ADAMA SCIENCE AND TECHNOLOGY UNIVERSITY

SCHOOL OF CIVIL ENGINEERING AND ARCHITECTURE

DEPARTMENT OF CIVIL ENGINEERING

INVESTIGATION OF SHEAR MODULUS AND DAMPING RATIO OF MODJO SILT AND SILTY SAND SOIL USING CYCLIC SIMPLE SHEAR TEST

By

Yohannes Hailemariam Asfaw

JUNE, 2015

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A Thesis Submitted to Adama Science and Technology University School of Graduate Studies In Partial Fulfillment of the Requirements for the Degree of Master of Science in Civil Engineering (Geotechnical Engineering).

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JUNE, 2015

DECLARATION

This thesis is my original work, has not been presented for a degree in any other university and that all sources of material used are duly acknowledged.

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LIST OF ABBREVIATIONS AND NOTATIONS

AASHTO	American Association of State Highway and Transportation Officials;
ASTM	American Society for Testing and Materials;
DSS	Direct Simple Shear;
MD	Modjo dry port;
NMR	Near Exit of Minjar road;
SH	Shashemane road;
TK	Teklehaymanot church;
USCS	Unified Soil Classification System;
A	Area;
A_{loop}	Area of the stress - strain loop;
A_{Δ}	Area of triangle;
D	Damping ratio;
D_o	Minimum damping ratio;
e	Void ratio;
e_{max}, e_{min}	Maximum and minimum void ratios;
F	Shear force;
G_{max}, G_o	Maximum shear modulus;
G	Shear modulus;
G/G_{max}	Normalized shear modulus;
G_{sec}	Secant shear modulus;
k	Dimensionless quantity (exponential parameter) which is a function of PI;
K_o	Coefficient of lateral earth pressure;
LL	Liquid Limit;
LI	Liquidity Index;
LVDT	Linear Variable Differential Transformer, displacement sensor;
OCR	Over consolidation ratio;
P_c	Pre-consolidation pressure;
P_o	Present effective vertical pressure;

PI	Plasticity Index;
PL	Plasticity Limit;
w	Natural water content;
W_D	Energy dissipated during one cycle;
W_S	Maximum elastic stored energy;
σ'_o	Effective confining stress;
σ'_v	Vertical effective stress;
γ	Strain amplitude and
τ	Shear stress.

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ABSTRACT

The most important dynamic soil properties are shear modulus and damping ratio which plays a crucial role in prediction and analysis of soil responses in dynamic loadings. The behavior of soils subjected to dynamic loading is influenced by these soil properties. In this study an attempt was done to determine the shear modulus and damping ratio of Modjo town soils by giving emphasis to Modjo Dry Port. The soil samples were collected from Modjo town at four different locations, namely; Modjo dry port (MD), Teklehaymanot church (TK) and Shashemane road exit (SH) and Near minjar road (NMR).

Investigation of index properties of Modjo soils were done and classified using USCS and AASHTO soil classification system. Based on test results, the soil from MD, TK and SH were highly plastic silt soils and NMR was silty sand. The shear modulus and damping ratio values were determined using cyclic simple shear machine. Strain-controlled cyclic test were conducted at a cyclic loading frequency of 1Hz with a remoulded sample of 70mm diameter and 20mm hight. The tests were conducted as a function of cyclic strain amplitude of 0.01%, 0.1%, 1%, 3%, and 5% under axial stresses of 100kPa, 200kPa and 400kPa. The value of shear modulus was in the range of 0.11MPa to 22.98MPa and damping ratio values range between 0.25% and 25.63%.

This study systematically investigates the effect of cyclic shear strain amplitude, confining stress, number of loading cycles, void ratio and soil plasticity on the shear modulus (G) and damping ratio (D) values. As number of loading cycles and confining pressure increase, the shear modulus increases and damping ratio decreases. Shear modulus decreases and damping ratio increases with increase in cyclic shear strain amplitude. The shear modulus values of Modjo soils were normalized to compare with previously developed values in the literature. It was compared with sand and saturated clay soil values for different cases.

Key words:- *Cyclic loading, Shear modulus, Damping ratio, Normalized shear modulus, Cyclic simple shear test.*

1. INTRODUCTION

1.1 Background of the Study

Geotechnical earthquake engineering is a new discipline that was formally defined in the first international conference on geotechnical earthquake engineering in Tokyo in 1995. Soil dynamics is an essential part of geotechnical earthquake engineering. The dynamic properties of natural soil deposits are important to study geotechnical engineering problems involving soil-structure interactions, site responses of soil deposits and prediction of the ground motion. Two of the most important parameters required for dynamic analysis are the soil stiffness (Shear modulus) and material damping (damping ratio). These soil properties used to evaluate the dynamic response of soils at different strain levels. Dynamic soil responses needed for earthquake analysis, in machine foundation design, wind power plant foundations, fast transportation systems, blast resistant structures, the response of offshore soils and supported structures to ocean wave loads.

Developments of soil dynamics over the last decades have been motivated by the occurrence of catastrophic seismic events. These seismic hazards subjected to seismic loadings include building collapse, bridges failure, failure in slopes and earth retaining structures. Strictly speaking, the concept of dynamic loading of soil refers to the propagation of stress waves through soil layers. The term “cyclic” refers to systems oscillating with constant amplitude and frequency. Cyclic loadings are those loads that exhibit a degree of regularity both in its magnitude and frequency. Characterization of dynamic soil properties required for the analysis of foundation vibrations and geotechnical earthquake engineering problems.

Ethiopia is susceptible to Earthquake activities, as it has experienced some recorded earthquake events. Different studies in different places and in different times have been done on dynamic properties of soils in Ethiopia. On red clay soils in Gulelle area of Addis Ababa [7], on red brown clay soils in Kolfe Keraneo area of Addis Ababa [31], silt and silty sand soils of Adama city [17], dry koka sand [57], silty soils of Dessie town [1], Hawassa city soil [19] and Arba Minch town soil [12] and silty and silty sand soil of Ziway town [38] were previously studied.

Even though extensive amounts of earthquake records exist in Ethiopia, the structural damage to infrastructures in the vast past period was obviously very low due to the extreme limitation of built-up environments. Starting from the 1950s and 1960s noticeable building and infrastructure activities were characterized in the seismic-prone areas. Table 1.1 below shows some of the earthquake and its damage in Ethiopia [48].

In this study, the dynamic soil properties of Modjo town were determined to create awareness and to give dynamic soil information for future proper dynamic load resistance foundation in the town. Special attention was given to large infrastructures like; Modjo dry port, Tannery factories, Leather and Textile industries and the new giant international airport planned to be built around Modjo town. Correct evaluation of shear modulus and damping in soil is very important for both the fundamental understanding of soil behaviour and the practical application of soil modeling.

1.2 Objective of the Study

- ✓ Determination of shear modulus and damping ratio of Modjo town soil.
- ✓ To provide dynamic soil information for dynamic loading considered foundation designs.
- ✓ To assess some of the critical factors of dynamic soil properties.
- ✓ Analyze the test results from the different locations of Modjo town and come up with a conclusions and recommendations by comparing with reviewed researches.

1.3 Scope and Problem Statement of the Study

The scope of this study is limited to the determination of cyclic properties of Modjo town soil. Modjo town was chosen, as it is part of the Great Rift Valley region, which is earthquake prone area. It hosts the Modjo dry port, two Tannery Factories, one Textile Factory and others. Five Textile, six Leather, one Beer Factories are planned to be built in Modjo [58]. The responses of the soil to dynamic loadings are not considered in the previous geotechnical activities.

To address the objectives/goals of the study and to provide dynamic soil properties information, the basic index properties and cyclic properties were investigated. Disturbed samples were collected from four different locations of Modjo town. Index property test were done on these samples and classification was made according to USCS and AASHTO classification systems. The dynamic properties of soils can be determined either in the field or in the laboratory. The evaluation and characterization of dynamic soil properties by experimental methods is a powerful tool in geotechnical engineering and required before any geotechnical design. Laboratory determination of the dynamic properties is convenient and allows easy and precise control on different parameters that affect the soil properties. Laboratory determination of the dynamic properties may be affected by unknown sources of errors and unverified assumptions used in the analysis of data. In this study, the shear modulus and damping ratio of Modjo soil was determined using cyclic simple shear machine ASTM standard laboratory technique. It provides more consistent test results and considered as one of the most accurate ways to determine the dynamic properties of soils at high shear strain levels. For this test, remoulded soil samples were prepared by using the field density and natural moisture content.

Dynamic properties of soils used to solve problems such as response of foundations and structures to earthquake loads, machine excitations, wind and wave loads. The results from this study help geotechnical engineers to know the behavior of soil in a wide strains range from 0.01% to 5%. It will be applicable in designing of foundations for machines and other large-scale civil engineering structures and geotechnical activities in the town.

1.4 Description of the Sampling Area

Modjo or Mojo is a town in central Ethiopia at 73km from Addis Ababa, named after the nearby Modjo River. Modjo is located in the East Shewa zone of the Oromia region and has a latitude and longitude of 8°39′N 39°5′E with an elevation between 1788 and 1825 meters above sea level. It is the administrative center of Lome woreda.

It is not only accessible by road but has been the location of train station of the Addis Ababa – Djibouti railway since the line was extended from Dire Dawa to Akaki in 1915. Based on figures from the Central Statistical Agency in 2005, Modjo has an estimated total population of 39,316 of which 19,278 were males and 20,038 were females. From geographical evidences it is located in the great Rift Valley zone of Ethiopia which is prone to an earthquake activity and classified as seismic zone four [48]. Moreover, it is the center of distribution for the south eastern and central parts of Ethiopia, which exposed for further civil engineering works like high-rise buildings, residential complexes, Factories, large industrial and commercial centers etc.

Modjo town hosts Modjo dry port, two Tannery Factories, one Textile Factory and others. In such high-risk area, it is necessary to have knowledge of the properties of soils subjected to dynamic loads. Therefore, it is necessary to know the ground responses of soil deposits during active volcanic eruptions and other dynamic loadings. In order to understand the ground responses of soil deposits, it is important to know the dynamic soil properties of the area.

From previous research works, there were different earthquake activities recorded in different parts of Ethiopia. The Great Rift Valley region of Ethiopia is earthquake prone areas and experienced different magnitude of earthquakes as shown in Table 1.1. Nazareth earthquake, which has a magnitude of 5.1, was felt as far as Debre Zeit and Addis Ababa. Modjo, which is 26km from Nazareth, is located in Great Rift Valley of Ethiopia as shown in Fig.1.1 and it experiences the Nazareth earthquake.

Table 1.1 Some earthquakes and reported damages in Ethiopia [48]

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

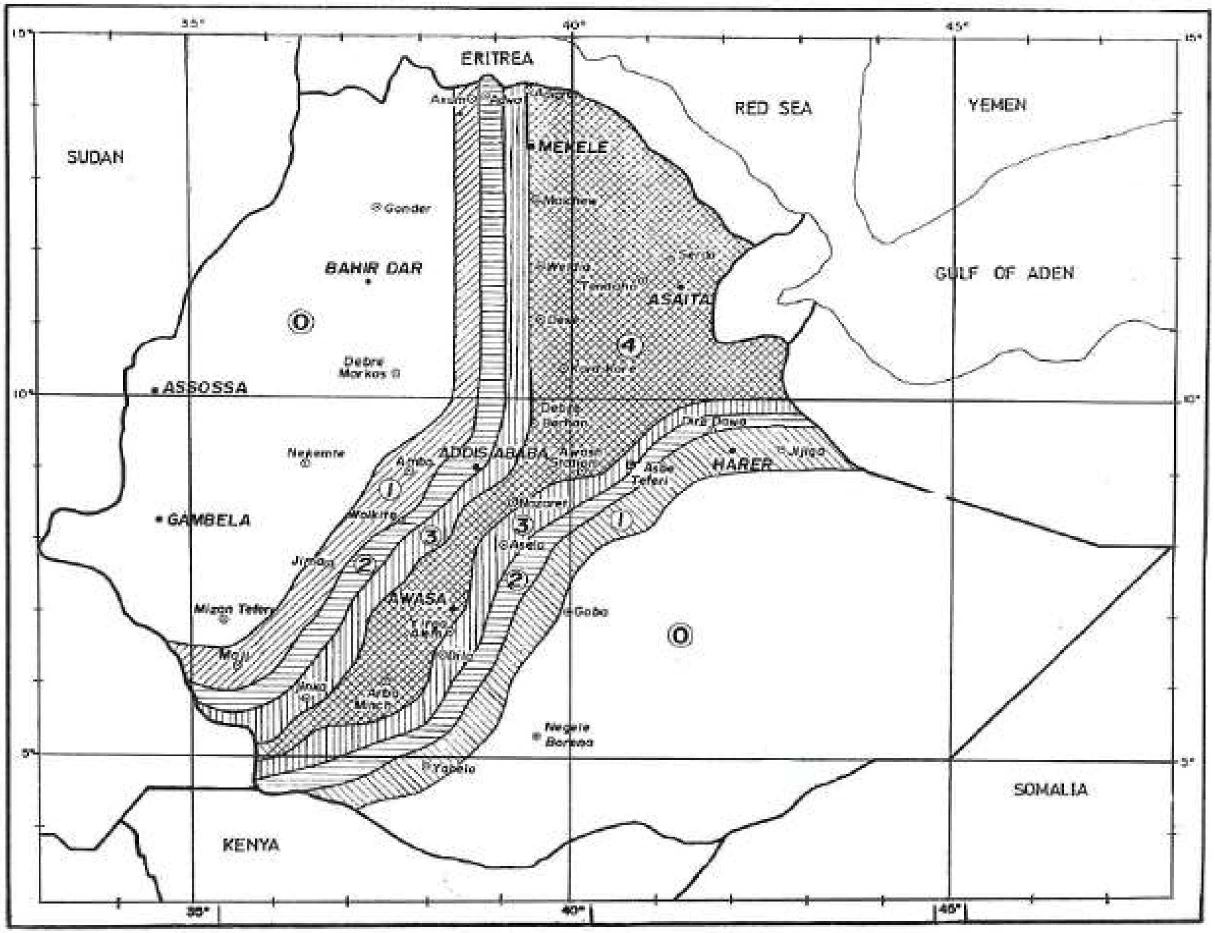

Figure 1.1 Seismic hazard map of Ethiopia for a return period of 100 years [56]

1.5 Structure of the Study

The content of the study is organized into five parts. The **first or introductory part** covers the background, objective, scope and problem statement of the study and descriptions about the sampling area. The **second part** reviews different literatures by giving a particular attention to review the available studies on shear modulus and damping ratio of different soils. Important notations necessary to understand the general responses of soil subjected to cyclic loadings and different critical factors of dynamic soil properties were reviewed.

The **third part** describes the materials and experimental techniques used. The description of the testing methods and the techniques developed to obtain high quality test results are the core of this part. In **part four**, the physical properties and cyclic properties test results are presented and analyzed. The shear modulus and damping ratio values are determined using a hysteresis relationship of stress-strain. Different factors, which influence the shear modulus and damping ratio of Modjo soil at high strain amplitudes, were discussed. **Part five** concludes the study and proposes perspectives for future research based on the numerical and laboratory results.

2. LITERATURE REVIEWS

Several researchers have been involved in exploring the complex behaviour of soils under various types of dynamic loading conditions. Damage due to dynamic loadings is influenced by the response of soil deposits and the soil response is governed by the dynamic soil properties. Literature Survey from different available books, research papers, thesis works and test manuals have been done. It serves as a plat form to begin and frame of the study properly.

2.1 Basic Index Properties Required in the Study of Dynamic Soil Properties

Basic and important physical (index) properties, which are necessary in the determination of the dynamic soil properties are; field density and moisture content, specific gravity, Atterberg`s limits, grain size distribution and compaction tests. These properties are important in cyclic loadings for shear modulus and damping ratio determination [50]. Hence, determination of the dynamic soil properties requires consideration of the above-mentioned influencing parameters.

2.2 Nature of Dynamic Loadings

In the field of soil mechanics, dynamic loadings are the results of numerous kinds of excitations and induce different oscillations of the ground. The various possible sources of excitations could be qualitatively classified as:

- ✓ *Seismic waves (Earthquake):-* upon motion of the different plates, large stresses accumulate in several points near the boundaries, where they eventually induce breaking along fault lines. The energy liberated by the sudden displacement creates seismic waves, which diffuse inside the plates and induce cyclic stress on the soil elements. The effects of earthquake on people, structures and on the environments, are fault displacement, subsidence (differential settlement), liquefaction, failure of sensitive or quick clays, landslides, mudflows, dam failures, water waves (tsunamis, seiches) and groundwater discharge changes.
- ✓ *Vibrations due to human activities:* - Pile driving compaction, machine foundation and traffic loads are human activities that induce vibration. Civil engineering activities (like

drilling, pile driving), circulation of heavy vehicles (trucks, train) and vibrations due to cyclic machines operation, can induce or increase settlement of soft soil layers.

- ✓ *Blasting and bombing (shock waves)*:- a more civil engineering application to blasting is linked to mining, underground work and foundation engineering for excavation technique or to densify loose ground before construction.

2.3 Cyclic Loadings and Soil Response

The evaluation of the soil response is one of the most important and the most commonly encountered problems in geotechnical earthquake engineering. Soil response analysis is used to evaluate dynamic stresses and strains and to determine earthquake induced forces that lead to instability of earth and earth-retaining structures.

The dynamic soil properties govern the responses of soil subjected to cyclic loadings. Appropriate evaluation of shear modulus and damping characteristics of soils subjected to dynamic loadings is the basic element to accurate seismic response analysis and soil modeling programs [20]. The responses obtained for different cyclic loadings needs to be analyzed to determine the cyclic soil properties. A typical soil subjected to cyclic loading exhibits non-linear and hysteresis response, which is the result of stress-strain curve as idealized in the Fig.2.1. The hysteresis loop is used for the calculation of shear modulus and damping ratio for each cycle. The area enclosed by the ellipse, A_{loop}, is related to the amount of energy dissipated by the material during a cycle loading. A_{Δ} is the maximum strain energy stored during that cycle. A relation between A_{loop} and A_{Δ} gives the damping ratio. When the materials are deformed, energy is absorbed and dissipated by the material itself. The effect is due to friction between the internal planes, which slip or slide as the deformations take place.

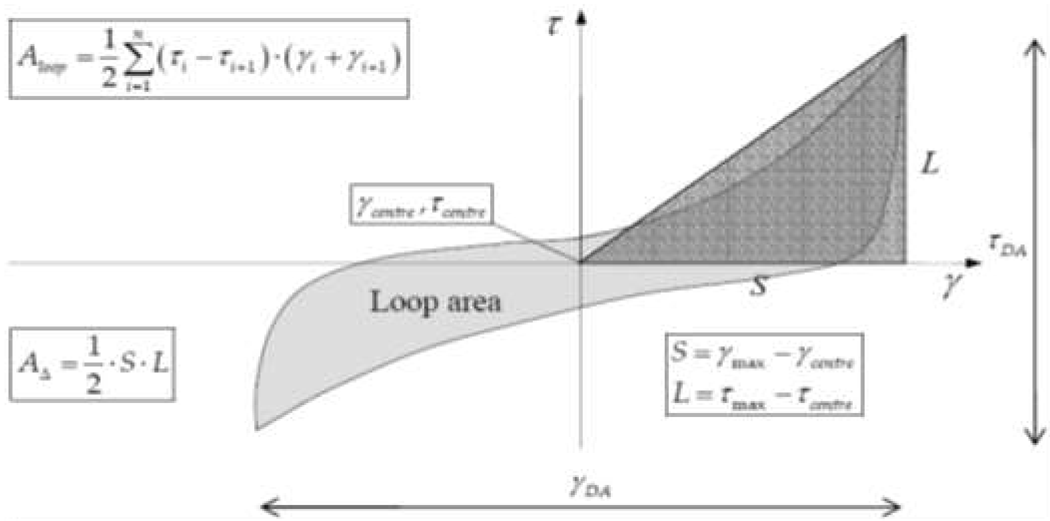

Figure 2.1 Idealized cyclic stress-strain loop [5]

2.4 Material Parameters Describing the Cyclic Soil Properties

The shear modulus and the damping ratio are two material parameters used for characterizing cyclic soil behaviour. The stiffness and damping characteristics of cyclically loaded soils are critical to the evaluation of seismic geotechnical problems. In this study, these soil properties were determined from cyclic simple shear test results at high strains.

Shear Modulus (G):- The shear modulus is the measurement of stiffness of soils and it is the most basic parameter to evaluate soil behaviour in dynamic analysis. The average shear modulus over one cycle is best described by the secant shear modulus G_{sec}, which is proportional to the slope of the line reaching the points of higher and lower shear strain over one cycle. The shear modulus conventionally expressed as the secant shear modulus in soil dynamics. The most reliable method of producing representative moduli has been to evaluate the difference in maximum and minimum stress and the difference in maximum and minimum strain developed in the hysteresis loop. The ratio of these two values used for shear modulus calculation as shown in equation 2.1.

$$\text{Shear modulus,G} = \frac{\text{Amplitude of cyclic shear stress, } \Delta\tau}{\text{Amplitude of cyclic shear strain, } \Delta\gamma} \text{ ----------------- (2.1)}$$

Where, $\Delta\tau$ is the difference between the maximum and the minimum values of shear stress and $\Delta\gamma$ is the difference between the maximum and the minimum values shear strain.
The shear modulus used to perform more advanced soil modeling and dynamic response of the soil-structure interactions.

