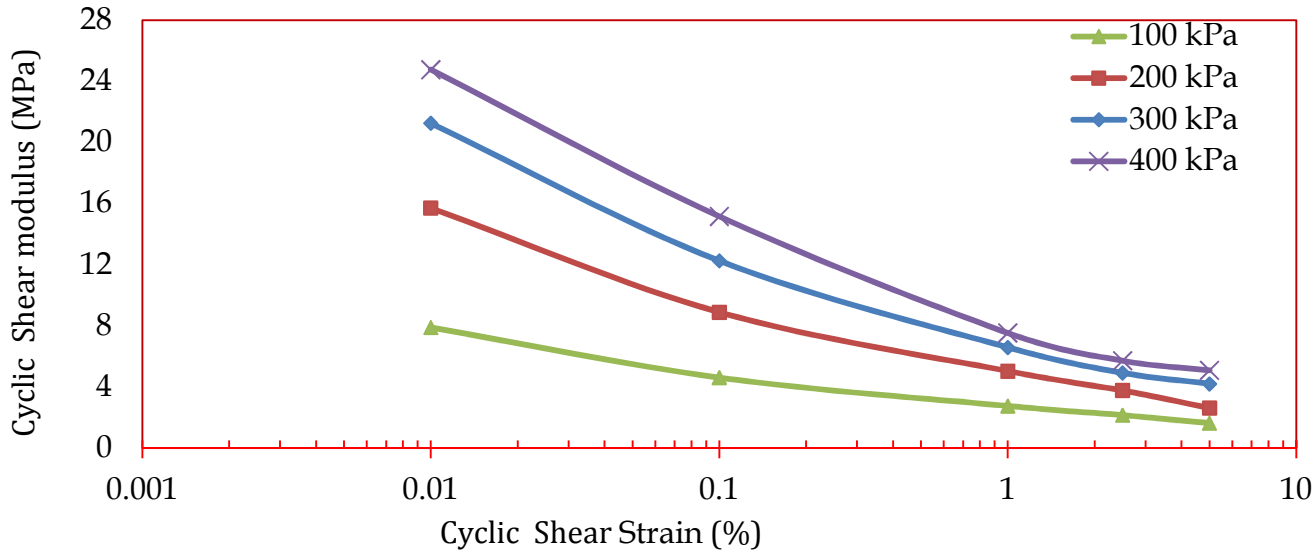

Damping ratio ,(%)
30
25
20
15
10
5
0
1
6
11
16
21
26
31
36
41
Number of cycle ,N
γ=5%
γ=2.5%
γ=1%
γ=0.1%
γ=0.01%
(b)


Number of cycles
40 cycles
20
1
40 cycles
20
1
σ'v =400kPa
σ'v =200kPa
Shear m Mdulus ,G(MPa)
Shearing Starin Amplitude ,γ(%)
30
25
20
15
10
5
0
0.001
0.01
0.1
1
10


Damping ratio ,(%)
30
25
20
15
10
5
0
0.001
0.01
0.1
1
10
Shearing Starin Amplitude ,γ
Number of cycles
1 cycle
20 cycles
40
1
20
40
σ'v =200kPa
σ'v =400kPa


Cyclic Shear modulus (MPa)
20
16
12
8
4
0
0.001
0.01
0.1
1
10
Cyclic Shear Strain (%)
100 kPa
200 kPa
300 kPa
400 kPa


Cyclic Shear modulus (MPa)
24
20
16
12
8
4
0
0.001
0.01
0.1
1
10
Cyclic Shear Strain (%)
100 kPa
200 kPa
300 kPa
400 kPa


Cyclic Shear modulus (MPa)
28
24
20
16
12
8
4
0
0.001
0.01
0.1
1
10
Cyclic Shear Strain (%)
100 kPa
200 kPa
300 kPa
400 kPa

5.3. Influence of effective vertical stress on Damping values

Fig.5-6 to 5-8 show the influence of effective vertical stress on the damping ratio. It could be observed from the figures, the damping ratio decreases as the confining pressure increases. As mentioned previously, densification or reduction in void ratio of soils causes due to confining pressure. This reduction in void ratio of soils leads to the reduction of damping.

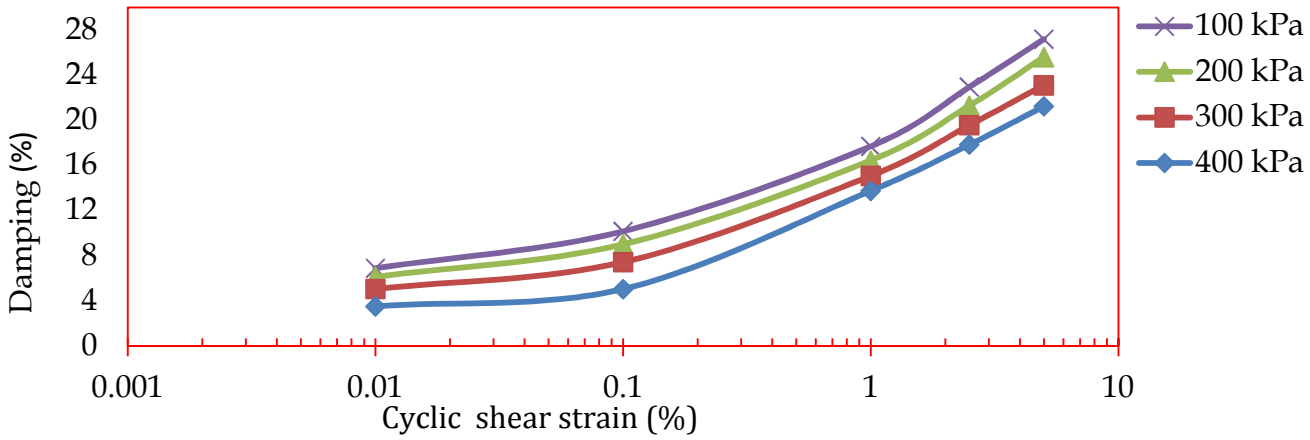


Figure: 5-6 Effect of confining pressure on damping curve for silty sand soil, TP1.

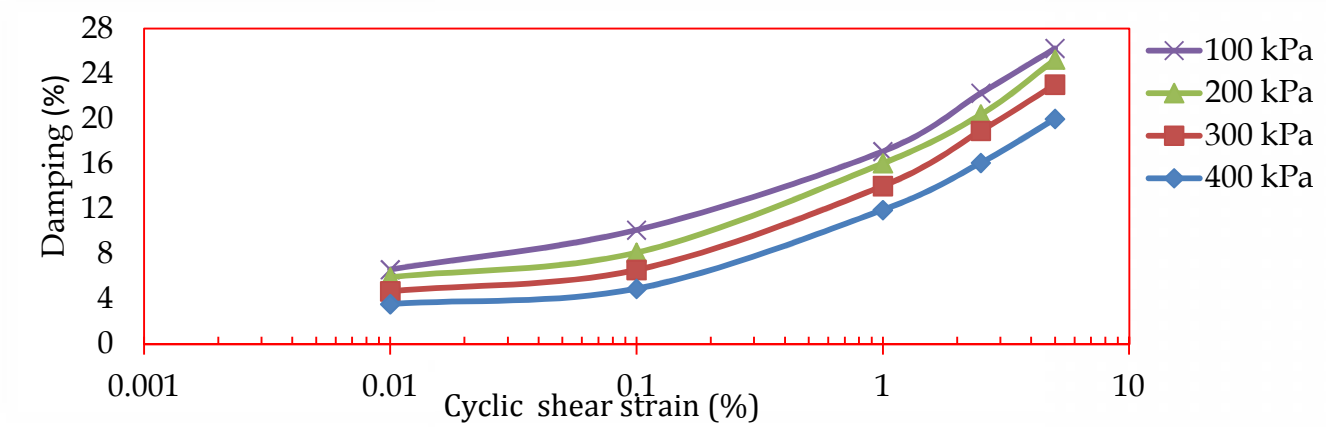


Figure 5-7: Effect of confining pressure on damping curve for silty sand soil, TP2

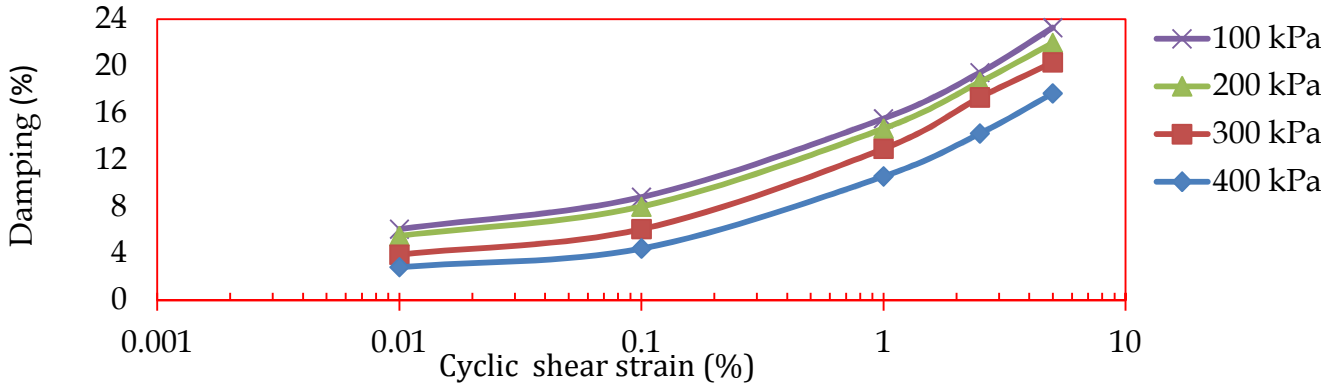
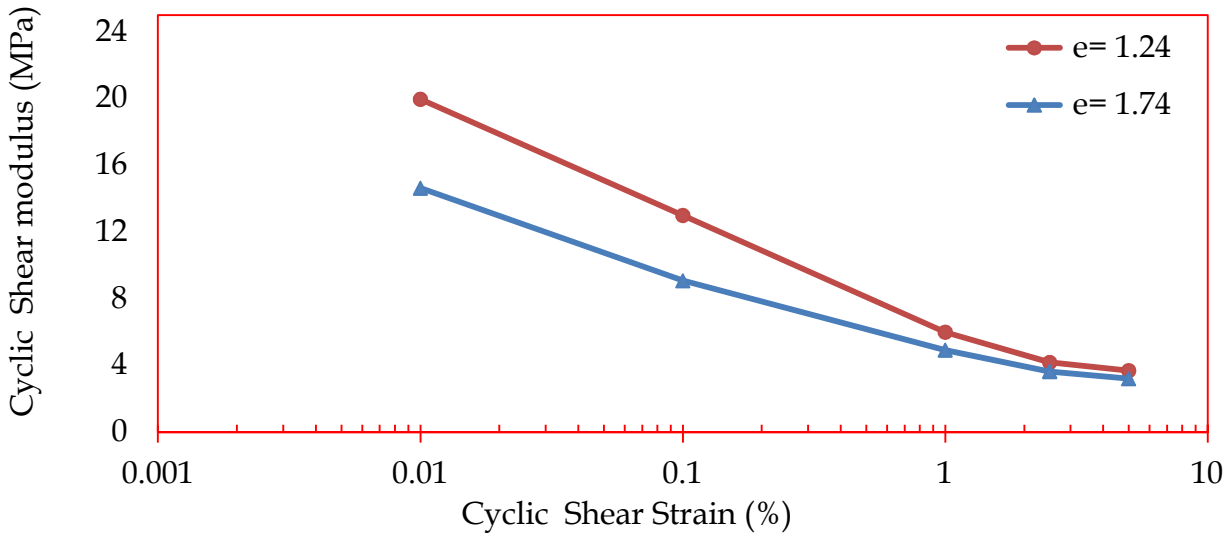
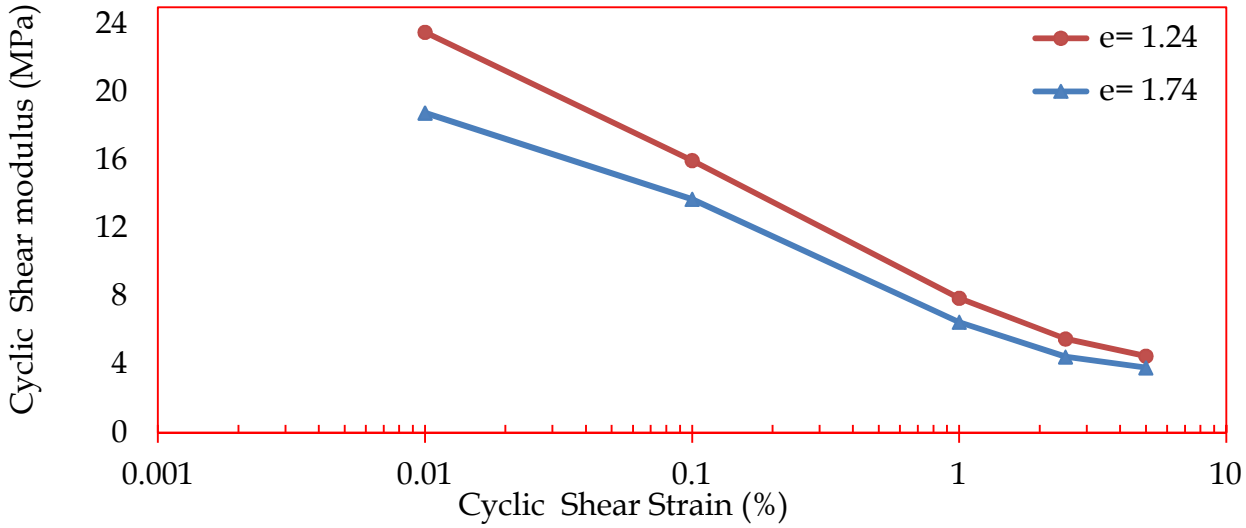
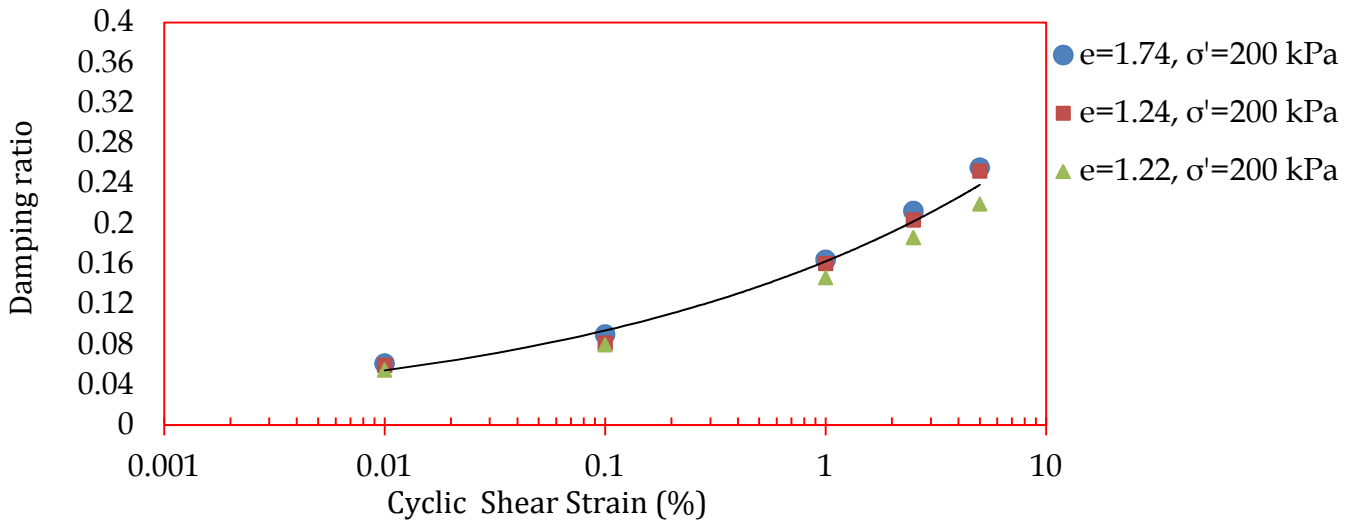
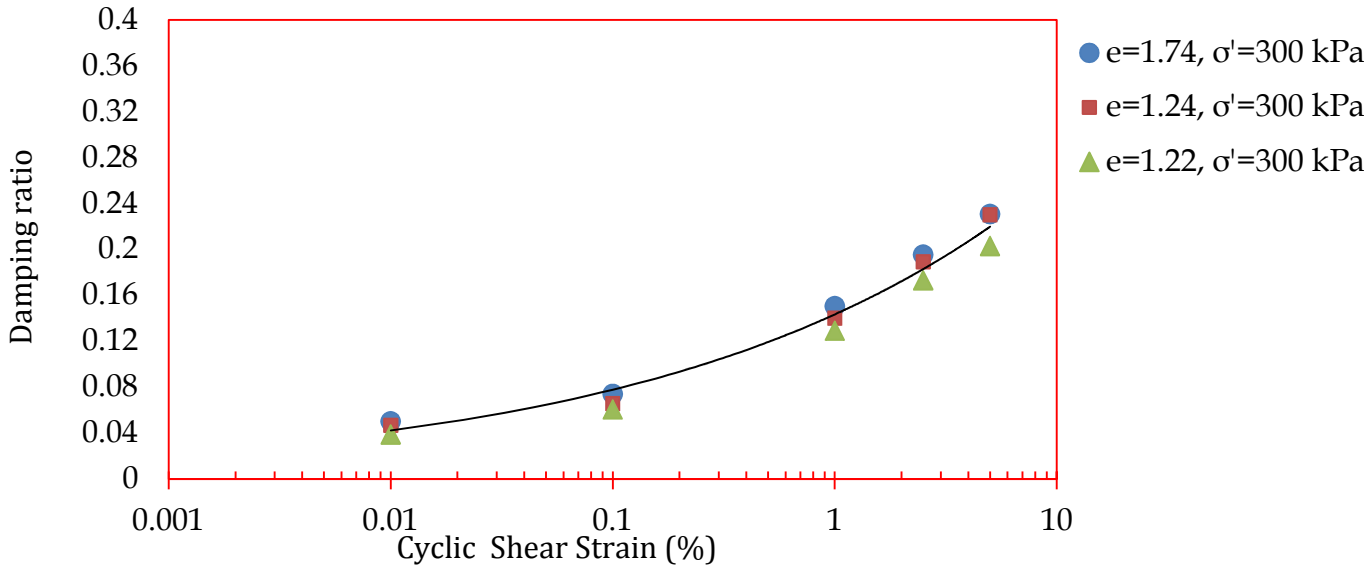


Figure 5-8: Effect of confining pressure on damping curve for silt soil, TP4


Cyclic Shear modulus (MPa)
24
20
16
12
8
4
0
0.001
0.01
0.1
1
10
Cyclic Shear Strain (%)
e= 1.24
e= 1.74


Cyclic Shear modulus (MPa)
24
20
16
12
8
4
0
0.001
0.01
0.1
1
10
Cyclic Shear Strain (%)
e= 1.24
e= 1.74


0.4
0.36
0.32
0.28
0.24
0.2
0.16
0.12
0.08
0.04
0
Damping ratio
0.001
0.01
0.1
1
10
Cyclic Shear Strain (%)
e=1.74, σ'=200 kPa
e=1.24, σ'=200 kPa
e=1.22, σ'=200 kPa


0.4
0.36
0.32
0.28
0.24
0.2
0.16
0.12
0.08
0.04
0
Damping ratio
0.001
0.01
0.1
1
10
Cyclic Shear Strain (%)
e=1.74, σ'=300 kPa
e=1.24, σ'=300 kPa
e=1.22, σ'=300 kPa

5.6. Comparison of Test Results with Previous Findings

Maximum Shear modulus values

The small strain shear modulus Gmax describes soil response in the initial, elastic stress strain range and is a function of the stress state and degree of compactness of the soil. Since cyclic simple shear tests are high strain tests (0.01 to 5%) one cannot measure shear modulus and damping values at low strain levels. So, the maximum shear modulus, Gmax which corresponds to very low strain levels cannot be determined from such tests. For the sake of comparison the maximum shear modulus, Gmax of each specimen is determined using Eq.2-1written below, and the calculated Gmax is used to obtain the normalized shear modulus which is then compared with those obtained from literature. [12]

$$Gmax = 3.23 * \frac{((2.97 - e)^2)}{1 + e} * (OCR)^K * (\sigma'_0)^{0.5} \qquad (4.4)[12]$$

$$\sigma'_0 = \frac{(\sigma'_V + 2K_0\sigma'_V)}{3}$$

Where: e = void ratio

OCR = Over-consolidation ratio $=P_c/P_o$

P_c = Pre consolidation pressure of a specimen

P_c = Present effective vertical pressure

σ'_0 = Effective confining stress

σ'_v = Effective vertical stress

K_O = Coefficient of lateral earth pressure at rest

K = Dimensionless quantity which is a function of PI, it can be obtained from Table 2-1.

K_O= is the coefficient of lateral pressure at rest. For cohesionless soils K_O = 0.43 to 0.67, with a value of 0.5 often used. [5]

Although Eq.4.4 is developed for cohesive soils, this equation was found to be applicable to cohessionless soils simply by setting K equal to 0 (PI is equal to 0) [8].

For example, for the specimen mentioned in section 4.4, a specimen having a PI of 2.68, from Table 2-1, by interpolation K=0.0243 and the value of void ratio at the natural state of the soil is 1.22 (see Appendix B, Table B-1). And also from consolidation test result the value of pre-consolidation pressure, P_C=45KPa (see Appendix F, Figure F-2).

So, OCR=P_C/P_O =45/200 =0.225

σ'_o = (200+2*0.5*200)/3 =133.33kPa.

$$Gmax = 3.23 * \frac{((2.97 - e)^2)}{1 + e} * (OCR)^K * (\sigma'_0)^{0.5}$$

$$Gmax = 3.23 * \frac{((2.97 - 1.22)^2)}{1 + 1.22} * (0.225)^{0.024} * (133.33)^{0.5}$$

Thus, Gmax = 49,950 kPa

For this specimen the fifth cycle cyclic shear modulus is 3,610 kPa. So, G/Gmax =3,610kPa/49,950 kPa

=0.0722

Similarly, Gmax for each specimen is calculated and the result presented in Table 5-1.

Table 5-1: Maximum shear modulus for each specimen

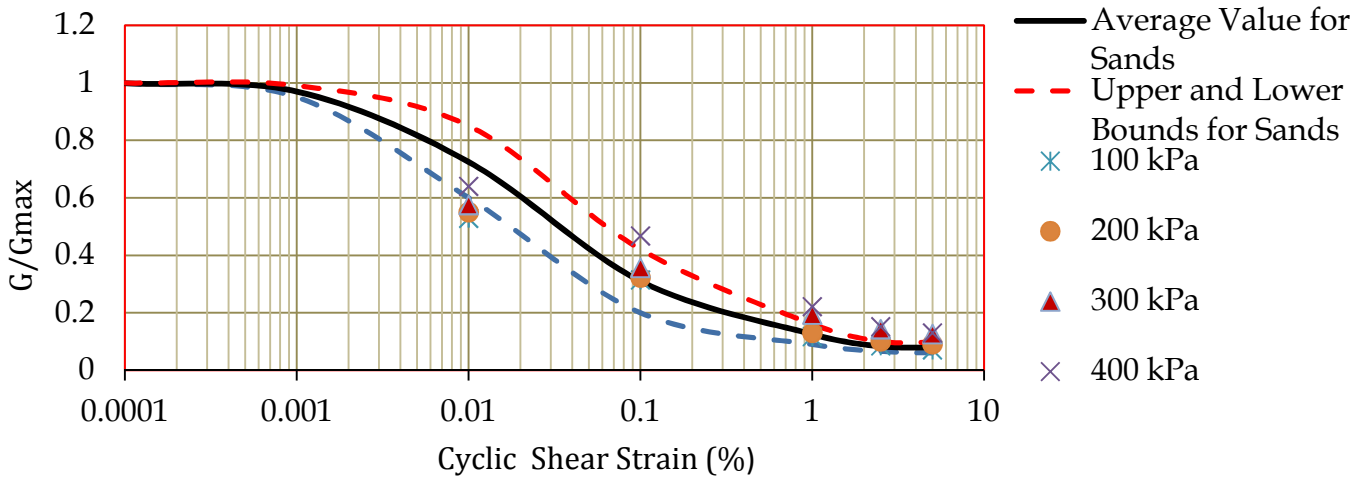
	σ'_o (kPa)	66.7	133.3	200.0	266.7
TP1	Gmax(MPa)	14.69	20.77	25.44	29.37
TP2	Gmax (MPa)	35.25	49.86	61.06	70.51
TP4	Gmax (MPa)	35.92	49.95	60.58	69.47

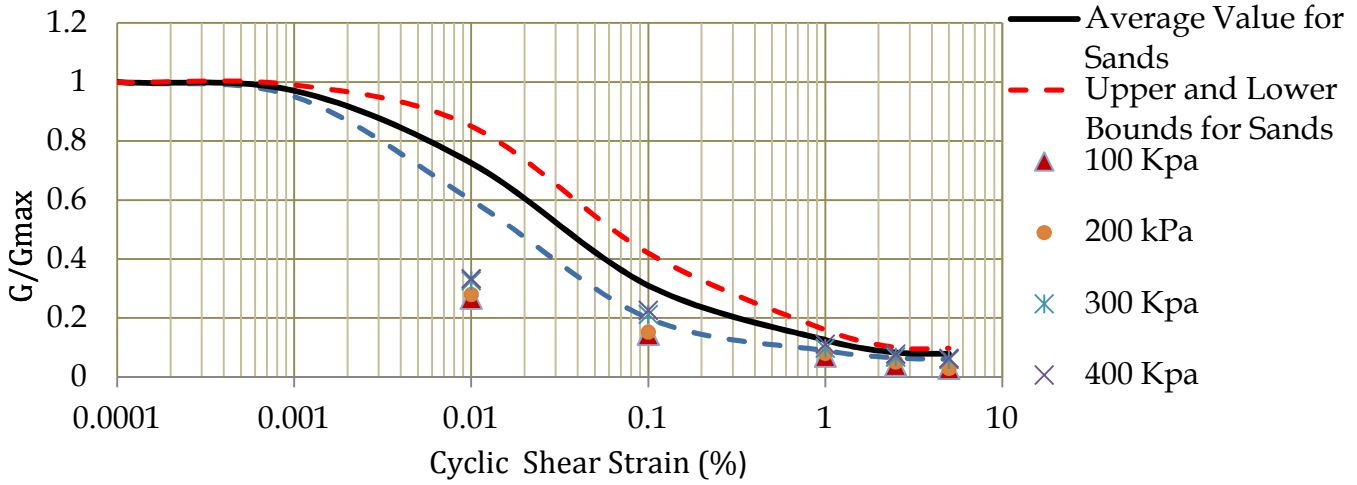
For each specimen the fifth cycle normalized shear modulus (G/Gmax) and material damping is tabulated in Table 5-2.

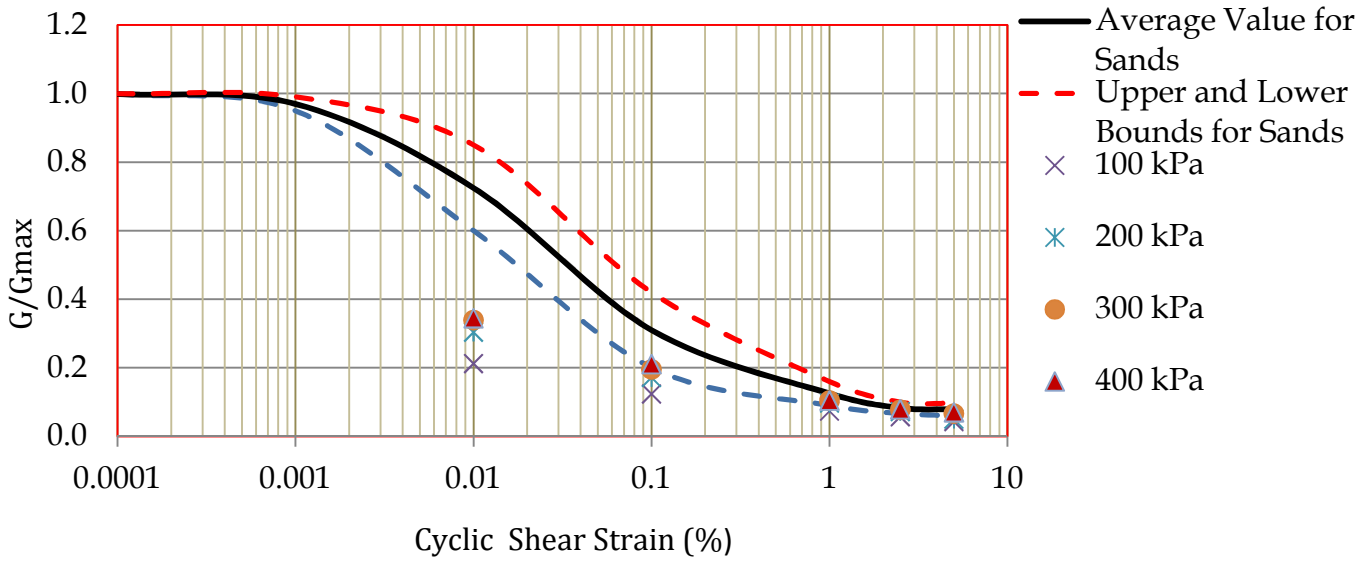
Table 5-2:

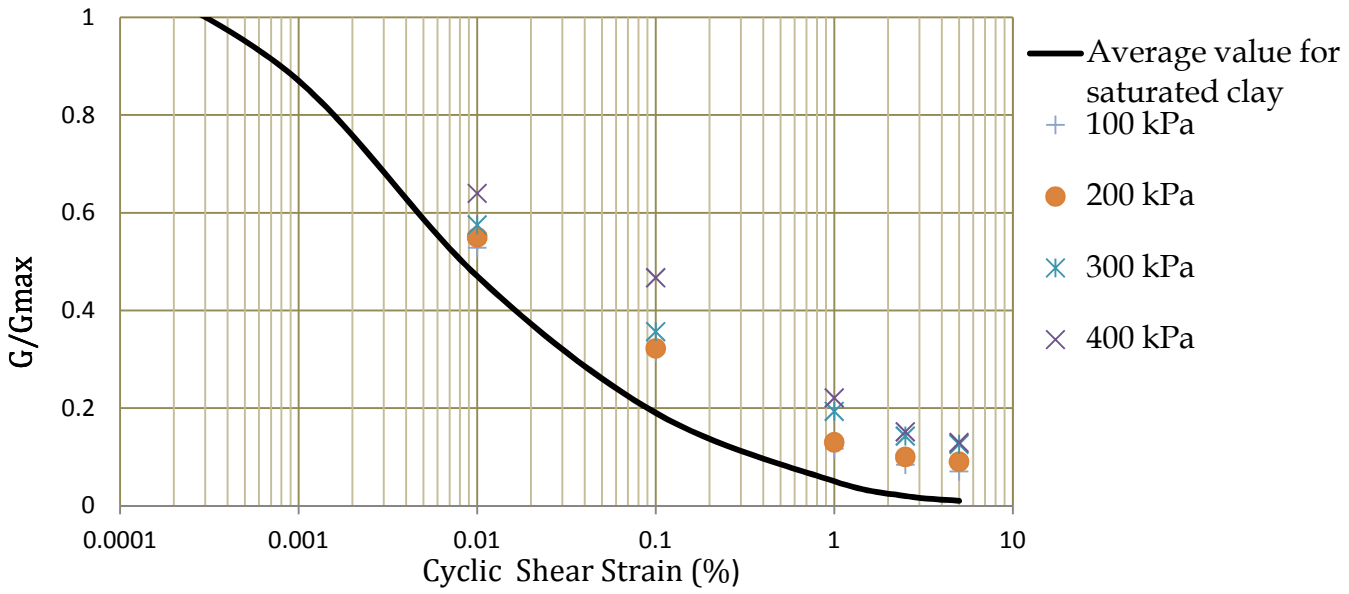
Variation in normalized shear modulus and material damping ratio with shearing strain for TP1, TP2 and TP4; under an axial stress of 100, 200, 300, and 400kPa.

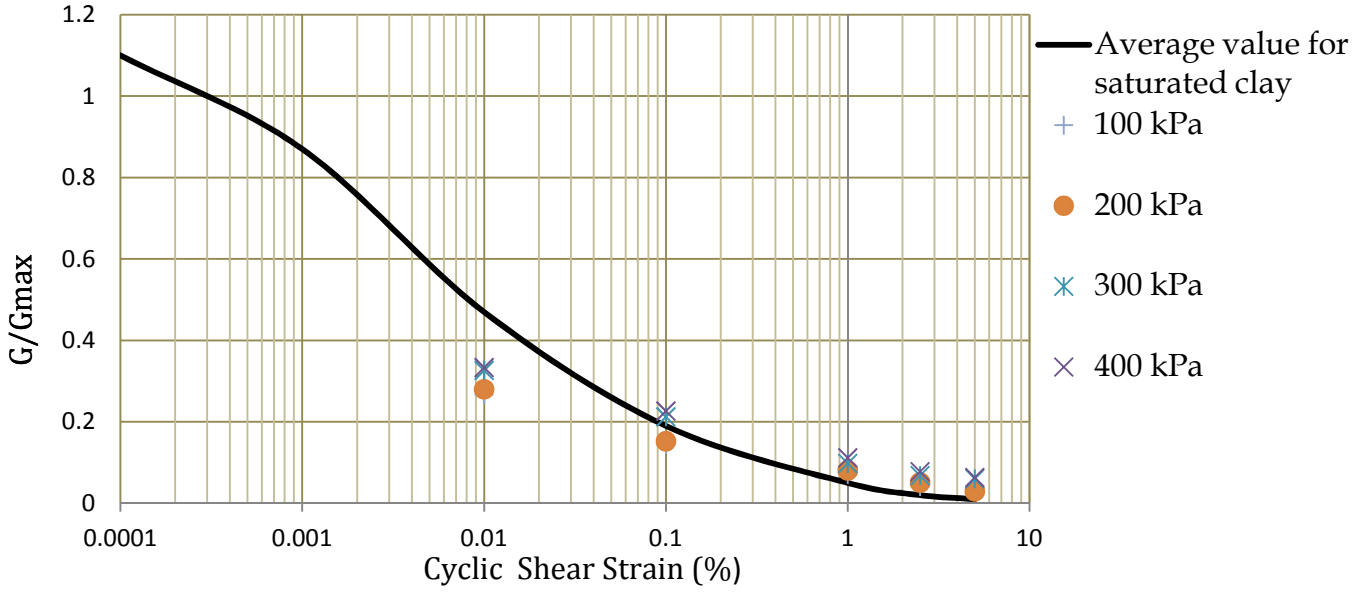
		TP1(SM) 26% Fines		TP2(SM) 41%fines		TP4(ML) 62%fines	
	Shear strain (%)	G/Gmax	D (%)	G/Gmax	D (%)	G/Gmax	D (%)
	0.01	0.64	3.50	0.33	3.57	0.35	2.85
	0.1	0.47	5.04	0.23	4.93	0.21	4.44
	1	0.22	13.75	0.11	11.92	0.11	10.60
	2.5	0.15	17.85	0.08	16.10	0.08	14.26
400 kPa	5	0.13	21.25	0.06	19.99	0.07	17.68
	0.01	0.58	5.05	0.33	4.70	0.34	3.91
	0.1	0.36	7.44	0.21	6.60	0.20	6.09
	1	0.19	15.08	0.10	14.04	0.11	12.95
	2.5	0.14	19.57	0.07	18.94	0.08	17.34
300 kPa	5	0.13	23.11	0.06	23.04	0.07	20.33
	0.01	0.55	6.14	0.28	5.97	0.30	5.50
	0.1	0.32	9.02	0.15	8.15	0.17	8.01
	1	0.13	16.45	0.08	16.07	0.10	14.67
	2.5	0.10	21.30	0.05	20.40	0.07	18.65
200 kPa	5	0.09	25.60	0.03	25.26	0.05	21.99
	0.01	0.53	6.89	0.27	6.63	0.21	6.09
	0.1	0.31	10.17	0.15	10.13	0.12	8.82
	1	0.12	17.69	0.07	17.11	0.07	15.52
	2.5	0.08	22.96	0.04	22.27	0.06	19.45
100 kPa	5	0.07	27.19	0.03	26.25	0.04	23.29

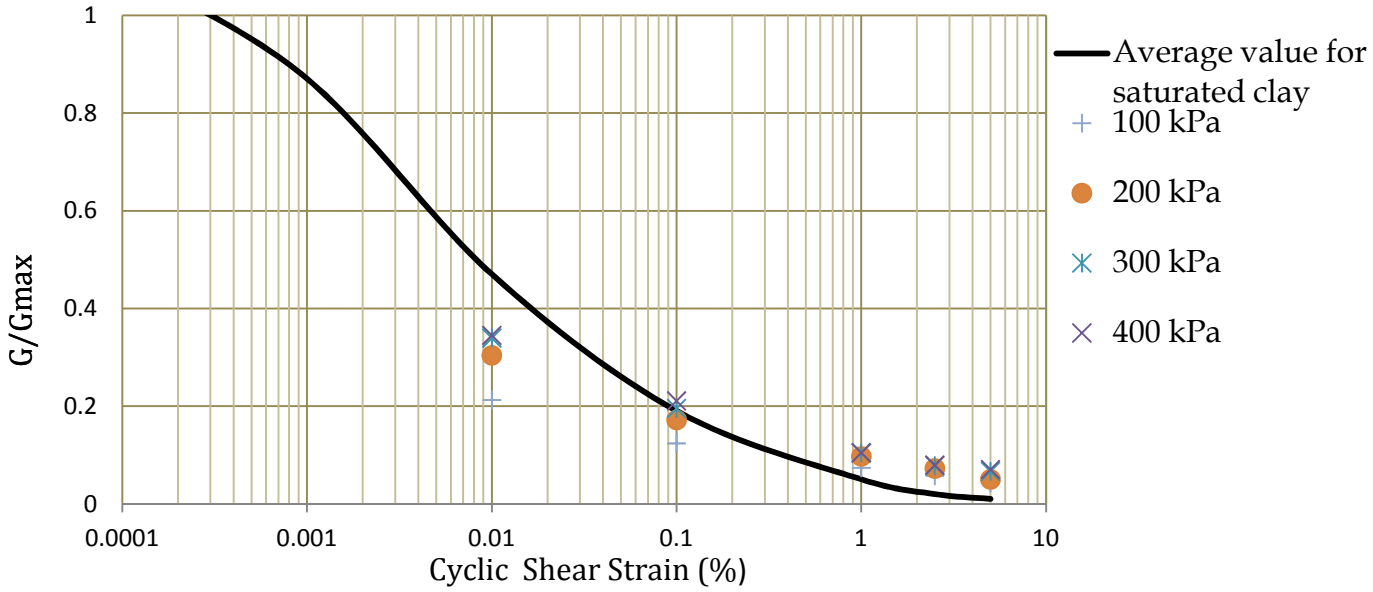

1.2
1
0.8
0.6
0.4
0.2
0
G/Gmax
0.0001
0.001
0.01
0.1
1
10
Cyclic Shear Strain (%)
Average Value for Sands
Upper and Lower Bounds for Sands
100 kPa
200 kPa
300 kPa
400 kPa

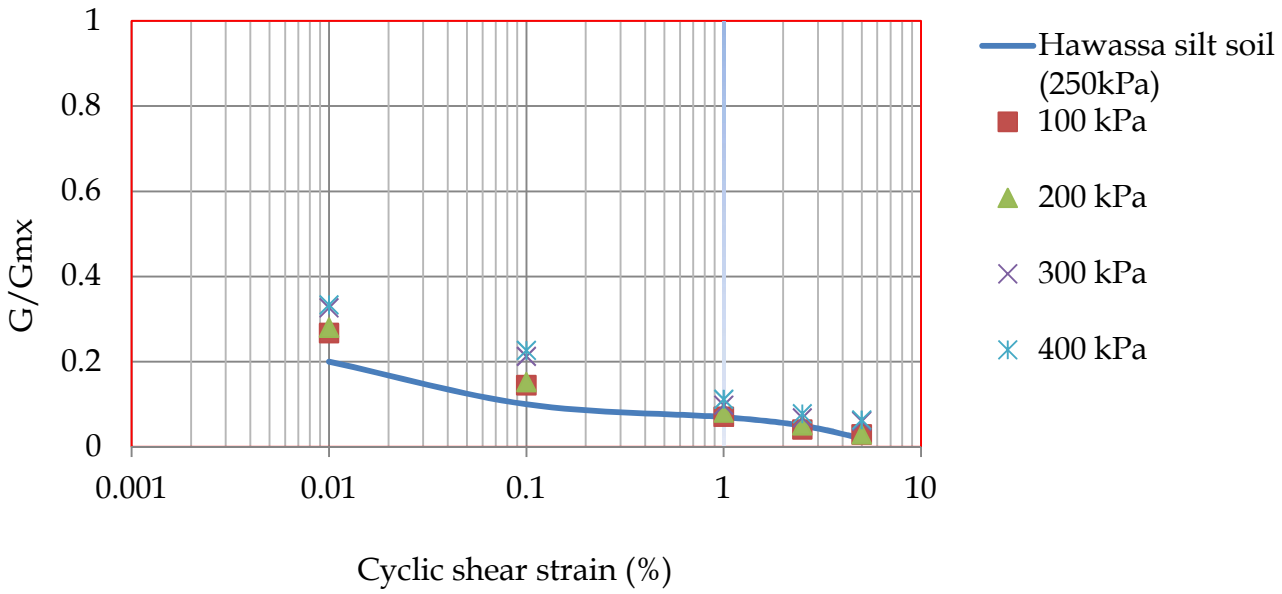

1.2
1
0.8
0.6
0.4
0.2
0
G/Gmax
0.0001
0.001
0.01
0.1
1
10
Cyclic Shear Strain (%)
Average Value for Sands
Upper and Lower Bounds for Sands
100 Kpa
200 kPa
300 Kpa
400 Kpa

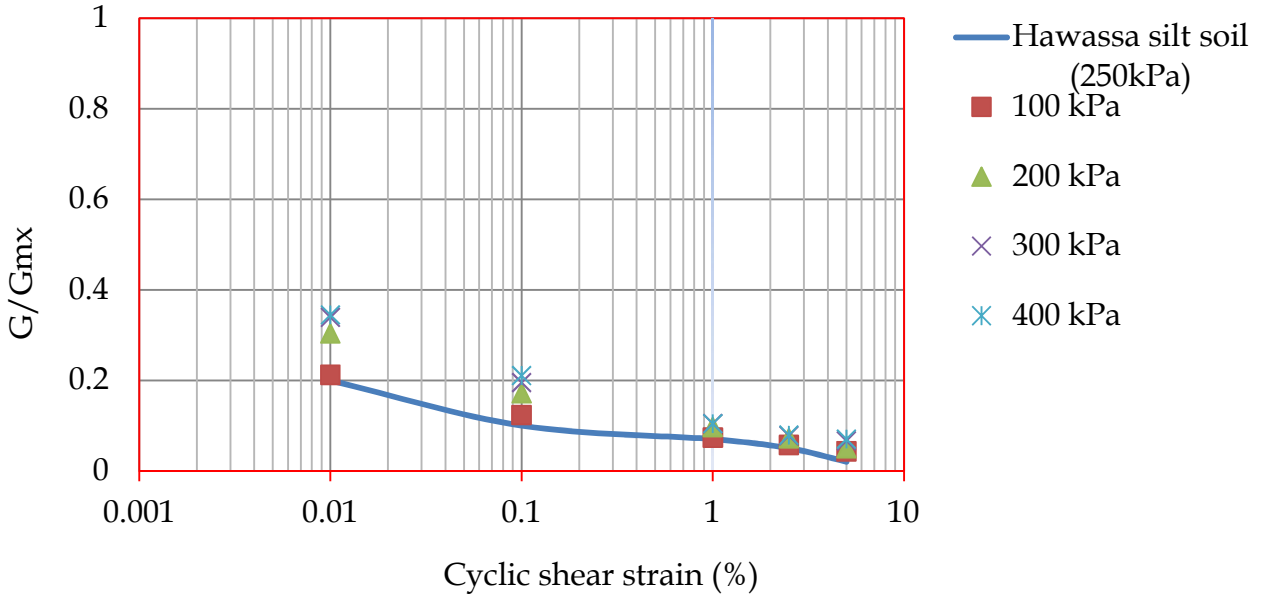

1.2
1.0
0.8
0.6
0.4
0.2
0.0
G/Gmax
0.0001
0.001
0.01
0.1
1
10
Cyclic Shear Strain (%)
Average Value for Sands
Upper and Lower Bounds for Sands
100 kPa
200 kPa
300 kPa
400 kPa

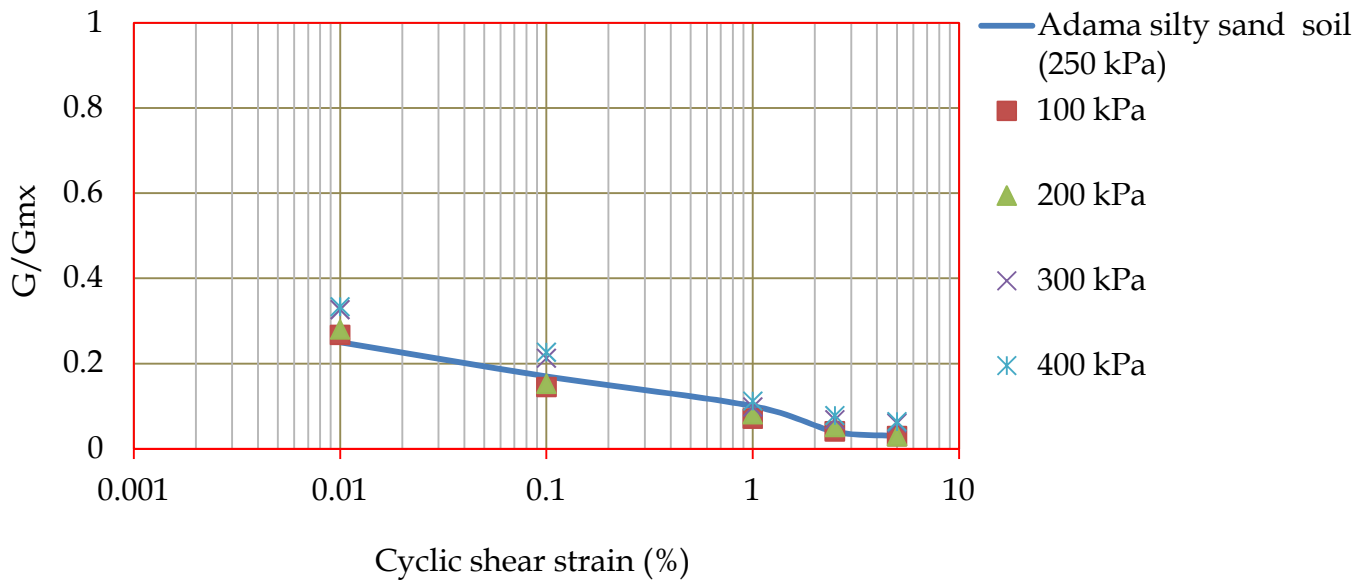

1
0.8
0.6
0.4
0.2
0
G/Gmax
0.0001
0.001
0.01
0.1
1
10
Cyclic Shear Strain (%)
Average value for saturated clay
100 kPa
200 kPa
300 kPa
400 kPa

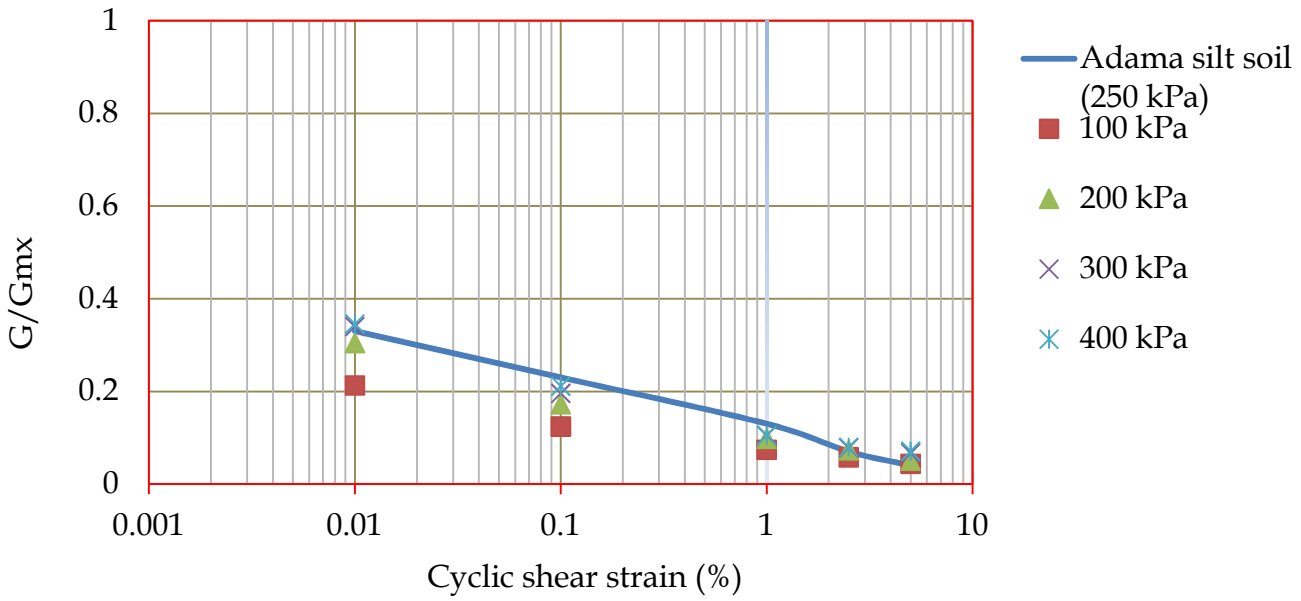

1.2
1
0.8
0.6
0.4
0.2
0
G/Gmax
0.0001
0.001
0.01
0.1
1
10
Cyclic Shear Strain (%)
Average value for saturated clay
100 kPa
200 kPa
300 kPa
400 kPa

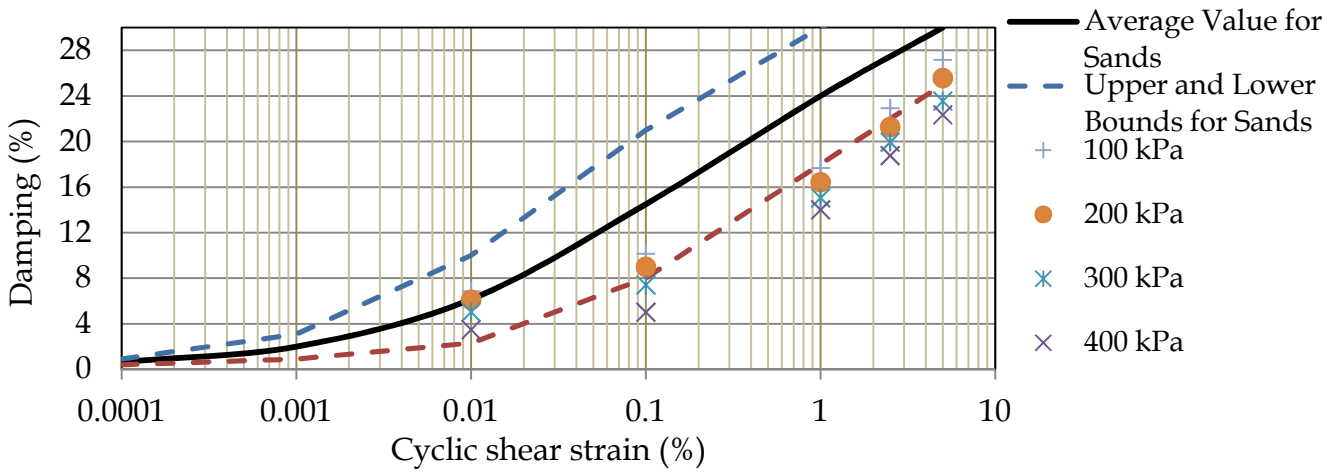

1
0.8
0.6
0.4
0.2
0
G/Gmax
0.0001
0.001
0.01
0.1
1
10
Cyclic Shear Strain (%)
Average value for saturated clay
100 kPa
200 kPa
300 kPa
400 kPa

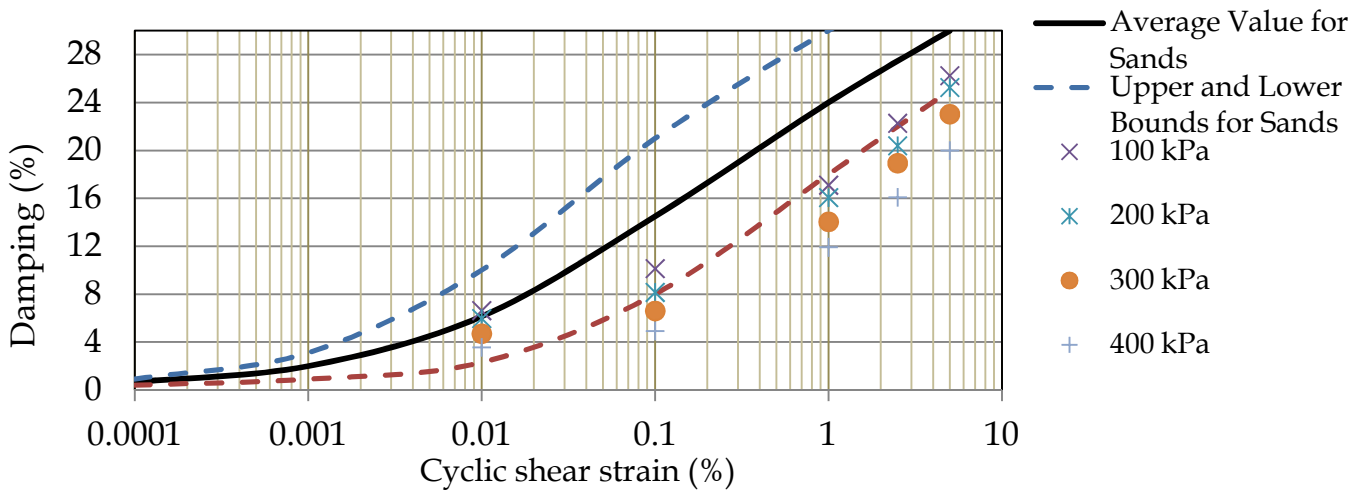

1
0.8
0.6
0.4
0.2
0
G/Gmx
0.001
0.01
0.1
1
10
Cyclic shear strain (%)
Hawassa silt soil (250kPa)
100 kPa
200 kPa
300 kPa
400 kPa

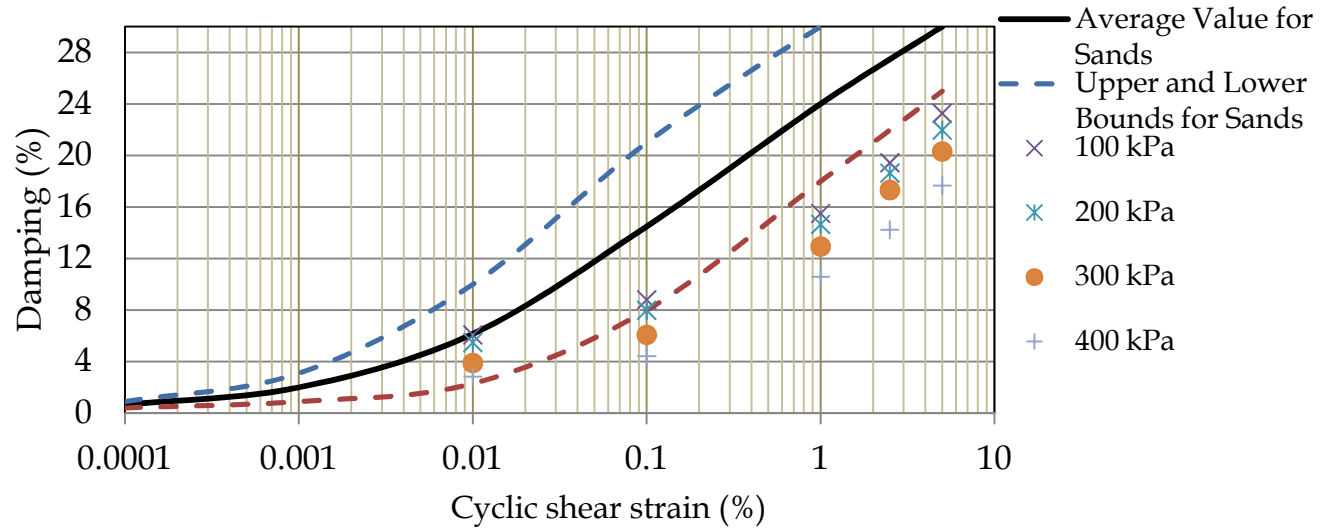

1
0.8
0.6
0.4
0.2
0
G/Gmx
0.001
0.01
0.1
1
10
Cyclic shear strain (%)
Hawassa silt soil (250kPa)
100 kPa
200 kPa
300 kPa
400 kPa

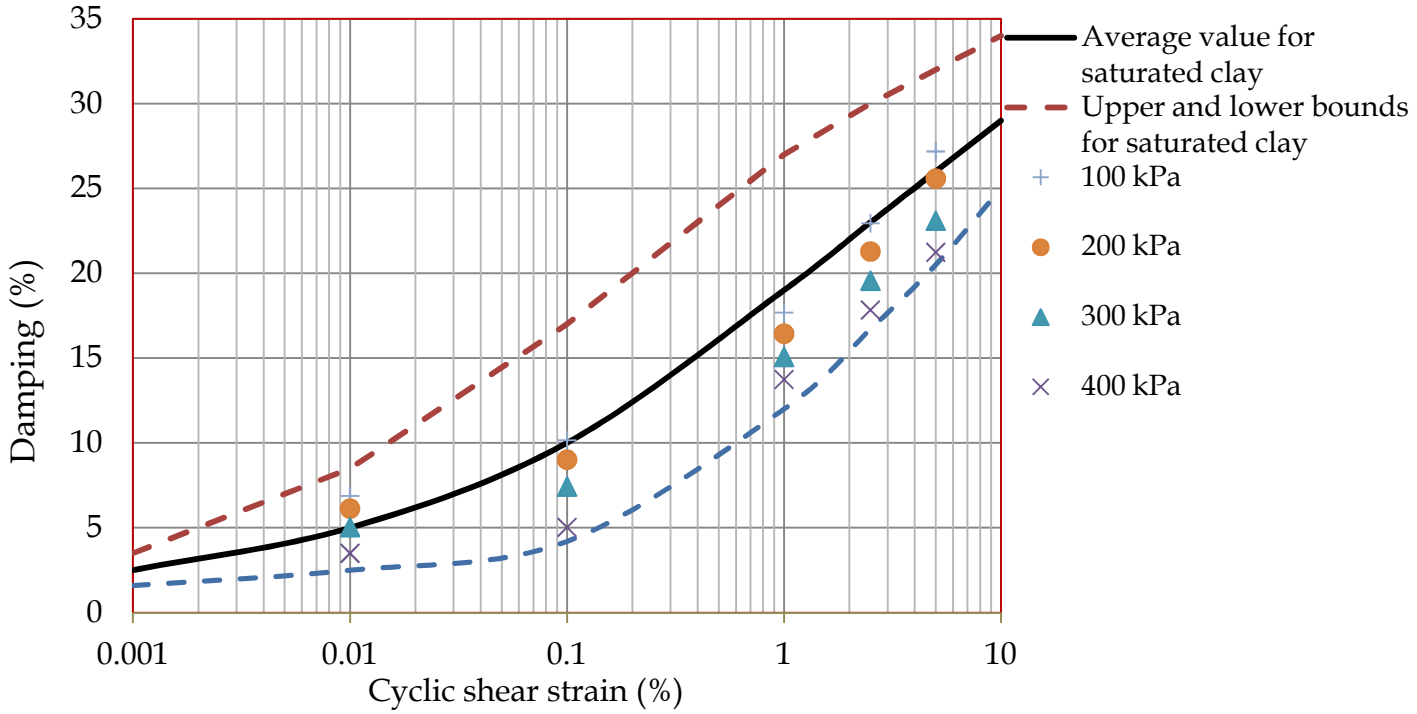

1
0.8
0.6
0.4
0.2
0
G/Gmx
0.001
0.01
0.1
1
10
Cyclic shear strain (%)
Adama silty sand soil (250 kPa)
100 kPa
200 kPa
300 kPa
400 kPa