Damping Ratio (D):- In the real world, undamped freely vibrating structure can lost energy by the structure`s motion and the magnitude of the oscillation decreases until the oscillation stops. Every non-conservative system experiences some energy loss that attributed to material non-linearity and internal or external frictional behavior. This energy dissipation is damping, which occurs when any vibration wave passes through the soil.

Damping is the dissipation of strain energy during cyclic loading in the soil and damping ratio is the dissipated energy divided by the maximum stored (i.e. elastic) energy per cycle. In several dynamic analyses, it is often expressed as damping ratio (D or ξ) and provides realistic motion attenuation. In geotechnical engineering, the most common way to understand the energy loss of a soil subject to cyclic loading is the damping ratio. The damping ratio was obtained experimentally, from the geometry of stress-strain loops using equation 2.2 [15]. Energy dissipation of cyclically loaded soils is frictional nature and the deformation of the system is essentially due to rearrangement of the soil matrix during both loading and unloading parts of the cycle. The sliding or slipping of grains involves friction at interparticle contact, which is associated with hysteretic damping ratio.

$$\text{Damping ratio, } D = \frac{1}{4\pi}\,\frac{\text{Area of the hysteresis loop}}{\text{Area of triangle}} = \frac{A_{loop}}{4\pi A_{\Delta}} \text{ ------------- } (2.2)$$

Where, A_{Δ} is the maximum strain stored energy and A_{loop} is the energy loose per cycle represented by the area enclosed inside the hysteresis loop as shown in Fig.2.2 [46].

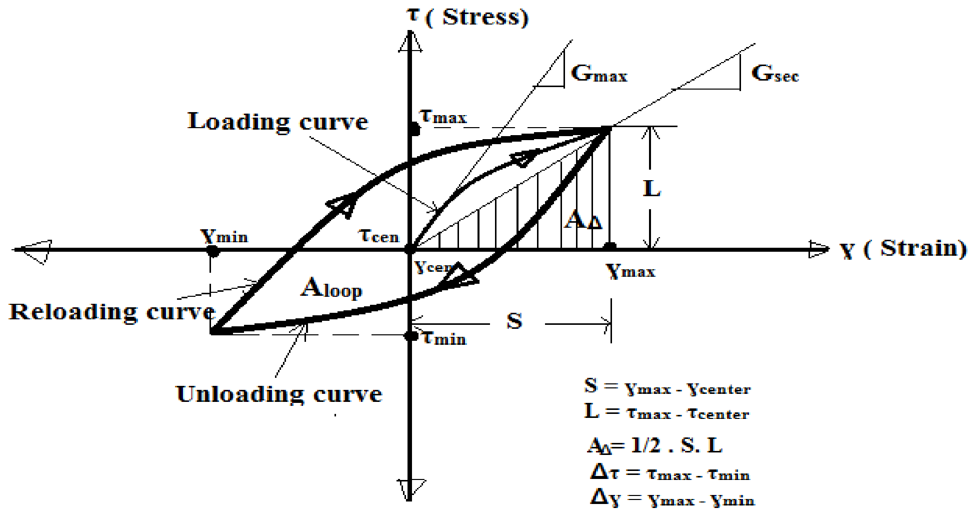

Figure 2.2 Hysteresis loop

$$A_{loop} = \frac{1}{2}\sum_{i=1}^{n}(\tau_i - \tau_{i+1}).(\gamma_i + \gamma_{i+1}) \text{ -- } (2.3)$$

The shear stress and shear strain were evaluated from lateral force and lateral LVDT test results.

$$Shear\ stress,\ \tau = \frac{Shear\ Force}{Area\ of\ sample} = \frac{F}{A} \text{ -------------------------------- } (2.4)$$

$$Shear\ Strain,\ \gamma = \frac{Lateral\ LVDT}{Height\ of\ the\ sample} \text{ -------------------------------- } (2.5)$$

Where, LVDT is linear variable differential transformer, axial deformation measurement.

Initial Shear Modulus (G_{max}):- the initial or maximum shear modulus, G_{max} is widely regarded as one of the most essential parameters for earthquake engineering, traffic engineering, vibration machine foundation, vibration isolation measures and analysis of dynamic soil structure interactions [32]. In recent years, many studies were performed to investigate the behaviour of soil at small strain level.

It is a very important parameter not only for seismic ground response analysis but also for a variety of geotechnical applications. A considerable number of empirical relationships have been proposed for estimating initial shear modulus for different kind of soils. Since cyclic simple shear tests are high strain tests (0.01% to 5%), the maximum shear modulus, G_{max} that corresponds to very low strain levels cannot be determined from such tests. For this study the maximum shear modulus, G_{max} of each specimen was determined using equation 2.6 from Hardin B.O. and W. L. Black [23]. The calculated value of G_{max} was used to obtain the normalized shear modulus. Generally, the values of the initial shear modulus of soil ranges from 2,750kPa to 69,000kPa [17].

$$G_{max} = 3220 \times \left(\frac{2.976 - e}{1+e}\right)^2 \times (OCR)^k \times (\sigma'_o)^{K_o} \quad \text{------------------------------ (2.6)}$$

$$\sigma'_o = \frac{(\sigma'_v + 2K_o \times \sigma'_v)}{3}$$

Where: e = void ratio

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

P_c = Pre consolidation pressure of a specimen

P_o = Present effective vertical pressure

σ'_0 = Mean effective 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

For cohesionless soils K_o = 0.43 to 0.67, with a value of 0.5 often used [20].

Table 2.1 Empirical values of exponential parameter (k) [17]

PI	0	20	40	60	80	>100
k	0	0.18	0.3	0.41	0.48	0.5

Normalized shear modulus (G/G_{max}): - It is the ratio of the shear modulus (G) and the maximum shear modulus (G_{max}). The results of the shear modulus of the cyclic simple shear tests were normalized to compare with the results of other tests. The relation between the normalized shear modulus and cyclic shear strain is shown in the Fig.2.3.

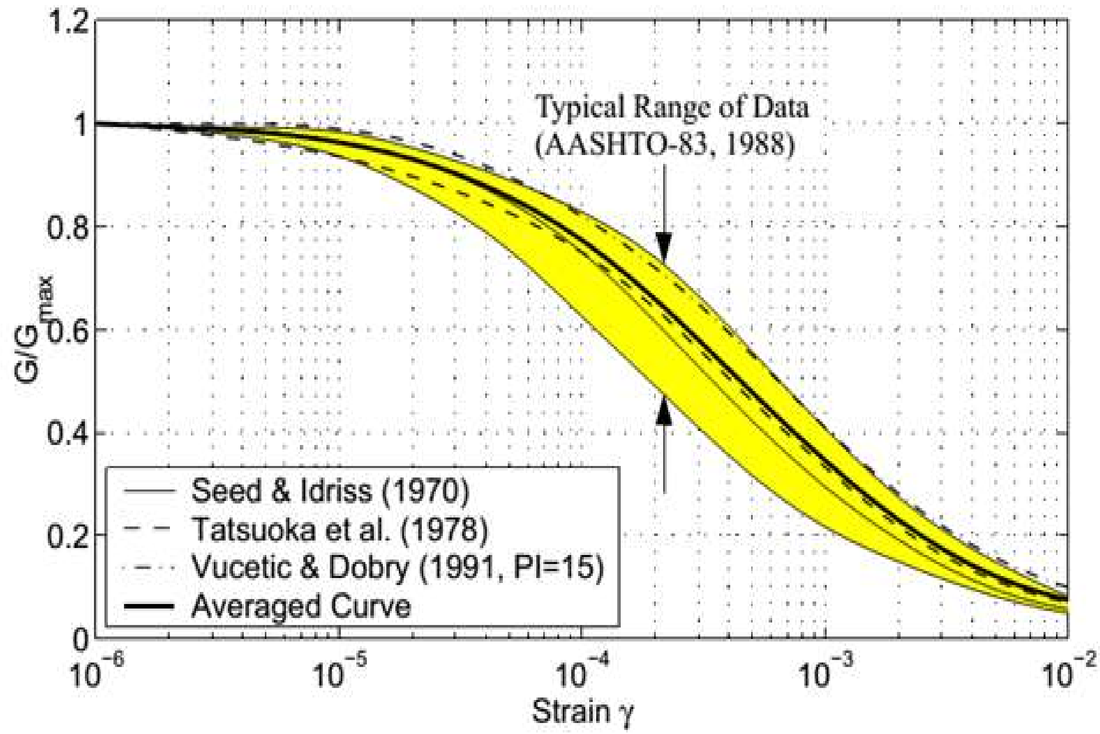

Figure 2.3 Normalized soil shear modulus as function of shear strain [35]

2.5 Methods of Determination of Shear Modulus and Damping Ratio

Wide varieties of field and laboratory test techniques are available with different advantage and limitations. In current practice of geotechnical engineering, the measurement of dynamic shear modulus and damping ratio is performed independently.

Table 2.2 Field and laboratory tests for investigation of dynamic soil properties [50]

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%	Shear Modulus; Damping
	Simple shear	10^{-2} to 5%	Shear Modulus; Damping
	Torsional shear	10^{-2} to 5%	Shear Modulus; Damping
Forced vibration	Longitudinal	10^{-4} to 10^{-2}%	Shear Modulus; Damping
	Torsional vibrations	10^{-4} to 10^{-2}%	Shear Modulus; Damping
	Shear vibrations-lab	10^{-4} to 10^{-2}%	Shear Modulus; Damping
	Shear vibrations-field	10^{-4} to 10^{-2}%	Shear Modulus
Free vibration tests	Longitudinal	10^{-3} to 1%	Shear Modulus; Damping
	Torsional vibrations	10^{-3} to 1%	Shear Modulus; Damping
	Shear vibrations-lab	10^{-3} to 1%	Shear Modulus; Damping
	Shear vibrations-field	10^{-3} to 1%	Shear Modulus
Field wave velocity Measurements	Compression waves	~$5x10^{-4}$%	Shear Modulus
	Shear waves	~$5x10^{-4}$%	Shear Modulus

In this study, direct determination of stress-strain relationships was used for shear modulus and damping ratio determination from cyclic simple shear test. The dynamic properties of soil can be determined in field and laboratory investigation methods. The different methods used for dynamic soil properties investigation are shown in the Fig. 2.4 [50].

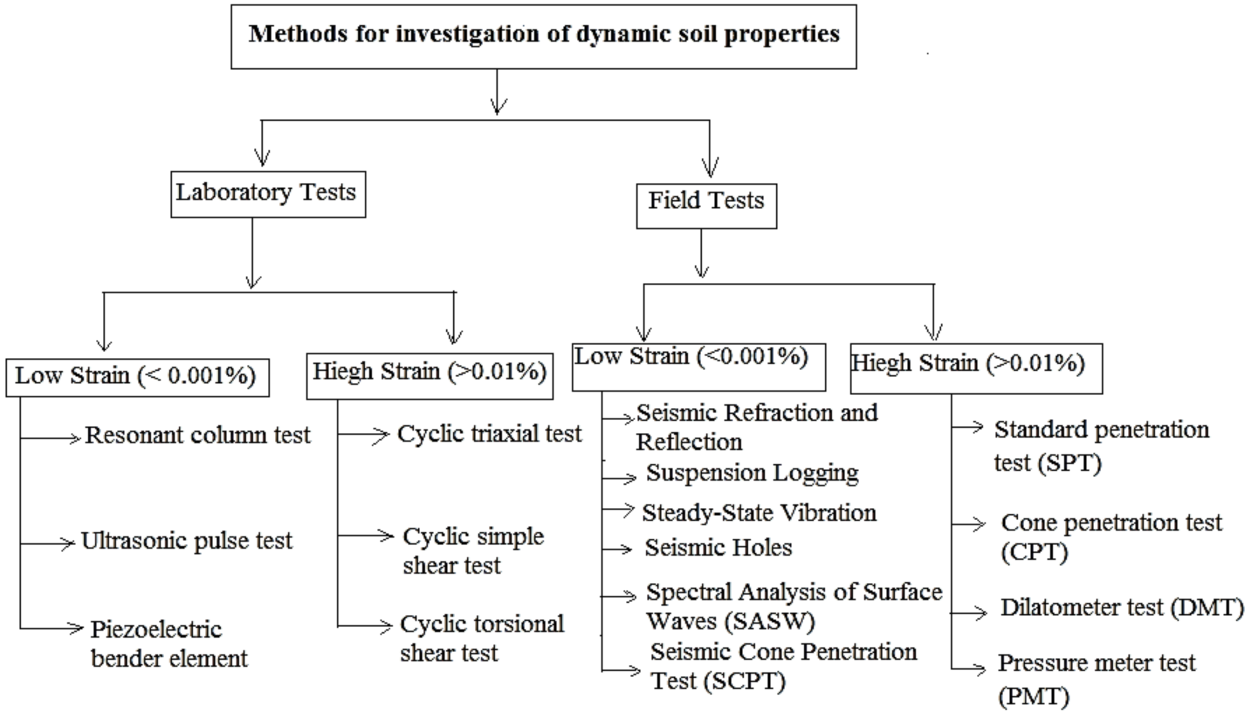

Figure 2.4 Methods of investigation of dynamic soil properties [50]

2.6 Factors affecting Shear Modulus and Damping Ratio of Soils

The most important factors that affect the dynamic behaviour of soils divided into two main categories [19]. Firstly, external variables such as stress/strain path, stress/strain magnitude, stress/strain rate and stress/strain duration can affect the dynamic property of soils. Secondly, characteristics of the soil: such as soil type, size and shape of soil particles and void ratio can affect the response of soil to dynamic loadings. These factors are; method of sample preparation in laboratory, confining pressure, methods of loading, over consolidation ratio, shear strain levels, loading frequency, soil plasticity, percentage of fines, void ratio, relative density and soil type. Out these factors: confining pressure, soil plasticity, number of cycles and shear strain levels were discussed in this study.

2.6.1 Variation of Shear Modulus and Damping Ratio with Shear Strain Amplitude

Different laboratory and in-situ tests have shown that the shear modulus and damping ratio of cyclically loaded soils are strongly influenced by the shear strain levels. At low strain levels (< 0.001%), a given soil has high shear modulus and low damping ratio with soil stress-strain being relatively linear. The damping ratio does not reach zero even at small strain, it is always between zero and one. At higher strains (>0.01%), stress-strain behavior of soil exhibit nonlinearity effect and result in high damping ratio values. Therefore, the shear modulus of soil decreases with an increase in strain amplitude and damping ratio increases with strain amplitude. This is because at higher values of shear strain, the soils strength becomes smaller to resist deformation and more energy released to yield high deformation [50]. Damping ratio not significantly affected by methods of sample preparation while the shear modulus of undisturbed sand soil sample depicted almost double than the disturbed soil sample as shown in Fig.2.5. The normalized shear modulus (G/G_{max}) of undisturbed specimen is greater than G/G_{max} of the remoulded specimen at the same shear strain amplitude [50].

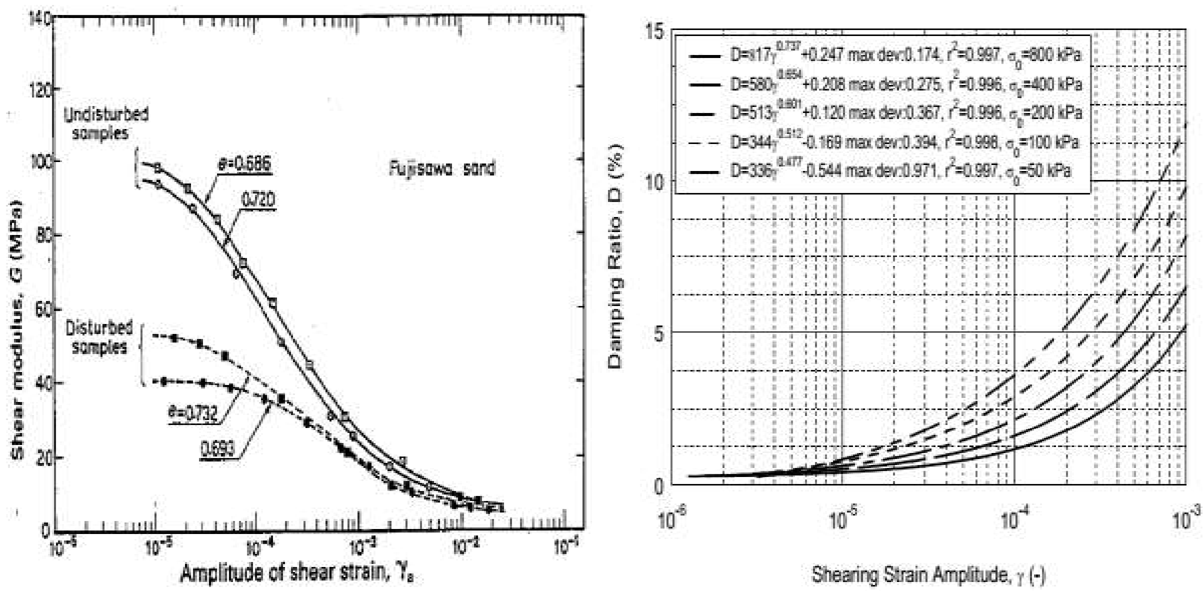

Figure 2.5 Variation of shear modulus of Fujisawa dense sand and damping ratio for Berlin sand with shear strain amplitude ([50], [32])

2.6.2 Variation of Shear Modulus and Damping Ratio with Number of Cycles

In general, the shear modulus slightly increased and damping ratio significantly decreased with increasing number of loading cycles as shown in Fig.2.6. The primary increase in shear modulus and decrease in damping ratio occurred within the first 10 cycles of loading [32].

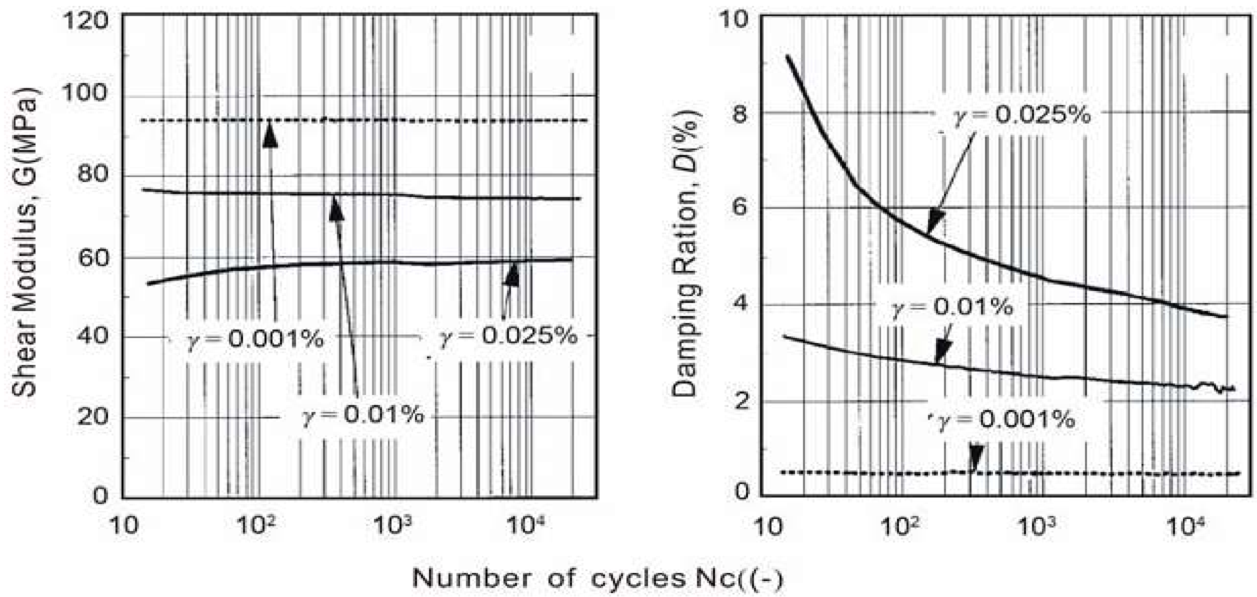

Figure 2.6 Variation of shear modulus and damping of dry sand with number of cycles [32]

2.6.3 Variation of Shear Modulus and Damping with Void Ratio

Void ratio is recognized as the very important parameter, which influence the small-strain shear modulus of soil. As the void ratio becomes lesser under the application of load, soil particles come closer to each other resulting in densification of soil sample. As shown in Fig.2.7, the small-strain shear modulus, G_{max} decreases with increasing void ratio. The decrease of shear modulus with void ratio is due to the influence of confining pressure and method of sample preparation [50].

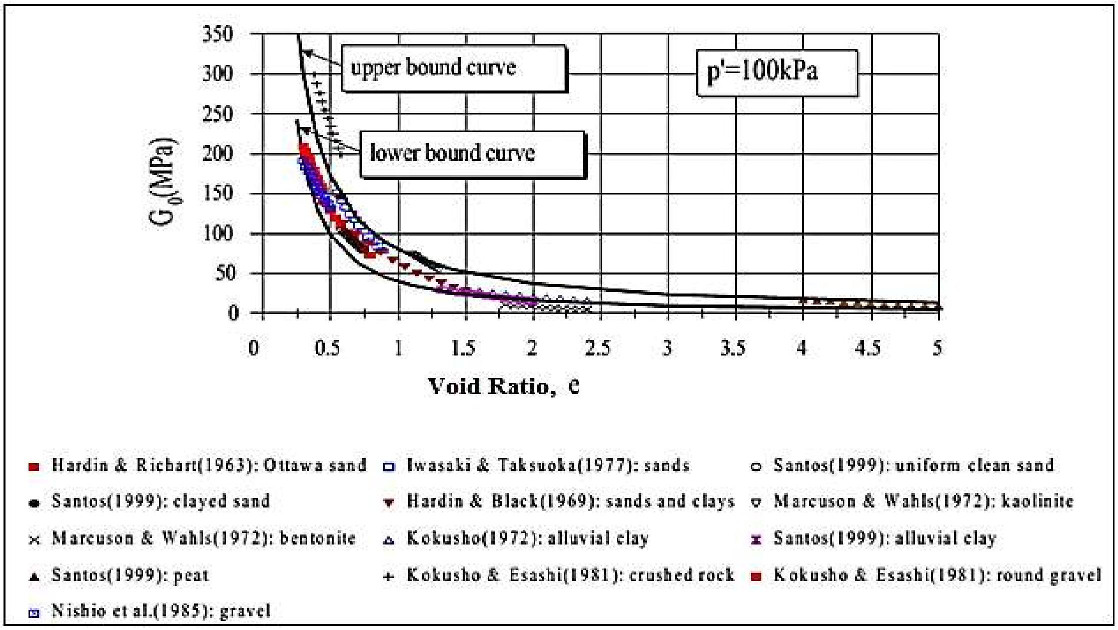

Figure 2.7 Variation of initial shear modulus with void ratio [32]

2.6.4 Variation of Shear Modulus and Damping Ratio with Confining Pressure

The shear modulus increases and damping ratio decreases as confining pressure increases. Fig.2.8 shows the effects of confining pressure on shear modulus and damping ratio.

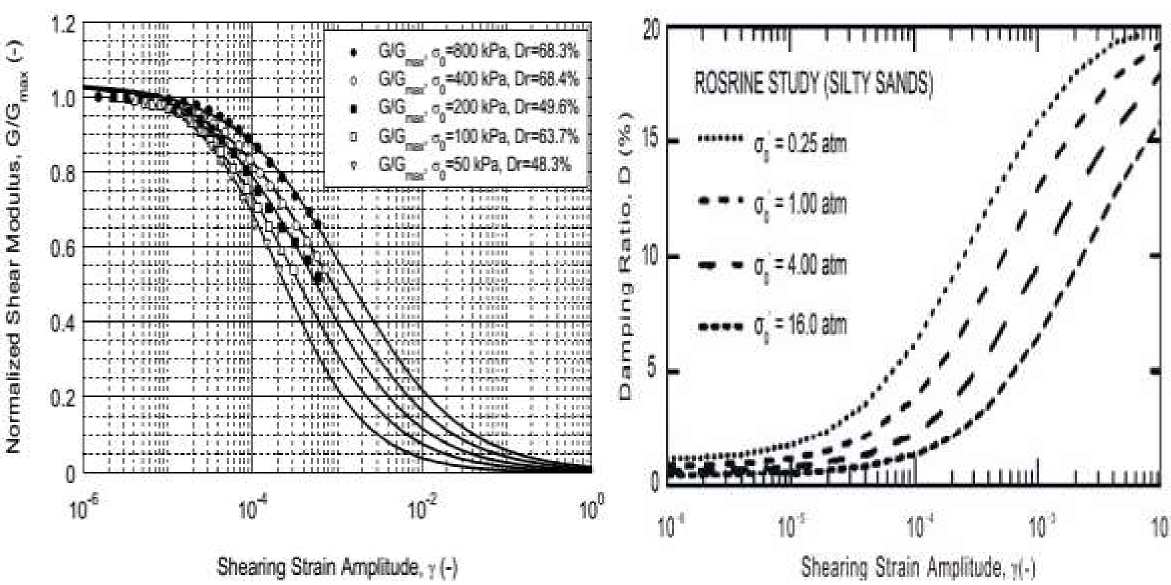

Figure 2.8 Variation of G/G_{max} of Berlin sand and D of silty sand with confining pressure [32]

2.6.5 Variation of Shear Modulus and Damping Ratio with Soil Plasticity

The effect of soil plasticity was studied by comparing the results of specimens of different plasticity tested at the same confining stress. The shape of the stress-strain curve appears to be more symmetrical as the plasticity of the soil increases. It can be concluded that in fine-grained soils the plasticity index is the most important parameter for the stress-strain behavior [37]. Soils with higher plasticity generally exhibit a more linear stress-strain behavior. The variation of shear modulus and damping ratio with soil plasticity is shown in the Fig.2.9.

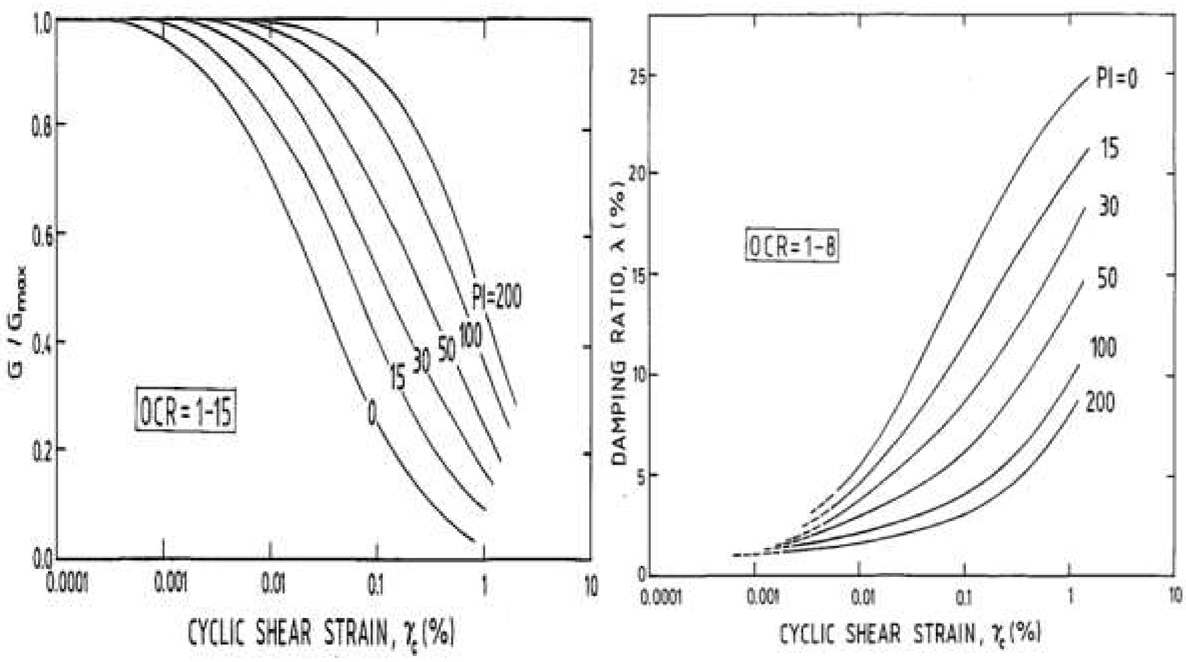

Figure 2.9 Variation of G/G_{max} and damping ratio with plasticity index [50]

3. MATERIALS AND METHODS

3.1 Materials

3.1.1 Soil

Visual site investigations were tried in the selection of test pit areas to take sample evenly in the town. Four representative test pit areas were selected from different locations of the town as shown in Fig.3.1. Test pits were excavated to the maximum depth of three meters and samples were collected at any depth wherever there was a soil layer change. Only disturbed samples were collected because of the soil nature and sampling material problems. Sand cone for in-situ measurement of field density, different bags for collections of soil samples were used.

Field tests to determine field density using sand replacement method and natural moisture were conducted. About 30kg of disturbed soil samples from each layer were collected in bulk randomly for the static and dynamic tests. The laboratory works were done in Addis Ababa Institute of Technology geotechnical laboratory in two parts, the index tests and the cyclic simple shear tests.

Figure 3.1 Location of test pits

3.1.2 Cyclic Simple Shear machine

There are different types of cyclic simple shear apparatuses in use today. In this research, model 31-WF7500 cyclic simple shear machine was used. The machine is found in Addis Ababa Institute of Technology geotechnical laboratory. The general feature of the cyclic simple shear machine is shown in Fig.3.2. The UTS004 software application program controls the complete system. In this machine, the shear modulus and damping ratio of Modjo soil were investigated. It is a convenient method for the determination of shear modulus and damping ratio of soils.

Compared to triaxial tests, the main advantage of simple shear tests is that the principle is straightforward: the shear stress applied in the horizontal direction. This helps cyclic simple shear test to simulate the in-situ conditions. It`s major shortcoming, there is the effect of non-uniformity stress condition. At the top and bottom of the specimen, the supporting platens are rough which control the non-uniformity of stress [17]. The cyclic simple shear test represents more accurately the stress state (field condition) and most nearly simulates earthquake-loading condition. In addition to accurate representation of natural condition of stress state, it can measure dynamic soils properties over wide ranges of strain, from 0.01 % to 5 % [11].

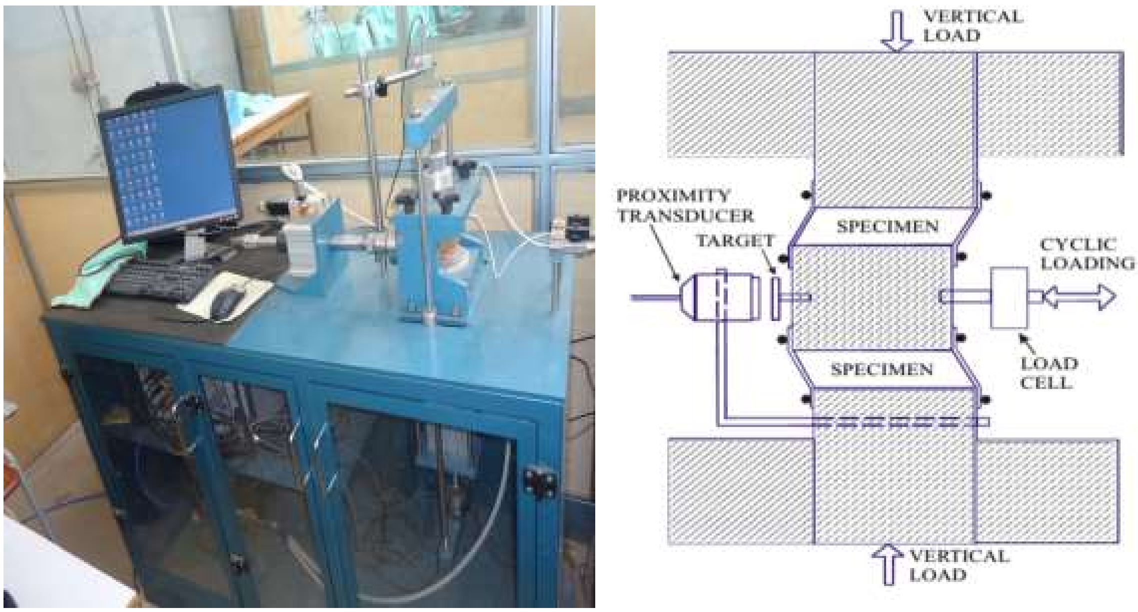

Figure 3.2 31-WF7500 model cyclic shear machine used for this study [17]

3.2 Methodology

Different activities were carried out to meet the objective of the study. Available and important literatures were revised to collect accepted theories and practices on dynamic soil properties. Using ASTM procedure Atterberg`s limit, particle size determination, standard compaction, specific gravity tests were conducted in laboratory to determine the basic physical soil properties.

Cyclic simple shear test was performed to determine shear modulus and damping ratio of the soil and the results were compared with previous developed values. This is the most important part of the study. The test results together with the visual identification and theoretical background were compiled, interpreted and reported.

Owing to the difficulties in the prevention of drainage in a simple shear test, the undrained shear tests were carried out as constant-volume tests. The height of the specimen was kept constant by the vertical actuator in a closed control loop with the vertical displacement transducer. The constant-volume test is equivalent to an undrained test and the change of applied vertical stress on the specimen is equivalent to the change in pore pressure would have occurred in the specimen if the specimen had been prevented from draining for a condition of constant vertical stress application. At the beginning of all tests, the soil specimen first consolidated by applying vertical loads to the loading rod. After consolidating completed, the shear test was performed by applying a horizontal shear strain to the specimen at a predetermined rate.

3.2.1 Sample Preparation for Cyclic Test

Pulverized soil samples that sieved on sieve No.4 (4.75mm) were remoulded at the field density and natural moisture. Then cylindrical 20mm height and 70mm diameter samples were prepared and placed in rubber membrane, which mounted on bottom plate of cyclic simple shear machine.

Shear modulus and damping ratio were determined at high strain amplitude by applying strain controlled sinusoidal loading under constant volume or undrained conditions. Constant volume simple shear test is a reliable method for measuring undrained shear strength of undisturbed or compacted soil samples. The sample height kept constant to have a constant volume. Cyclic simple shear test is most similar to the CU triaxial test in that samples are consolidated prior to shearing [42].

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 and the system is designed to allow a sample to be consolidated and sheared [20]. In this method, a soil specimen usually 20-30m high with a diameter of 60-80m is subjected to a vertical effective stress and a cyclic shear stress [11]. Remoulded specimen of diameter 70mm and height 20mm were used and subjected to cyclic loading with a constant lateral deformation.

The axial stresses (pressures) during consolidation may be 20, 50, 100, 150, 200, 250, 300, 350 and 400kPa. The strain ranges between 0.01% and 5% and 0.5mm-2mm amplitude range. The dynamic behavior of soils is relatively insensitive to the frequency of applied cyclic loading within the range of 0.5 to 2 Hz [56]. Generally, sinewave is used for cyclic loading which gives approximately 30% higher cyclic strength than the rectangular or triangular wave forms [50].

For this study, sinusoidal wave with 1Hz frequency, 40 numbers of cycles were used. Axial/normal stresses of 100kPa, 200kPa and 400kPa and 0.01%, 0.1%, 1%, 3% and 5% shear strains were also selected. Cyclic simple shear test gives simply raw data from 50 data points and 40 numbers of cycles for single cyclic loading in the form of Microsoft excel. Hence, for complete test of any selected pressure and amplitude, 2000 data points were recorded.

3.2.2 Cyclic Loading Procedure

Strain–controlled cyclic simple shear tests were carried out on the soil samples under constant- volume equivalent-undrained conditions to simulate essentially undrained field conditions during earthquake. During the shearing stage, the vertical actuator in a closed control loop with the vertical displacement transducer maintained the constant vertical height of the sample. The rings maintain a constant sample diameter and the test was undrained to maintain a constant volume. Cyclic loadings were applied on the specimens using pneumatic actuator at a constant lateral deformation. Test stages include saturation, consolidation, shearing and post-testing recordings.

- ✓ **Saturation stage: -** In saturation stage, specimens first fully saturated by circulating de-aired water and isotropicaly consolidated with effective confining stresses (which are equal to the in-situ mean stresses). After fully saturated, the lateral stresses stopped and the axial stresses applied for consolidation. Full saturation is required to perform constant-volume undrained tests. There was no saturation stage for this study.
- ✓ **Consolidation Stage: -** The objective of the consolidation phase of the test was to produce in-situ stress conditions by applying vertical stresses, which simulate the loads from overburden material located over the soil sample. Thus, the consolidation stage is

the application of a static axial loading stress to the specimen while the lateral loading (shear) axis held stationary. The consolidation stage continues until the stress-time graph makes straight horizontal line at the applied pressure as shown in the Fig.3.3.

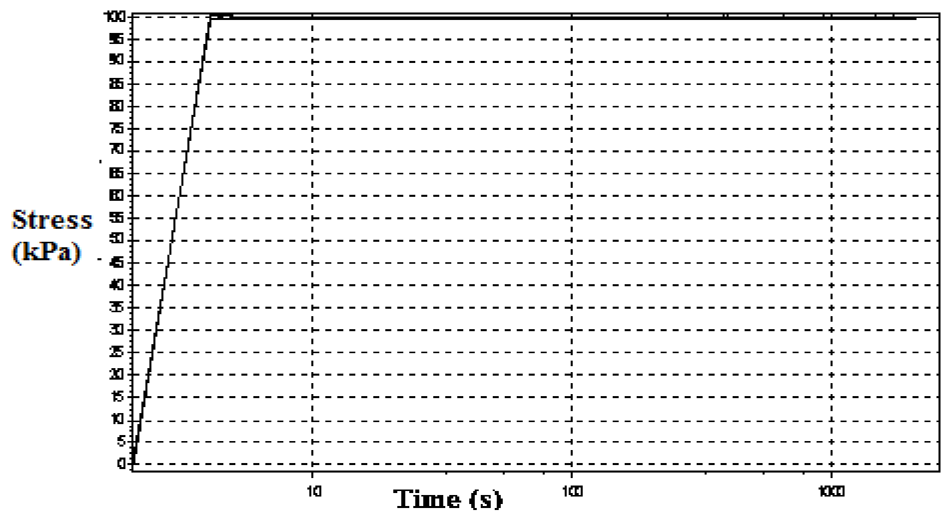

Figure 3.3 Consolidation stage of TK at 100kPa axial stress and 1% shear strain amplitude

- ✓ **Shearing stage: -** The cyclic shearing stage was took place after consolidation was completed, by applying a lateral cyclic shear force under specified amplitude. The lateral cyclic shear force tends to slide the rings over each other though the volume of the specimen was unchanged. The constant volume was maintained by keeping constant the specimen height during shearing stage.

4. TEST RESULTS AND DISCUSSIONS

4.1 Index Property Tests

Index properties/physical properties are commonly used for identification and classification soils, to group soils in major strata for both static and dynamic loading conditions.

The important index properties done in this study are listed below.

- ✓ Field density and natural moisture content
- ✓ Atterberg`s limits
- ✓ Grain size analysis
- ✓ Specific gravity
- ✓ Standard compaction test and

4.1.1 Field Density and Natural Moisture Content Test

The test was done at in-situ using sand replacement method. Sand-cone density apparatus and Clean, uniformly graded sand were used. This test method was used for the determination of the in-place density and unit weight of in-situ soils. The test results are shown in Table 4.1 and used for sample preparation in consolidation and cyclic simple shear tests.

Table 4.1 Field test results

Test Pit	Depth (m)	Bulk field density (g/cm^3)	Dry field density (g/cm^3)	Natural water content (%)
MD	1.5	1.03	1.21	17.68
	2	1.07	1.38	29.17
	3	1.15	1.49	28.82
TK	1.25	1.09	1.38	26.17
	2	1.13	1.46	29.08
	3	1.16	1.49	28.43
SH	1.5	1.10	1.39	26.02
	2	1.13	1.43	26.65
	3	1.14	1.34	17.27
NMR	1.5	1.20	1.53	26.79
	3	1.21	1.36	12.29

4.1.2 Grain Size Distribution Test

In order to classify a soil for engineering purposes, it needs to know the distribution of the size of grains in a given soil mass. The distribution of particle sizes larger than 75 µm (retained on the No. 200 sieve) was determined by wet sieving, while a sedimentation process using a hydrometer determines the distribution of particle sizes smaller than 75µm. This test was done according to ASTM D 422-98 and the summary of the grain size distribution curve is shown in Fig.4.1.