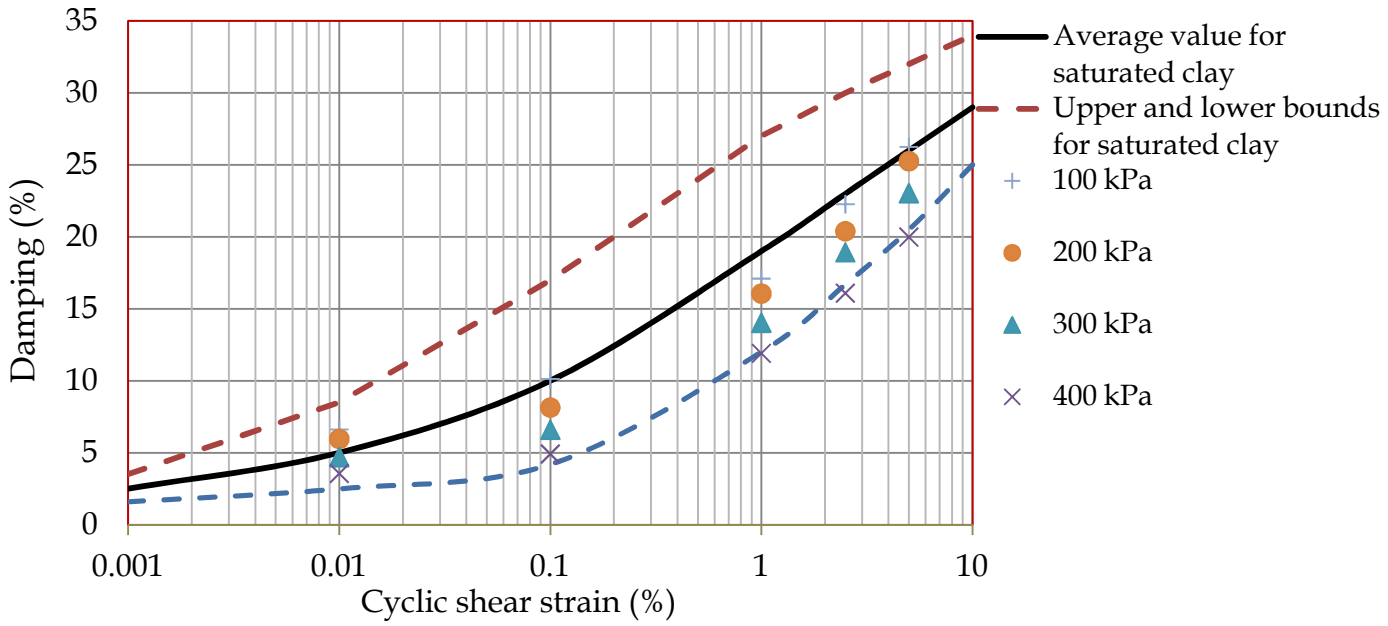

1
0.8
0.6
0.4
0.2
0
G/Gmx
0.001
0.01
0.1
1
10
Cyclic shear strain (%)
Adama silt soil (250 kPa)
100 kPa
200 kPa
300 kPa
400 kPa

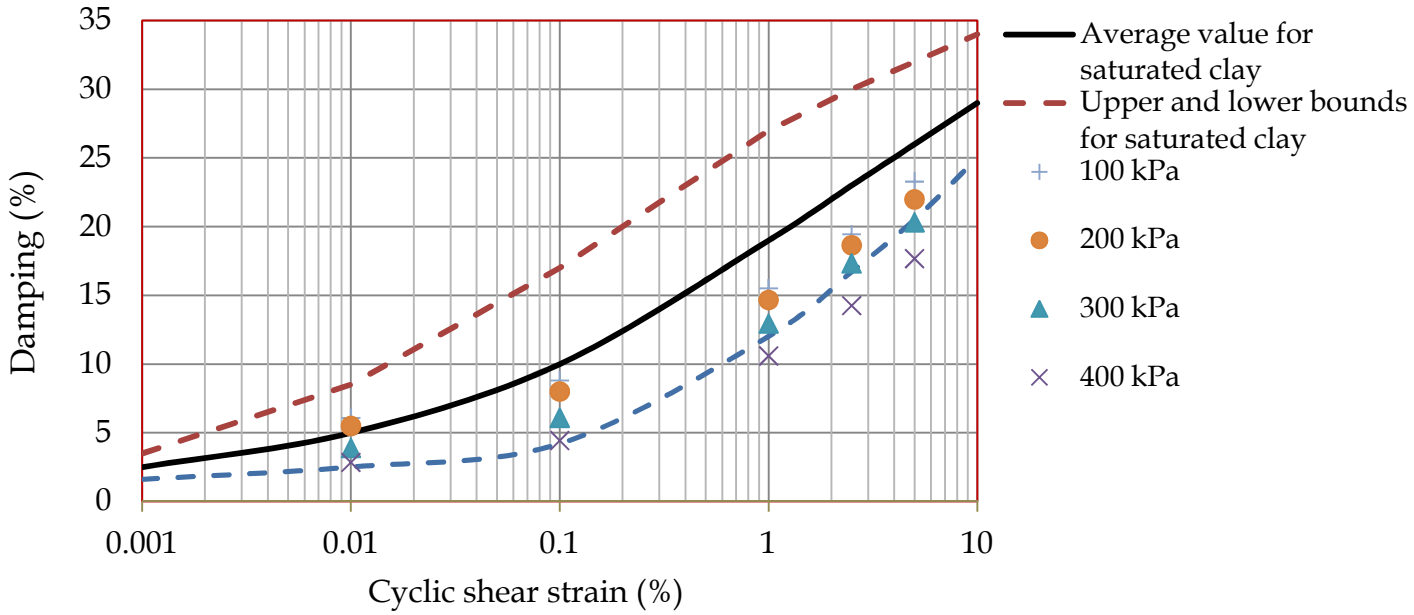

Damping (%)
28
24
20
16
12
8
4
0
0.0001
0.001
0.01
0.1
1
10
Cyclic shear strain (%)
Average Value for Sands
Upper and Lower Bounds for Sands
100 kPa
200 kPa
300 kPa
400 kPa

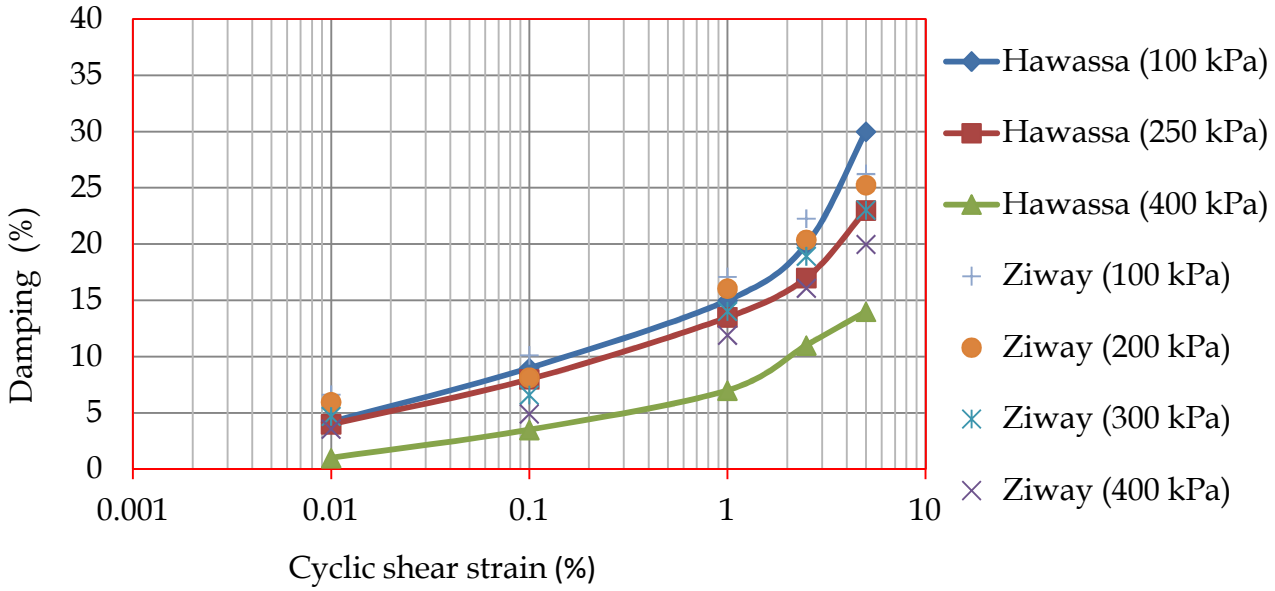

Damping (%)
28
24
20
16
12
8
4
0
0.0001
0.001
0.01
0.1
1
10
Cyclic shear strain (%)
Average Value for Sands
Upper and Lower Bounds for Sands
100 kPa
200 kPa
300 kPa
400 kPa

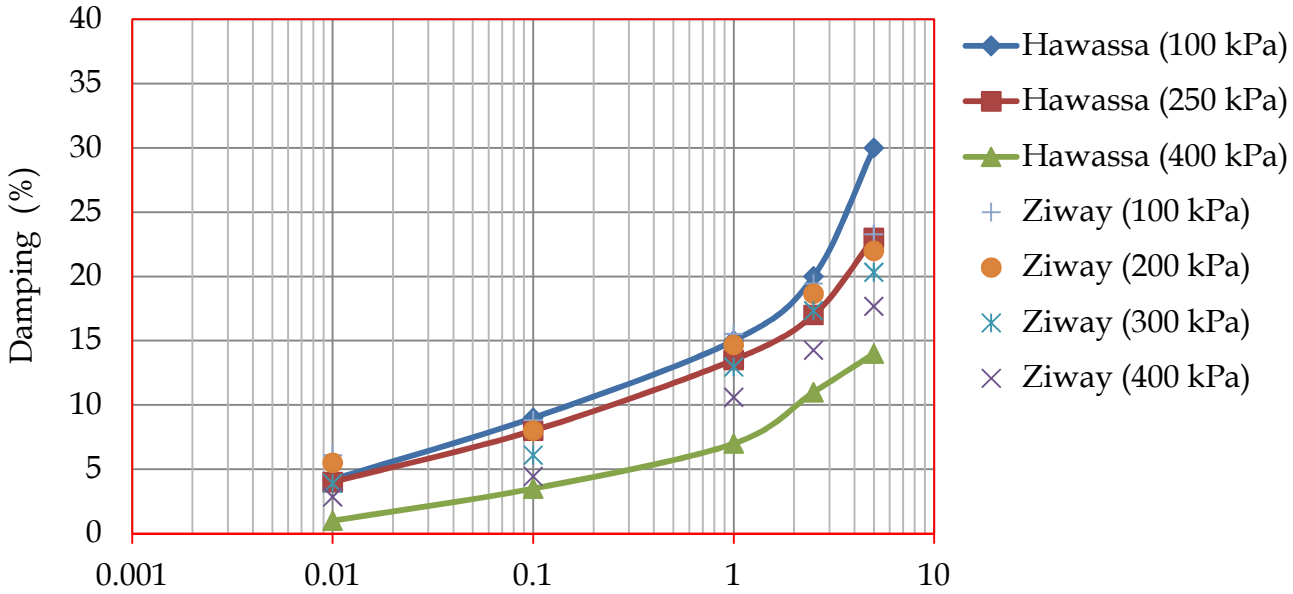

Damping (%)
28
24
20
16
12
8
4
0
0.0001
0.001
0.01
0.1
1
10
Cyclic shear strain (%)
Average Value for Sands
Upper and Lower Bounds for Sands
100 kPa
200 kPa
300 kPa
400 kPa

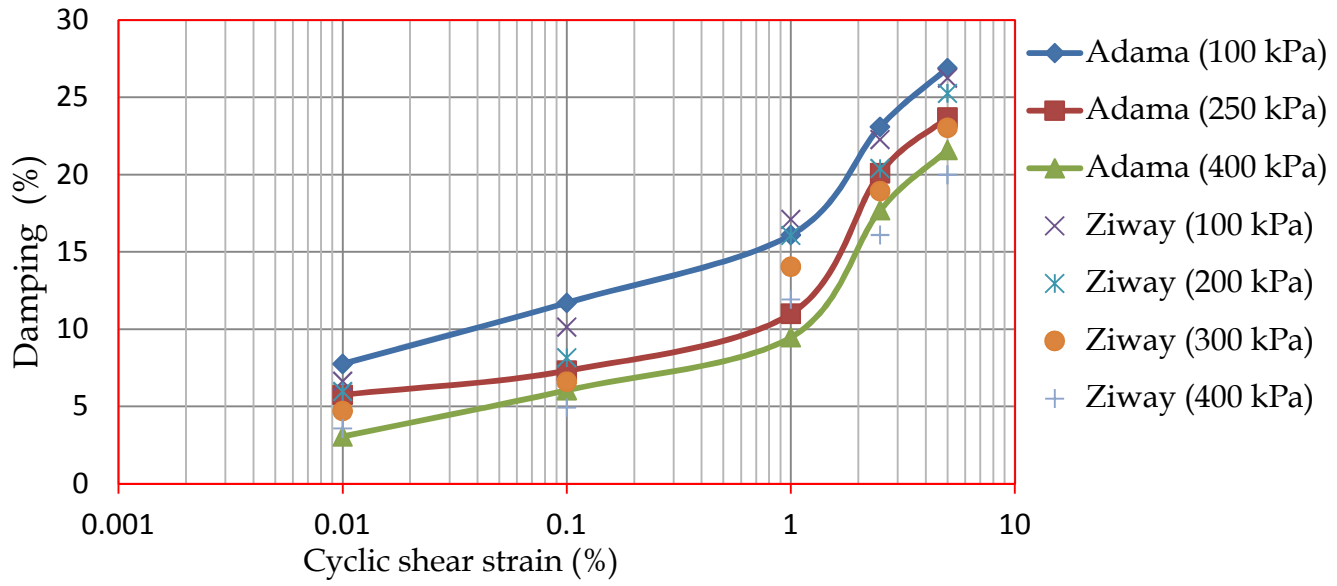

Damping (%)
35
30
25
20
15
10
5
0
0.001
0.01
0.1
1
10
Cyclic shear strain (%)
Average value for saturated clay
Upper and lower bounds for saturated clay
100 kPa
200 kPa
300 kPa
400 kPa

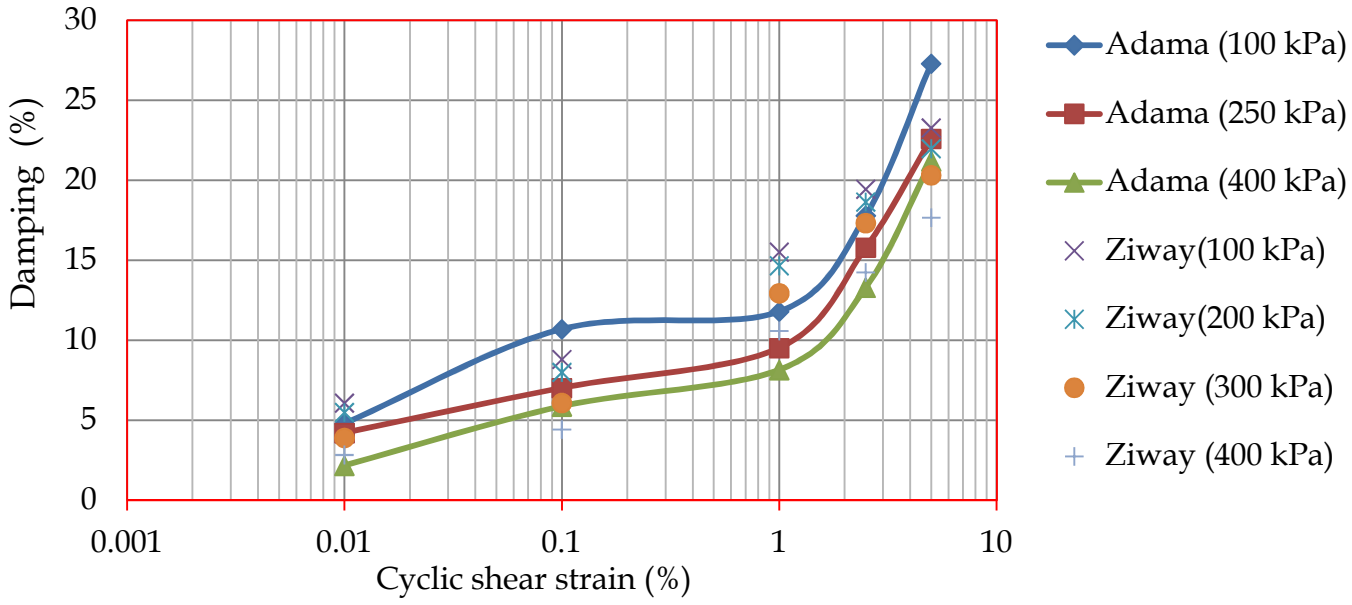

35
30
25
20
15
10
5
0
Damping (%)
0.001
0.01
0.1
1
10
Cyclic shear strain (%)
Average value for saturated clay
Upper and lower bounds for saturated clay
100 kPa
200 kPa
300 kPa
400 kPa


35
30
25
20
15
10
5
0
Damping (%)
0.001
0.01
0.1
1
10
Cyclic shear strain (%)
Average value for saturated clay
Upper and lower bounds for saturated clay
100 kPa
200 kPa
300 kPa
400 kPa


40
35
30
25
20
15
10
5
0
Damping (%)
0.001
0.01
0.1
1
10
Cyclic shear strain (%)
Hawassa (100 kPa)
Hawassa (250 kPa)
Hawassa (400 kPa)
Ziway (100 kPa)
Ziway (200 kPa)
Ziway (300 kPa)
Ziway (400 kPa)


40
35
30
25
20
15
10
5
0
Damping (%)
0.001
0.01
0.1
1
10
Hawassa (100 kPa)
Hawassa (250 kPa)
Hawassa (400 kPa)
Ziway (100 kPa)
Ziway (200 kPa)
Ziway (300 kPa)
Ziway (400 kPa)


30
25
20
15
10
5
0
Damping (%)
0.001
0.01
0.1
1
10
Cyclic shear strain (%)
Adama (100 kPa)
Adama (250 kPa)
Adama (400 kPa)
Ziway (100 kPa)
Ziway (200 kPa)
Ziway (300 kPa)
Ziway (400 kPa)


30
25
20
15
10
5
0
Damping (%)
0.001
0.01
0.1
1
10
Cyclic shear strain (%)
Adama (100 kPa)
Adama (250 kPa)
Adama (400 kPa)
Ziway(100 kPa)
Ziway(200 kPa)
Ziway (300 kPa)
Ziway (400 kPa)

Chapter six

6. CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusions

The dynamic properties (G and D) of Ziway soils are addressed based on cyclic simple shear tests on two silty sand and one silt soil samples.

From the results of this study, the following can be stated:

- The value of shear modules is in the range of 1.0 to 8MPa for medium strain level (γ <0.1 %) and 8.0 to 25MPa for higher strain level (γ >0.1 %). The damping ratio values range between 2.85 to 10% for medium strain level (γ <0.1%) and 10.0 to 27.0% for higher strain level (γ >0.1 %).
- As it was expected the shear modulus increases moderately while the damping ratio decreases as the number of cycle increases, this property was observed within the first 20 cycles of loading.
- The shear modulus increases with the number of cycles, which is similar to the conclusion drown by Silver and Seed. However, the damping ratio clearly decreases with increasing number of cycles.
- The normalized shear modulus values of the investigated soils are located lower than those suggested in literature, especially at lower strains. For higher strains the obtained normalized shear values agree with those suggested by Seed, H.B. and Idriss,I.M. This shows that testing conditions and sample preparation appear to have significant effect on the shear modulus values, especially at small strain level (<0.01%).
- The damping values for both silty and silty sand soils are almost lower than the sand soil curves developed by Seed, H.B. and Idriss,I.M. But those values are in the range of saturated clay by Seed, H.B. and Idriss,I.M. This shows that the position of damping ratio curves for silty and silty sand soil results are in between the curve for sand and clay.

- The damping values for both silt and silty sand soils are almost in the range of silt soil curves developed by Ayalew G. and silt and silty sand soil curves developed by Abu G.
- It was also observed that specimens having higher void ratio have lower shear modulus.
- The void ratio has no significant influence on damping ratio at any shearing strain amplitude under all confining pressures.

6.2. Practical implication of the results

In this thesis strain based approach was used to determine shear modulus and damping ratio of silt and silty sand soils found in Ziway town. Those values can be used as input parameters: 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.

6.3. Recommendations for Future Work

- The scope of this research program was limited to investigating shear modulus and material damping of Ziway soil using cyclic simple shear apparatus. But the present investigation studied the dynamic soil parameters under field moisture and field density so, to observe the effect of saturation and other parameter that affect dynamic properties of Ziway soils (like pore-water pressure and degree of compaction) it is necessary to determine dynamic properties under saturation condition as well as under different degree of compaction.

- In this research samples of soil were collected only from four test pits, by increasing the number of sampling area in-depth investigation should be done in the future.

Reference

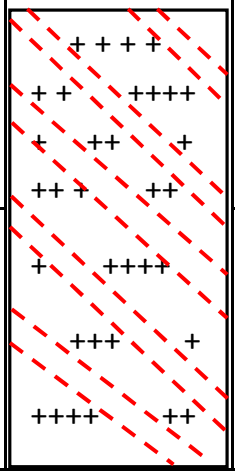
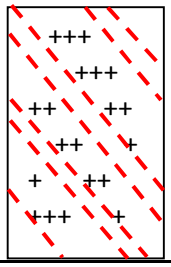
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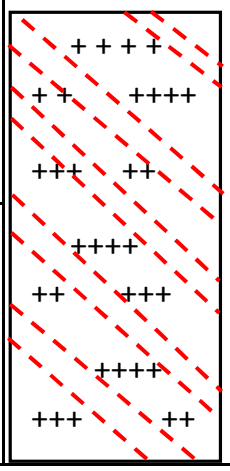
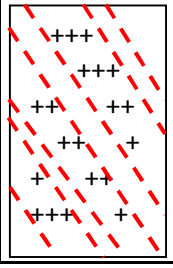
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APPENDIX -A

Test pit – log

Test Pit:1					
Location: Near Lake				**Sampled Date:10/12/2013**	
Depth (m)	Symbol	Soil description	Sample	Field test type	Sampled for
0.3		Gray, soft , non-plasticity Silt-Sand mixture with trace of gravel		~	~
1.0		Gray, soft , non-plasticity Silt-Sand mixture with trace of gravel		Field Density and moisture content	Moisture content, Gs, Grain size analysis , Cyclic Simple Shear test

Test Pit:2					
Location: Near Stadium				**Sampled Date:10/12/2013**	
Depth	Symbol	Soil description	Sample	Field test type	Sampled for
0.5		Yellowish, soft , non-plasticity Silt-Sand mixture with trace of gravel		~	~
1.5		Yellowish, soft , non-plasticity Silt-Sand mixture with trace of gravel		~	~
2.7		Yellowish, soft , non-plasticity Silt-Sand mixture with trace of gravel		Field Density and moisture content	Moisture content, Gs ,Grain size analysis , Cyclic Simple Shear test

Test Pit:3					
Location: Sher-Flower Farm				**Sampled Date:10/12/2013**	
Depth, (m)	Symbol	Soil description	Sample	Field test type	Sampled for
0.5	+ + + + + + +	Low plasticity Silt with trace of silt, gravel and grassroots		~	~
1.5	+ + + + + + +	Yellowish, Medium stiff, Low plasticity Silt			
2.7	+ + + + + + + + + + + + + +	Yellowish to Grey, Medium stiff, Low plasticity Silt with some fine sand	+ ++ + + + ++ + + + ++	Field Density and moisture content	Moisture content, Gs ,Grain size analysis ,Consistency limit

Test Pit: 4					
Location: Near Stadium				**Sampled Date:10/12/2013**	
Depth,(m)	Symbol	Soil description	Sample	Field test type	Sampled for
0.5		Low plasticity Silt with trace of silt, gravel and grassroots		~	~
2.0	+ + + + + + + + + + + + + +	Yellowish, Medium stiff, Low plasticity Silt	+ ++ + + + ++ + + + ++ + + + ++ + + + ++ + +	Field Density and moisture content	Moisture content, Gs ,Grain size analysis ,Consistency limit
3.0	+ + + + + + + + + + + + + +	Yellowish to Grey, stiff, Low plasticity Silt with some fine sand		Field Density and moisture content	Moisture content, Gs ,Grain size analysis ,Consistency limit Cyclic Simple Shear test

APPENDIX - B

Bulk density and field moisture content

Table B-1: Soil Bulk Density determination

Ring No.	Lab No.	Wt of empty ring + cover	Wt of ring +cover +ADS	Wt of ring + cover + ODS	Wt of ODS	Radius of ring in cm	Height of ring in cm	Vol. of Soil	Dry density in g/cc	Bulk den-sity in g/cc	Void ratio (e)	Remark
1	A	108.89	236.77	220.17	111.28	2.50	5.00	98.13	1.13	1.30	1.24	
2	B	109.47	255.92	199.14	89.67	2.50	5.00	98.13	0.91	1.49	1.74	
3	C	108.52	246.75	222.25	113.73	2.50	5.00	98.13	1.16	1.41	1.22	
4	D1	108.94	235.19	211.23	102.29	2.50	5.00	98.13	1.04	1.29	1.51	@2m
5	D2	108.29	244.99	220.33	112.04	2.50	5.00	98.13	1.14	1.39	1.22	@3m

Table B-2: Soil moisture determination

Tin no	Lab no	Wt of Empty tin	Wt of tin+A. D.S	Wt of A.D.S	Wt tin +O.D.S	Wt. O.D.S	Wt. of moistu re	Moist ure Conte nt (%)	Average moisture Content (%)	Remark
1	A1	13.45	28.45	15.00	26.91	13.46	1.54	11.47		
2	A2	13.02	28.02	15.00	26.08	13.07	1.94	14.81	13.73	
	A3	108.89	236.77	127.88	220.17	111.28	16.60	14.92		
3	B1	12.76	27.76	15.00	21.80	9.04	5.96	65.91		
4	B2	12.69	27.69	15.00	21.90	9.20	5.80	63.03	64.09	
	B3	109.47	255.92	146.45	199.14	89.67	56.78	63.32		
5	C1	12.67	27.67	15.00	25.45	12.77	2.23	17.43	20.53	
6	C2	12.78	27.78	15.00	25.01	12.23	2.77	22.61		
	C3	108.52	246.75	138.23	222.25	113.73	24.50	21.54		
8	D11	12.96	27.96	15.00	25.04	12.09	2.92	24.12	23.07	at-2m
	D12	108.29	244.99	136.70	220.33	112.04	24.66	22.01		
7	D21	12.58	27.58	15.00	24.57	11.99	3.01	25.09	24.26	at-3m
	D22	108.94	235.19	126.25	211.23	102.29	23.96	23.42		

APPENDIX - C

Sieve analysis

Table C-1:dry sieve analysis for TP1

Sieve opening (mm)	Mass of sieve (g)	Mass of sieve with retained soil (g)	Mass of retained soil (g)	Percentage retained, %	Cumulative percentage retained, %	Cumulative percentage passing, %
9.5	463.2	463.4	0.2	0.02	0.02	99.98
4.75	350.6	376.5	25.9	2.59	2.61	97.39
2.36	416.4	446	29.6	2.96	5.57	94.43
2	400.9	420	19.1	1.91	7.48	92.52
1.18	372.3	437.6	65.3	6.53	14.01	85.99
0.6	326.9	420.1	93.2	9.32	23.33	76.67
0.425	305.8	393.1	87.3	8.73	32.06	67.94
0.3	305.3	370.9	65.6	6.56	38.62	61.38
0.15	271.1	441.5	170.4	17.04	55.66	44.34
0.075	261.3	444.6	183.3	18.33	73.99	26.01
Pan	255.7	515.8	260.1	26.01	100	0
Total	3266.3	4729.5	1000	99.98		