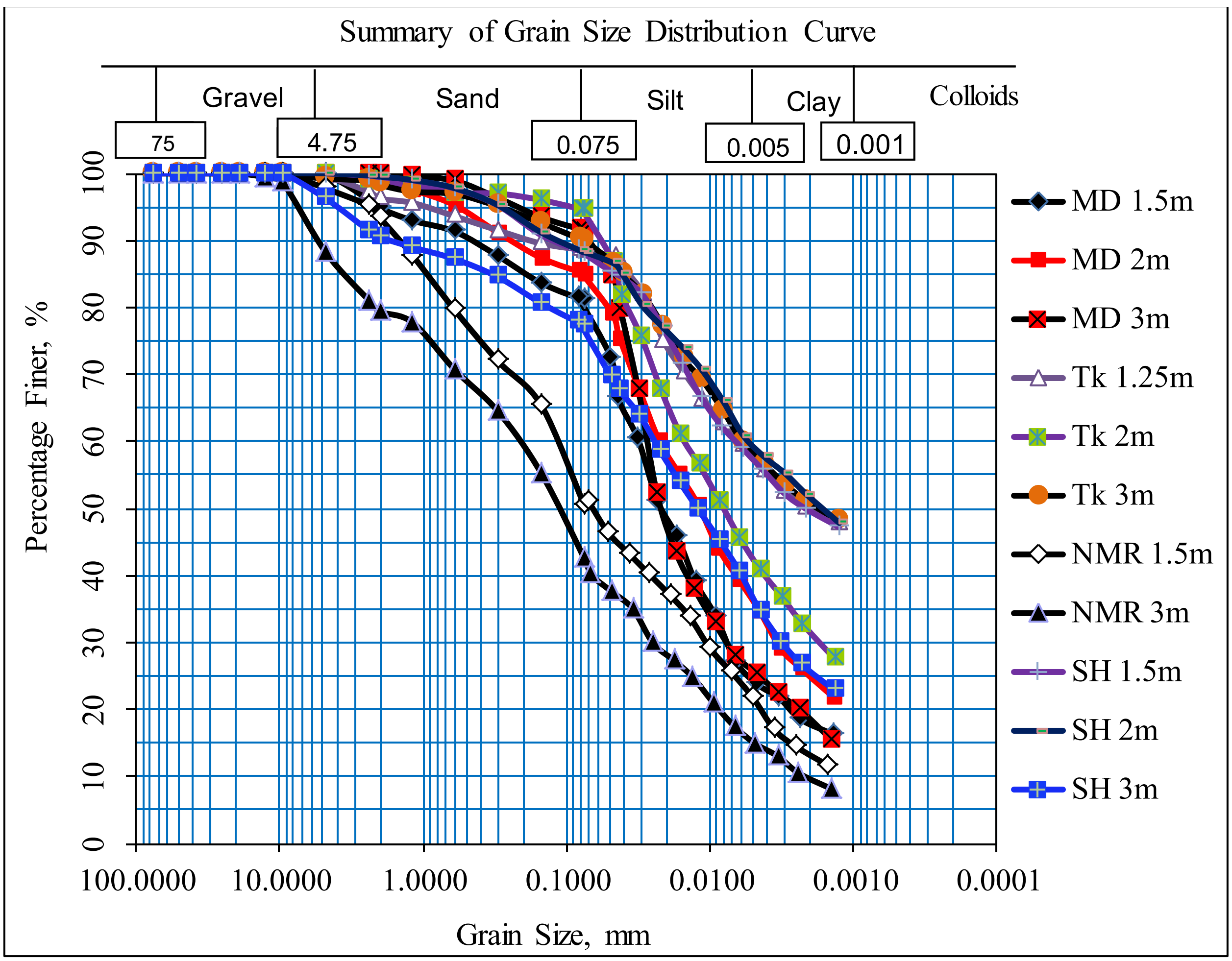

Figure 4.1 Summary of grain size distribution curve

4.1.3 Atterberg Limits Test

Atterberg`s limits refer limits at which the cohesive soil will pass from one limit to the other. The Liquid Limit, Plastic Limit and Plasticity Index are Atterberg`s limits test done in this study. The liquid limit and the plasticity index of cohesive soils are important parameters for classification purposes. The tests were performed in accordance with ASTM D4318-00 passing 425-micron sieve and the test results are shown in Fig.4.2.

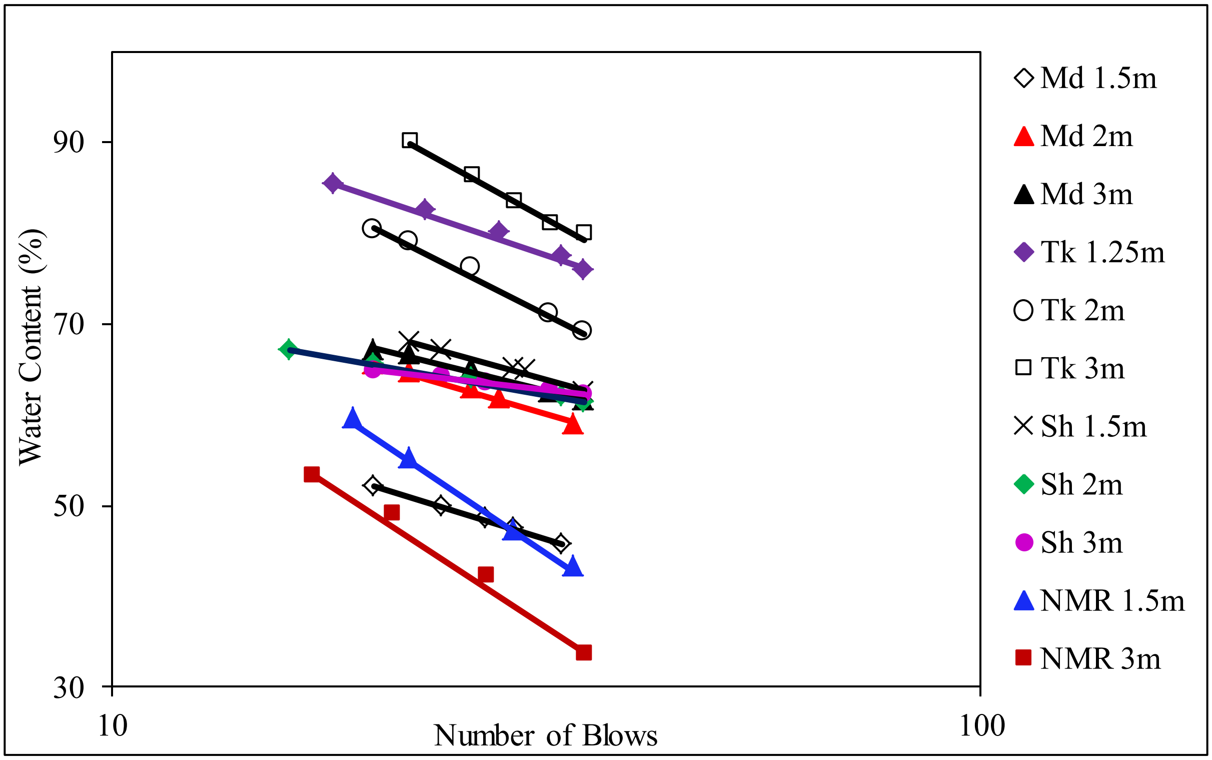

Figure 4.2 Summary of liquid limit test results

4.1.4 Specific Gravity Test

The specific gravity of a given material is defined as the ratio of the weight of a given volume of the material to the weight of an equal volume of distilled water. In soil mechanics, the specific gravity of soil is an important parameter for calculation of the weight-volume relationship, such as void ratio and degree of saturation. This test was done by means of a water pycnometer using ASTM D 854-02 for oven dried soil specimens that pass the 4.75mm (No.4) sieve. Clean and dry volumetric flask and vacuum pump to remove the air from the soil-water mixture were used. The procedure is shown in TK test result in Table 4.2. Additional test results are shown in Table 4.3. The specific gravity values of Modjo soil is slightly low, due to uncertainty air removal from soil-water mixture and soaking time.

Table 4.2 Specific gravity of TK soil at 3m depth

Test Pit	Teklehaymanot Church		
[A] Calibration of pycnometer			
Pycnometer Number	P_1	P_2	P_3
Weight of dry, clean pycnometer, w_p (g)	45.4	46.2	45.8
Weight of pycnometer + water, w_{pw} (g)	144.6	145.1	144.1
Observed temperature of water, T_i (^{o}c)	19.1	20	19
[B] Specific Gravity Determination			
Determination Number	1	2	3
Pycnometer Number	P_1	P_2	P_3
Weight of pycnometer + soil + water, W_{pws} (g)	160.1	160.3	160.1
Temperature, T_x (^{o}c)	22.4	22.5	22.8
Weight of pycnometer + water at T_x , $W_{pw}(atT_x)$ (g)	144.54	144.53	144.51
Weight of dry soil , w_s (g)	25	25	25
Conversion factor , K	0.9991	0.9993	0.9993
Specific gravity of soil at 20°c	2.65	2.71	2.65
Average specific gravity of soil	2.67		

4.1.5 Standard Compaction Test

Compaction test is a laboratory test used to determine the relationship between the moisture content and the dry density of a soil. The test was done according ASTM D698-98 standard method. For one each around 4.6kg air-dried soil passing No.4 sieve size was used. The summary test results are shown in the Fig.4.3. Form the test result, it was observed that NMR at 3m has higher dry density and lower water content; this is due to that the soil is coarser than the rest. Since the initial moisture contents were determine, one can use the compaction test results in road construction during field compactions.

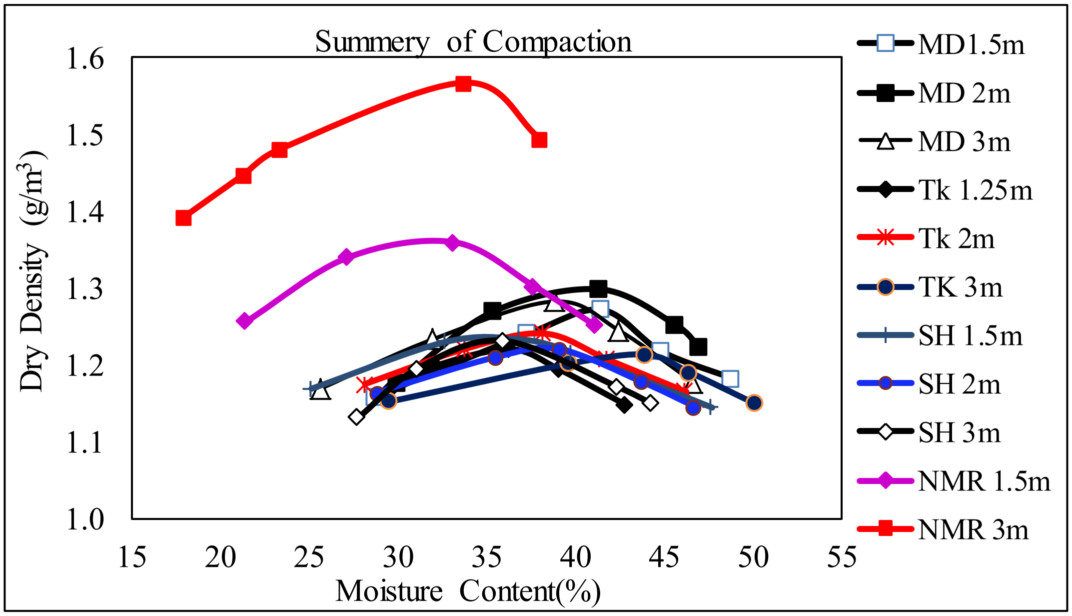

Figure 4.3 Summary of compaction test results

The field and laboratory index test results are summarized in the Table 4.3. Soil classifications were done after the determinations of these tests.

Table 4.3 Summary of index properties test results

Test Pit		MD			TK			SH			NMR	
Depth (m)		1.5	2	3	1.25	2	3	1.5	2	3	1.5	3
ρ_{bulk} (g/cm^3)		1.21	1.38	1.49	1.38	1.46	1.49	1.39	1.43	1.34	1.53	1.36
ρ_d (g/cm^3)		1.03	1.07	1.16	1.1	1.13	1.16	1.1	1.13	1.14	1.21	1.21
Void Ratio, e		1.56	1.47	1.28	1.39	1.35	1.31	1.29	1.31	1.33	1.22	1.23
w (%)		17.68	29.17	28.82	26.17	29.08	28.43	26.02	26.65	17.27	26.79	12.29
LL (%)		51	63	65	81	76	87	67	64	64	63	29
PL (%)		33	48	45	47	49	48	42	45	44	34	18
PI (%)		18	15	20	31	27	40	24	19	20	30	11
FSI (%)		60	50	45	50	40	30	30	50	40	35	28
G_s		2.64	2.64	2.63	2.62	2.65	2.67	2.52	2.62	2.66	2.69	2.72
Grain Size (%Passing)	Gravel	0.3	0.1	0.1	0.5	1.1	0.1	0.4	0.3	3.8	2.3	2.1
	Sand	18.7	14.79	8.44	11.38	4.33	9.94	11.49	11.5	18.91	50.85	58.37
	Silt	64.74	63.32	76.11	48.2	66.99	51.67	50.79	47.78	54.46	38.79	36.15
	Clay	16.29	21.77	15.39	39.91	27.55	38.28	37.34	40.41	22.85	8.07	3.43
Initial Moisture (%)		13.58	17.03	16.36	15.07	14.3	15.64	14.46	13.64	12.86	9.88	7.45
Soil Type		MH	MH	MH	MH	MH	MH	MH	MH	MH	SM	SM

FSI = Free swell index.

4.1.6 One Dimensional Consolidation Test

A soil may have been pre-consolidated during the geologic past by the weight of geologic overburden like; thick layers of overburden soil that have been eroded or excavated away and heavy structural loads, which no longer exist.

This test was done to understand the stress history of the soil under investigation. The test was done using ASTM D2435-96 test manual and odometer apparatus for all test pits at 3m depth. Sample size of 50mm in diameter and 20mm high was remoulded at field conditions and subjected to one-dimensional consolidation. From this test, the pre-consolidation pressure was determined which used in computation of the maximum shear modulus. Pre-consolidation pressures of MD, TK, SH and NMR were 98, 90, 95 and 68 respectively. In the Fig.4.4 and Fig.4.5, it has been observed that the pre-consolidation values were low as the tests were done on remoulded samples.

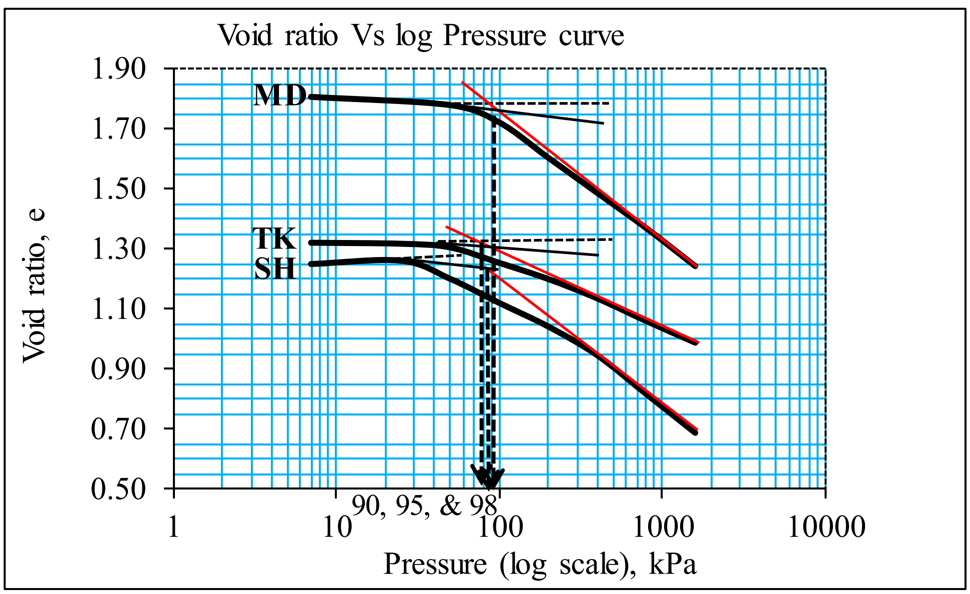

Figure 4.4 Pre-consolidation result of silt soil

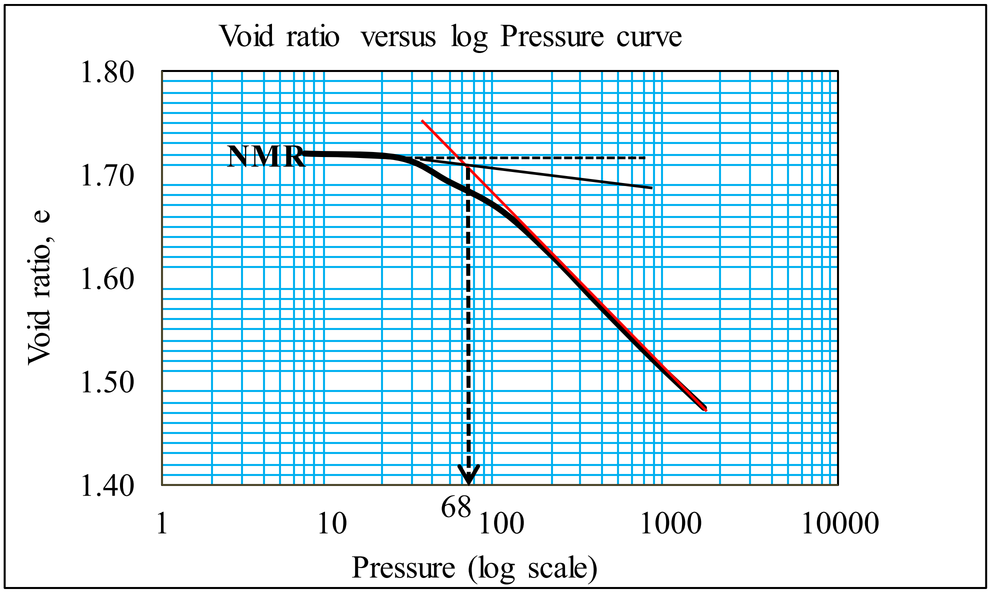

Figure 4.5 Pre-consolidation result of silty sand soil

4.2 Soil Classification

The soil classification was done based on Unified Soil Classification System (USCS) and American Association of State Highway and Transportation Officials (AASHTO) using the combination of particle size and measures of plasticity. Based on these two classifications the soil from MD, TK and SH are highly plastic silt (MH) and NMR is silty sand soil (SM) as shown in Fig.4.6 and Fig.4.7.

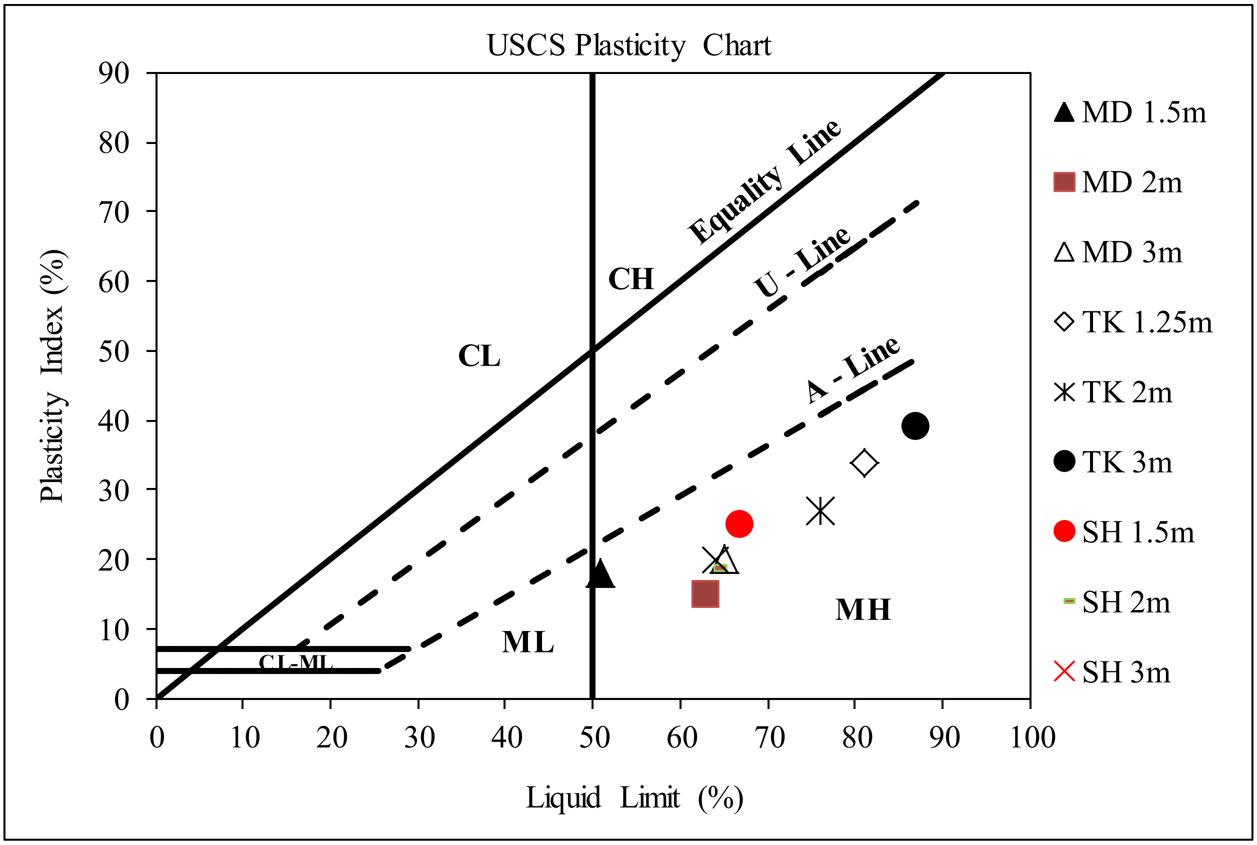

Figure 4.6 USCS plasticity chart

Based on AASHTO classification MD, TK and SH soil, fall below PI = LL-30 line which result A-7-5 soil type. Whereas soil in test pit NMR has less than 50% particle passing No.200 sieve, a liquid limit of more than 41% and plasticity index of more than 10% fall below PI = LL-30 line and result in A-2-7 soil type.

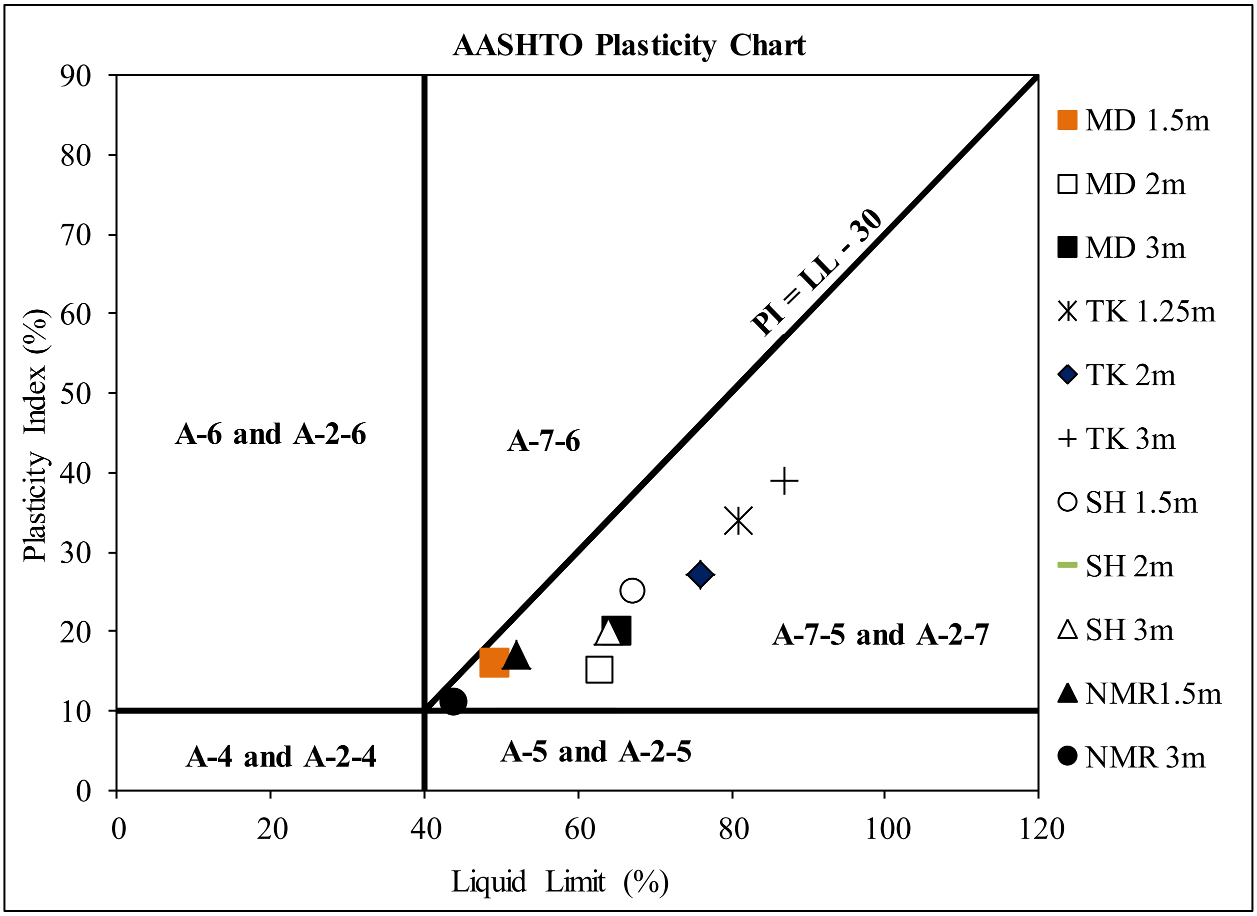

Figure 4.7 AASHTO plasticity chart

4.3 Cyclic Simple Shear Test Results

For single cyclic loading, the cyclic simple shear test gives raw data of Axial Lvdt, Axial Force, Ext Axial Lvdt, Lateral Lvdt and Lateral Force of 50 data points. These data are displayed in the form of wave shapes, charts and tables and logged by the system to an archive data file. Out of these data, Lateral Lvdt (specimen displacements) and Lateral force were used to determine the shear modulus and damping ratio of the soil.

4.3.1 Hysteresis Loop and Values of Shear Modulus and Damping Ratio

To determine shear modulus and damping ratio hysteresis loop were developed from stress-strain relationship. In most seismic events, the number of significant cycles is likely to be less than 20 and for all practical purposes, the shear modulus and damping ratio values determined at 5th cycles are likely to provide reasonable values [11]. Fig.4.8 shows the hysteresis loops of TK soil under 100kPa axial pressure and 0.01%, 0.1%, 3% and 5% cyclic shear strain at the 5th cycle.

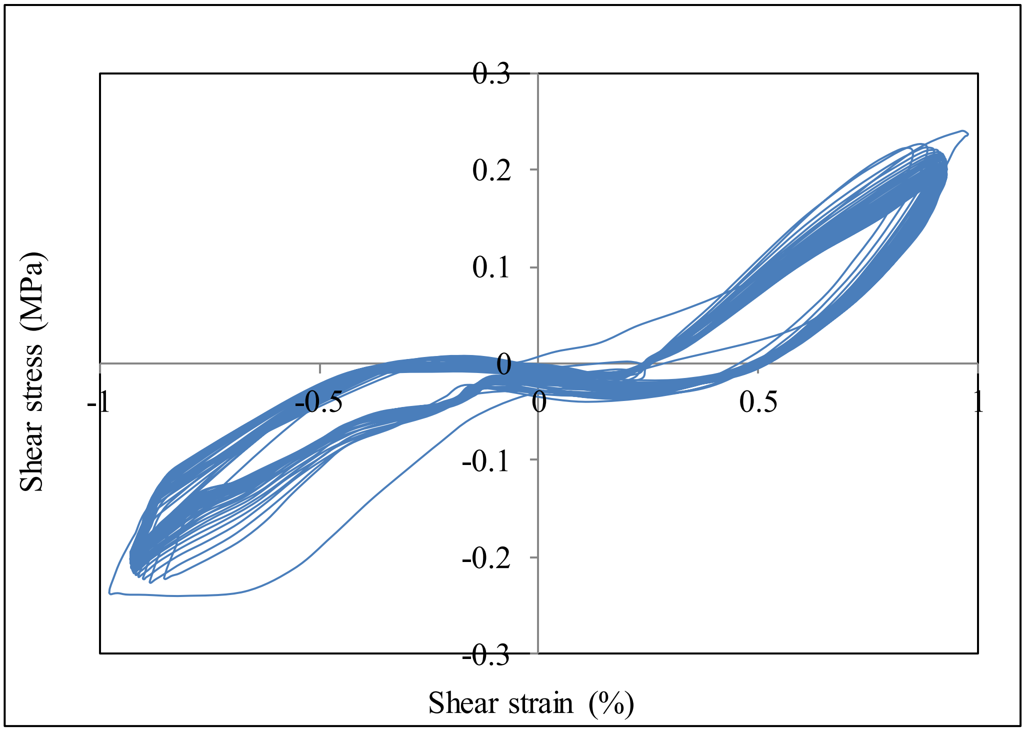

Figure 4.8 Hysteresis loops from TK under 100kPa axial stress

4.3.2 Determination of Shear Modulus and Damping Ratio

The values of shear modulus and damping ratio were determined from hysteresis loop, based on the raw data obtained from cyclic simple shear test as shown in Table 4.4. The shear stress and the shear strain were computed from the raw data and used for shear modulus and damping ratio determination. The shear stress determined simply by dividing the shear force by the area of the specimen and the shear strain from the ratio of the shear displacement and specimen height after consolidation (final height obviously less 20mm).

Table 4.4 Shear stress and shear strain values of TK at 100kPa axial stress and 5th cycle

Time	Axial Lvdt	Axial Force	Ext. Axial Lvdt	Lateral Lvdt	Lateral Force	Shear (MPa)	Strain
0	-4.47675	0.45253	0.30885	-0.37834	-0.03105	0.004	-0.99295
0.019	-4.46825	0.45104	0.31898	-0.1692	0.00112	0.01463	0.11025
0.038	-4.46325	0.4461	0.32223	0.19495	-0.00139	0.01844	0.6985
0.057	-4.46362	0.44597	0.33279	0.34089	0.00332	0.0253	1.31735
0.076	-4.46508	0.43236	0.33054	0.39834	0.00245	0.03498	1.91345
0.095	-4.46571	0.41653	0.32717	0.4371	0.01419	0.04219	2.42455
0.114	-4.46428	0.3916	0.33325	0.50545	0.04017	0.05041	2.9221
0.133	-4.46436	0.35768	0.33222	0.57881	0.06921	0.05845	3.3544
0.152	-4.46242	0.32106	0.33795	0.65463	0.10025	0.06406	3.7442
0.171	-4.46199	0.27988	0.34144	0.7317	0.13077	0.07332	4.09425
0.19	-4.46193	0.23743	0.34546	0.80589	0.15846	0.07968	4.3735
0.209	-4.46439	0.19216	0.34689	0.87498	0.18111	0.08357	4.59005
0.228	-4.46837	0.14575	0.34882	0.93378	0.19956	0.08692	4.75115
0.247	-4.47306	0.09984	0.3467	0.98384	0.21339	0.08942	4.86355
0.266	-4.47938	0.05536	0.34557	1.02118	0.2232	0.09269	4.98899
0.285	-4.48602	0.01223	0.34214	1.04779	0.22884	0.09344	4.99988
0.304	-4.51692	0.00517	0.34012	1.06401	0.23000	0.06649	4.96515
0.323	-4.56825	0.00510	0.34121	1.07408	0.23010	0.06087	4.9331
0.342	-4.62286	0.00514	0.34014	1.07834	0.22783	0.04691	4.8278
0.361	-4.67774	0.00458	0.34011	1.07769	0.22435	0.02910	4.6387
0.399	-4.81501	0.00482	0.33745	1.06747	0.20864	-0.00466	3.51405
0.418	-4.84331	-0.03330	0.33073	1.04355	0.18965	-0.01132	2.57535
0.437	-4.85449	-0.05808	0.32230	1.00084	0.15971	-0.01287	2.27505
0.456	-4.86339	-0.06605	0.31250	0.94167	0.12329	-0.01561	1.8369
0.475	-4.87195	-0.05794	0.30232	0.85447	0.07732	-0.01719	0.8587
0.494	-4.88476	-0.03946	0.28819	0.71508	0.02589	-0.01826	0.67375
0.513	-4.89993	-0.01824	0.26791	0.53549	-0.01689	-0.02232	-0.18425
0.532	-4.90608	-0.00368	0.26077	0.23406	-0.02367	-0.02531	-0.78235
0.551	-4.90324	-0.00217	0.25045	0.02606	-0.01435	-0.03153	-1.1137
0.57	-4.89721	0.00471	0.24437	-0.01316	-0.02918	-0.04551	-2.0498
0.589	-4.88213	0.00475	0.24258	-0.07741	-0.04362	-0.05097	-2.32315
0.608	-4.85143	0.00401	0.23463	-0.18505	-0.05801	-0.06071	-2.8011
0.627	-4.79433	0.00447	0.23181	-0.29002	-0.07569	-0.07198	-3.43355
0.646	-4.72752	0.00413	0.22154	-0.35997	-0.09793	-0.07514	-3.65505
0.665	-4.66312	0.02466	0.21503	-0.43041	-0.12299	-0.07994	-4.04315
0.684	-4.59294	0.06124	0.21166	-0.50096	-0.14511	-0.08387	-4.4084
0.703	-4.58255	0.14635	0.21187	-0.57415	-0.16357	-0.08637	-4.58675
0.722	-4.57191	0.21390	0.2206	-0.63632	-0.17817	-0.088	-4.7617
0.741	-4.55892	0.27381	0.22775	-0.68209	-0.1902	-0.09169	-4.9105
0.76	-4.55057	0.31527	0.23256	-0.70881	-0.19839	-0.09328	-4.98988
0.779	-4.54396	0.34443	0.23997	-0.72381	-0.20424	-0.06429	-4.96515
0.798	-4.53658	0.37307	0.24368	-0.73473	-0.20775	-0.0625	-4.9647
0.817	-4.53097	0.39792	0.24761	-0.74091	-0.21005	-0.06099	-4.96185
0.836	-4.52771	0.41344	0.25405	-0.74403	-0.21111	-0.0552	-4.9109
0.855	-4.5227	0.43205	0.25568	-0.74521	-0.21018	-0.0387	-4.70995
0.874	-4.51878	0.44596	0.26102	-0.74392	-0.2081	-0.02013	-4.2652
0.893	-4.51549	0.45474	0.26437	-0.73714	-0.19999	-0.00494	-3.2759
0.912	-4.51000	0.46508	0.26861	-0.72243	-0.18216	-0.00286	-2.7177
0.931	-4.50559	0.46655	0.27660	-0.69236	-0.15414	0.0039	-1.02185

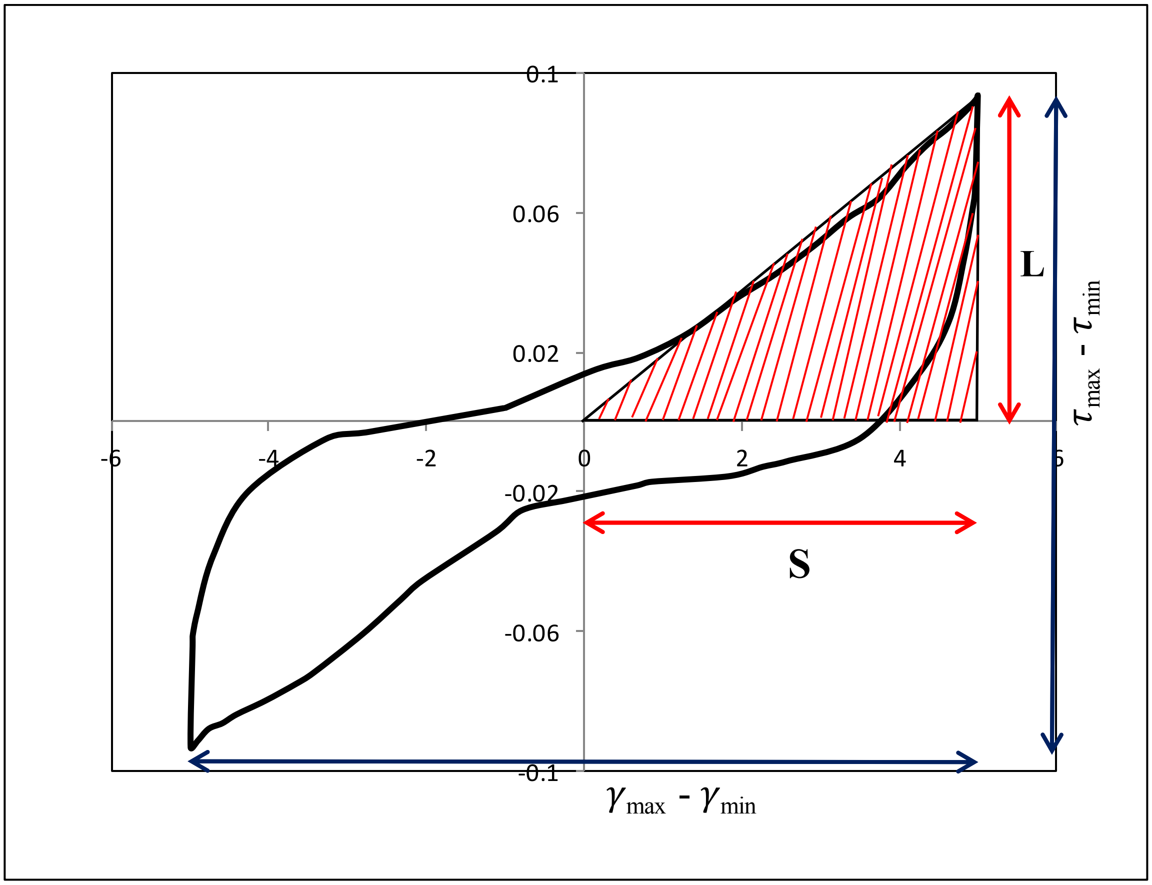

Figure 4.9 Hysteresis loop and triangle using shear- strain values of TK at 5th cycle

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

Height of the sample = 20mm and Diameter of sample = 70mm.

Area of sample (A) = π x 35^2 = 3,848.45cm^2

$$\text{Shear Strain, } \gamma = \frac{\text{Lateral LVDT}}{\text{Height of the sample}}$$

$$\text{Shear modulus, G} = \frac{\text{Amplitude of cyclic shear stress, } \Delta\tau}{\text{Amplitude of cyclic shear strain, } \Delta\gamma}$$

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

$$\text{Damping ratio, } D = \frac{1}{4\pi}\frac{\text{Area of the hysteresis loop}}{\text{Area of triangle}} = \frac{A_{loop}}{4\pi A_{\Delta}}$$

L = 0.091442 and S = 0.05

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

A_Δ = 0.5 (L x S) = 0.5 x (0.091442 x 0.05) = 0.002286

Table 4.5 Calculation of shear modulus and damping ratio of TK at 100kPa and 5th cycle

Shear Modulus		Damping Ratio	
L	0.092	$A_{loop} = \frac{1}{2}\sum_{i=1}^{n}(\tau_i - \tau_{i+1})\times(\gamma_i + \gamma_{i+1})$	0.578
S	0.05		
τ_{max}	0.092		
τ_{min}	-0.092		
$\tau_{max} - \tau_{min} = \Delta\tau = 2L$	0.183		
γ_{max}	0.05	$A_\Delta = \frac{1}{2}(S \times L)$	0.0023
γ_{min}	-0.05		
$\gamma_{max} - \gamma_{min} = \Delta\gamma = 2S$	0.10		
G (MPa) $= \frac{\Delta\tau}{\Delta\gamma}$	1.83	D (%) $= \frac{A_{loop}}{4\pi A_\Delta}$ x 100	20.13

The shear modulus and damping ratio values of the other test pits at respective axial stresses and shear strains are shown under Appendix-A.

Table 4.6 Shear modulus and damping ratio of TK at 100kPa

Strain (%) / Cycle No.	**0.01**	**0.1**	**1**	**3**	**5**	**0.01**	**0.1**	**1**	**3**	**5**
	Shear modulus, G (MPa)					**Damping Ratio, D (%)**				
1	9.31	5.87	2.52	1.19	0.38	6.91	11.51	18.15	21.64	24.86
2	9.59	5.81	3.00	1.49	0.69	6.08	10.48	17.71	20.58	23.84
3	9.70	5.89	3.06	1.54	0.74	5.90	10.47	17.57	20.55	23.79
4	9.82	5.96	3.26	1.76	0.80	5.88	10.46	16.81	20.49	23.75
5	9.95	6.54	3.12	**1.83**	0.98	5.86	10.45	16.75	**20.13**	23.70
6	10.22	7.05	3.44	1.86	0.99	5.84	10.38	16.32	20.11	23.69
7	10.31	7.07	3.48	1.87	1.00	5.84	10.29	16.24	20.09	23.35
8	10.34	7.09	3.50	1.88	1.05	5.82	10.18	16.21	19.7	23.24
9	10.39	7.11	3.53	1.90	1.10	5.81	9.90	16.16	19.56	23.20
10	10.42	7.13	3.58	1.98	1.18	5.80	9.89	16.12	18.9	23.14
11	10.46	7.15	3.62	2.04	1.24	5.79	9.88	15.9	18.9	23.04
12	10.48	7.18	3.66	2.09	1.29	5.78	9.88	15.88	18.83	23.03
13	10.52	7.16	3.70	2.16	1.36	5.77	9.87	15.86	18.73	23.01
14	10.55	7.18	3.72	2.22	1.42	5.76	9.87	15.85	18.71	22.85
15	10.59	7.19	3.76	2.26	1.47	5.75	9.87	15.76	18.71	22.73
16	10.68	7.21	3.78	2.32	1.52	5.74	9.86	15.64	18.68	22.56
17	10.73	7.22	3.82	2.37	1.57	5.73	9.85	15.62	18.61	22.46
18	10.76	7.23	3.84	2.41	1.61	5.71	9.84	15.62	18.61	22.32
19	10.78	7.25	3.88	2.46	1.66	5.71	9.84	15.57	18.47	22.31
20	10.83	7.26	3.91	2.53	1.77	5.18	9.53	15.56	18.45	22.30
21	10.86	7.27	3.94	2.54	1.78	5.69	9.83	15.56	18.44	22.29
22	10.92	7.28	3.96	2.58	1.83	5.69	9.82	15.55	18.41	21.62
23	10.95	7.30	3.98	2.63	1.89	5.67	9.82	15.55	18.41	21.55
24	10.98	7.31	4.01	2.67	1.94	5.65	9.80	15.54	18.41	21.48
25	11.01	7.33	4.04	2.71	1.99	5.65	9.78	15.52	18.41	21.45
26	11.05	7.35	4.10	2.75	2.03	5.64	9.76	15.51	18.41	21.44
27	11.08	7.37	4.12	2.79	2.08	5.64	9.76	15.5	18.41	21.41
28	11.20	7.39	4.18	2.84	2.12	5.64	9.75	15.49	18.15	21.35
29	11.23	7.41	4.20	2.88	2.17	5.63	9.74	15.47	18.15	21.31
30	11.26	7.43	4.22	2.92	2.21	5.63	9.72	15.44	18.14	21.25
31	11.29	7.46	4.24	2.96	2.26	5.63	9.72	15.42	18.14	21.21
32	11.34	7.49	4.31	3.00	2.31	5.61	9.72	15.41	18.13	21.15
33	11.37	7.56	4.34	3.05	2.35	5.61	9.70	15.39	18.12	21.15
34	11.42	7.59	4.46	3.09	2.40	5.59	9.68	15.36	18.12	21.11
35	11.46	7.62	4.52	3.14	2.44	5.57	9.68	15.11	18.01	21.10
36	11.93	7.71	4.58	3.19	2.48	5.57	9.68	14.92	17.71	21.09
37	11.99	7.82	4.64	3.25	2.52	5.57	9.66	14.88	17.49	21.08
38	12.03	7.92	4.70	3.33	2.57	5.55	9.58	14.84	17.45	21.07
39	12.10	8.02	4.73	3.44	2.61	5.21	9.41	14.76	17.38	21.06
40	12.16	8.21	4.79	3.51	3.09	4.36	8.35	14.31	17.35	21.04

4.4 Determination of the Initial Shear Modulus

Maximum shear modulus is one of the most important parameters in seismic response of soil. The initial shear modulus /maximum shear modulus was determined from empirical correlations of soil type and index properties that were developed by different researchers. It is an important parameter for computation of normalized shear modulus.