Table C-2:Wet sieve analysis for TP1

Elapsed Time (min)	Actual Hydro meter Reading	Composite Correction	Corrected Hydro meter Reading	Effective Depth (cm)	Coefficient K	Grain Size (mm)	(%) Finer	Percents Finer for Combined analysis
0.5	1.0240	-0.0029	1.0211	9.95	0.013778	0.0615	68.25	17.75
1	1.0200	-0.0029	1.0171	11.01	0.013778	0.0457	55.31	14.39
2	1.0170	-0.0029	1.0141	11.01	0.013778	0.0323	45.61	11.86
4	1.0140	-0.0029	1.0111	11.80	0.013778	0.0237	35.90	9.34
8	1.0110	-0.0029	1.0081	12.60	0.013778	0.0173	26.20	6.81
15	1.0090	-0.0029	1.0061	13.39	0.013778	0.0130	19.73	5.13
30	1.0065	-0.0029	1.0036	13.92	0.013778	0.0094	11.64	3.03
60	1.0050	-0.0029	1.0021	14.58	0.013778	0.0068	6.79	1.77
120	1.0040	-0.0029	1.0011	14.98	0.013778	0.0049	3.56	0.93
240	1.0040	-0.0029	1.0011	15.24	0.013778	0.0035	3.56	0.93
480	1.0040	-0.0029	1.0011	15.24	0.013778	0.0025	3.56	0.93
1440	1.0040	-0.0029	1.0011	15.2	0.013778	0.0	3.56	0.93

Table C-3:dry sieve analysis for TP2

Sieve opening (mm)	Mass of sieve (g)	Mass of sieve with retained soil (g)	Mass of retained soil (g)	Percentage retained, %	Cumulative percentage retained, %	comulative Percentage passing, %
9.5	463.2	480	16.8	1.68	1.68	98.32
4.75	350.6	390	39.4	3.94	5.62	94.38
2.36	416.4	441.6	25.2	2.52	8.14	91.86
2	400.9	406.8	5.9	0.59	8.73	91.27
1.18	372.3	388.8	16.5	1.65	10.38	89.62
0.6	326.9	357.8	30.9	3.09	13.47	86.53
0.425	305.8	335.4	29.6	2.96	16.43	83.57
0.3	305.3	323.4	18.1	1.81	18.24	81.76
0.15	271.1	438.8	167.7	16.77	35.01	64.99
0.075	261.3	438.4	177.1	17.71	52.72	47.28
Pan	255.7	721.1	465.4	46.54	99.26	0.74
Total	3266.3	4722.1	992.6	97.58		

Table C-4:Wet sieve analysis for TP2

Elapsed Time (min)	Actual Hydro meter Reading	Composite Correction	Corrected Hydro meter Reading	Effective Depth (cm)	Coefficient K	Grain Size (mm)	(%) Finer	Percents Finer for Combined analysis
0.5	1.0220	-0.0029	1.0191	10.48	0.013778	0.0631	61.78	25.37
1	1.0190	-0.0029	1.0161	11.27	0.013778	0.0463	52.08	21.39
2	1.0180	-0.0029	1.0151	11.54	0.013778	0.0331	48.84	20.06
5	1.0150	-0.0029	1.0121	12.33	0.013778	0.0216	39.14	16.07
8	1.0130	-0.0029	1.0101	12.86	0.013778	0.0175	32.67	13.42
15	1.0120	-0.0029	1.0091	13.13	0.013778	0.0129	29.43	12.09
30	1.0100	-0.0029	1.0071	13.65	0.013778	0.0093	22.97	9.43
60	1.0080	-0.0029	1.0051	14.18	0.013778	0.0067	16.50	6.78
120	1.0060	-0.0029	1.0031	14.71	0.013778	0.0048	10.03	4.12
240	1.0050	-0.0029	1.0021	14.98	0.013778	0.0034	6.79	2.79
480	1.0050	-0.0029	1.0021	14.98	0.013778	0.0024	6.79	2.79
1440	1.0050	-0.0029	1.0021	15.0	0.013778	0.0	6.79	2.79

Table C-5:dry sieve analysis for TP3

Sieve opening (mm)	Mass of sieve (g)	Mass of sieve with retained soil (g)	Mass of retained soil (g)	Percentage retained, %	Cumulative percentage retained, %	Cumulative Percentage passing, %
9.5	463.2	477.9	14.7	1.47	1.47	98.53
4.75	350.6	390.2	39.6	3.96	5.43	94.57
2.36	416.4	434.5	18.1	1.81	7.24	92.76
2	400.9	406.3	5.4	0.54	7.78	92.22
1.18	372.3	386.1	13.8	1.38	9.16	90.84
0.6	326.9	343.7	16.8	1.68	10.84	89.16
0.425	305.8	328.5	22.7	2.27	13.11	86.89
0.3	305.3	343.4	38.1	3.81	16.92	83.08
0.15	271.1	409.3	138.2	13.82	30.74	69.26
0.075	261.3	372.6	111.3	11.13	41.87	58.13
Pan	255.7	837	581.3	58.13	100	0
Total	3266.3	4729.5	1000	100		

Table C-6:Wet sieve analysis for TP3

Elapsed Time (min)	Actual Hydrometer Reading	Composite Correction	Corrected Hydrometer Reading	Effective Depth (cm)	Coefficient K	Grain Size (mm)	(%) Finer	Percents Finer for Combined analysis
0.5	1.0220	-0.0029	1.0191	10.48	0.013778	0.0631	61.21	35.58
1	1.0200	-0.0029	1.0171	11.01	0.013778	0.0457	54.80	31.86
2	1.0180	-0.0029	1.0151	11.54	0.013778	0.0331	48.39	28.13
5	1.0150	-0.0029	1.0121	12.33	0.013778	0.0216	38.78	22.54
8	1.0130	-0.0029	1.0101	12.86	0.013778	0.0175	32.37	18.82
15	1.0110	-0.0029	1.0081	13.39	0.013778	0.0130	25.96	15.09
30	1.0100	-0.0029	1.0071	13.65	0.013778	0.0093	22.75	13.23
60	1.0080	-0.0029	1.0051	14.18	0.013778	0.0067	16.34	9.50
120	1.0065	-0.0029	1.0036	14.58	0.013778	0.0048	11.54	6.71
240	1.0060	-0.0029	1.0031	14.71	0.013778	0.0034	9.93	5.78
480	1.0050	-0.0029	1.0021	14.98	0.013778	0.0024	6.73	3.91
1440	1.0050	-0.0029	1.0021	15.0	0.013778	0.0	6.73	3.91

Table C-7:dry sieve analysis for TP4 @2.0m

Sieve opening (mm)	Mass of sieve (g)	Mass of sieve with retained soil (g)	Mass of retained soil (g)	Percentage retained, %	Cumulative percentage retained, %	comulative Percentage passing, %
9.5	463.2	468.5	5.3	0.53	0.53	99.47
4.75	350.6	384.1	33.5	3.35	3.88	96.12
2.36	416.4	439	22.6	2.26	6.14	93.86
2	400.9	410.2	9.3	0.93	7.07	92.93
1.18	372.3	391.9	19.6	1.96	9.03	90.97
0.6	326.9	354.1	27.2	2.72	11.75	88.25
0.425	305.8	345.9	40.1	4.01	15.76	84.24
0.3	305.3	351.1	45.8	4.58	20.34	79.66
0.15	271.1	362.9	91.8	9.18	29.52	70.48
0.075	261.3	344.9	83.6	8.36	37.88	62.12
Pan	255.7	876.9	621.2	62.12	100	0
Total	3266.3	4729.5	1000	100		

Table C-8:Wet sieve analysis for TP4@2.0m

Elapsed Time (min)	Actual Hydro meter Reading	Composite Correction	Corrected Hydro meter Reading	Effective Depth (cm)	Coefficient K	Grain Size (mm)	(%) Finer	Percents Finer for Combined analysis
0.5	1.0220	-0.0029	1.0191	10.48	0.013778	0.0631	61.78	38.38
1	1.0200	-0.0029	1.0171	11.01	0.013778	0.0457	55.31	34.36
2	1.0180	-0.0029	1.0151	11.01	0.013778	0.0323	48.84	30.34
5	1.0165	-0.0029	1.0136	11.54	0.013778	0.0209	43.99	27.33
8	1.0140	-0.0029	1.0111	11.94	0.013778	0.0168	35.90	22.30
15	1.0120	-0.0029	1.0091	12.60	0.013778	0.0126	29.43	18.28
30	1.0100	-0.0029	1.0071	13.13	0.013778	0.0091	22.97	14.27
60	1.0080	-0.0029	1.0051	13.65	0.013778	0.0066	16.50	10.25
120	1.0070	-0.0029	1.0041	14.18	0.013778	0.0047	13.26	8.24
240	1.0060	-0.0029	1.0031	14.45	0.013778	0.0034	10.03	6.23
480	1.0050	-0.0029	1.0021	14.71	0.013778	0.0024	6.79	4.22
1440	1.0040	-0.0029	1.0011	15.0	0.013778	0.0	3.56	2.21

Table C-9:dry sieve analysis for TP4 @3.0m

Sieve opening (mm)	Mass of sieve (g)	Mass of sieve with retained soil (g)	Mass of retained soil (g)	Percentage retained, %	Cumulative percentage retained, %	comulative Percentage passing, %
9.5	463.2	463.2	0	0	0	100
4.75	350.6	359.5	8.9	0.89	0.89	99.11
2.36	416.4	430.7	14.3	1.43	2.32	97.68
2	400.9	404.9	4	0.4	2.72	97.28
1.18	372.3	387.2	14.9	1.49	4.21	95.79
0.6	326.9	350.9	24	2.4	6.61	93.39
0.425	305.8	329.4	23.6	2.36	8.97	91.03
0.3	305.3	333	27.7	2.77	11.74	88.26
0.15	271.1	336	64.9	6.49	18.23	81.77
0.075	261.3	336.7	75.4	7.54	25.77	74.23
Pan	255.7	998	742.3	74.23	100	0
Total	3266.3	4266.3	1000	100		

Table C-10:Wet sieve analysis for TP4 @3.0m

Elapsed Time (min)	Actual Hydrometer Reading	Composite Correction	Corrected Hydrometer Reading	Effective Depth (cm)	Coefficient K	Grain Size (mm)	(%) Finer	Percents Finer for Combined analysis
0.5	1.0260	-0.0029	1.0231	9.42	0.013778	0.0598	74.03	54.95
1	1.0250	-0.0029	1.0221	9.69	0.013778	0.0429	70.83	52.57
2	1.0240	-0.0029	1.0211	9.95	0.013778	0.0307	67.62	50.20
5	1.0230	-0.0029	1.0201	10.22	0.013778	0.0197	64.42	47.82
8	1.0220	-0.0029	1.0191	10.48	0.013778	0.0158	61.21	45.44
15	1.0190	-0.0029	1.0161	11.27	0.013778	0.0119	51.60	38.30
30	1.0180	-0.0029	1.0151	11.54	0.013778	0.0085	48.39	35.92
60	1.0170	-0.0029	1.0141	11.80	0.013778	0.0061	45.19	33.54
120	1.0150	-0.0029	1.0121	12.33	0.013778	0.0044	38.78	28.79
240	1.0130	-0.0029	1.0101	12.86	0.013778	0.0032	32.37	24.03
480	1.0080	-0.0029	1.0051	14.18	0.013778	0.0024	16.34	12.13
1440	1.0070	-0.0029	1.0041	14.4	0.013778	0.0024	13.14	9.75

APPENDIX- D

(Atterberg limit test results)

Table D-1: Determination of Liquid Limit, Plastic Limit and Plastic Index (for TP3)

	Liquid limit				Plastic limit	
Trial No.	1	2	3	4	1	2
Can No.	A82	A25	D22	C31		
Mass of can(g)	22.00	22.50	24.90	22.10	20.80	22.20
Mass of can + wet soil (g)	44.00	43.90	49.40	46.40	24.30	24.90
Mass of can + dry soil (g)	39.00	39.00	43.60	40.50	23.50	24.30
Mass of water (g)	5.00	4.90	5.80	5.90	0.80	0.60
Mass of dry soil(g)	17.00	16.50	18.70	18.40	2.70	2.10
water content (%)	29.41	29.70	31.02	32.07	29.63	28.57
No. blows	32.00	28.00	22.00	15.00	29.10	

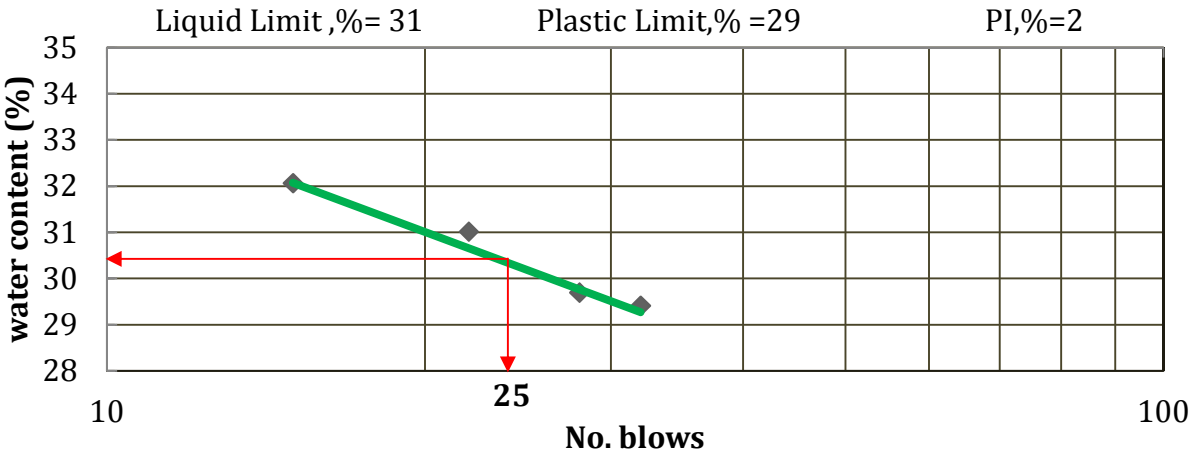


Figure D-1: Water content versus No. blows

Table D-2: Determination of Liquid Limit, Plastic Limit and Plastic Index (for TP4 @2.0m)

	Liquid limit				Plastic limit	
Trial No.	1	2	3	4	1	2
Can No.	D15	D31	1A	A31	66	45
Mass of can(g)	22.2	22.2	22.1	22	20.7	22.2
Mass of can + wet soil (g)	49.9	54.8	50.4	50.3	25.2	26.5
Mass of can + dry soil (g)	43.50	46.80	43.30	43.50	24.20	25.50
Mass of water (g)	6.40	8.00	7.10	6.80	1.00	1.00
Mass of dry soil(g)	21.30	24.60	21.20	21.50	3.50	3.30
Water content (%)	30.05	32.52	33.49	31.63	28.57	30.30
No. blows	32.00	21.00	17.00	25.00		

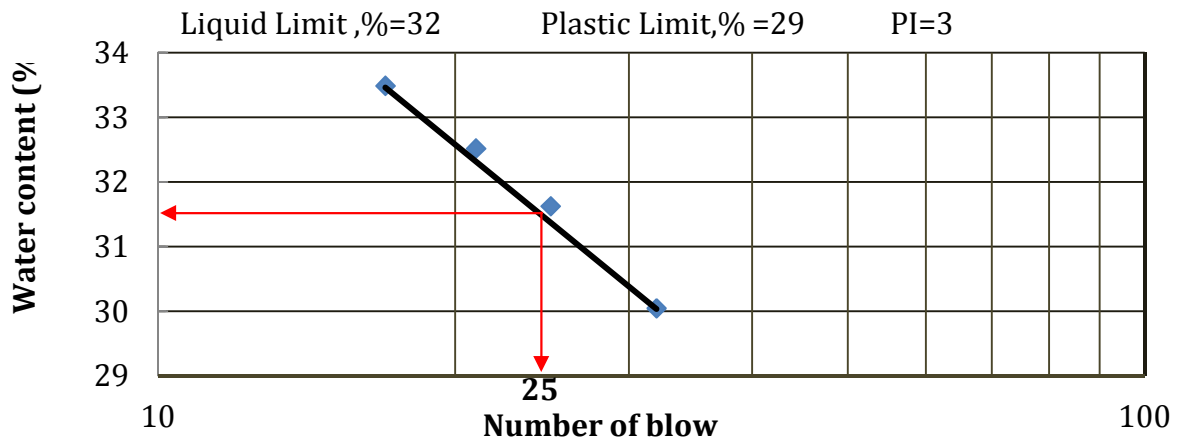


Figure D-2: Water content versus No. blows

Table D-3: Determination of Liquid Limit, Plastic Limit and Plastic Index (for TP4@3.0m)

	Liquid limit				Plastic limit	
Trial No.	1	2	3	4	1	2
Can No.	86	D11	C18			
Mass of can(g)	6.40	22.40	21.80	22.30	22.10	22.10
Mass of can + wet soil (g)	29.50	50.50	43.70	42.90	30.70	26.30
Mass of can + dry soil (g)	24.00	43.40	38.00	37.80	29.00	25.40
Mass of water (g)	5.50	7.10	5.70	5.10	1.70	0.90
Mass of dry soil(g)	17.60	21.00	16.20	15.50	6.90	3.30
Water content (%)	31.25	33.81	35.19	32.90	24.64	27.27
No. blows	32.00	20.00	15.00	23.00		

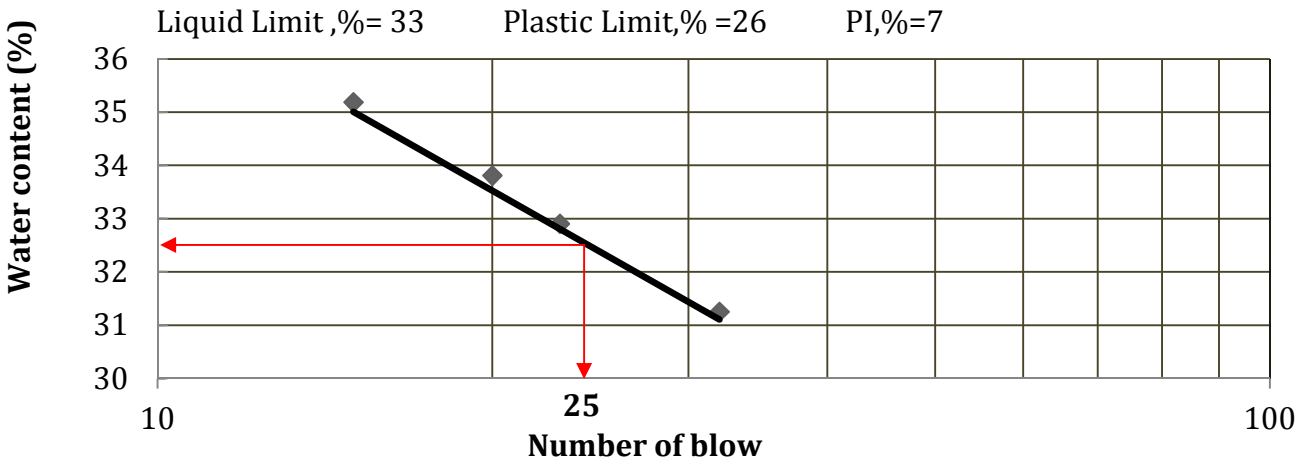


Figure D-3: Water content versus No. blows

APPENDIX- E

(Specific Gravity)

Table E-1: Specific Gravity Determination for (TP1)

Determination No.	1	2	3
Pycnometer No.	1	2	3
Weight of pycnometer + soil + water, W_{pws} *(g)*	164	164	162.6
Temperature, T_x*(°c)*	23	23	23
Weight of pycnometer + water at T_x , $W_{pw}(atT_x)$ *(g)*	148.81	148.84	147.64
Weight of dry soil , w_s *(gm)*	25.10	25.30	25.10
Conversion factor	1.00	1.00	1.00
Specific gravity of soil at 20°c.	2.50	2.52	2.47
Average specific gravity of soi	2.50		

Table E-2: Specific Gravity Determination for (TP2)

Determination No.	1	2	3
Pycnometer No.	1	2	3
Weight of pycnometer + soil + water, W_{pws} (g)	164.3	164.1	163
Temperature, T_x(°c)	23	23	23
Weight of pycnometer + water at T_x , $W_{pw}(atT_x)$ *(g)*	148.84	148.84	147.64
Weight of dry soil , w_s (gm)	25.10	25.60	25.20
Conversion factor , K	1.00	1.00	1.00
Specific gravity of soil at 20°c.	2.52	2.55	2.56
Average specific gravity of soil.	2.54		

Table E-3: Specific Gravity Determination for (TP3)

Determination No.	1	2	3
Pycnometer No.	1	2	3
Weight of pycnometer + soil + water, W_{pws} *(g)*	164	164.2	163.3
Temperature, T_x*(°c)*	23	23	23
Weight of pycnometer + water at T_x , $W_{pw}(atT_x)$ *(g)*	148.81	148.81	147.71
Weight of dry soil , w_s *(gm)*	25.00	25.30	25.20
Conversion factor , K	1.00	1.00	1.00
Specific gravity of soil at 20°c.	2.50	2.60	2.62
Average specific gravity of soil.	2.57		

Table E-4: Specific Gravity Determination for (TP4@2.0m)

Determination No.	1	2	3
Pycnometer No.	1	2	3
Weight of pycnometer + soil + water, W_{pws} *(g)*	164.1	164.1	164.2
Temperature, T_x*(°c)*	23	23	23
Weight of pycnometer + water at T_x , $W_{pw}(atT_x)$ *(g)*	148.81	148.81	148.81
Weight of dry soil , w_s *(gm)*	25.40	25.40	25.20
Conversion factor , K	1.00	1.00	1.00
Specific gravity of soil at 20°c.	2.51	2.51	2.57
Average specific gravity of soil .	2.53		

Table E-5: Specific Gravity Determination for (TP4@3.0m)

Determination No.	1	2	3
Pycnometer No.	1	2	3
Weight of pycnometer + soil + water, W_{pws} *(g)*	191.2	164.4	163.2
Temperature, T_x*(°c)*	23	23	23
Weight of pycnometer + water at T_x , $W_{pw}(atT_x)$ *(g)*	175.71	148.81	147.61
Weight of dry soil , w_s *(gm)*	25.20	25.10	25.10
Conversion factor , K	1.00	1.00	1.00
Specific gravity of soil at 20°c.	2.61	2.62	2.64
Average specific gravity of soil .	2.62		

APPENDIX - F

(Consolidation test results)

Table F-1: Determination of Pre-consolidation pressure for TP1

[a] In the beginning of the test

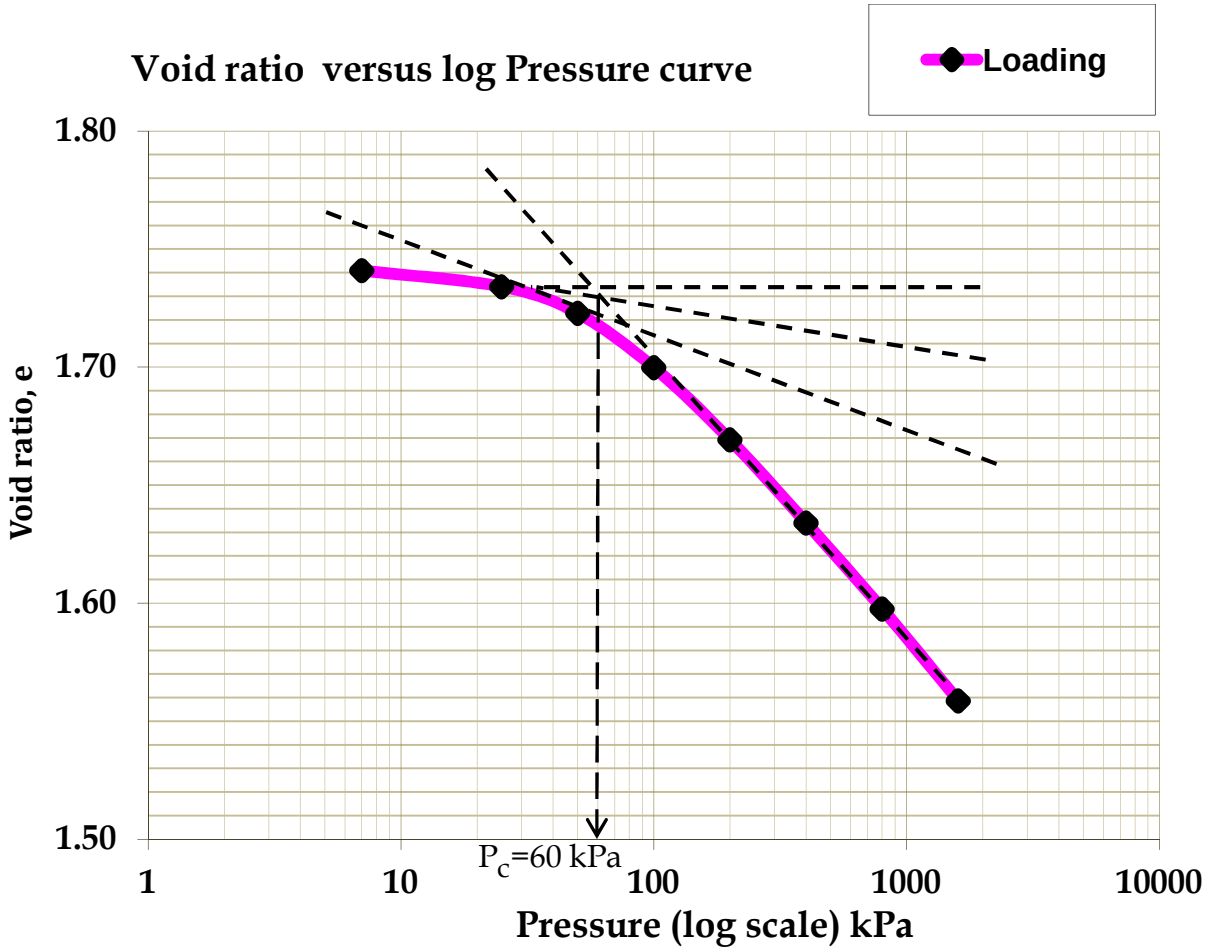
Sample type :	Disturbed
Ring Area,cm^2:	19.625
Height of sample, mm:	20
Seating Load, Kpa	7
Initial Void Ratio, e_o:	1.76
Initial moisture content,%	64.09
Specific Gravity:	2.5
Wet density, g/cm3	1.49

[b] In the end of the test

Final Moisture Content,%	57.18
Dry specimen wt (m_s), gm:	35.8
Dry density, g/cm3	0.97
Height of Solids(H_s), mm	7.30
Final Void Ratio, e_f:	1.56

[c]Calculation table:

Applied pressure P (kPa)	Final Dial Reading (mm)	Change In Specimen Height (mm)	Final Specimen Height (mm)	Void Height,H_v (mm)	Void Ratio, e
Loading					
7	1.400	0.00	20.00	12.70	1.74
25	1.450	0.05	19.95	12.65	1.73
50	1.582	0.13	19.87	12.57	1.72
100	1.750	0.30	19.70	12.40	1.70
200	1.973	0.52	19.48	12.18	1.67
400	2.230	0.78	19.22	11.92	1.63
800	2.496	1.05	18.95	11.66	1.60
1600	2.780	1.33	18.67	11.37	1.56



[a] In the beginning of the test

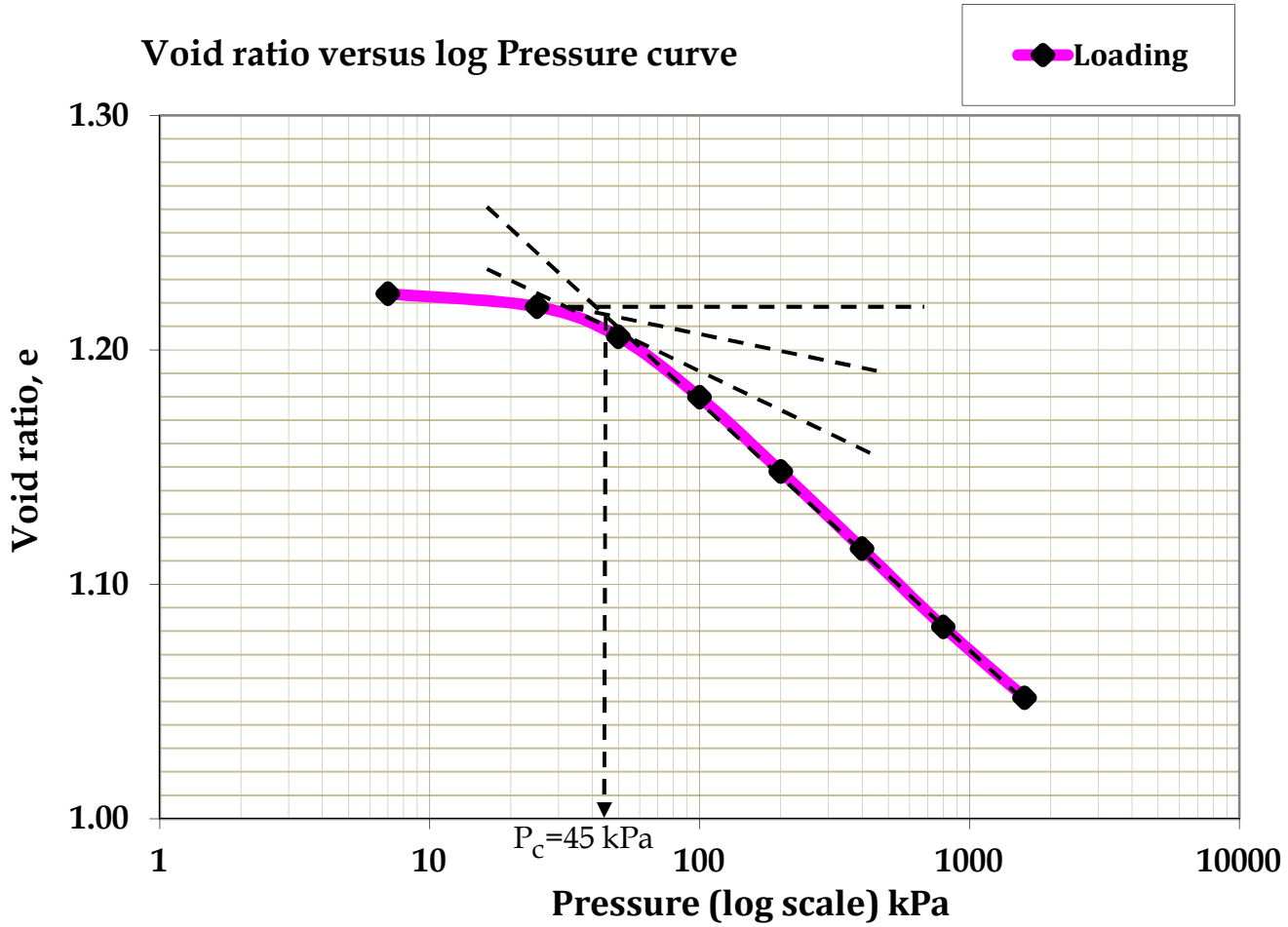
Sample type :	Disturbed
Ring Area,cm^2:	19.625
Height of sample, mm:	20
Seating Load, Kpa	7
Initial Void Ratio, e_o:	1.22
Initial moisture content,%	23.55
Specific Gravity:	2.53
Wet density, g/cm3	1.40

[b] In the end of the test

Final Moisture Content,%	23.60
Dry specimen wt (m_s), gm:	44.65
Dry density, g/cm3	1.23
Height of Solids(H_s), mm	8.99
Final Void Ratio, e_f:	1.05

[c]Calculation table:

Applied pressure P (kPa)	Final Dial Reading (mm)	Change In Specimen Height (mm)	Final Specimen Height (mm)	Void Height, H_v (mm)	Void Ratio, e
Loading					
7	0.550	0.00	20.00	11.01	1.22
25	0.600	0.05	19.95	10.96	1.22
50	0.765	0.17	19.84	10.84	1.21
100	0.997	0.40	19.60	10.61	1.18
200	1.282	0.68	19.32	10.33	1.15
400	1.578	0.98	19.02	10.03	1.12
800	1.878	1.28	18.72	9.73	1.08
1600	2.150	1.55	18.45	9.46	1.05



APPENDIX - G

Cyclic Simple Shear Test Result

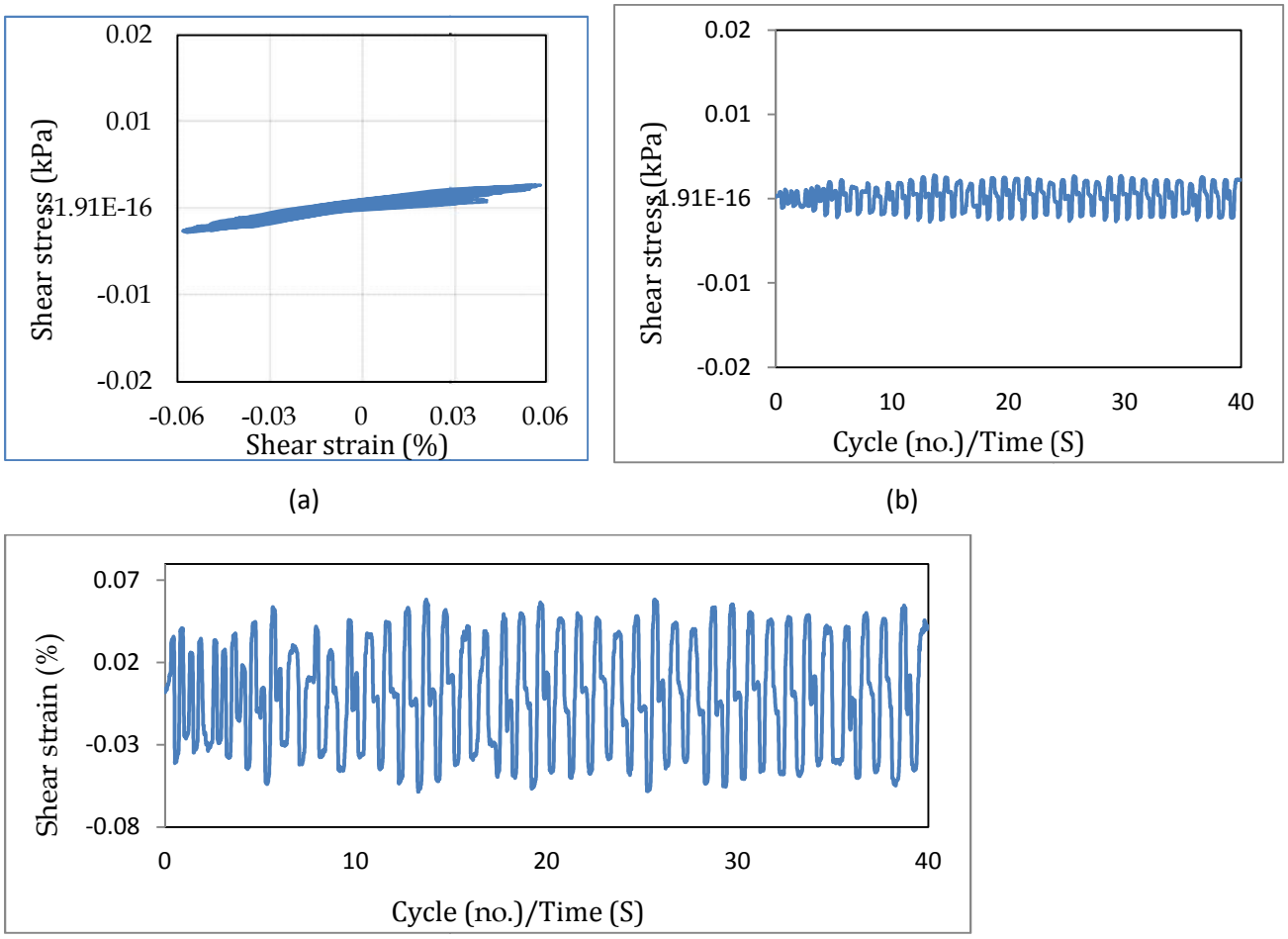
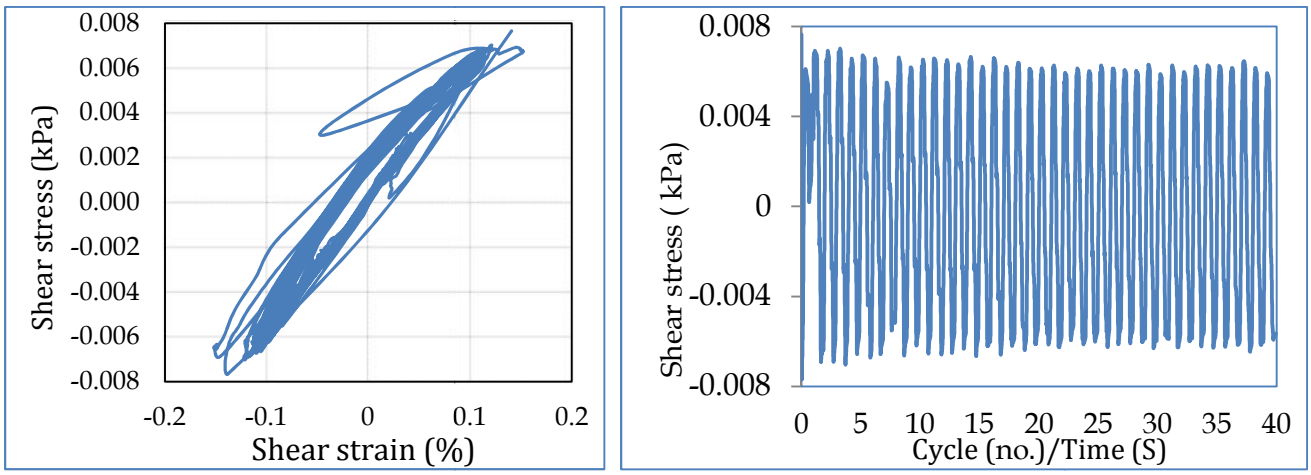
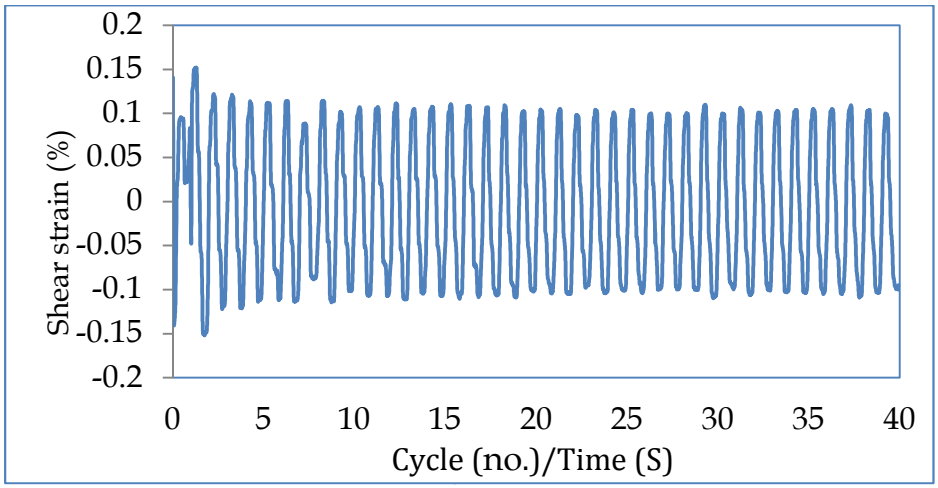


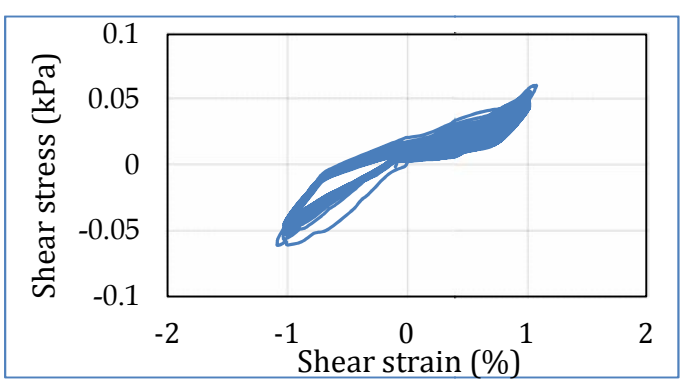
Figure G-1: Results of a strain controlled test (γ=0.05%, frequency =1Hz, σ'v=200 kPa): (a) shear stress versus shear strain; (b) shear stress versus number of cycles; (c)shear strain versus number of cycles.



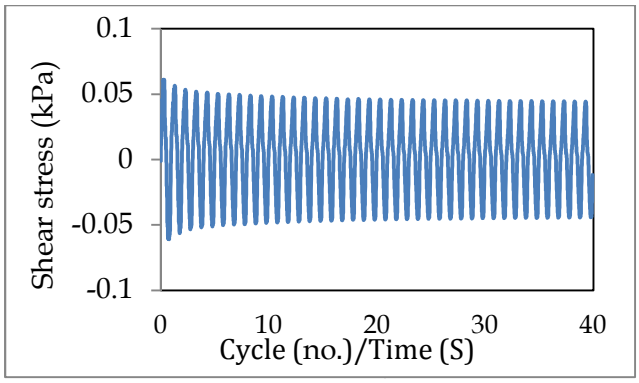


(c)

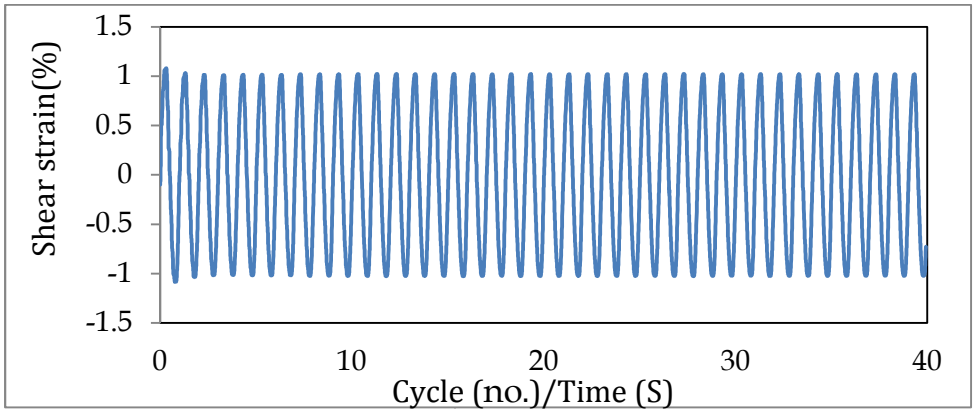
Figure G-2: Results of a strain controlled test (γ=0.1%, frequency =1Hz, σ'v =200 kPa): (a) shear stress versus shear strain; (b) shear stress versus number of cycles; (c)shear strain versus number of cycles.



(a)

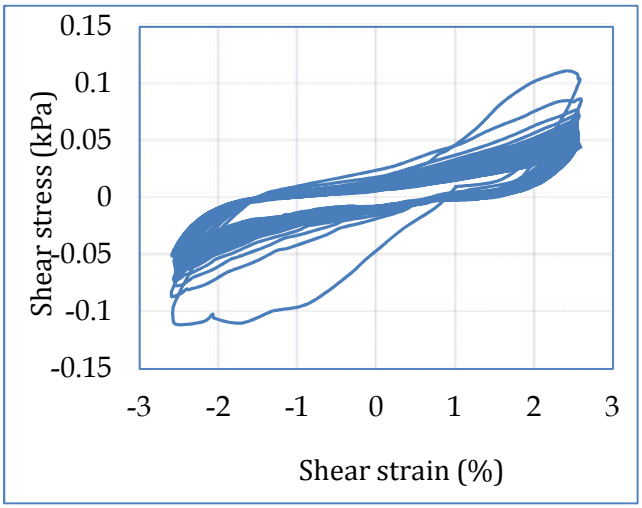


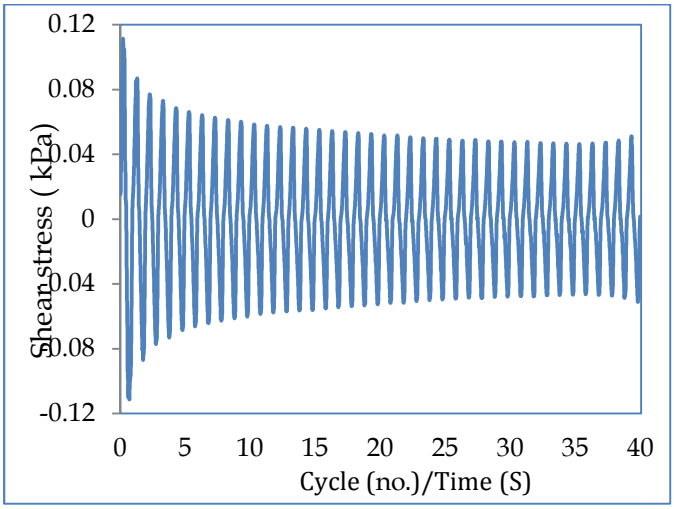
(b)

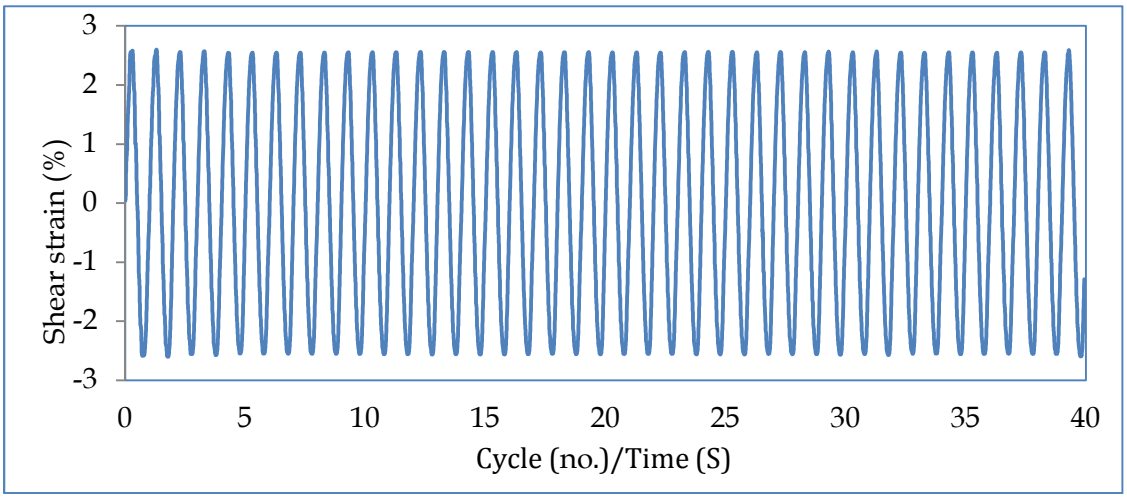


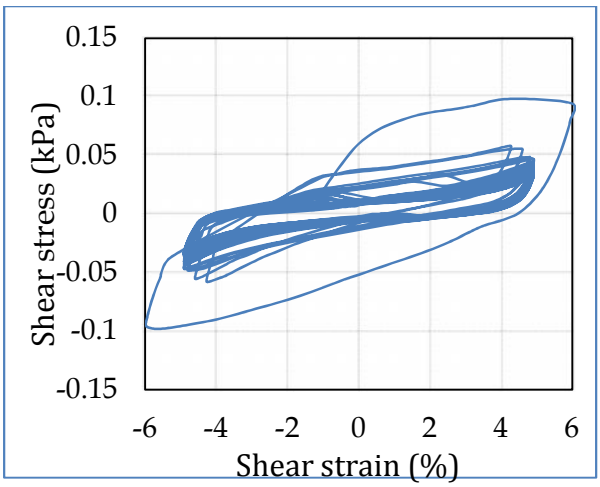
(c)

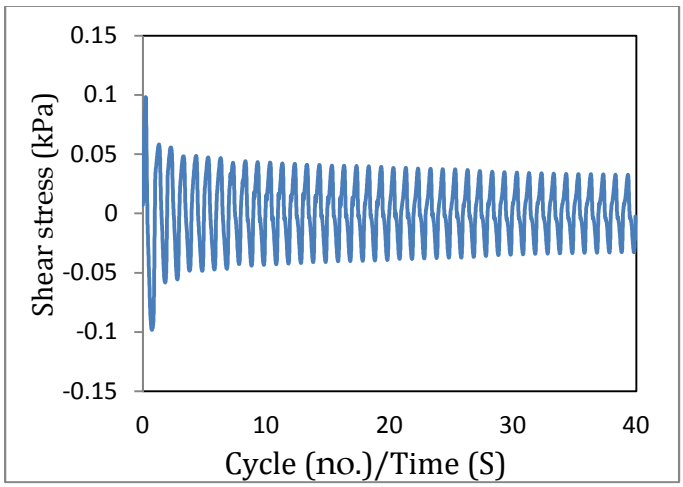
Figure G-3: Results of a strain controlled test (γ =1%, frequency =1Hz, σ'v =200 kPa): (a) shear stress versus shear strain; (b) shear stress versus number of cycles; (c)shear strain versus number of cycles.

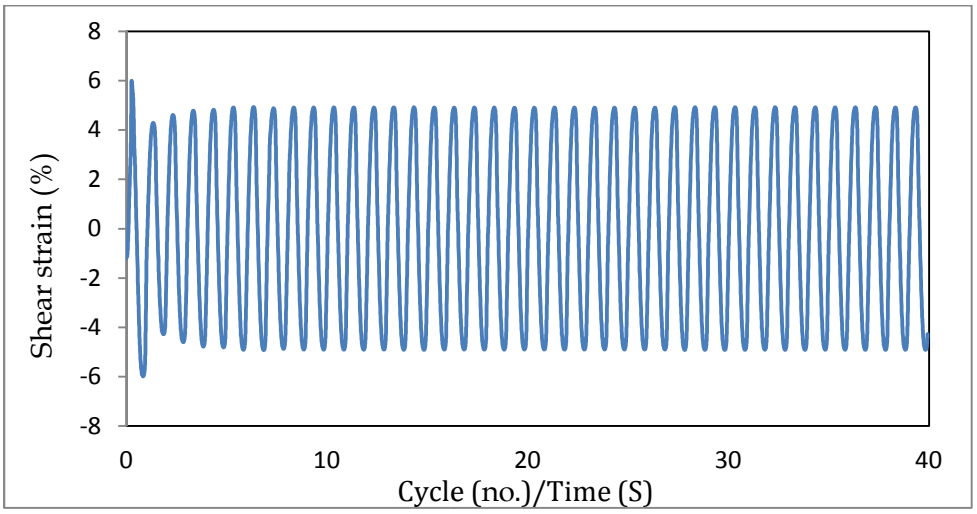

0.15
0.1
0.05
0
-0.05
-0.1
-0.15
Shear stress (kPa)
-3
-2
-1
0
1
2
3
Shear strain (%)


0.12
0.08
0.04
0
-0.04
-0.08
-0.12
Shear stress (kPa)
0
5
10
15
20
25
30
35
40
Cycle (no.)/Time (S)


3
2
1
0
-1
-2
-3
Shear strain (%)
0
5
10
15
20
25
30
35
40
Cycle (no.)/Time (S)


0.15
0.1
0.05
0
-0.05
-0.1
-0.15
Shear stress (kPa)
-6
-4
-2
0
2
4
6
Shear strain (%)


0.15
0.1
0.05
0
-0.05
-0.1
-0.15
Shear stress (kPa)
0
10
20
30
40
Cycle (no.)/Time (S)



(c)

Figure G-5: Results of a strain controlled test (γ =5%, frequency =1Hz, σ'_v=200 kPa): (a) shear stress versus shear strain; (b) shear stress versus number of cycles; (c)shear strain versus number of cycles.

Table G-1: Shear modulus and damping values for silty sand (TP1) soil under an axial stress of 100kPa.

Strain level	0.01%	0.10%	1%	2.50%	5%	0.01%	0.10%	1%	2.50%	5%
CyclesNo.	G (MPa)					D (%)				
1	7.00	3.99	1.22	0.90	0.50	7.23	10.69	18.19	23.00	27.69
2	7.30	4.22	1.39	1.18	0.67	7.11	10.56	18.05	22.98	27.55
3	7.49	4.30	1.43	1.19	0.87	7.09	10.45	17.91	22.89	27.35
4	7.65	4.45	1.61	1.21	0.96	6.98	10.35	17.80	22.81	27.25
5	7.76	4.62	1.72	1.24	1.04	6.88	10.16	17.69	22.95	26.95
6	7.81	4.69	1.78	1.26	1.11	6.78	10.00	17.78	22.83	26.09
7	7.88	4.71	1.77	1.29	1.11	6.78	9.87	17.01	22.56	25.75
8	7.89	4.73	1.75	1.29	1.11	6.78	9.85	16.55	22.10	25.64
9	7.92	4.70	1.77	1.31	1.11	6.78	9.81	16.46	21.96	25.60
10	7.93	4.74	1.81	1.35	1.23	6.78	9.75	16.34	21.30	25.54
11	7.95	4.71	1.83	1.37	1.23	6.78	9.75	16.24	21.30	25.44
12	7.97	4.76	1.85	1.38	1.23	6.77	9.73	16.22	21.23	25.43
13	8.00	4.82	1.87	1.41	1.23	6.78	9.73	16.20	21.13	25.41
14	7.95	4.73	1.87	1.43	1.23	6.77	9.73	16.19	21.11	25.25
15	7.98	4.79	1.89	1.43	1.23	6.78	9.73	15.91	21.08	25.13
16	8.07	4.79	1.91	1.45	1.27	6.78	9.73	15.98	21.11	24.96
17	8.10	4.70	1.93	1.46	1.27	6.77	9.73	15.86	21.01	24.86
18	8.11	4.76	1.95	1.47	1.26	6.78	9.70	16.10	21.01	24.72
19	8.13	4.77	1.95	1.49	1.25	6.78	9.70	15.96	20.87	24.19
20	8.15	4.75	1.91	1.46	1.27	6.78	9.70	15.90	20.85	24.11
21	8.19	4.73	1.89	1.47	1.27	6.78	9.71	15.89	20.84	24.06
22	8.11	4.86	1.95	1.53	1.27	6.78	9.71	15.87	20.81	24.02
23	8.21	4.85	1.94	1.52	1.31	6.77	9.70	15.80	20.81	23.95
24	8.21	4.76	1.96	1.52	1.31	6.77	9.70	15.84	20.81	23.88
25	8.19	4.75	1.97	1.51	1.31	6.78	9.70	15.96	20.81	23.85
26	8.21	4.74	2.01	1.51	1.31	6.69	9.71	15.90	20.81	23.84
27	8.25	4.77	2.01	1.51	1.31	6.63	9.70	15.89	20.81	23.81
28	8.35	4.75	2.05	1.50	1.31	6.57	9.71	15.87	20.55	23.75
29	8.36	4.76	2.05	1.50	1.31	6.53	9.93	15.80	20.54	23.71
30	8.37	4.81	2.05	1.49	1.31	6.48	9.76	15.84	20.53	23.65
31	8.38	4.87	2.05	1.49	1.32	6.44	9.67	15.81	20.52	23.61
32	8.41	4.85	2.11	1.49	1.30	6.36	9.99	15.75	20.55	23.55
33	8.42	4.84	2.11	1.49	1.30	6.35	9.66	15.70	20.54	23.55
34	8.45	4.82	2.11	1.48	1.33	6.34	9.66	15.70	20.52	23.51
35	8.47	4.87	2.10	1.48	1.33	6.27	9.79	15.10	20.41	23.51
36	8.47	4.82	2.10	1.48	1.33	6.13	9.73	15.06	20.11	23.51
37	8.47	4.83	2.10	1.48	1.33	6.18	9.64	15.18	19.89	23.51
38	8.48	4.86	2.11	1.47	1.33	6.18	9.73	15.22	19.85	23.41
39	8.48	4.86	2.18	1.48	1.33	6.28	9.69	15.26	19.78	23.41
40	8.48	4.89	2.21	1.47	1.33	6.31	9.69	15.37	19.77	23.40

Table G-2: Shear modulus and damping values for silty sand (TP1) soil under an axial stress of 200kPa

Strain level	0.01%	0.1%	1%	2.5%	5%	0.01%	0.1%	1%	2.5%	5%
Cycles No.	G (MPa)					D (%)				
1	10.57	5.65	2.04	1.55	1.05	6.39	9.99	18.71	22.83	26.95
2	10.96	5.96	2.36	2.01	1.41	6.31	9.52	17.78	22.56	26.09
3	11.05	6.27	2.49	2.02	1.62	6.23	9.11	17.01	22.10	25.75
4	11.29	6.51	2.54	2.06	1.75	6.12	9.02	16.55	21.96	25.64
5	11.42	6.71	2.71	2.08	1.88	6.14	9.02	16.46	21.30	25.6
6	11.5	6.78	2.88	2.11	1.88	6.14	9.02	16.34	21.30	25.54
7	11.52	6.79	2.91	2.11	1.89	6.12	8.82	16.24	21.23	25.48
8	11.55	6.83	2.93	2.13	1.89	6.10	8.73	16.19	21.13	25.43
9	11.57	6.91	2.96	2.15	1.91	6.05	8.65	16.18	21.11	25.41
10	11.59	6.95	3.01	2.15	1.91	6.04	8.49	16.14	21.08	25.35
11	11.69	6.98	3.11	2.16	1.91	6.04	8.38	15.91	21.11	25.33
12	11.79	7.01	3.22	2.16	1.93	6.02	8.28	15.98	21.01	24.96
13	11.79	7.11	3.23	2.17	1.94	6.01	7.97	15.86	21.01	24.86
14	11.81	7.24	3.25	2.18	1.95	5.82	7.52	16.1	20.87	24.72
15	11.89	7.31	3.24	2.18	1.96	5.41	7.24	15.96	20.85	24.19
16	11.85	7.38	3.23	2.19	1.97	5.44	7.28	15.9	20.84	24.11
17	11.89	7.44	3.22	2.21	1.98	5.13	6.99	15.89	20.81	24.06
18	11.86	7.54	3.31	2.22	1.95	5.16	6.78	15.87	20.79	24.02
19	11.85	7.63	3.35	2.23	1.92	5.09	6.69	15.8	20.75	23.95
20	11.87	7.78	3.39	2.25	1.95	5.06	6.63	15.84	20.73	23.88
21	11.89	7.86	3.38	2.26	1.99	4.91	6.57	15.87	20.71	23.85
22	11.89	7.87	3.47	2.28	1.97	4.82	6.53	15.79	20.68	23.84
23	11.93	7.99	3.46	2.25	1.95	4.95	6.48	15.87	20.67	23.81
24	11.95	7.97	3.45	2.31	1.93	4.7	6.44	15.74	20.62	23.75
25	11.99	7.94	3.44	2.33	1.92	4.69	6.36	15.91	20.61	23.71
26	12.09	7.99	3.44	2.35	1.93	4.7	6.35	15.88	20.61	23.65
27	12.17	7.94	3.43	2.35	1.94	4.66	6.34	15.70	20.6	23.61
28	12.18	7.99	3.42	2.35	1.93	4.62	6.27	15.78	20.58	23.55
29	12.24	7.96	3.42	2.35	1.93	4.53	6.13	15.81	20.57	23.55
30	12.27	7.97	3.41	2.38	1.93	4.47	6.02	15.65	20.56	23.51
31	12.25	7.96	3.41	2.37	1.95	4.42	5.98	15.90	20.56	23.41
32	12.26	7.96	3.41	2.33	1.99	4.42	5.89	15.72	20.55	23.41
33	12.29	7.98	3.41	2.36	2.00	4.38	5.74	15.87	20.54	23.31
34	12.35	7.99	3.43	2.36	2.01	4.34	5.74	15.75	20.53	23.29
35	12.35	7.97	3.45	2.38	2.03	4.43	5.69	15.74	20.52	23.28
36	12.37	8.01	3.48	2.39	2.05	4.35	5.62	15.71	20.55	23.21
37	12.37	8.01	3.48	2.41	2.05	4.27	5.55	15.67	20.54	23.21
38	12.36	8.03	3.51	2.41	2.02	4.24	5.51	15.58	20.52	23.21
39	12.36	8.08	3.56	2.43	2.02	4.25	5.49	15.58	20.49	23.18
40	12.39	8.08	3.61	2.43	2.05	4.18	5.49	15.58	20.41	23.15