It is scare to find such reports about the influence of maximum shear modulus on dynamic shear modulus ratio, damping ratio and on seismic response of soil presently. How to measure maximum shear modulus exactly is a problem that is worthy to study further.

$$G_{max} = 3220 \times \left(\frac{(2.976 - e)}{(1 + e)}\right)^2 \times (OCR)^K \times (\sigma'_o)^{K_o}$$

$$\sigma'_o = \frac{(\sigma'_v + 2K_o\sigma'_v)}{3}$$

Typically, TK with PI value of 40, from Table 2.1 by interpolation has k value of 0.3 and void ratio of 1.31 at the natural state and 100kPa axial stress. From one-dimensional consolidation test result pre-consolidation pressure (Pc) of TK at 3m was 90kPa.

$$\text{So, } OCR = \frac{P_C}{P_O} = \frac{90}{100} = 0.9$$

$$\sigma'_o = \frac{(100 + 2\times0.5\times100)}{3}$$

$$\sigma'_o = 66.67\text{kPa}$$

$$G_{max} = 3220 \times \left(\frac{(2.976 - 1.31)}{(1 + 1.31)}\right)^2 \times (0.9)^{0.3} \times (66.67)^{0.5}$$

$$\text{Thus, } G_{max} = 30487.72\text{kPa}$$

$$G_{max} = 30.49\text{MPa}$$

From Table 4.6, the 5th cycle shear modulus at 0.01% shear strain was 9.95MPa

So, G/G_{max} = 9.95/30.49MPa

= 0.33

Similarly, G_{max} for each specimen was calculated and the results are presented in Table 4.7.

Table 4.7 Maximum shear modulus and normalized shear modulus values

Confining Pressure	Shear Strain (%)	MD		TK		SH		NMR	
		G_{max} (MPa)	G/G_{max}	G_{max} (MPa)	G/G_{max}	G_{max} (MPa)	G/G_{max}	G_{max} (MPa)	G/G_{max}
100 kPa	0.01	15.41	0.49	**30.49**	**0.33**	30.17	0.21	35.92	0.35
	0.1		0.28		0.22		0.14		0.24
	1		0.11		0.10		0.07		0.13
	3		0.06		0.05		0.03		0.09
	5		0.02		0.02		0.02		0.07
200 kPa	0.01	19.23	0.49	35.02	0.37	37.66	0.25	50.80	0.31
	0.1		0.33		0.25		0.17		0.22
	1		0.18		0.13		0.10		0.14
	3		0.12		0.07		0.07		0.10
	5		0.06		0.04		0.06		0.08
400 kPa	0.01	24.01	0.52	40.23	0.39	47.01	0.27	68.71	0.28
	0.1		0.34		0.27		0.19		0.21
	1		0.14		0.14		0.12		0.14
	3		0.10		0.09		0.09		0.11
	5		0.09		0.05		0.08		0.09

4.5 Variation of Shear Modulus and Damping with shear Strain and Confining Pressure

The shear modulus and damping ratio of cyclically loaded soils are strongly influenced by the shear strain levels. From Fig.4.10, Fig.4.12, Fig.4.14 and Fig.4.16, it was observed that shear modulus decreases with increase in shear strain amplitude. This is because at higher values of shear strain, the soil strength becomes smaller to resist deformation and more energy released to yield high deformation. In the Fig.4.13, Fig.4.15, Fig.4.17 and Fig.4.19, the damping ratio increases with increase in shear strain amplitude due to energy dissipation during deformation of soil.

The confining stress has a major influence on shear modulus and damping values. The figures of shear modulus and damping ratio with shear strain were drawn for 100kPa 200kPa and 400kPa confining pressures. As shown in those figures, shear modulus values at vertical confining stress of 400kPa is significantly larger than at vertical confining stress of 100kPa. This shows that shear modulus increase with increase in confining pressure and damping ratio decreases. As the confining pressure increases, the soil particles become closer to each other resulting in densification of soil. Densification causes an increase in density that further results in the increment of stiffness or shear modulus. Whereas, densification reduces the deformation of soils, which leads to the reduction of energy loss or damping ratio.

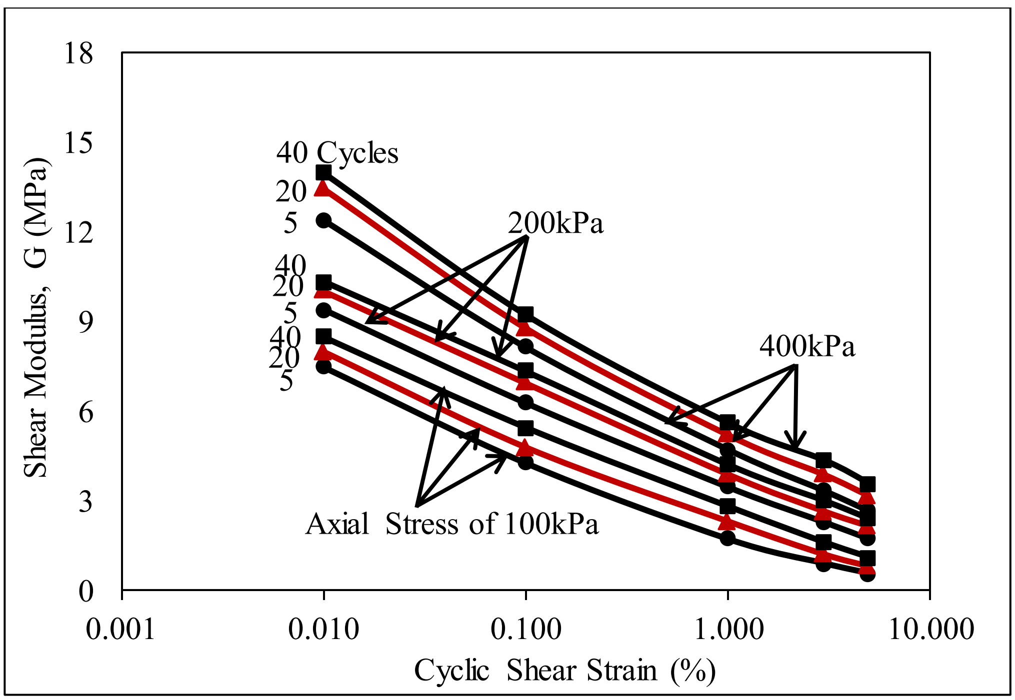

Figure 4.10 Variation of shear modulus of MD with shear strain amplitude

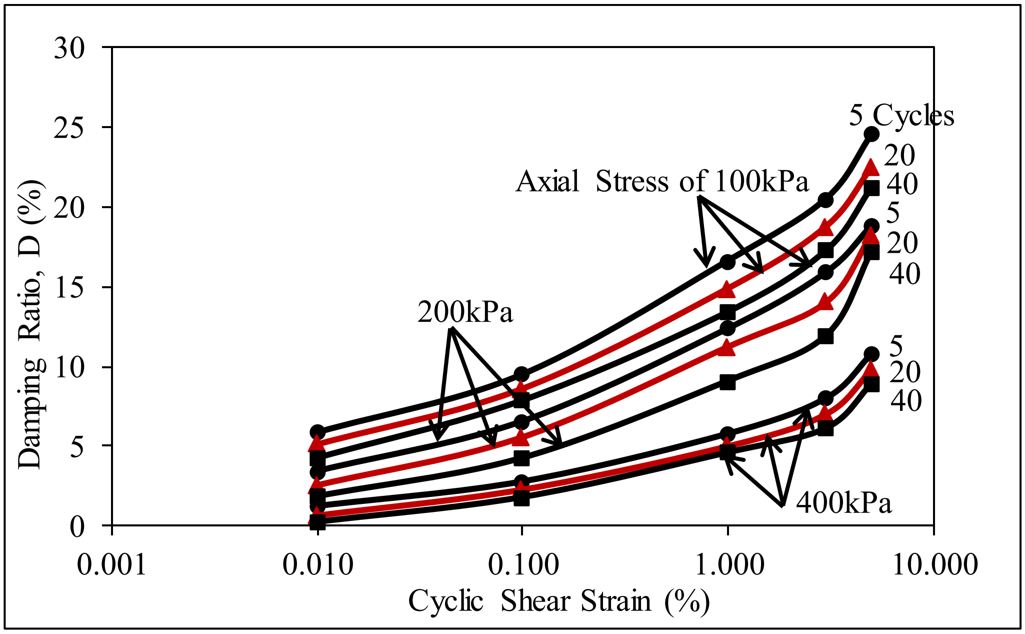

Figure 4.11 Variation of damping ratio of MD with shear strain amplitude

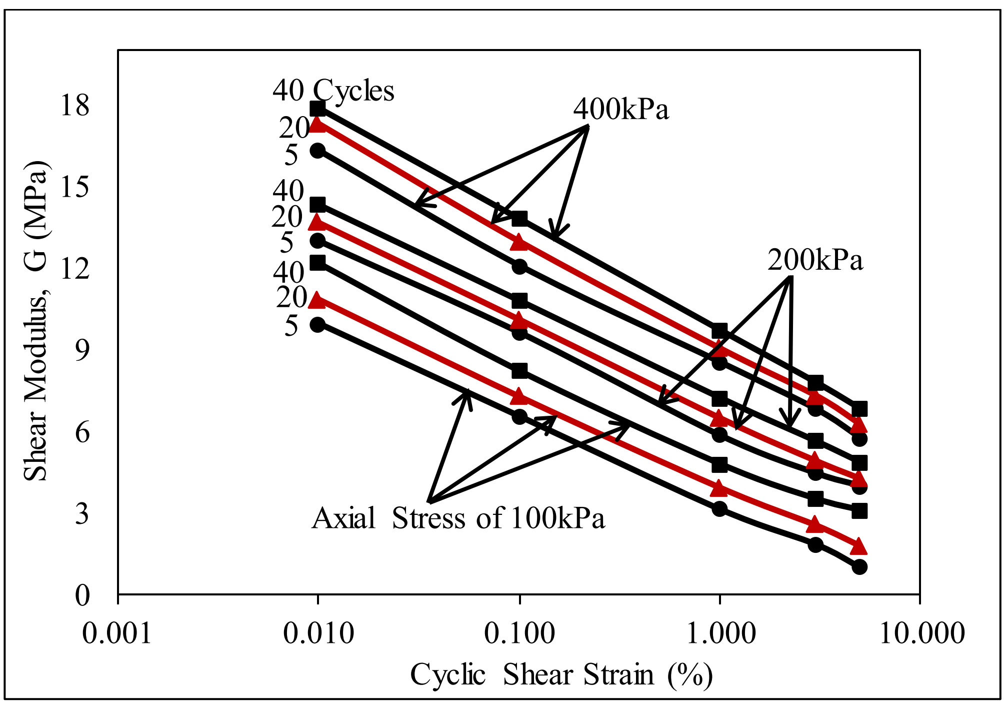

Figure 4.12 Variation of shear modulus of TK with shear strain amplitude

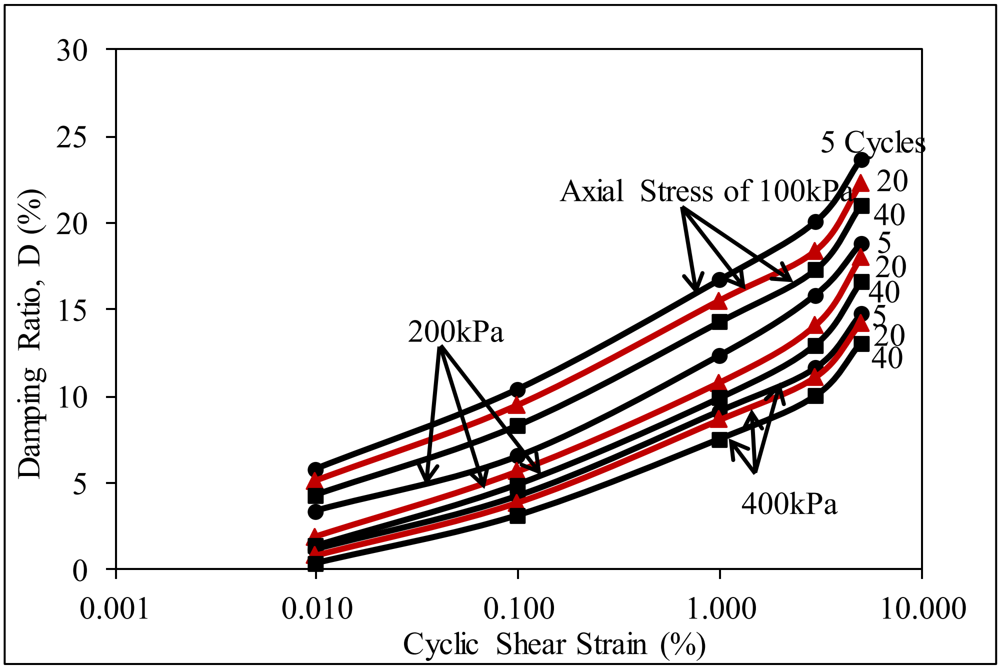

Figure 4.13 Variation of damping ratio of TK with shear strain amplitude

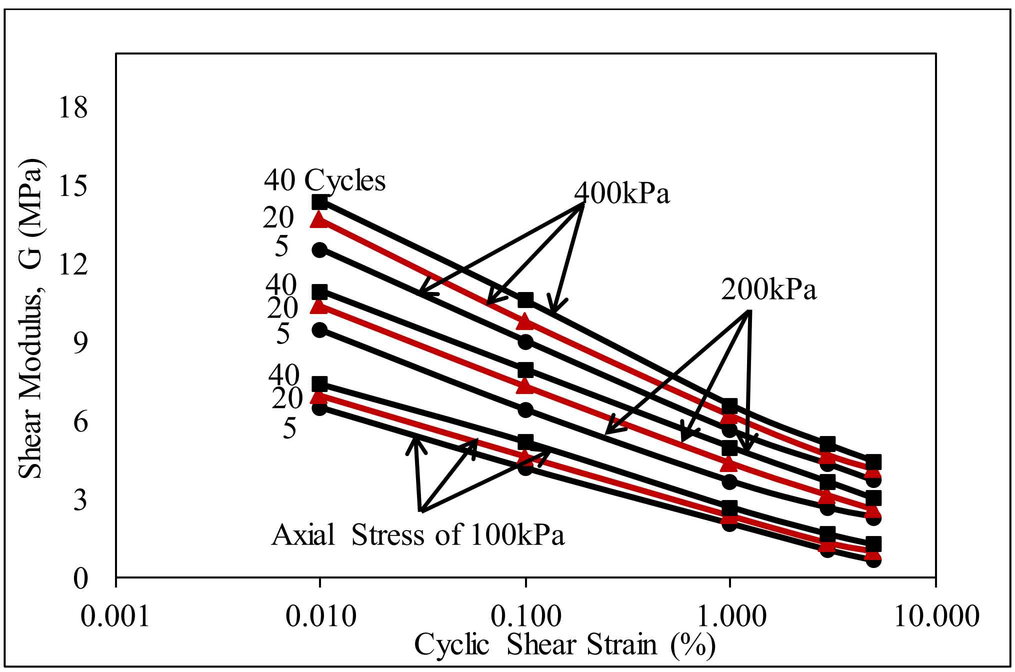

Figure 4.14 Variation of shear modulus of SH with shear strain amplitude

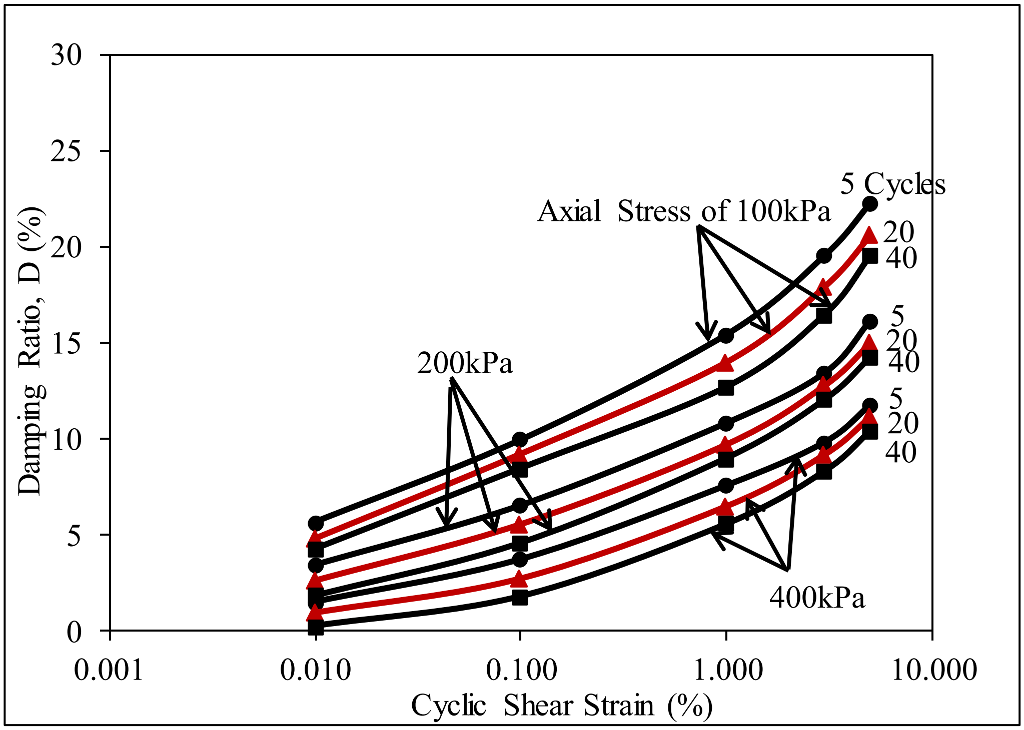

Figure 4.15 Variation of damping ratio of SH with shear strain amplitude

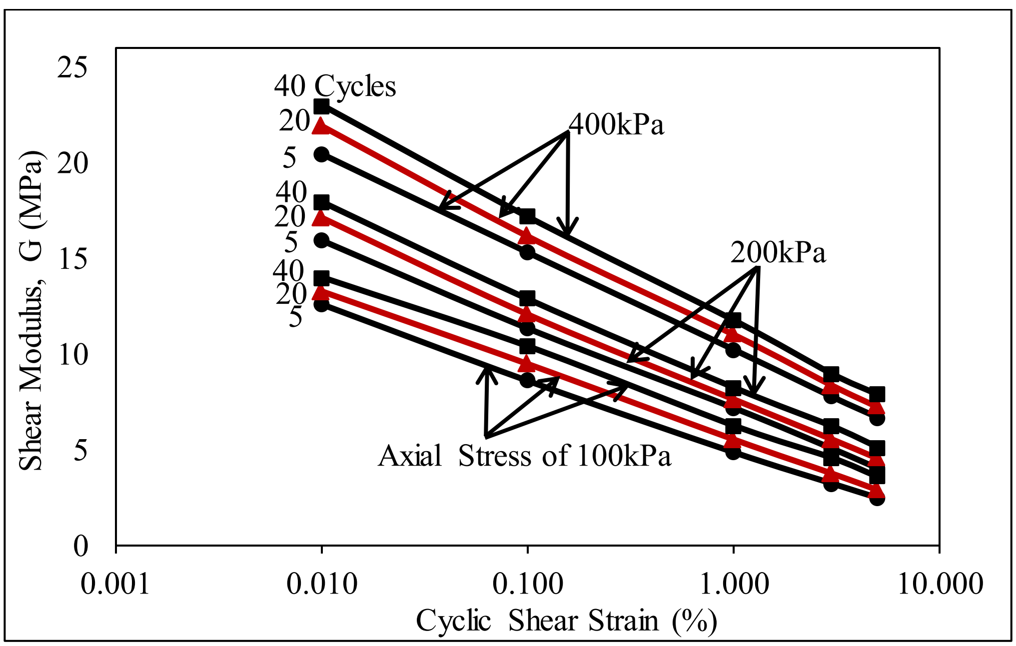

Figure 4.16 Variation of shear modulus of NMR with shear strain amplitude

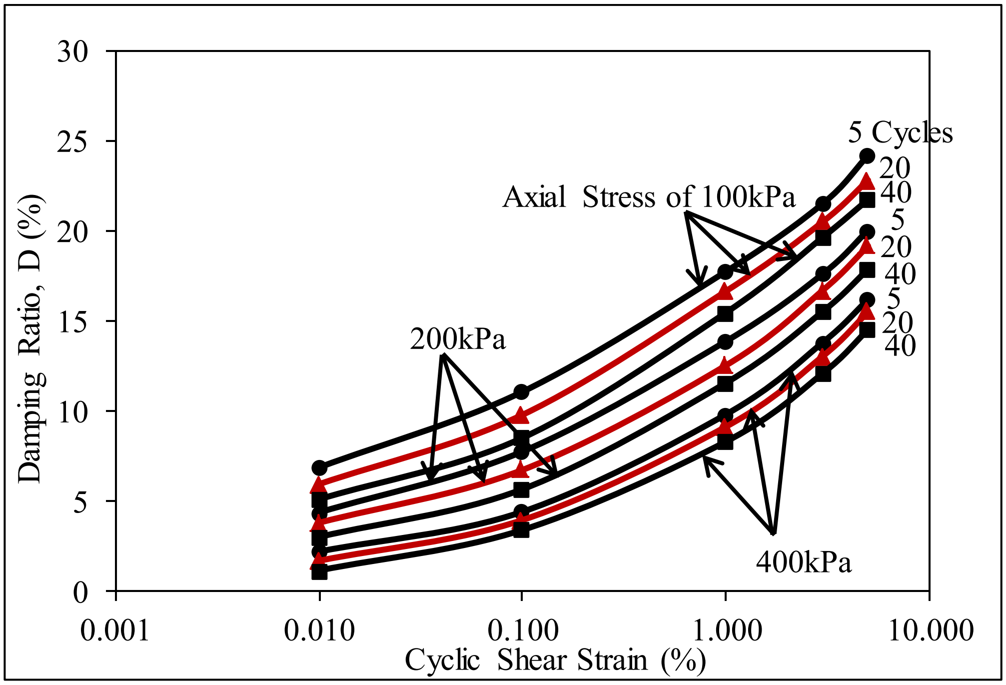

Figure 4.17 Variation of damping ratio of NMR with shear strain amplitude

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

The values of shear modulus and damping ratio against number of cycles were plotted as indicated in Fig.4.18 and Fig.4.19 at selected shear strains. It was observed that, the shear modulus increases and the damping ratio decreases with increasing number of cycles.

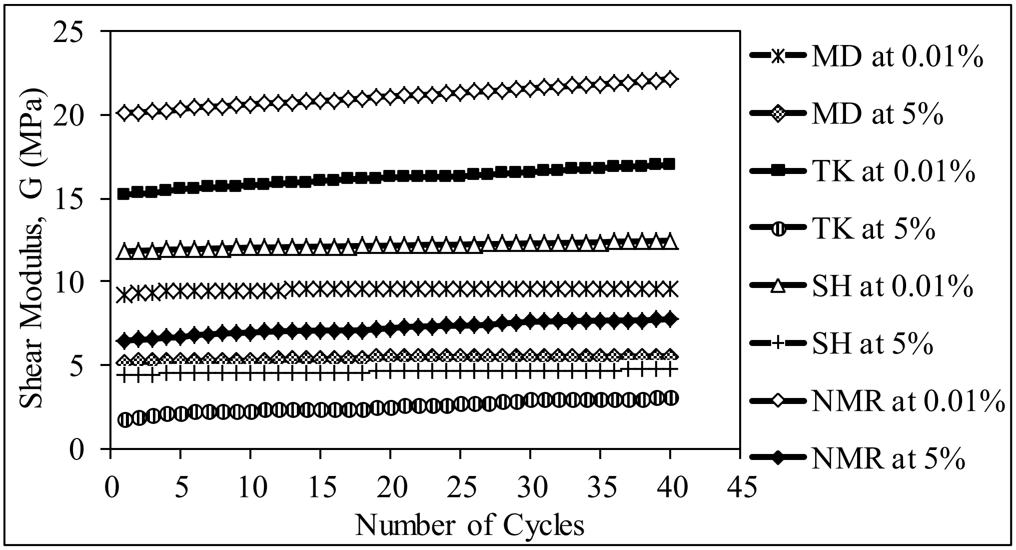

Figure 4.18 Variation of shear modulus of Modjo soil with number of cycles

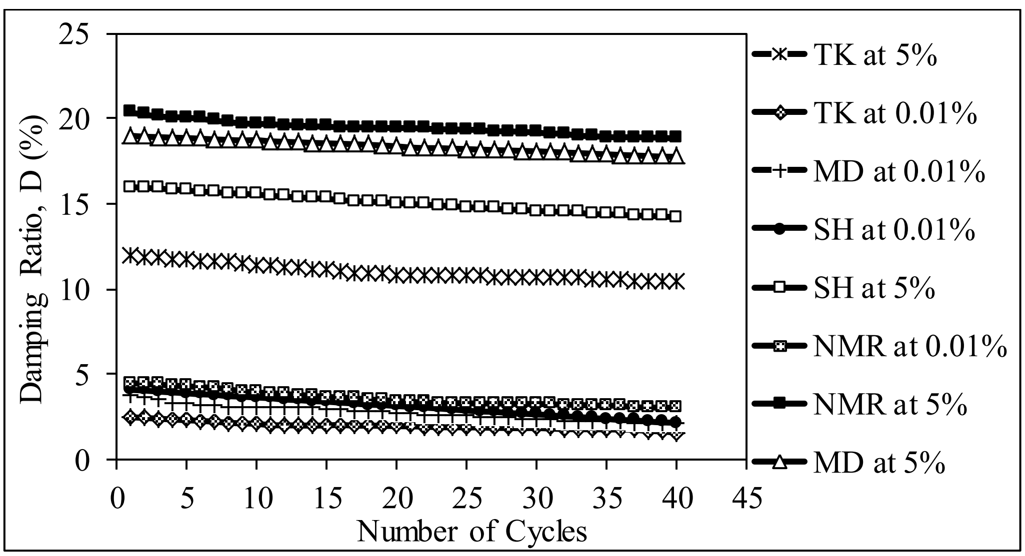

Figure 4.19 Variation of damping ratio of Modjo soil with number of cycles

4.7 Variation of Shear Modulus and Damping Ratio with Void Ratio

The variation of initial shear modulus with void ratio was observed by plotting Modjo soil results with existing curves as shown in the Fig.4.20. As the void ratio increase, the initial shear modulus decreases and has no significant influence on damping ratio at any shearing strain amplitude under all confining pressures.

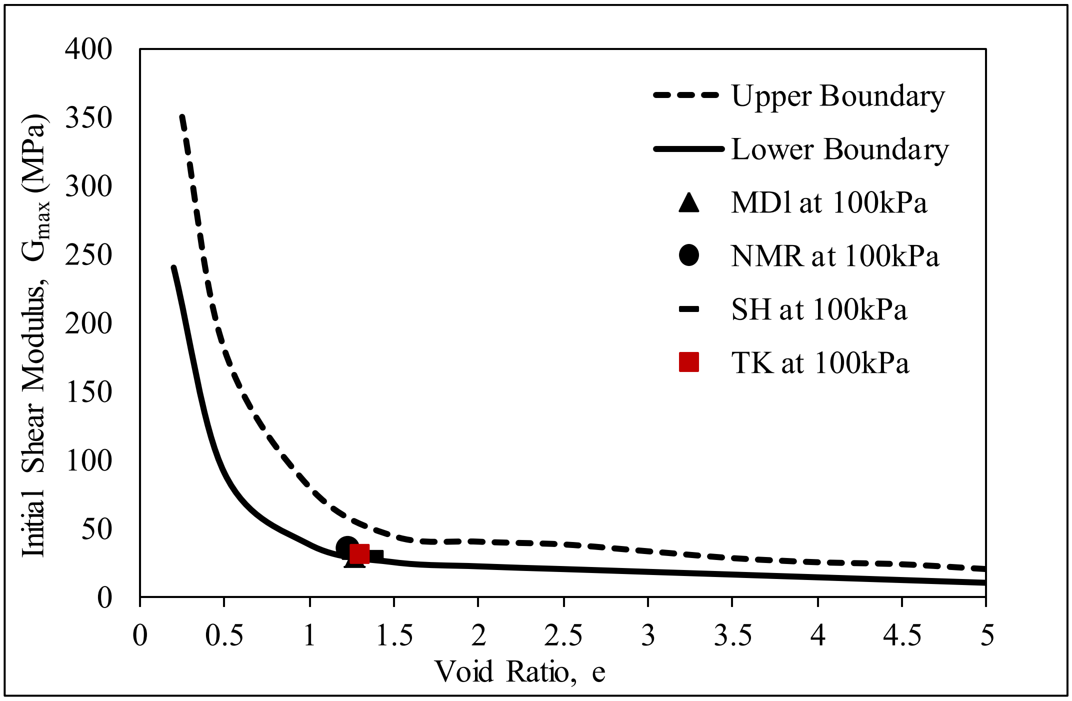

Figure 4.20 Variation of initial shear modulus of Modjo soil with void ratio

4.8 Variation of Shear Modulus and Damping Ratio with of Soil Plasticity

Plasticity of has effects on both the shear modulus and damping ratio of soil. As shown in the Fig.4.21 and Fig.4.22, the normalized shear modulus increase and the damping ratio decrease as the soil plasticity increase with same axial stress.

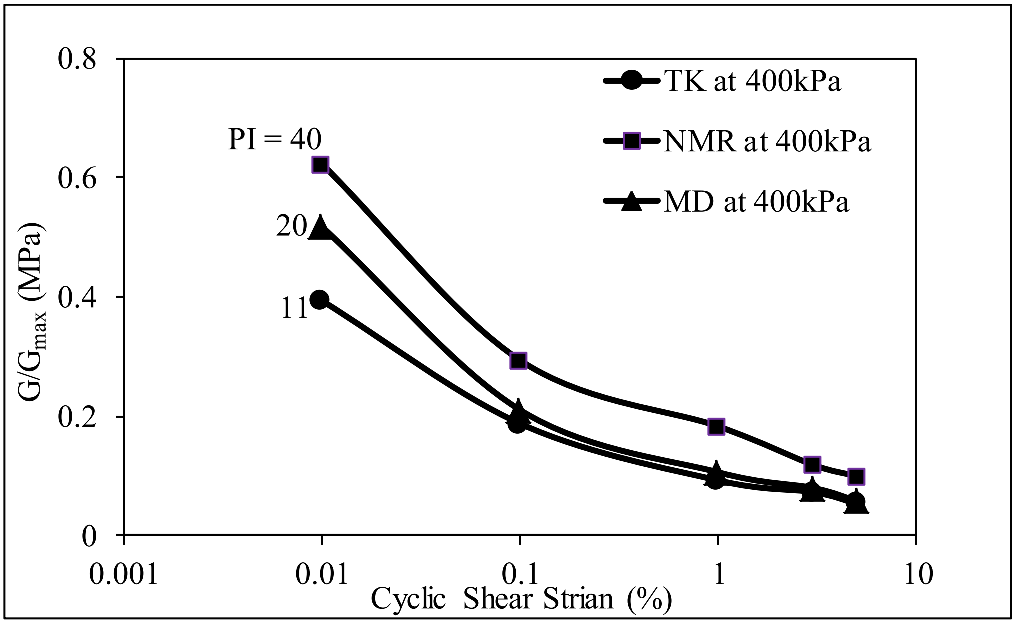

Figure 4.21 Variation of normalized shear modulus of Modjo soil with soil plasticity

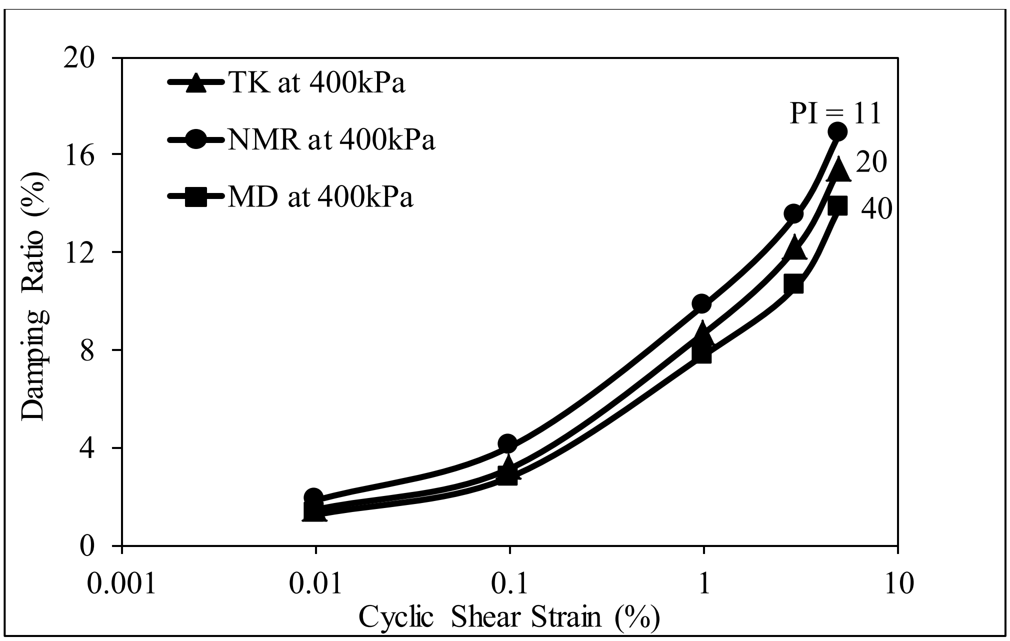

Figure 4.22 Variation of damping ratio of Modjo soil with soil plasticity

4.9 Comparison of Cyclic Test Results with Previous Studies

The variation of normalized shear modulus with shear strain is described graphically by modulus reduction curve. Previously, some researchers developed different normalized shear modulus and damping ratio curves for different soil. Normalized shear modulus and damping ratio curves of sandy and saturated clay soils developed by Seed H.B and Idriss [49] were used for comparison. In the Fig.4.23 and Fig.4.24, the normalized shear modulus (G/G_{max}) and damping ratio values were plotted against shear strain on the curves of Seed H.B and Idriss [49].

It has been seen that, the shear modulus reduction values of the Modjo silty and silty sand soil were lower than sand values. In general, it can be said that the results of shear modulus reduction and damping ratio values of the Modjo soils are comparable with previously published values.

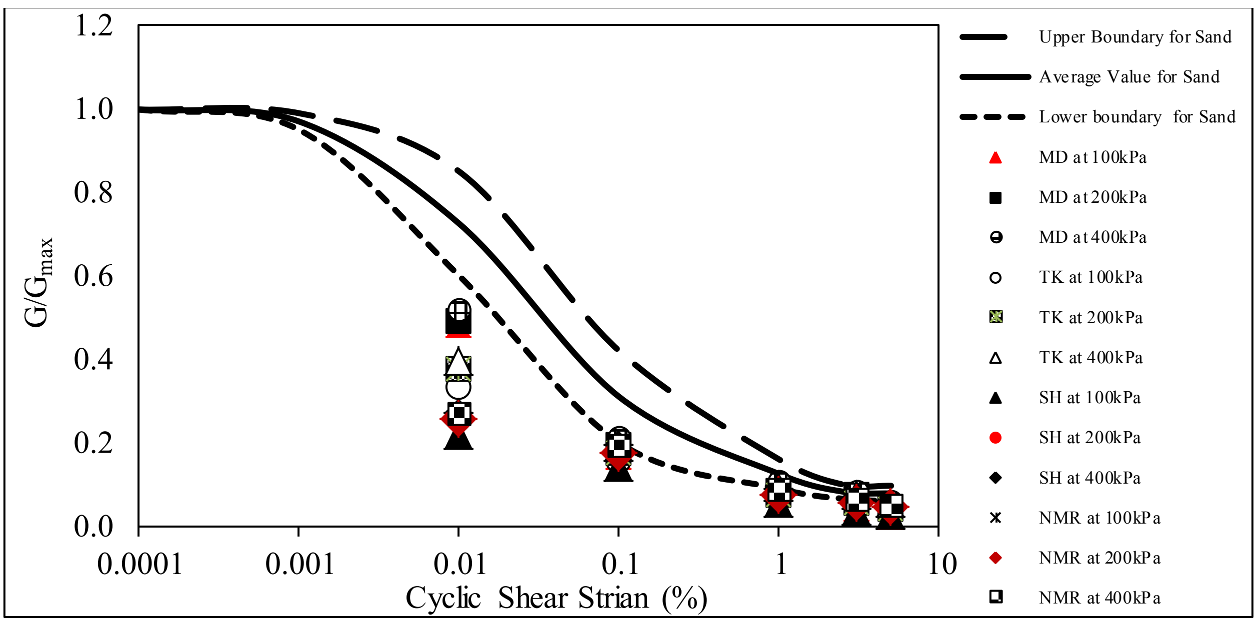

Figure 4.23 Comparison of Normalized shear modulus values of Modjo soil with the curves developed for sand by Seed and Idriss [49]

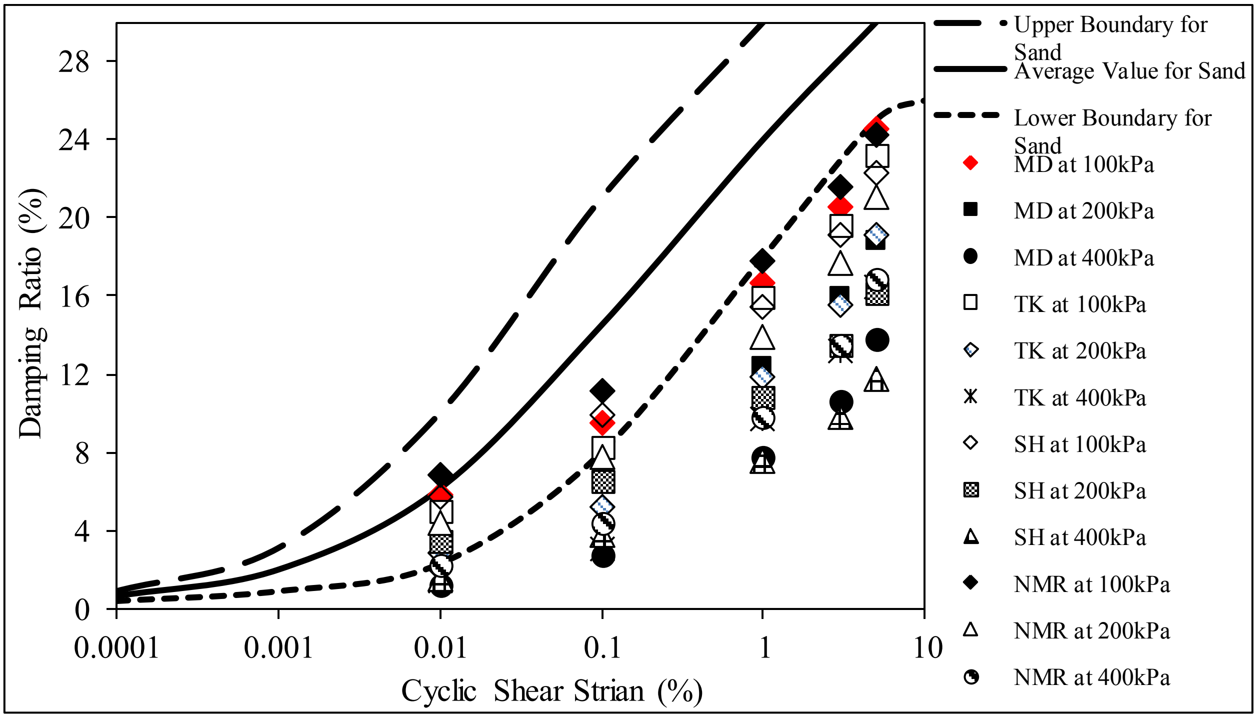

Figure 4.24 Comparison of damping ratio values of Modjo soil with the curves developed for sands by Seed and Idriss [49]

The normalized shear modulus and damping ratio values for silt and silty sand soils are expected to be below the sand and above the clay curves. From Fig.4.25 and Fig.4.26, the normalized shear modulus values Modjo soil were higher than saturated clay soils, which is in a good agreement. However, the damping ratio values of Modjo soil were lower than the aveage saturated clay curves. This is because Modjo soil is highly plastic soil, which has high clay content, due to sample disturbance and testing conditions problems.