Table G-3: Shear modulus and damping values for silty sand (TP1) soil under an axial stress of 300kPa

Strain level	0.01%	0.1%	1%	2.5%	5%	0.01%	0.1%	1%	2.5%	5%
Cycles No.	G (MPa)					D (%)				
1	13.79	8.58	4.37	3.01	2.55	5.24	7.78	16.88	20.91	25.21
2	14.16	8.91	4.89	3.44	3.11	5.18	7.58	16.28	20.31	23.82
3	14.35	8.93	4.91	3.55	3.16	5.15	7.56	16.16	20.01	23.79
4	14.46	9.07	4.92	3.61	3.18	5.09	7.44	15.68	19.99	23.63
5	14.63	9.08	4.93	3.64	3.21	5.05	7.44	15.08	19.97	23.58
6	14.74	9.11	4.95	3.65	3.22	5.02	7.14	15.04	19.97	23.57
7	14.76	9.12	4.97	3.66	3.22	5.01	7.08	14.67	19.88	23.55
8	14.85	9.12	4.98	3.67	3.27	4.98	6.98	14.65	19.88	23.51
9	14.99	9.13	4.98	3.69	3.33	4.97	6.92	14.23	19.87	23.48
10	15.01	9.25	4.99	3.71	3.38	4.95	6.82	14.26	19.88	23.45
11	15.16	9.35	4.99	3.72	3.46	4.92	6.55	14.09	19.86	23.44
12	15.43	9.43	5.01	3.73	3.51	4.89	6.38	14.06	19.72	23.38
13	15.53	9.53	5.03	3.75	3.52	4.88	6.16	14.05	19.64	23.36
14	15.59	9.58	5.05	3.78	3.59	4.85	6.18	13.77	19.61	23.31
15	15.71	9.58	5.08	3.78	3.57	4.84	6.17	13.76	19.61	23.29
16	15.78	9.63	5.11	3.75	3.56	4.79	6.21	13.76	19.58	23.25
17	15.88	9.75	5.13	3.74	3.54	4.65	6.14	13.73	19.57	23.24
18	15.92	9.81	5.14	3.75	3.59	4.64	6.13	13.65	19.52	23.22
19	15.94	9.78	5.26	3.78	3.61	4.51	6.12	13.69	19.42	23.25
20	16.03	9.81	5.28	3.82	3.62	4.48	6.13	13.60	19.32	23.22
21	16.13	9.86	5.31	3.81	3.65	4.31	5.97	13.64	19.22	23.21
22	16.13	9.88	5.38	3.81	3.67	3.99	5.95	13.53	19.22	23.21
23	16.16	9.89	5.47	3.81	3.68	3.97	5.89	13.44	19.23	23.18
24	16.16	9.89	5.59	3.94	3.69	3.95	5.88	13.58	19.23	23.14
25	16.27	9.89	5.63	3.94	3.71	3.94	5.78	13.38	19.21	23.13
26	16.28	9.99	5.64	3.94	3.71	3.91	5.72	13.46	19.2	23.11
27	16.29	10.04	5.65	3.95	3.72	3.96	5.72	13.46	19.19	23.09
28	16.31	10.09	5.66	3.96	3.72	3.94	5.64	13.52	19.17	23.02
29	16.33	9.99	5.67	3.97	3.72	3.92	5.62	13.38	19.15	23.02
30	16.34	10.16	5.67	3.97	3.73	3.89	5.55	13.41	19.16	22.98
31	16.41	10.36	5.66	3.97	3.74	3.91	5.52	13.37	19.12	22.88
32	16.42	10.45	5.67	3.98	3.79	3.87	5.51	13.33	19.11	22.88
33	16.44	10.42	5.66	3.98	3.78	3.85	5.48	13.33	19.09	22.74
34	16.55	10.44	5.66	3.99	3.78	3.83	5.42	13.21	19.06	22.75
35	16.55	10.45	5.65	4.04	3.81	3.81	5.41	13.25	19.01	22.67
36	16.56	10.49	5.66	4.04	3.82	3.81	5.39	13.22	18.99	22.68
37	16.57	10.49	5.67	4.05	3.83	3.72	5.31	13.27	18.97	22.67
38	16.63	10.51	5.67	4.09	3.85	3.71	5.29	13.25	18.97	22.65
39	16.65	10.59	5.67	4.09	3.87	3.69	5.24	13.27	18.95	22.64
40	16.65	10.62	5.69	4.11	3.88	3.69	5.24	13.23	18.88	22.61

Table G-4: Shear modulus and damping values for silty sand (TP1) soil under an axial stress of 400kPa

Strain level	0.01%	0.1%	1%	2.5%	5%	0.01%	0.1%	1%	2.5%	5%
Cycles No.	G (MPa)					D (%)				
1	17.51	12.63	5.89	4.11	3.11	3.59	5.39	14.49	19.03	22.68
2	18.31	13.21	6.21	4.25	3.41	3.55	5.28	14.35	19.01	22.54
3	18.51	13.51	6.31	4.35	3.56	3.51	5.18	14.31	18.99	22.49
4	18.72	13.62	6.45	4.41	3.71	3.51	5.04	14.15	18.95	22.48
5	18.79	13.72	6.5	4.45	3.81	3.50	5.04	14.03	18.79	22.37
6	19.01	13.77	6.63	4.45	3.82	3.45	5.02	14.01	18.79	22.31
7	19.36	13.78	6.71	4.55	3.82	3.42	5.02	13.98	18.64	22.22
8	19.37	13.80	6.74	4.61	3.83	3.41	4.98	13.88	18.54	22.19
9	19.41	13.81	6.67	4.57	3.82	3.41	4.96	13.83	18.51	22.18
10	19.44	13.87	6.68	4.59	3.85	3.39	4.93	13.82	18.51	22.17
11	19.58	13.87	6.73	4.61	3.84	3.42	4.96	13.81	18.49	22.16
12	19.68	13.93	6.67	4.64	3.92	3.41	4.94	13.79	18.48	22.16
13	19.75	13.97	6.63	4.64	3.95	3.41	4.87	13.75	18.47	22.13
14	19.79	13.97	6.7	4.65	3.96	3.4	4.87	13.65	18.45	22.11
15	19.88	14.02	6.66	4.66	3.97	3.39	4.84	13.64	18.41	22.09
16	20.01	14.11	6.65	4.67	3.98	3.38	4.83	13.62	18.39	22.08
17	20.22	14.15	6.62	4.68	3.98	3.37	4.81	13.61	18.39	22.06
18	20.26	14.22	6.62	4.71	3.99	3.36	4.81	13.60	18.37	22.05
19	20.34	14.24	6.66	4.73	4.05	3.35	4.78	13.57	18.35	22.03
20	20.35	14.32	6.69	4.74	4.11	3.33	4.77	13.55	18.33	22.01
21	20.36	14.34	6.65	4.75	4.18	3.33	4.74	13.53	18.31	21.98
22	20.35	14.35	6.73	4.76	4.21	3.34	4.74	13.51	18.29	21.91
23	20.38	14.38	6.75	4.78	4.23	3.32	4.73	13.49	18.27	21.88
24	20.39	14.37	6.74	4.79	4.25	3.28	4.72	13.47	18.26	21.85
25	20.41	14.42	6.82	4.81	4.26	3.27	4.71	13.46	18.27	21.84
26	20.48	14.44	6.86	4.83	4.28	3.26	4.71	13.45	18.25	21.81
27	20.49	14.52	6.82	4.85	4.32	3.23	4.65	13.43	18.24	21.81
28	20.75	14.52	6.83	4.87	4.39	3.23	4.64	13.41	18.22	21.79
29	20.75	14.51	6.84	4.89	4.45	3.17	4.63	13.39	18.19	21.78
30	20.87	14.62	6.84	4.89	4.49	3.16	4.61	13.38	18.18	21.78
31	20.88	14.61	6.84	4.91	4.51	3.15	4.59	13.35	18.17	21.77
32	20.89	14.62	6.85	4.92	4.53	3.14	4.58	13.35	18.15	21.76
33	20.89	14.62	6.92	4.93	4.55	3.12	4.57	13.33	18.13	21.75
34	20.9	14.65	6.97	4.95	4.55	3.11	4.56	13.26	18.11	21.76
35	20.9	14.65	6.94	4.96	4.57	3.01	4.55	13.23	18.11	21.74
36	20.89	14.66	6.96	4.98	4.58	2.99	4.53	13.25	18.09	21.71
37	20.89	14.84	6.96	4.98	4.58	2.98	4.51	13.21	18.09	21.69
38	20.91	14.88	7.02	4.99	4.59	2.96	4.49	13.19	18.08	21.67
39	20.91	14.93	7.05	5.05	4.61	2.95	4.45	13.16	18.06	21.67
40	20.91	14.97	7.09	5.15	4.63	2.91	4.42	13.12	18.01	21.65

Table G-5: Shear modulus and damping values for silty sand (TP2) soil under an axial stress of 100kPa

Strain level	0.01%	0.10%	1%	2.50%	5%	0.01%	0.10%	1%	2.50%	5%
Cycles No.	G (MPa)					D (%)				
1	8.41	3.88	2.22	1.17	0.71	6.81	10.31	17.50	22.87	26.37
2	8.69	4.55	2.26	1.27	0.75	6.80	10.23	17.39	22.67	26.35
3	8.98	4.75	2.36	1.31	0.81	6.75	10.18	17.35	22.57	26.32
4	9.23	5.09	2.45	1.35	0.95	6.70	10.15	17.25	22.55	26.29
5	9.43	5.12	2.50	1.45	1.05	6.63	10.13	17.10	22.27	26.24
6	9.51	5.15	2.50	1.47	1.11	6.60	9.85	17.00	22.25	26.16
7	9.55	5.45	2.57	1.47	1.15	6.50	9.80	16.83	22.13	26.15
8	9.57	5.55	2.60	1.47	1.17	6.75	9.41	17.22	21.86	25.71
9	9.57	5.65	2.57	1.47	1.19	6.37	9.17	16.45	21.76	25.41
10	9.61	5.65	2.60	1.47	1.21	6.40	8.76	17.40	21.71	25.26
11	9.67	5.69	2.58	1.47	1.28	6.81	8.35	15.87	21.68	25.12
12	9.77	5.99	2.59	1.51	1.27	6.77	8.15	17.24	21.69	25.01
13	9.77	6.12	2.57	1.51	1.26	6.60	8.14	16.63	21.67	24.89
14	9.77	6.23	2.59	1.51	1.25	6.66	8.13	16.78	21.66	24.88
15	9.77	6.50	2.57	1.51	1.24	6.80	8.11	16.78	21.65	24.83
16	9.70	6.67	2.58	1.51	1.22	6.92	8.05	16.69	21.62	24.82
17	9.70	6.75	2.56	1.51	1.21	6.67	8.02	16.66	21.57	24.81
18	9.70	6.96	2.58	1.51	1.23	6.78	7.97	15.68	21.59	24.79
19	9.70	6.97	2.56	1.53	1.23	7.06	7.92	15.22	21.55	24.75
20	9.70	6.97	2.56	1.51	1.23	7.16	7.88	15.50	21.55	24.71
21	9.79	6.97	2.54	1.50	1.20	7.02	7.85	15.82	21.55	24.61
22	9.79	6.96	2.57	1.50	1.24	7.08	7.86	15.80	21.45	24.65
23	9.79	6.95	2.54	1.55	1.23	7.28	7.85	15.16	21.35	24.69
24	9.79	7.11	2.56	1.55	1.24	7.10	7.82	14.90	21.35	24.69
25	9.81	7.21	2.53	1.55	1.23	6.69	7.84	15.27	21.34	24.69
26	9.80	7.26	2.56	1.55	1.25	6.53	7.82	15.21	21.23	24.69
27	9.80	7.25	2.54	1.55	1.25	6.41	7.81	16.86	21.17	24.55
28	9.85	7.35	2.55	1.50	1.23	6.22	7.79	16.26	21.10	24.55
29	9.85	7.29	2.51	1.50	1.23	5.93	7.79	15.63	20.87	24.45
30	9.85	7.31	2.55	1.50	1.25	6.14	7.79	15.56	20.71	24.35
31	9.85	7.29	2.53	1.50	1.25	6.43	7.79	15.35	20.18	24.35
32	9.85	7.28	2.54	1.58	1.23	6.38	7.79	15.32	20.09	24.31
33	9.87	7.31	2.51	1.57	1.26	6.11	7.84	15.68	19.99	24.31
34	9.87	7.31	2.54	1.57	1.26	6.04	7.82	15.55	19.79	24.29
35	9.87	7.30	2.52	1.58	1.27	6.33	7.81	15.55	19.65	24.27
36	9.87	7.31	2.53	1.58	1.27	6.29	7.81	15.55	19.35	24.25
37	9.87	7.29	2.50	1.59	1.27	6.09	7.81	15.55	19.17	24.22
38	9.87	7.33	2.53	1.59	1.29	6.06	7.81	15.47	19.02	24.21
39	9.89	7.30	2.55	1.59	1.29	6.31	7.77	15.47	19.02	24.19
40	9.91	7.35	2.63	1.59	1.29	6.34	7.77	15.46	19.02	24.15

Table G-6: Shear modulus and damping values for silty sand (TP2) soil under an axial stress of 200kPa

Strain level	0.01%	0.1%	1%	2.5%	5%	0.01%	0.1%	1%	2.5%	5%
Cycles No.	G (MPa)					D (%)				
1	13.71	7.35	3.55	2.35	0.98	6.99	9.41	16.99	23.55	26.99
2	13.76	7.41	3.78	2.42	1.25	6.55	9.17	16.61	22.55	26.15
3	13.86	7.42	3.81	2.45	1.35	6.25	8.76	16.35	21.63	25.71
4	13.96	7.55	3.85	2.51	1.38	6.15	8.35	16.15	20.91	25.41
5	13.98	7.62	4.05	2.56	1.49	5.97	8.15	16.07	20.40	25.26
6	13.99	7.64	4.08	2.57	1.49	5.95	8.14	16.05	20.04	25.12
7	13.99	7.65	4.18	2.58	1.5	5.94	8.13	16.03	19.83	25.01
8	14.01	7.65	4.28	2.59	1.51	5.91	8.11	16.01	19.83	24.89
9	14.02	7.66	4.28	2.61	1.53	5.9	8.05	16.06	19.61	24.88
10	14.03	7.67	4.29	2.63	1.55	5.89	8.02	16.06	19.55	24.83
11	14.05	7.67	4.31	2.63	1.57	5.85	7.97	15.99	19.47	24.82
12	14.06	7.68	4.32	2.65	1.58	5.84	7.92	15.97	19.37	24.81
13	14.08	7.68	4.35	2.67	1.58	5.83	7.88	15.95	19.35	24.79
14	14.11	7.69	4.38	2.68	1.58	5.82	7.85	15.94	19.37	24.75
15	14.12	7.69	4.41	2.68	1.59	5.83	7.86	15.87	19.35	24.71
16	14.14	7.71	4.42	2.68	1.61	5.86	7.85	15.87	19.34	24.65
17	14.16	7.72	4.45	2.69	1.63	5.82	7.82	15.86	19.32	24.61
18	14.21	7.74	4.47	2.71	1.66	5.82	7.84	15.86	19.29	24.58
19	14.19	7.74	4.49	2.73	1.65	5.81	7.82	15.86	19.29	24.46
20	14.21	7.75	4.51	2.73	1.64	5.79	7.81	15.85	19.25	24.46
21	14.21	7.76	4.53	2.75	1.65	5.78	7.79	15.84	19.24	24.43
22	14.22	7.77	4.55	2.75	1.65	5.76	7.78	15.83	19.19	24.37
23	14.33	7.81	4.58	2.76	1.68	5.73	7.76	15.82	19.18	24.36
24	14.35	7.81	4.62	2.77	1.69	5.72	7.74	15.79	19.15	24.34
25	14.37	7.83	4.62	2.78	1.71	5.72	7.71	15.75	19.13	24.31
26	14.38	7.84	4.63	2.79	1.72	5.71	7.69	15.75	19.11	24.3
27	14.41	7.84	4.65	2.79	1.73	5.69	7.65	15.74	19.08	24.15
28	14.42	7.85	4.66	2.8	1.75	5.68	7.55	15.73	19.02	24.11
29	14.43	7.86	4.68	2.81	1.75	5.67	7.45	15.71	18.92	24.06
30	14.45	7.88	4.71	2.82	1.75	5.68	7.43	15.7	18.89	23.94
31	14.46	7.89	4.73	2.84	1.77	5.65	7.44	15.69	18.79	23.91
32	14.47	7.87	4.75	2.86	1.78	5.62	7.39	15.67	18.75	23.88
33	14.49	7.89	4.77	2.87	1.79	5.61	7.38	15.65	18.71	23.84
34	14.51	7.93	4.77	2.88	1.81	5.61	7.37	15.59	18.70	23.83
35	14.52	7.92	4.78	2.88	1.82	5.60	7.35	15.57	18.69	23.81
36	14.53	7.94	4.79	2.91	1.83	5.59	7.31	15.52	18.59	23.74
37	14.55	7.93	4.8	2.93	1.85	5.57	7.31	15.48	18.56	23.74
38	14.56	7.94	4.81	2.95	1.85	5.51	7.3	15.48	18.51	23.72
39	14.58	7.95	4.81	2.95	1.85	5.48	7.29	15.47	18.51	23.7
40	14.59	7.96	4.82	2.96	1.87	5.41	7.29	15.47	18.48	23.68

Table G-7: Shear modulus and damping values for silty sand (TP2) soil under an axial stress of 300kPa

Strain level	0.01%	0.1%	1%	2.5%	5%	0.01%	0.1%	1%	2.5%	5%
Cycles No.	G (MPa)					D (%)				
1	19.36	12.51	4.55	2.35	1.01	6.28	7.19	14.99	21.89	25.97
2	19.63	12.71	5.28	2.42	1.35	5.55	6.89	14.26	20.71	24.11
3	19.77	12.84	5.55	2.45	1.49	5.22	6.75	14.11	20.08	23.45
4	19.79	12.98	5.85	2.67	1.67	5.02	6.60	14.09	19.41	23.15
5	19.96	13.00	6.00	2.70	1.68	4.70	6.60	14.04	18.94	23.04
6	19.99	13.1	6.09	2.75	1.69	4.61	6.42	14.01	18.18	23.02
7	20.08	13.18	6.16	2.74	1.75	4.59	6.41	13.98	17.81	23.01
8	20.13	13.21	6.23	2.74	1.76	4.55	6.4	13.82	17.46	22.97
9	20.18	13.24	6.27	2.76	1.78	4.41	6.38	13.71	17.32	22.95
10	20.19	13.25	6.28	2.79	1.77	4.26	6.35	13.66	17.13	22.85
11	20.21	13.27	6.33	2.81	1.79	4.24	6.23	13.49	16.89	22.74
12	20.23	13.26	6.34	2.83	1.81	4.22	6.11	13.46	16.87	22.73
13	20.25	13.28	6.37	2.85	1.83	4.16	6.07	13.43	16.71	22.61
14	20.24	13.27	6.38	2.92	1.82	4.15	5.93	13.36	16.55	22.41
15	20.26	13.33	6.41	2.93	1.85	4.17	5.92	13.25	16.54	22.25
16	20.27	13.35	6.41	2.95	1.86	4.15	5.75	13.19	16.34	22.13
17	20.28	13.35	6.41	2.97	1.87	4.13	5.69	13.01	16.13	21.86
18	20.29	13.37	6.41	2.97	1.89	4.13	5.68	12.88	15.85	21.76
19	20.29	13.37	6.48	2.99	1.89	4.09	5.65	12.74	15.74	21.71
20	20.31	13.37	6.48	2.99	1.89	4.06	5.63	12.69	15.64	21.68
21	20.32	13.38	6.54	3	1.89	4.06	5.74	12.54	15.53	21.69
22	20.33	13.38	6.56	3.04	1.92	3.84	5.67	12.37	15.48	21.67
23	20.35	13.37	6.59	3.04	1.93	3.81	5.66	12.26	15.29	21.66
24	20.41	13.34	6.62	3.05	1.94	3.75	5.65	12.17	15.18	21.65
25	20.42	13.39	6.6	3.11	1.96	3.79	5.58	12.14	14.85	21.62
26	20.43	13.43	6.62	3.13	1.97	3.71	5.58	12.12	14.84	21.57
27	20.49	13.43	6.59	3.18	1.99	3.72	5.53	12.09	14.84	21.59
28	20.42	13.48	6.59	3.23	1.99	3.73	5.51	12.05	14.84	21.55
29	20.43	13.49	6.57	3.23	2.05	3.68	5.42	12.04	14.83	21.51
30	20.45	13.48	6.57	3.25	2.06	3.64	5.41	12.01	14.77	21.52
31	20.43	13.49	6.56	3.25	2.09	3.61	5.38	12.01	14.69	21.51
32	20.37	13.51	6.54	3.27	2.11	3.64	5.37	11.97	14.61	21.49
33	20.39	13.65	6.54	3.31	2.13	3.65	5.35	11.89	14.61	21.43
34	20.41	13.64	6.54	3.36	2.15	3.63	5.33	11.88	14.6	21.41
35	20.41	13.65	6.53	3.36	2.15	3.62	5.31	11.87	14.58	21.39
36	20.43	13.66	6.51	3.37	2.14	3.63	5.29	11.85	14.57	21.38
37	20.43	13.67	6.51	3.38	2.14	3.57	5.14	11.84	14.55	21.35
38	20.45	13.67	6.5	3.38	2.17	3.53	5.09	11.81	14.55	21.35
39	20.49	13.67	6.5	3.38	2.19	3.51	5.08	11.80	14.53	21.33
40	20.49	13.69	6.47	3.38	2.25	3.49	5.08	11.78	14.51	21.31

Table G-8: Shear modulus and damping values for silty sand (TP2) soil under an axial stress of 400kPa

Strain level	0.01%	0.1%	1%	2.5%	5%	0.01%	0.1%	1%	2.5%	5%
Cycles No.	G (MPa)					D (%)				
1	23.05	15.11	7.03	4.26	3.05	4.01	5.01	12.75	17.51	21.18
2	23.09	15.61	7.33	4.99	3.85	3.91	4.96	12.22	16.54	20.41
3	23.18	15.65	7.57	5.32	4.29	3.83	4.95	12.19	16.33	20.18
4	23.27	15.99	7.63	5.44	4.39	3.65	4.93	11.97	16.24	20.09
5	23.54	16.00	7.9	5.51	4.5	3.57	4.93	11.92	16.10	19.99
6	23.55	16.03	7.93	5.52	4.51	3.55	4.92	11.83	16.10	19.79
7	23.57	16.05	7.94	5.53	4.53	3.54	4.86	11.78	15.98	19.65
8	23.59	16.08	7.98	5.62	4.55	3.51	4.84	11.77	15.88	19.35
9	23.59	16.16	8.06	5.65	4.61	3.47	4.82	11.75	15.83	19.17
10	23.62	16.23	8.07	5.67	4.71	3.46	4.81	11.75	15.81	19.02
11	23.65	16.28	8.06	5.68	4.73	3.44	4.79	11.74	15.78	18.7
12	23.65	16.3	8.13	5.67	4.75	3.41	4.76	11.73	15.76	18.66
13	23.67	16.31	8.15	5.69	4.77	3.41	4.75	11.73	15.77	18.53
14	23.68	16.33	8.17	5.71	4.78	3.38	4.74	11.73	15.77	18.51
15	23.71	16.38	8.18	5.73	4.81	3.38	4.72	11.71	15.76	18.38
16	23.75	16.41	8.19	5.74	4.91	3.37	4.71	11.7	15.75	18.24
17	23.76	16.47	8.23	5.75	4.92	3.35	4.7	11.67	15.74	18.01
18	23.78	16.48	8.24	5.78	4.94	3.33	4.69	11.67	15.71	17.92
19	23.81	16.54	8.23	5.81	4.95	3.29	4.69	11.63	15.71	17.88
20	23.88	16.58	8.24	5.82	4.96	3.29	4.68	11.57	15.70	17.87
21	23.89	16.57	8.25	5.83	4.97	3.27	4.67	11.56	15.69	17.84
22	23.89	16.58	8.26	5.84	4.99	3.25	4.65	11.55	15.68	17.83
23	23.91	16.59	8.28	5.85	5.01	3.23	4.64	11.53	15.65	17.78
24	23.91	16.61	8.38	5.87	5.05	3.21	4.64	11.53	15.62	17.77
25	23.99	16.63	8.44	5.88	5.02	3.19	4.63	11.52	15.60	17.69
26	24.01	16.64	8.45	5.91	5.07	3.18	4.62	11.53	15.59	17.68
27	24.02	16.64	8.46	5.95	5.08	3.17	4.62	11.51	15.45	17.64
28	24.03	16.65	8.47	5.96	5.15	3.17	4.59	11.49	15.52	17.58
29	24.16	16.67	8.48	5.96	5.15	3.16	4.57	11.48	15.43	17.58
30	24.16	16.69	8.49	5.97	5.15	3.14	4.57	11.47	15.34	17.54
31	24.17	16.67	8.51	5.99	5.17	3.13	4.55	11.45	15.33	17.53
32	24.23	16.75	8.53	5.99	5.18	3.14	4.53	11.43	15.32	17.53
33	24.27	16.77	8.59	6.01	5.17	3.12	4.51	11.38	15.31	17.45
34	24.35	16.79	8.61	6.08	5.19	3.11	4.47	11.35	15.25	17.44
35	24.38	16.81	8.62	6.17	5.22	3.11	4.46	11.36	15.24	17.44
36	24.37	16.82	8.63	6.18	5.23	3.10	4.43	11.35	15.17	17.37
37	24.36	16.83	8.64	6.19	5.25	3.09	4.43	11.34	14.99	17.33
38	24.37	16.85	8.64	6.25	5.27	3.08	4.41	11.31	14.98	17.32
39	24.39	16.85	8.66	6.26	5.28	3.07	4.39	11.27	14.95	17.31
40	24.41	16.85	8.67	6.26	5.31	3.02	4.37	11.23	14.91	17.31

Table G-9: Shear modulus and damping values for silt (TP4) soil under an axial stress of 100kPa

Strain level	0.01%	0.10%	1%	2.50%	5%	0.01%	0.10%	1%	2.50%	5%
Cycles No.	G (MPa)					D (%)				
1	5.88	4.11	2.55	1.95	1.25	6.69	9.21	15.91	19.99	24.45
2	6.84	4.23	2.61	2.00	1.37	6.55	9.11	15.81	19.71	23.90
3	7.23	4.41	2.65	2.05	1.44	6.51	8.98	15.75	19.67	23.59
4	7.60	4.44	2.70	2.11	1.45	6.44	8.88	15.65	19.55	23.55
5	7.90	4.60	2.75	2.15	1.63	6.41	8.82	15.52	19.45	23.28
6	7.91	4.61	2.79	2.18	1.72	6.39	8.76	14.99	18.82	23.00
7	7.95	4.62	2.85	2.22	1.78	6.26	8.35	14.26	18.71	22.55
8	7.95	4.69	2.95	2.17	1.77	5.39	8.15	14.11	17.78	22.35
9	7.99	4.72	3.12	2.21	1.75	5.28	8.14	14.09	17.01	22.27
10	8.12	4.78	3.19	2.25	1.77	5.18	8.13	14.04	16.66	22.25
11	8.22	4.78	3.21	2.27	1.81	5.04	8.11	14.01	16.62	22.19
12	8.31	4.78	3.26	2.31	1.83	5.04	8.05	13.98	16.59	22.13
13	8.35	4.78	3.45	2.31	1.85	5.02	8.02	13.82	16.59	22.05
14	8.18	4.79	3.54	2.31	1.87	5.02	7.97	13.71	16.56	22.03
15	8.39	4.79	3.60	2.31	1.87	4.98	7.92	13.66	16.54	21.93
16	8.39	4.79	3.54	2.35	1.89	4.96	7.88	13.49	16.53	21.85
17	8.45	4.82	3.62	2.35	1.91	4.93	7.85	13.46	16.53	21.82
18	8.55	4.82	3.53	2.30	1.93	4.96	7.86	13.43	16.52	21.66
19	8.83	4.86	3.55	2.30	1.95	4.96	7.85	13.36	16.51	21.67
20	8.88	4.85	3.68	2.35	1.95	4.96	7.82	13.25	16.1	21.62
21	8.90	4.85	3.60	2.37	1.95	4.96	7.84	13.19	15.96	21.62
22	8.90	4.85	3.69	2.35	1.95	4.96	7.82	13.01	15.9	21.59
23	8.90	4.85	3.49	2.36	1.91	4.98	7.82	12.88	15.89	21.51
24	8.75	4.85	3.65	2.37	1.93	4.96	7.82	12.74	15.91	21.51
25	8.90	4.85	3.53	2.37	1.93	4.93	7.82	12.69	15.98	21.51
26	8.75	4.85	3.50	2.41	1.95	4.96	7.77	13.19	15.86	21.51
27	8.75	4.85	3.66	2.41	1.97	5.01	7.78	13.16	16.1	21.51
28	8.64	4.89	3.59	2.41	2.05	5.11	7.77	13.13	15.96	21.49
29	8.26	4.89	3.66	2.41	2.05	5.05	7.66	13.16	15.9	21.49
30	8.33	4.90	3.49	2.41	2.05	5.05	7.66	13.15	15.89	21.49
31	8.54	4.90	3.58	2.43	2.03	5.05	7.66	13.19	15.89	21.47
32	8.61	4.86	3.59	2.43	2.03	4.94	7.66	13.01	15.89	21.47
33	8.52	4.85	3.54	2.43	2.03	4.87	7.66	12.88	15.89	21.48
34	8.52	4.86	3.54	2.45	2.09	4.87	7.69	12.74	15.89	21.48
35	8.69	4.90	3.51	2.54	2.09	4.84	7.65	12.69	15.81	21.47
36	8.59	4.91	3.58	2.55	2.11	4.83	7.55	12.69	15.79	21.47
37	8.31	4.91	3.56	2.51	2.13	4.795	7.45	12.6	15.69	21.45
38	8.97	4.95	3.64	2.50	2.11	4.77	7.43	12.6	15.69	21.37
39	8.48	4.95	3.64	2.54	2.13	4.745	7.44	12.59	15.61	21.37
40	8.76	4.97	3.61	2.58	2.15	4.72	7.34	12.59	15.61	21.37

Table G-10: Shear modulus and damping values for silt (TP4) soil under an axial stress of 200kPa

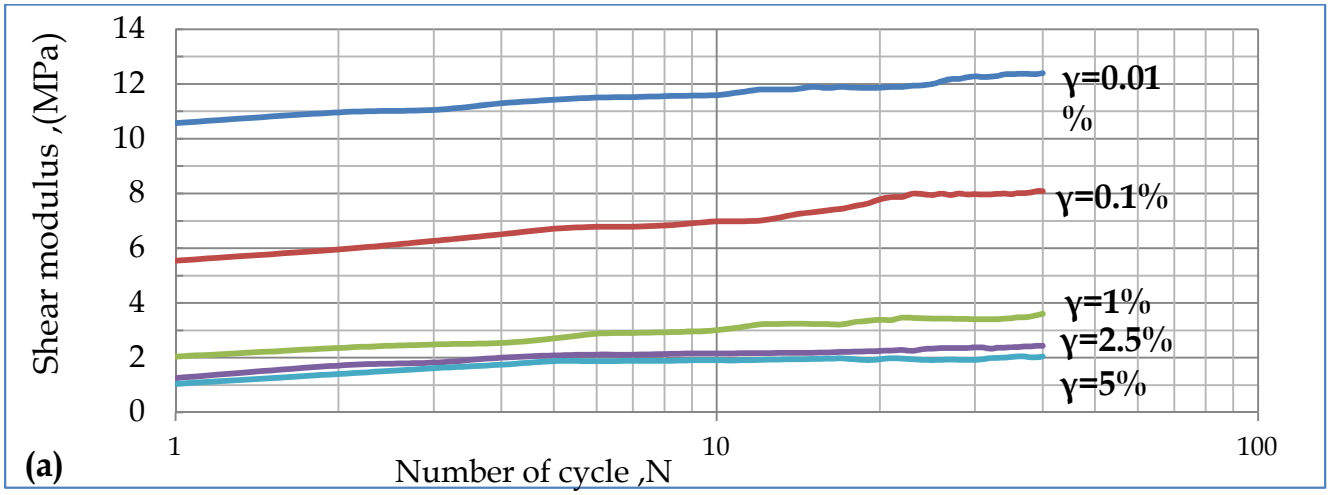
Strain level	0.01%	0.1%	1%	2.5%	5%	0.01%	0.1%	1%	2.5%	5%
Cycles No.	G (MPa)					D (%)				
1	15.04	7.86	3.55	2.14	1.25	5.71	8.91	16.56	23.36	25.72
2	15.32	8.27	4.45	2.68	1.83	5.71	8.51	16.03	21.35	24.61
3	15.43	8.62	4.79	3.22	2.34	5.66	8.27	15.54	20.02	23.91
4	15.49	8.79	5.02	3.47	2.52	5.58	8.01	15.19	19.21	23.34
5	15.7	8.89	5.04	3.61	2.62	5.5	8.01	14.67	18.65	22.99
6	15.78	8.92	5.11	3.63	2.65	5.41	7.92	14.65	18.41	22.81
7	15.84	8.98	5.19	3.63	2.66	5.39	7.91	14.63	18.26	22.79
8	15.85	9.18	5.21	3.64	2.68	5.37	7.84	14.54	18.16	22.66
9	15.92	9.25	5.29	3.66	2.74	5.35	7.77	14.45	17.99	22.58
10	15.93	9.31	5.34	3.68	2.75	5.33	7.75	14.43	17.71	22.55
11	15.95	9.35	5.41	3.72	2.77	5.25	7.71	14.41	17.32	22.45
12	15.97	9.38	5.47	3.75	2.78	5.25	7.61	14.38	17.11	22.38
13	15.98	9.45	5.54	3.76	2.81	5.16	7.42	14.35	16.89	22.37
14	15.99	9.47	5.62	3.79	2.83	5.05	7.22	14.28	16.84	22.31
15	16.01	9.51	5.69	3.81	2.87	4.99	7.19	13.99	16.75	22.27
16	16.02	9.65	5.67	3.81	2.94	4.89	7.13	13.91	16.72	22.25
17	16.05	9.64	5.65	3.82	2.93	4.87	6.99	13.89	16.76	22.19
18	16.15	9.64	5.72	3.85	2.95	4.86	6.99	13.88	16.72	22.13
19	16.16	9.71	5.73	3.91	2.97	4.79	6.97	13.84	16.71	22.05
20	16.18	9.72	5.75	3.88	2.99	4.79	6.93	13.63	16.66	22.03
21	16.19	9.75	5.79	3.88	2.99	4.75	6.83	13.56	16.62	21.93
22	16.19	9.76	5.77	3.89	2.98	4.74	6.76	13.41	16.59	21.85
23	16.2	9.78	5.78	3.91	2.99	4.71	6.74	13.39	16.59	21.82
24	16.2	9.84	5.79	3.93	3.05	4.69	6.74	13.27	16.56	21.66
25	16.21	9.85	5.81	3.91	3.09	4.65	6.68	13.25	16.54	21.67
26	16.21	9.85	5.82	3.93	3.11	4.64	6.67	13.16	16.53	21.62
27	16.22	9.86	5.83	3.95	3.14	4.67	6.65	12.94	16.53	21.62
28	16.22	9.94	5.83	3.96	3.19	4.67	6.66	12.84	16.52	21.59
29	16.23	9.95	5.83	3.97	3.19	4.57	6.65	12.73	16.51	21.51
30	16.25	9.98	5.85	3.98	3.21	4.55	6.67	12.73	16.45	21.49
31	16.26	9.99	5.87	3.98	3.24	4.54	6.65	12.65	16.45	21.46
32	16.27	9.97	5.89	3.98	3.22	4.45	6.63	12.63	16.42	21.44
33	16.28	10.01	5.91	3.99	3.25	4.44	6.63	12.59	16.42	21.39
34	16.29	10.08	5.93	4.08	3.29	4.43	6.63	12.58	16.41	21.38
35	16.28	10.11	5.94	4.11	3.31	4.39	6.53	12.49	16.41	21.36
36	16.29	10.13	5.96	4.11	3.31	4.34	6.47	12.49	16.36	21.33
37	16.31	10.21	5.96	4.12	3.32	4.32	6.43	12.42	16.37	21.29
38	16.32	10.21	5.98	4.14	3.32	4.23	6.41	12.42	16.34	21.26
39	16.37	10.22	5.97	4.14	3.34	4.21	6.34	12.36	16.34	21.24
40	16.39	10.23	5.99	4.15	3.34	4.18	6.34	12.27	16.31	21.21

Table G-11: Shear modulus and damping values for silt (TP4) soil under an axial stress of 300kPa

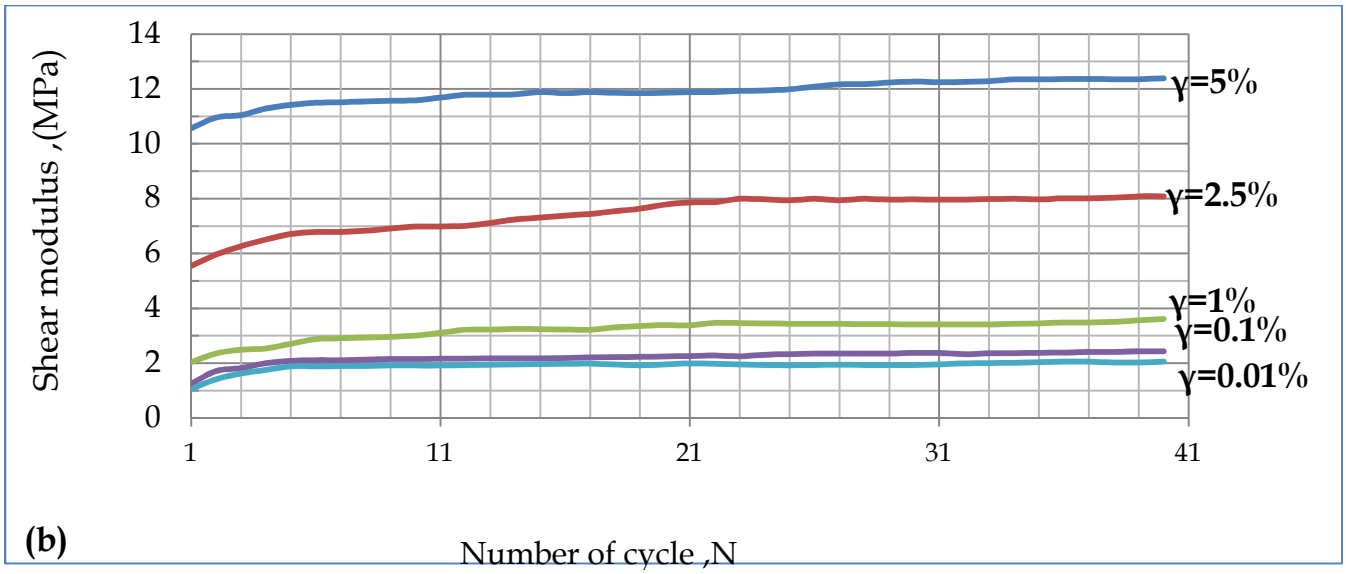
Strain level	0.01%	0.1%	1%	2.5%	5%	0.01%	0.1%	1%	2.5%	5%
Cycles No.	G (MPa)					D (%)				
1	20.25	10.25	6.33	4.14	3.35	3.99	6.23	13.96	18.64	20.99
2	20.99	11.01	6.47	4.55	3.65	3.97	6.21	13.13	17.94	20.89
3	21.13	11.63	6.47	4.73	4.03	3.94	6.21	12.99	17.74	20.83
4	21.23	12.18	6.51	4.76	4.11	3.92	6.09	12.97	17.67	20.77
5	21.26	12.25	6.58	4.91	4.2	3.91	6.09	12.95	17.34	20.33
6	21.34	12.59	6.62	4.93	4.24	3.85	6.03	12.94	17.24	19.96
7	21.35	12.68	6.66	4.92	4.29	3.81	5.99	12.94	17.14	19.81
8	21.36	12.79	6.73	4.94	4.31	3.77	5.99	12.93	17.14	19.77
9	21.37	12.83	6.81	4.96	4.33	3.77	5.78	12.89	17.11	19.78
10	21.41	12.85	6.84	4.97	4.35	3.73	5.63	12.83	17.12	19.8
11	21.45	12.87	6.83	4.96	4.38	3.71	5.54	12.79	17.12	19.76
12	21.48	12.89	6.88	4.96	4.35	3.71	5.51	12.66	17.09	19.58
13	21.56	12.93	6.91	4.95	4.33	3.75	5.47	12.53	17.05	19.58
14	21.55	12.93	6.92	4.95	4.39	3.74	5.73	12.46	17.09	19.48
15	21.63	12.95	6.93	4.94	4.41	3.69	5.72	12.44	17.04	19.46
16	21.65	12.97	6.97	4.97	4.42	3.65	5.63	12.38	17.01	19.44
17	21.65	13.06	6.96	4.98	4.45	3.64	5.61	12.29	16.92	19.43
18	21.63	13.08	6.97	4.99	4.44	3.63	5.56	12.21	16.92	19.39
19	21.74	13.11	6.97	4.99	4.47	3.61	5.53	12.12	16.88	19.37
20	21.76	13.17	6.97	4.99	4.45	3.55	5.51	12.13	16.87	19.34
21	21.77	13.21	6.98	5.03	4.44	3.55	5.49	12.07	16.86	19.34
22	21.77	13.25	6.97	5.09	4.44	3.54	5.48	11.96	16.86	19.28
23	21.79	13.28	6.97	5.09	4.45	3.55	5.44	11.84	16.82	19.29
24	21.81	13.29	6.98	5.03	4.49	3.49	5.45	11.73	16.83	19.24
25	21.87	13.31	6.98	5.11	4.48	3.49	5.41	11.69	16.83	19.24
26	21.88	13.39	6.97	5.17	4.49	3.45	5.34	11.63	16.82	19.17
27	21.91	13.39	6.99	5.19	4.52	3.47	5.32	11.57	16.79	19.17
28	21.92	13.41	7.01	5.19	4.48	3.41	5.27	11.53	16.78	19.15
29	21.93	13.42	6.98	5.29	4.48	3.43	5.17	11.52	16.77	19.12
30	21.96	13.45	7.01	5.29	4.49	3.41	4.92	11.48	16.72	19.11
31	22.03	13.46	7.01	5.24	4.52	3.39	4.83	11.48	16.73	19.13
32	22.14	13.48	6.99	5.24	4.53	3.37	4.74	11.35	16.73	19.09
33	22.23	13.53	7.01	5.31	4.52	3.35	4.75	11.31	16.72	19.08
34	22.29	13.53	6.98	5.32	4.57	3.35	4.75	11.28	16.71	19.06
35	22.28	13.57	6.99	5.33	4.56	3.31	4.74	11.19	16.69	19.02
36	22.32	13.57	7.01	5.34	4.58	3.28	4.71	11.18	16.69	18.98
37	22.38	13.61	6.99	5.33	4.59	3.28	4.68	11.14	16.69	18.89
38	22.39	13.61	6.98	5.32	4.61	3.27	4.67	11.09	16.65	18.89
39	22.39	13.65	6.98	5.35	4.61	3.27	4.65	11.02	16.56	18.88
40	22.41	13.65	6.92	5.38	4.61	3.17	4.63	11.01	16.54	18.87

Table G-12: Shear modulus and damping values for silt (TP4) soil under an axial stress of 400kPa

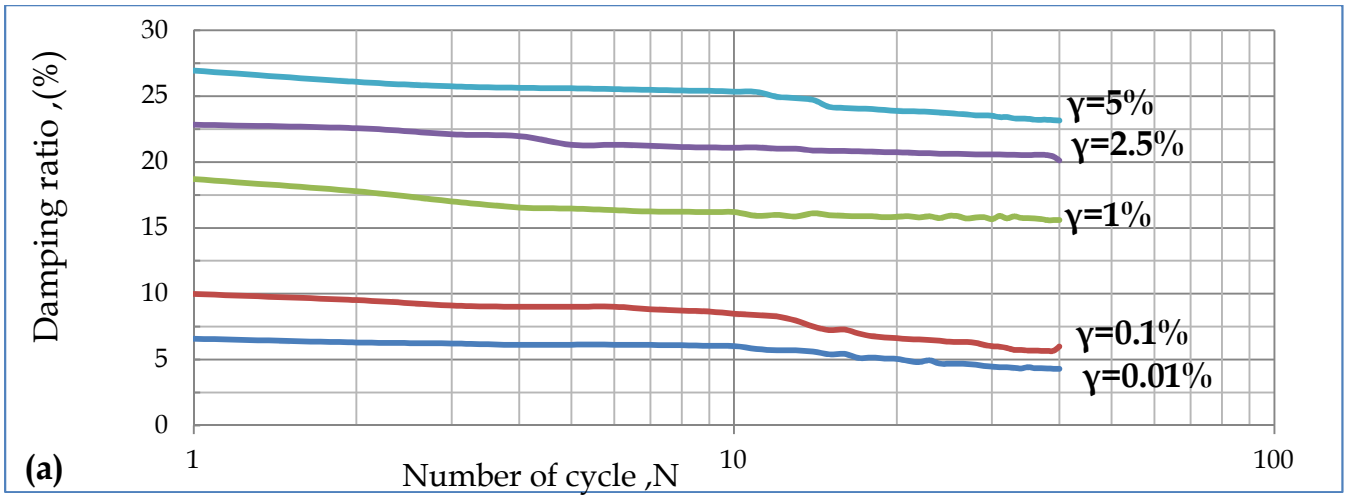
Strain level	0.01%	0.1%	1%	2.5%	5%	0.01%	0.1%	1%	2.5%	5%
Cycles No.	G (MPa)					D (%)				
1	24.05	14.06	6.89	4.85	3.95	3.51	5.15	10.89	14.88	18.68
2	24.37	14.36	7.26	5.46	4.65	3.29	4.88	10.76	14.25	18.28
3	24.52	14.75	7.36	5.66	4.85	3.26	4.46	10.75	14.32	18.17
4	24.64	14.99	7.48	5.69	5.01	3.15	4.44	10.64	14.29	17.87
5	24.77	15.16	7.53	5.72	5.09	2.85	4.44	10.6	14.26	17.68
6	24.79	15.22	7.46	5.71	5.13	2.79	4.38	10.53	14.26	17.04
7	24.81	15.27	7.55	5.72	5.16	2.72	4.39	10.34	14.23	16.89
8	24.82	15.27	7.56	5.72	5.27	2.74	4.36	10.11	14.23	16.69
9	24.88	15.28	7.59	5.79	5.28	2.68	4.37	9.87	14.22	16.65
10	24.92	15.36	7.68	5.79	5.24	2.68	4.35	9.84	13.5	16.56
11	24.97	15.38	7.68	5.83	5.24	2.64	4.34	9.61	14.23	16.61
12	24.99	15.43	7.67	5.84	5.25	2.58	4.34	9.53	14.21	16.33
13	25.05	15.43	7.68	5.84	5.27	2.58	4.28	9.41	14.22	16.14
14	25.07	15.46	7.68	5.87	5.28	2.59	4.29	9.34	14.26	16.16
15	25.05	15.44	7.68	5.88	5.32	2.59	4.26	9.25	14.21	16.16
16	25.11	15.48	7.69	5.93	5.34	2.57	4.25	9.11	14.21	16.15
17	25.15	15.49	7.71	5.98	5.33	2.56	4.24	9.13	14.19	16.14
18	25.13	15.52	7.72	5.99	5.33	2.58	4.15	9.11	14.17	16.07
19	25.18	15.53	7.76	6.09	5.34	2.54	4.09	8.99	14.18	15.99
20	25.16	15.63	7.86	6.04	5.37	2.52	3.95	8.98	14.11	15.73
21	25.19	15.67	7.88	6.07	5.38	2.52	3.93	8.88	13.89	15.72
22	25.19	15.69	7.89	6.05	5.38	2.52	3.83	8.86	13.87	15.65
23	25.21	15.71	7.9	6.13	5.39	2.46	3.79	8.83	13.79	15.42
24	25.26	15.76	7.91	6.16	5.4	2.49	3.75	8.82	13.74	15.35
25	25.24	15.78	7.97	6.16	5.41	2.44	3.72	8.85	13.72	15.34
26	25.24	15.78	7.99	6.14	5.41	2.45	3.74	8.81	13.76	15.35
27	25.27	15.79	8.07	6.17	5.41	2.46	3.68	8.81	13.73	15.36
28	25.26	15.81	8.11	6.16	5.41	2.41	3.66	8.79	13.65	15.34
29	25.28	15.86	8.19	6.15	5.43	2.39	3.63	8.79	13.65	15.28
30	25.32	15.87	8.18	6.17	5.42	2.33	3.64	8.71	13.62	15.31
31	25.37	15.89	8.17	6.16	5.42	2.33	3.64	8.73	13.61	15.27
32	25.35	15.92	8.16	6.16	5.43	2.33	3.61	8.68	13.6	15.23
33	25.38	15.93	8.27	6.16	5.43	2.28	3.56	8.61	13.58	15.25
34	25.42	15.93	8.28	6.17	5.45	2.26	3.56	8.58	13.48	15.25
35	25.43	15.94	8.28	6.18	5.45	2.29	3.53	8.64	13.41	15.21
36	25.48	15.95	8.29	6.26	5.46	2.32	3.47	8.54	13.29	15.21
37	25.48	15.96	8.31	6.28	5.46	2.26	3.46	8.51	13.13	15.19
38	25.51	15.98	8.35	6.36	5.47	2.24	3.47	8.53	12.95	15.18
39	25.52	15.99	8.34	6.36	5.48	2.2	3.43	8.53	12.78	15.18
40	25.54	15.99	8.36	6.36	5.48	2.05	3.41	8.44	12.26	15.18

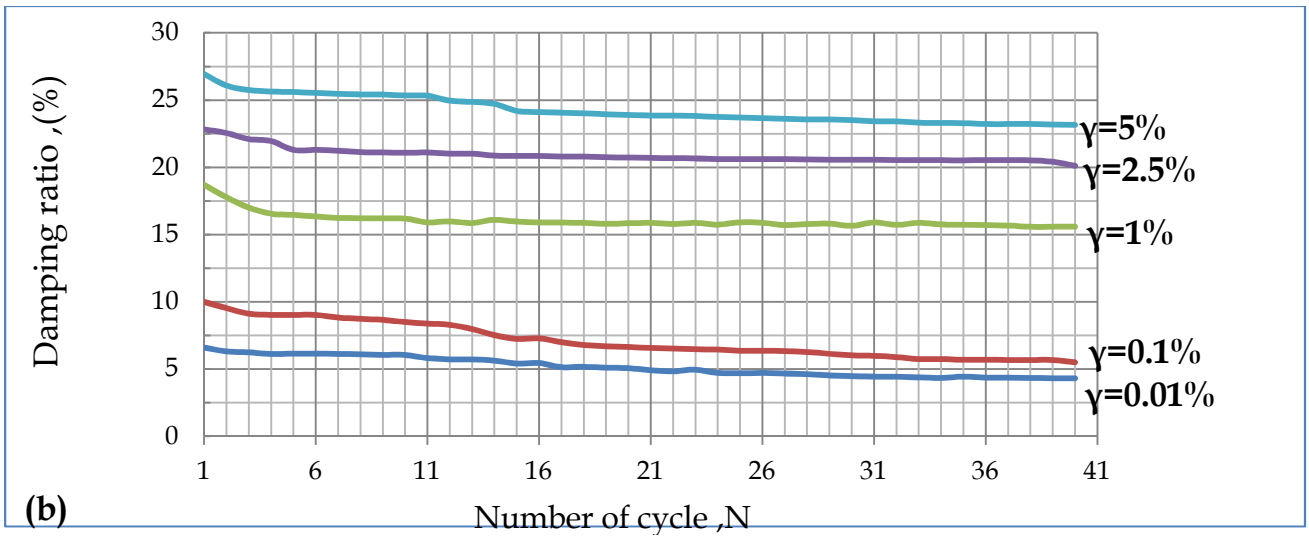

Shear modulus ,(MPa)
14
12
10
8
6
4
2
0
1
10
100
Number of cycle ,N
γ=0.01 %
γ=0.1%
γ=1%
γ=2.5%
γ=5%

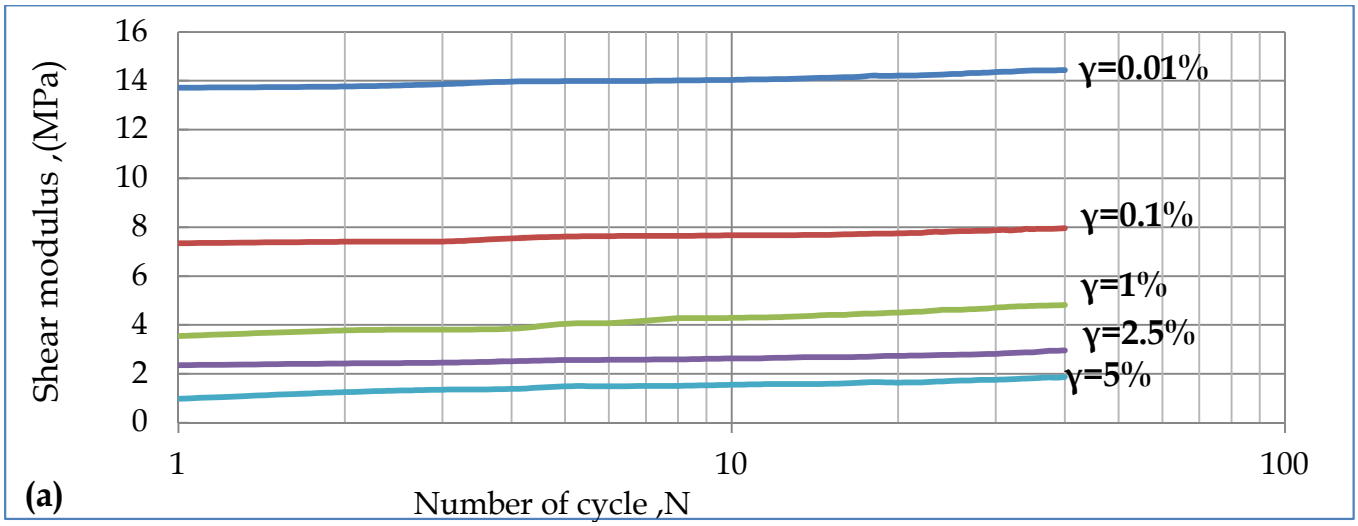
(a)

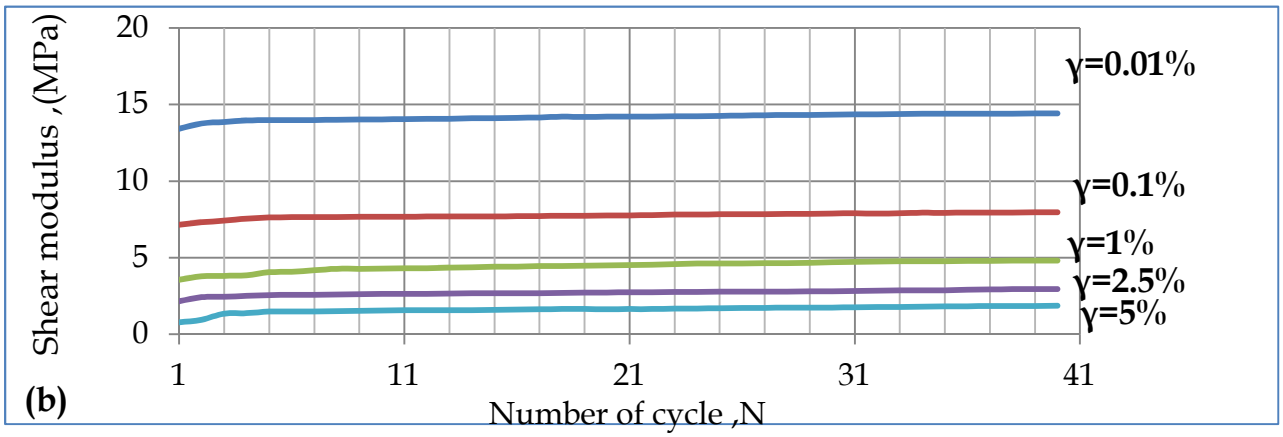

Shear modulus ,(MPa)
14
12
10
8
6
4
2
0
1
11
21
31
41
Number of cycle ,N
γ=5%
γ=2.5%
γ=1%
γ=0.1%
γ=0.01%

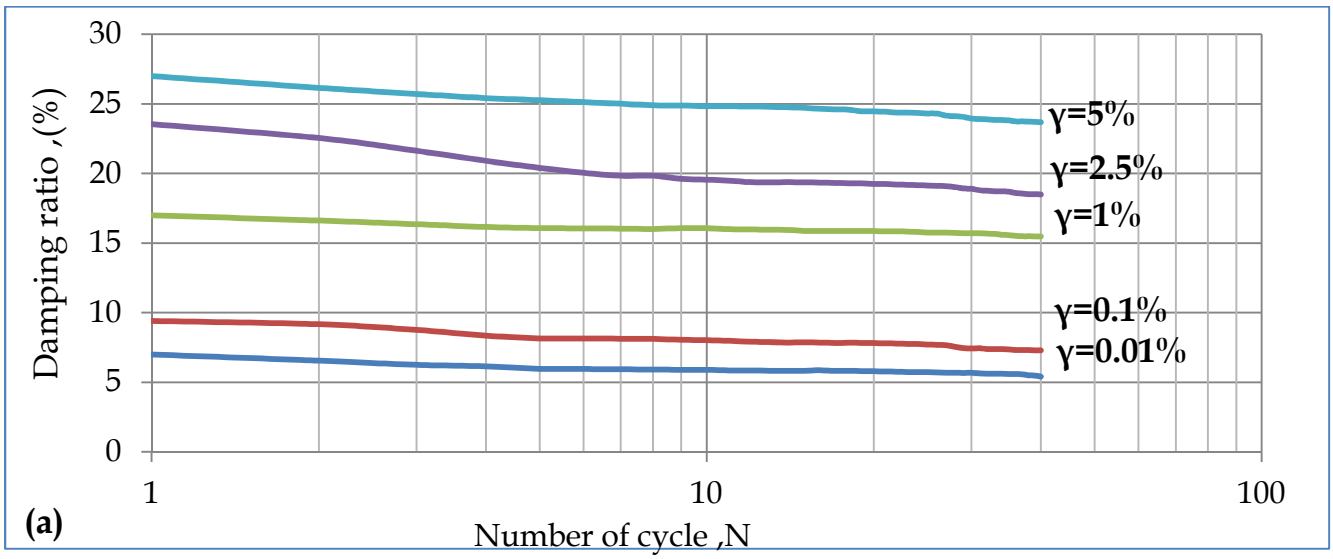
(b)

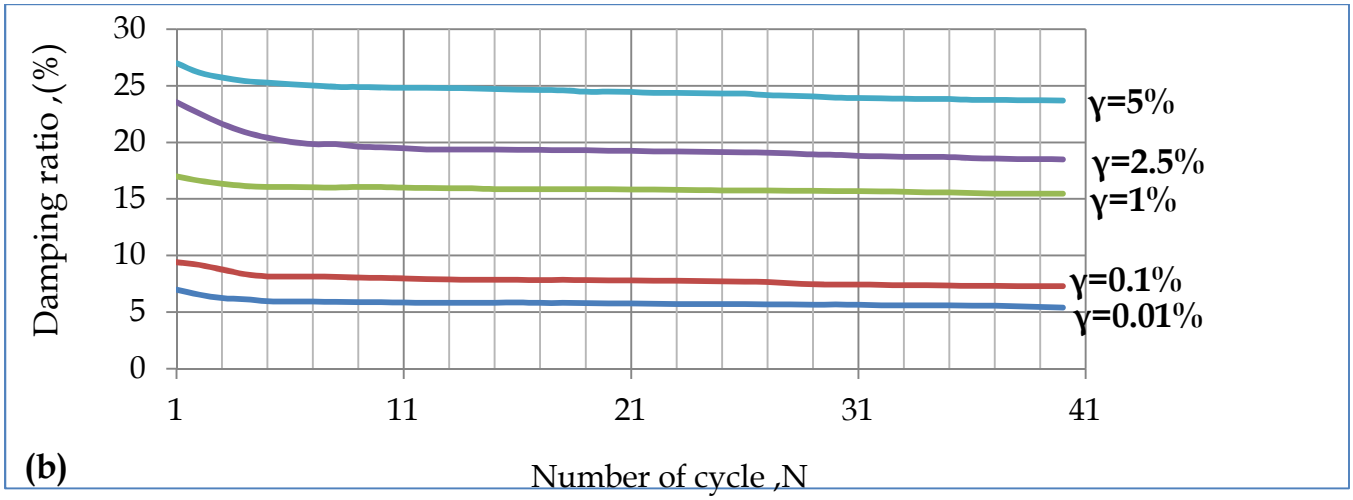

Damping ratio ,(%)
30
25
20
15
10
5
0
1
10
100
Number of cycle ,N
γ=5%
γ=2.5%
γ=1%
γ=0.1%
γ=0.01%
(a)

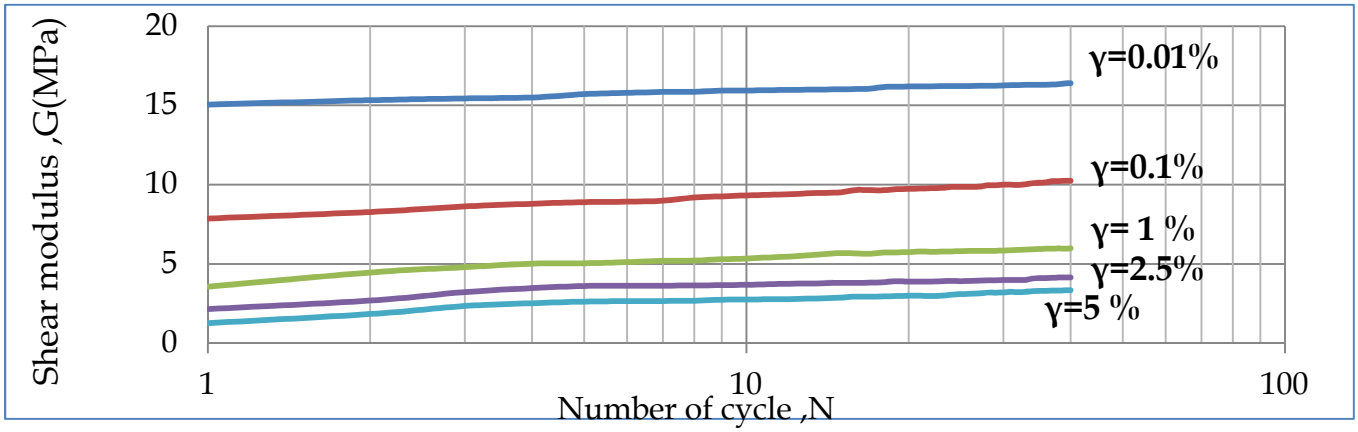

Damping ratio ,(%)
30
25
20
15
10
5
0
1
6
11
16
21
26
31
36
41
Number of cycle ,N
γ=5%
γ=2.5%
γ=1%
γ=0.1%
γ=0.01%
(b)

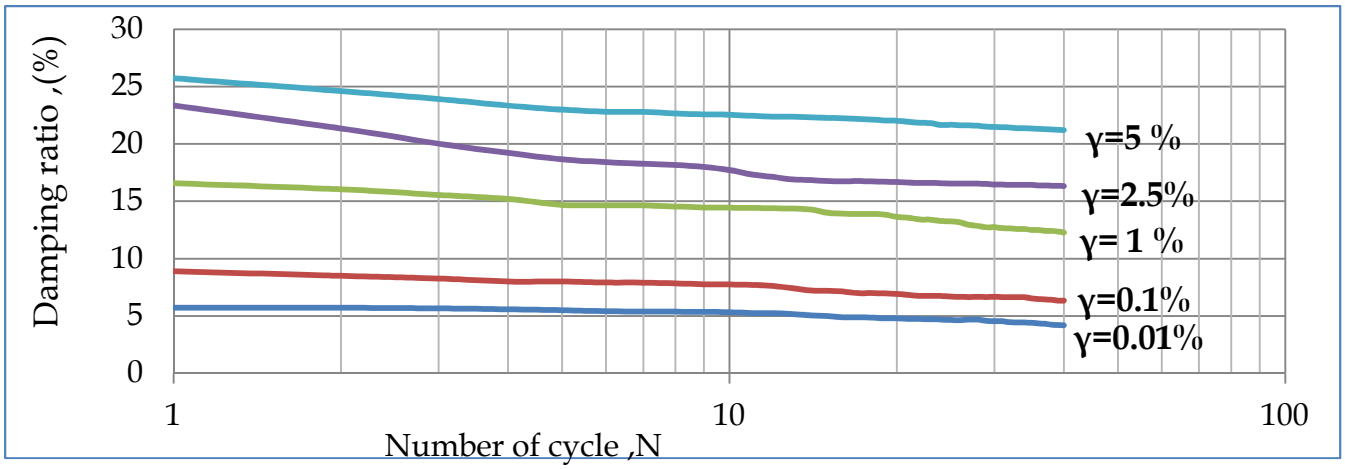

Shear modulus ,(MPa)
16
14
12
10
8
6
4
2
0
1
10
100
Number of cycle ,N
γ=0.01%
γ=0.1%
γ=1%
γ=2.5%
γ=5%
(a)

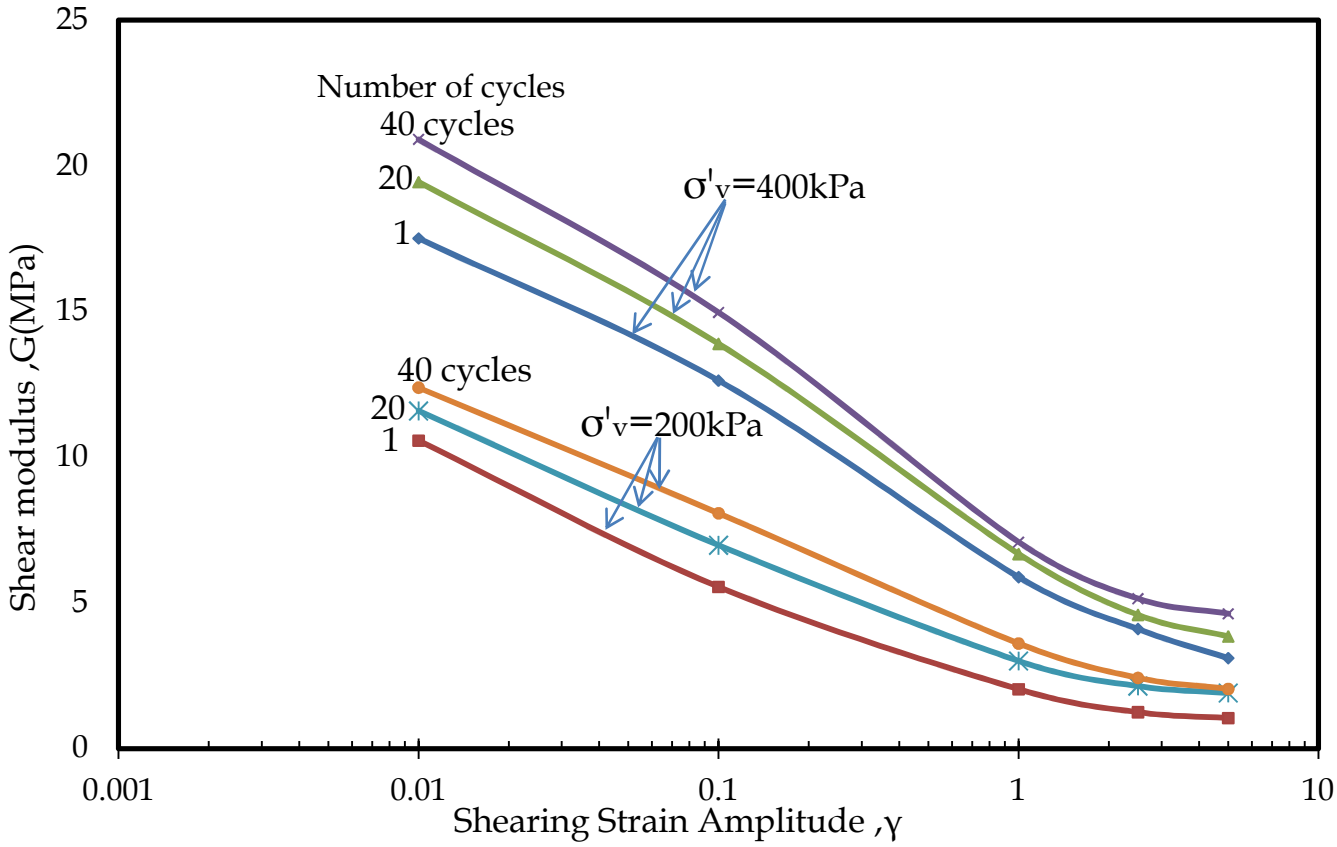

Shear modulus ,(MPa)
20
15
10
5
0
1
11
21
31
41
Number of cycle ,N
γ=0.01%
γ=0.1%
γ=1%
γ=2.5%
γ=5%
(b)

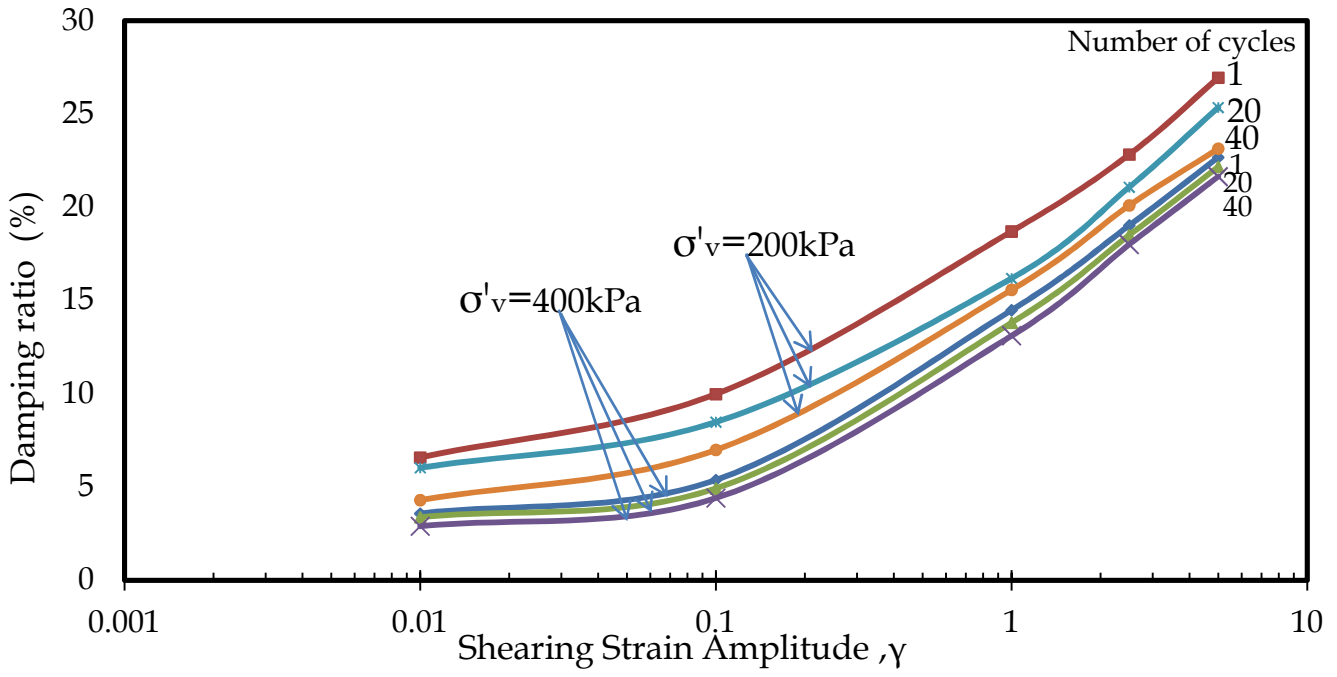

Damping ratio ,(%)
30
25
20
15
10
5
0
1
10
100
Number of cycle ,N
γ=5%
γ=2.5%
γ=1%
γ=0.1%
γ=0.01%
(a)

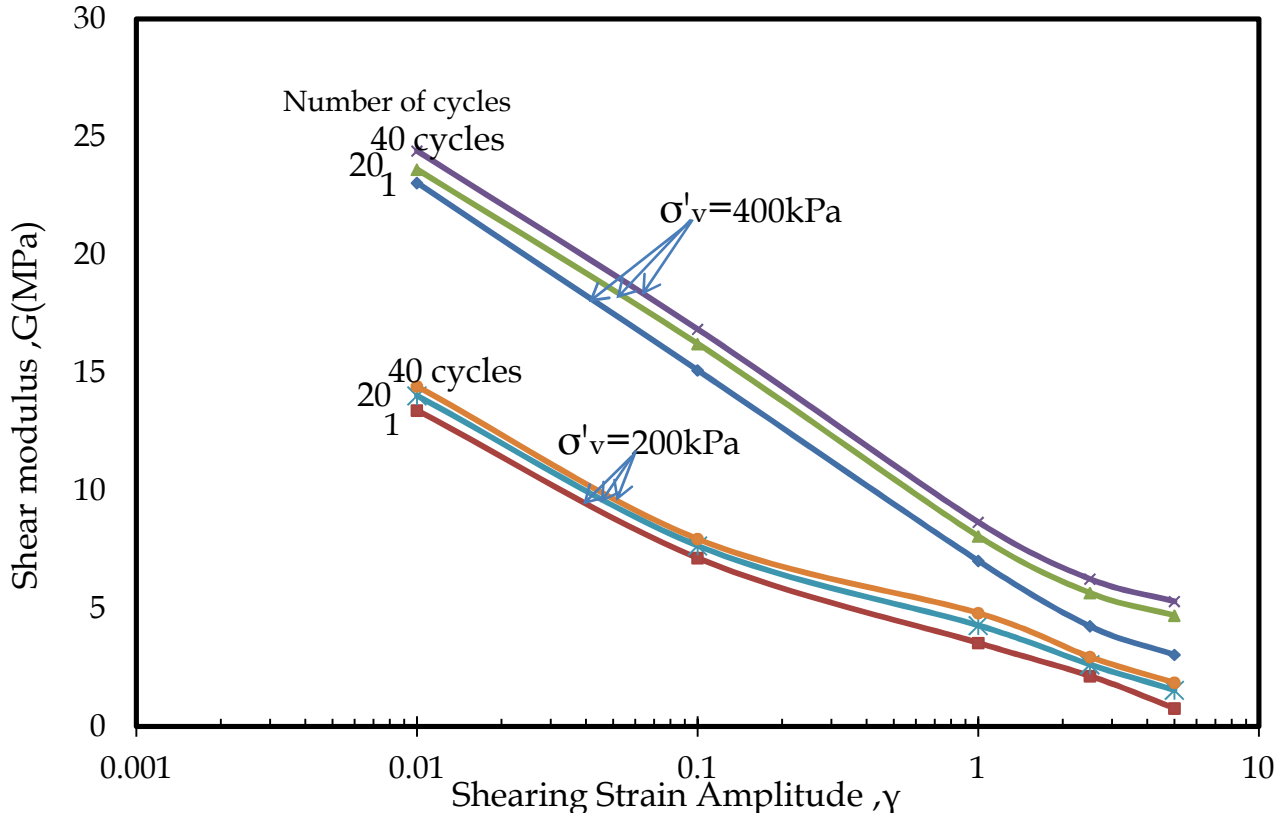

Damping ratio ,(%)
30
25
20
15
10
5
0
1
11
21
31
41
γ=5%
γ=2.5%
γ=1%
γ=0.1%
γ=0.01%
(b)
Number of cycle ,N

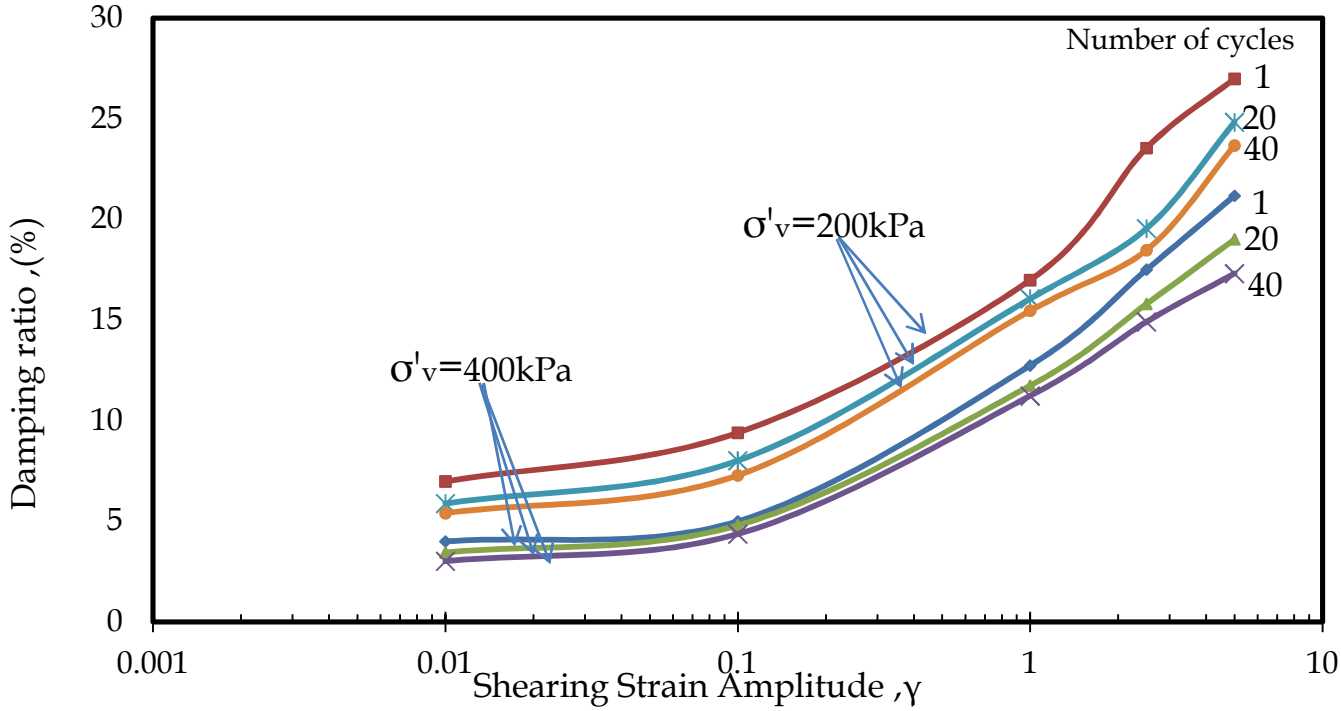

Shear modulus ,G(MPa)
20
15
10
5
0
1
10
100
γ=0.01%
γ=0.1%
γ= 1 %
γ=2.5%
γ=5 %
Number of cycle ,N

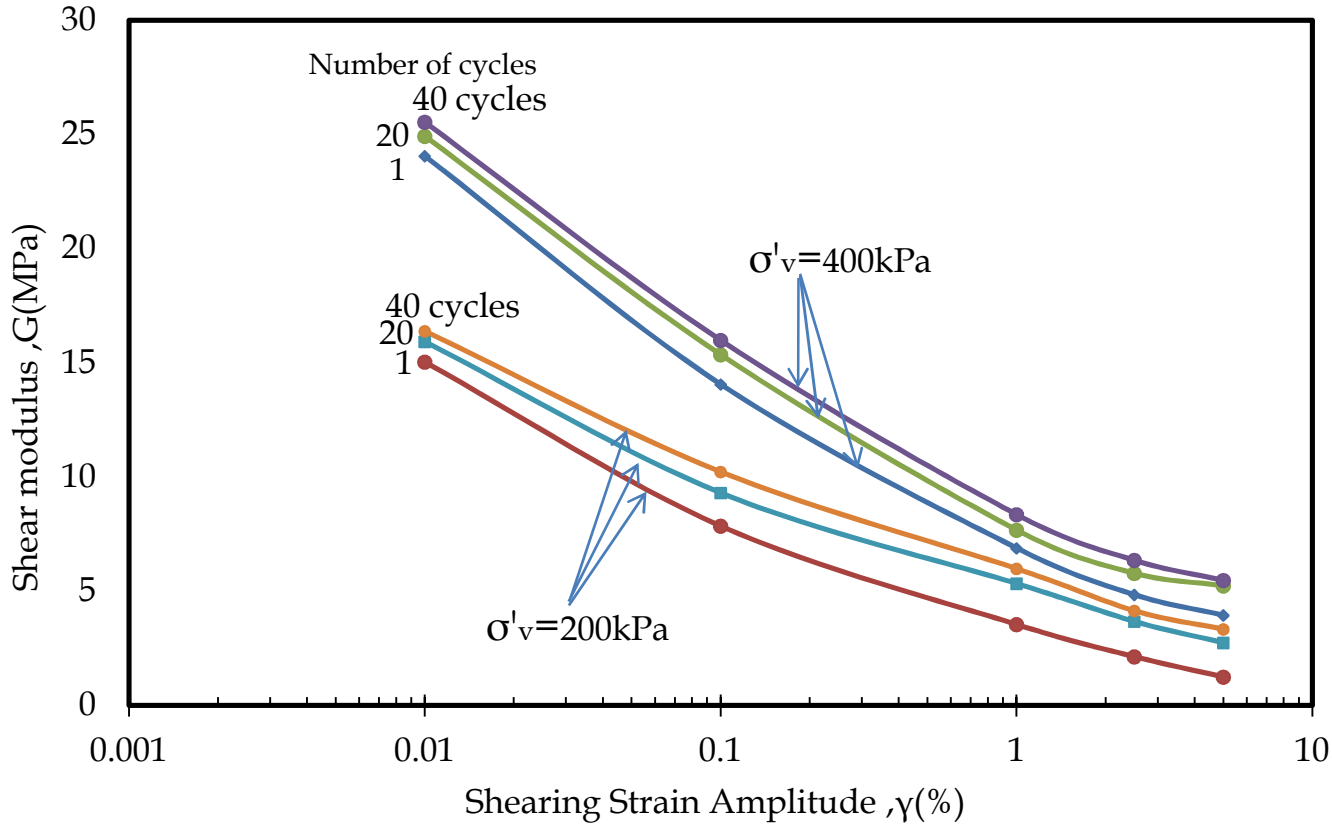

Damping ratio ,(%)
30
25
20
15
10
5
0
1
10
100
γ=5 %
γ=2.5%
γ= 1 %
γ=0.1%
γ=0.01%
Number of cycle ,N

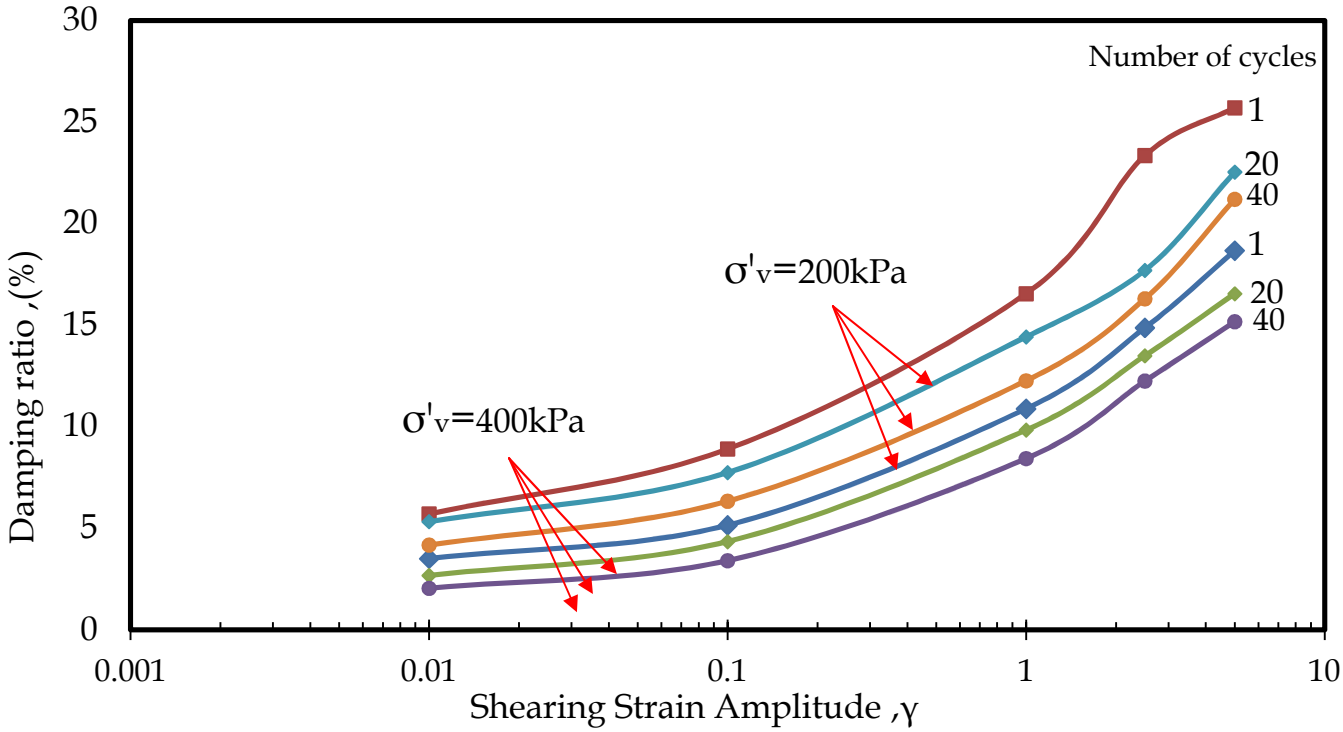

Number of cycles
40 cycles
20
1
σ'v=400kPa
40 cycles
20
1
σ'v=200kPa
Shear modulus ,G(MPa)
Shearing Strain Amplitude ,γ
0
5
10
15
20
25
0.001
0.01
0.1
1
10


Number of cycles
1
20
40
1
20
40
σ'v=200kPa
σ'v=400kPa
Damping ratio (%)
Shearing Strain Amplitude ,γ
0
5
10
15
20
25
30
0.001
0.01
0.1
1
10


Number of cycles
40 cycles
20
1
σ'v=400kPa
40 cycles
20
1
σ'v=200kPa
Shear modulus ,G(MPa)
Shearing Strain Amplitude ,γ
0
5
10
15
20
25
30
0.001
0.01
0.1
1
10


Number of cycles
1
20
40
1
20
40
σ'v=200kPa
σ'v=400kPa
Damping ratio ,(%)
Shearing Strain Amplitude ,γ
0
5
10
15
20
25
30
0.001
0.01
0.1
1
10


Number of cycles
40 cycles
20
1
σ'v=400kPa
40 cycles
20
1
σ'v=200kPa
Shear modulus ,G(MPa)
Shearing Strain Amplitude ,γ(%)
0
5
10
15
20
25
30
0.001
0.01
0.1
1
10


Number of cycles
1
20
40
1
20
40
σ'v=200kPa
σ'v=400kPa
Damping ratio ,(%)
Shearing Strain Amplitude ,γ
0
5
10
15
20
25
30
0.001
0.01
0.1
1
10

Declaration:

I, the undersigned, declare that the thesis is my original work, has not been presented for a degree in any other university and that all sources of materials used for the thesis have been duly acknowledged.

Name: Abraham Mengistu

Signature: _____

Place: Addis Ababa Institute of Technology,
Addis Ababa University,
Addis Ababa.

Date of Submission: February, 2015