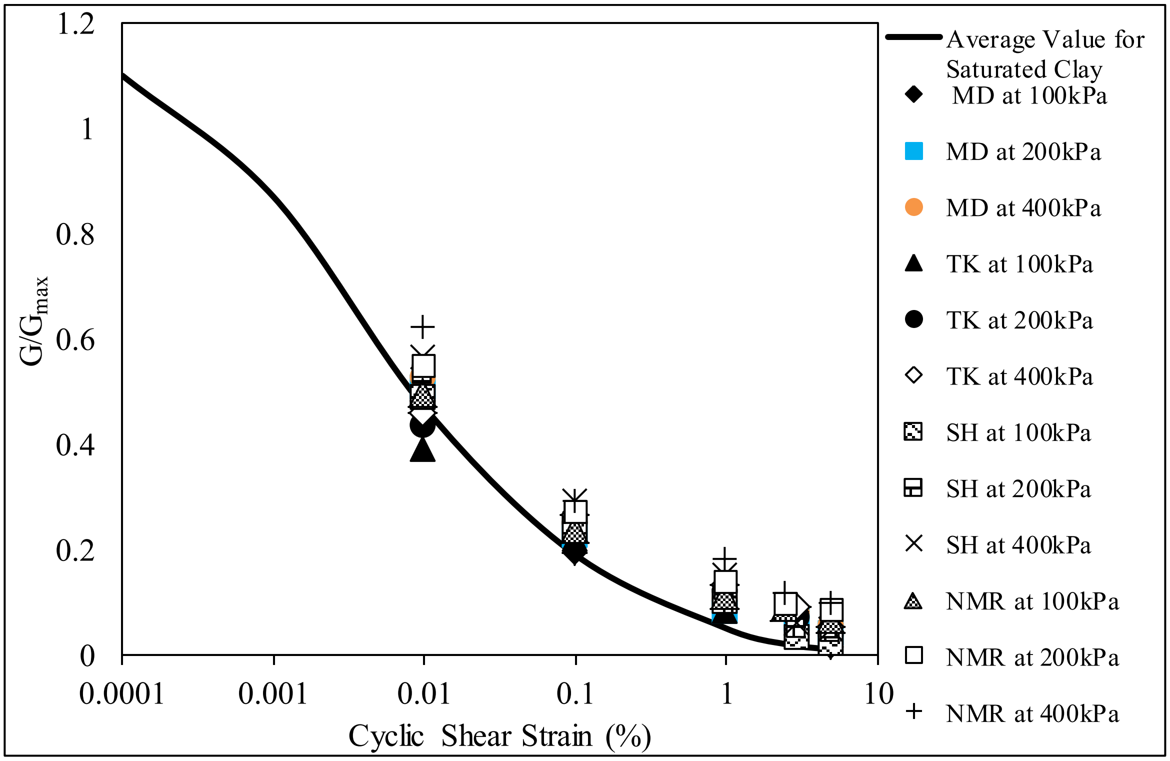

Figure 4.25 Comparison of Normalized shear modulus values of Modjo soil with the curve developed for saturated clay by Seed and Idriss [49]

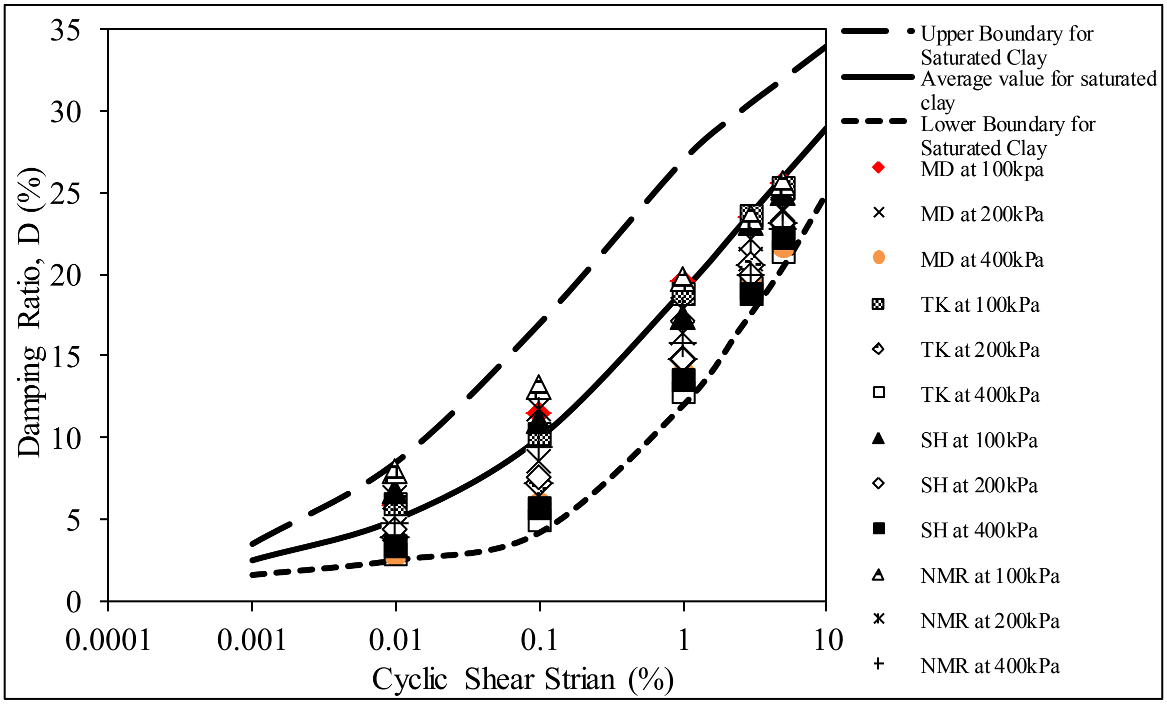

Figure 4.26 Comparison of damping ratio values of Modjo soil with the curve developed for saturated clay by Seed and Idriss [49]

Comparison of Modjo silt and silty sand soils with Adama and Ziway town silt and silty sand soils were done and the relationships are shown in following figures. From Fig.4.27, Fig.4.28, Fig.4.29 and Fig.4.30, the results of normalized shear modulus and damping ratio values of Modjo soils were in a good agreement with silt and silty sand soils of Adama and Ziway towns.

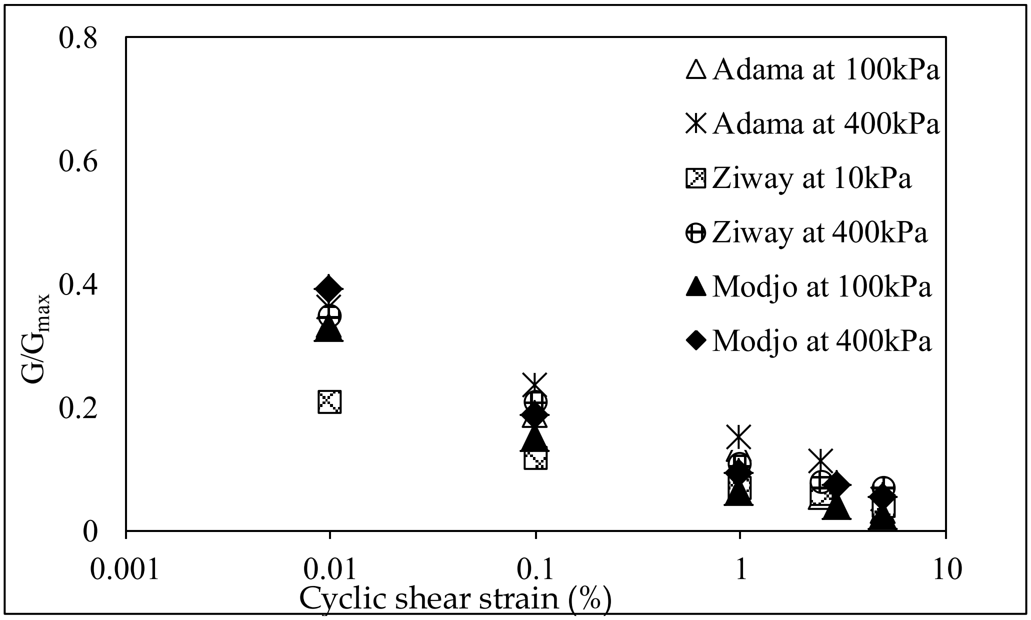

Figure 4.27 Comparison of Normalized shear modulus with the curve of F. Abu Gemechu [17] and M. Abraham [38] for silty soil.

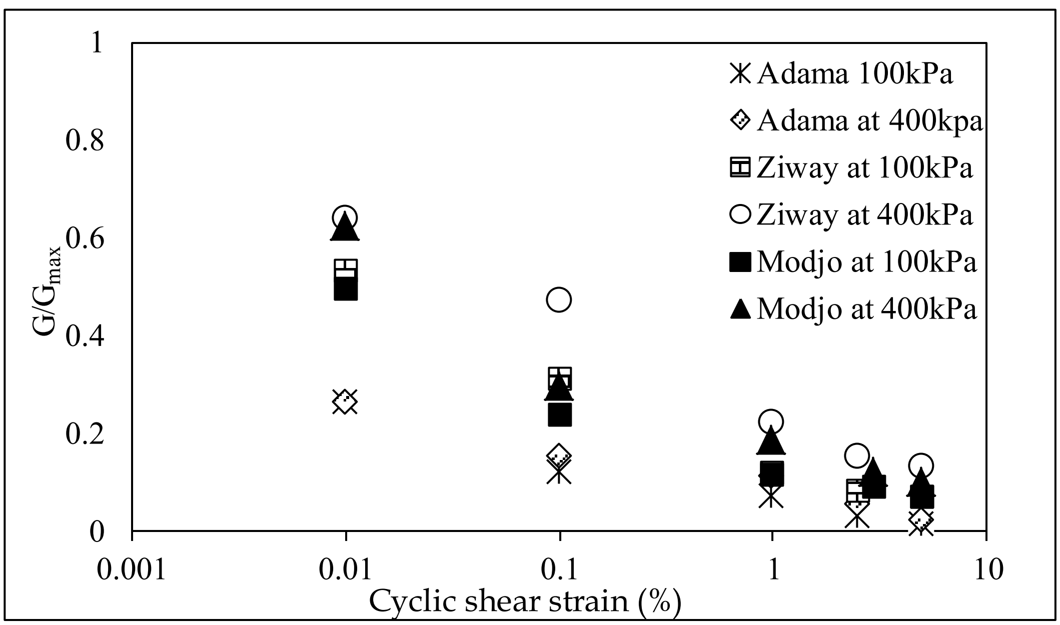

Figure 4.28 Comparison of Normalized shear modulus with the curve of F. Abu Gemechu [17] and M. Abraham [38] for silty sand soil.

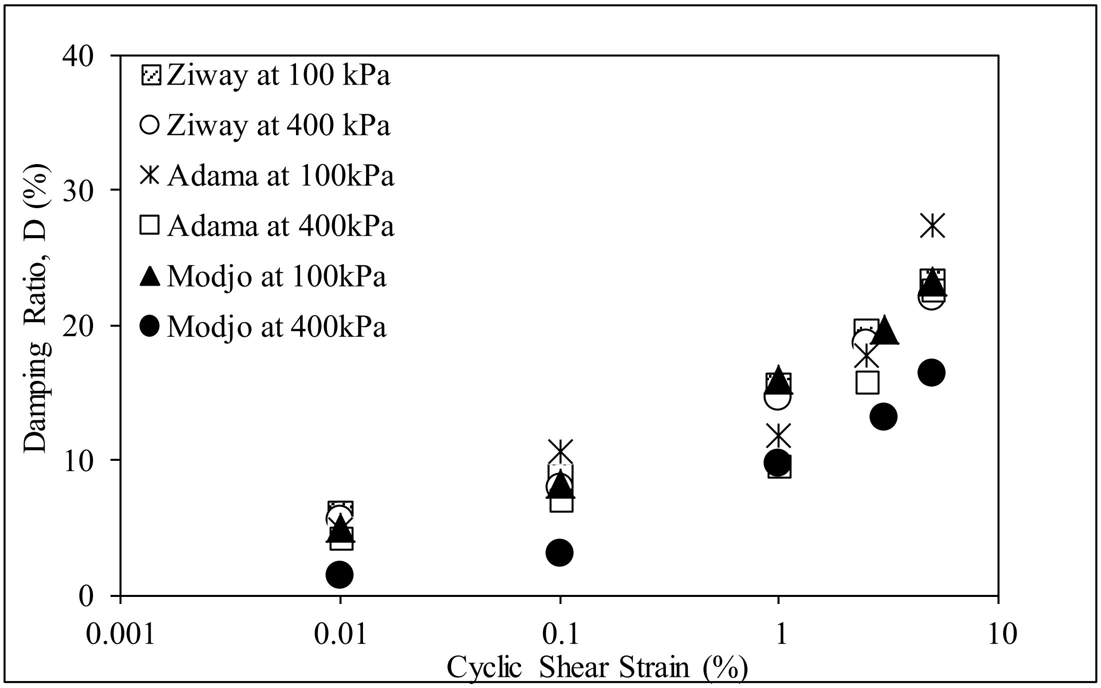

Figure 4.29 Comparison of damping ratio values with the curves F.Abu Gemechu [17] and M. Abraham [38] for silt soil.

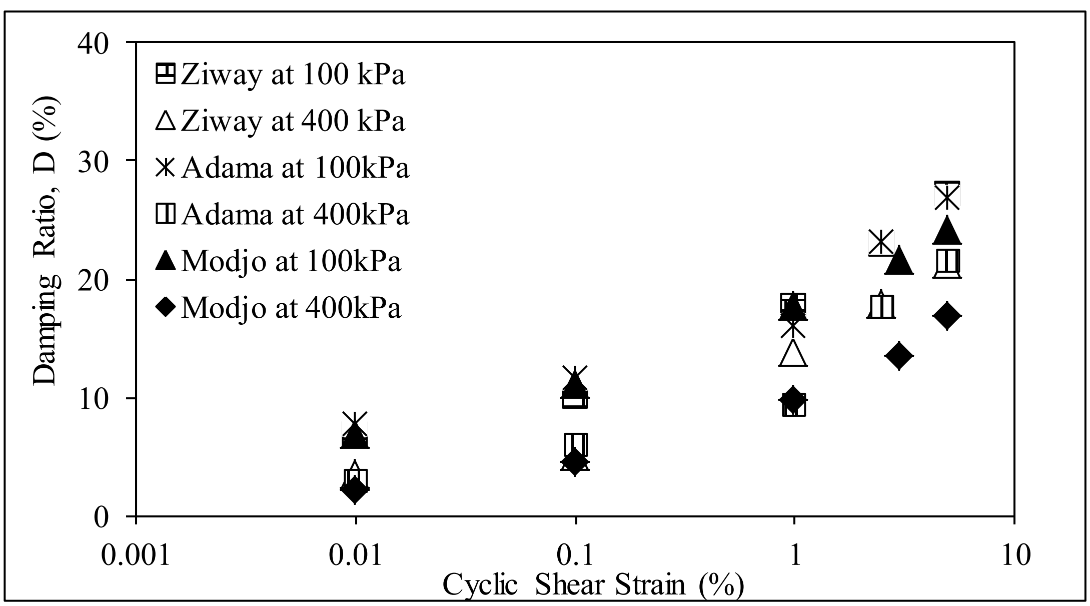

Figure 4.30 Comparison of damping ratio values with the curves of F. Abu Gemechu [17] and M. Abraham [38] for silt sand soil.

4.10 Contribution of the Study

Dynamic loading resistant design of new and evaluation of the safety of the existing structures requires the soil and the structure responses to dynamic loading. Pure dynamic loads do not occur in nature, it is always a combination of static and dynamic loadings. Hence, investigation of the behavior soil at static and dynamic state was very important to arrive at rational analysis and design of dynamic loads in soil. To design dynamic loading resistant foundation for earthquake, machine operation or loading unloading, depends on local soil condition and response.

Generally, determinations of static and dynamic properties of Modjo town soil providing input parameters for:

- ✓ design of foundation for machinery and vibratory equipment
- ✓ design of retaining walls and embankments
- ✓ assessment of permanent settlement due to vibratory compaction of foundation soil
- ✓ modelling of soil behavior under dynamic loadings
- ✓ analysis of soil-structure interactions

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. CONCLUSIONS

Reliable measurement of these soil properties is important for successful analysis of an important class of geotechnical problems such as seismic design and machine foundations. This study investigates the experimental determination of dynamic properties (G and D) of Modjo soil using cyclic simple shear machine. The effects of different factors on the dynamic properties of different soils were also discussed.

From the results of this study, the following points are drawn:

- ✓ The values of shear modules ranges from 0.11MPa to 22.98MPa, damping ratio are between 0.25% and 25.63% and maximum shear modulus values from 15.41MPa to 68.71MPa, which are acceptable for Modjo soil type based on the previous studies.
- ✓ The influences of some of the critical factors of dynamic soil properties were considered. The shear modulus increases and the damping ratio decreases with increasing number of cycles, confining pressure and soil plasticity, which agree with Lidong Bai conclusion. The shear modulus decreases with increase of shear strain amplitude and void ratio. However, the damping ratio increases with increase of shear strain amplitude and no change for void ratio.
- ✓ The shear modulus values were normalized and the normalized shear modulus values were compared with sand and saturated clay soils estimated by Seed, H.B. and Idriss, I.M. From this comparison, there is a good agreement between these values.
- ✓ The damping ratio values were also compared with the curves of Seed, H.B. and Idriss, I.M and slight difference was observed. It could be due to method of sample preparation, calibration of the machine or the imperfect coupling between the top caps and the specimens.
- ✓ The shear modulus and damping ratio values of Modjo soil showed similar shape and distribution with the curves of F. Abu Gemchu (Adama) and M. Abraham (Ziway) for both silty and silty sand soils.

5.2. RECOMMENDATIONS

The objective this study was limited to investigating shear modulus and material damping of Modjo town soil using cyclic simple shear apparatus. From the findings of the study using the cyclic simple shear apparatus, the following points are recommended.

- ✓ The dynamic soil properties were studied under natural conditions. However, to observe the effect of saturation, pore-water pressure and degree of compaction on dynamic properties of soil, it is necessary to investigate under saturation condition and under different degree of compaction.
- ✓ Due to economical and time factors, soil samples were taken from four test pits only. To obtain a better and comprehensive data more samples have to be tested.
- ✓ In cyclic simple shear machine, some of the O-rings are slightly deformed which leads to defect of data due to uneven stress distribution in the sample and development of frictions between the rings. Therefore, these rings have to be updated.
- ✓ This study was done using the cyclic simple shear apparatus only. It is important to supplement these results by cyclic triaxial test results.

Limitation of the study

In cyclic simple shear machine, the pore pressure and backpressure cells are not functional,

- ✓ the liquefaction

Limitation of the study

In cyclic simple shear machine, the pore pressure and backpressure cells are not functional,

- ✓ the liquefaction condition of the soil cannot be determine
- ✓ The comparisons of the test results were done with Seed and Idriss only due to limitation of available soil data.
- ✓ The samples for both index and cyclic test were disturbed samples due availability of sampling equipment and laboratory apparatus.

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APPENDIX-A

Shear Modulus and Damping Ratio Values

Table A.1 Shear modulus and damping ration values of MD at 100kPa

Test Pit	**Modjo Dry Port at 100kPa axial stress**									
Strain (%)	**0.01**	**0.1**	**1**	**3**	**5**	**0.01**	**0.1**	**1**	**3**	**5**
Cycle No.	**Shear modulus, G (MPa)**					**Damping Ratio, D (%)**				
1	7.01	3.78	1.46	0.57	0.11	6.66	10.71	17.51	21.70	25.63
2	7.20	4.22	1.66	0.81	0.21	6.54	9.60	16.99	20.88	25.08
3	7.27	4.23	1.68	0.91	0.23	6.42	9.58	16.87	20.76	24.85
4	7.28	4.25	1.71	0.91	0.23	6.14	9.57	16.71	20.60	24.60
5	7.48	4.27	1.73	0.91	0.25	5.87	9.52	16.64	20.53	24.57
6	7.48	4.30	2.05	1.11	0.35	5.52	9.33	16.53	20.42	24.29
7	7.49	4.31	2.09	1.16	0.41	5.52	8.97	16.26	20.15	24.28
8	7.49	4.35	2.09	1.17	0.43	5.49	8.97	16.23	20.12	24.07
9	7.60	4.35	2.17	1.17	0.44	5.40	8.96	16.15	20.04	23.80
10	7.90	4.36	2.18	1.18	0.45	5.33	8.93	15.97	19.86	23.76
11	7.90	4.36	2.18	1.18	0.45	5.33	8.93	15.94	19.82	23.73
12	7.91	4.39	2.18	1.18	0.45	5.33	8.89	15.84	19.73	23.69
13	7.90	4.40	2.18	1.18	0.45	5.31	8.86	15.83	19.71	23.50
14	7.91	4.50	2.20	1.19	0.45	5.28	8.80	15.80	19.69	23.30
15	7.94	4.59	2.24	1.19	0.46	5.25	8.79	15.36	19.25	23.13
16	7.95	4.62	2.26	1.20	0.46	5.25	8.74	15.03	18.92	23.01
17	7.98	4.67	2.28	1.21	0.46	5.22	8.70	14.96	18.85	22.96
18	7.98	4.70	2.28	1.21	0.47	5.19	8.66	14.94	18.83	22.76
19	7.99	4.79	2.32	1.21	0.47	5.18	8.65	14.92	18.81	22.72
20	8.00	4.80	2.32	1.21	0.48	5.11	8.61	14.90	18.79	22.50
21	8.00	5.42	2.33	1.21	0.48	5.11	8.58	14.84	18.73	22.48
22	8.19	5.43	2.33	1.22	0.48	5.11	8.56	14.76	18.65	22.46
23	8.20	5.43	2.35	1.22	0.49	5.06	8.54	14.68	18.57	22.22
24	8.21	5.43	2.39	1.22	0.49	5.04	8.53	14.65	18.54	22.19
25	8.35	5.43	2.40	1.23	0.50	5.01	8.52	14.17	18.06	22.07
26	8.36	5.43	2.42	1.23	0.50	4.99	8.51	14.09	17.98	21.83
27	8.36	5.43	2.43	1.24	0.50	4.99	8.48	14.05	17.94	21.67
28	8.36	5.43	2.43	1.24	0.51	4.95	8.47	14.00	17.89	21.64
29	8.37	5.44	2.47	1.24	0.51	4.93	8.39	13.90	17.79	21.45
30	8.39	5.44	2.57	1.25	0.53	4.93	8.36	13.79	17.68	21.44
31	8.39	5.44	2.57	1.25	0.53	4.92	8.35	13.74	17.63	21.42
32	8.39	5.44	2.59	1.25	0.53	4.92	8.31	13.72	17.61	21.35
33	8.40	5.44	2.63	1.26	0.54	4.88	8.30	13.70	17.59	21.35
34	8.47	5.45	2.66	1.26	0.54	4.84	8.29	13.59	17.48	21.32
35	8.47	5.45	2.66	1.26	0.55	4.83	8.14	13.58	17.47	21.29
36	8.48	5.45	2.69	1.27	0.55	4.82	8.13	13.56	17.45	21.24
37	8.48	5.45	2.69	1.27	0.55	4.81	8.07	13.47	17.36	21.24
38	8.48	5.46	2.76	1.28	0.56	4.79	8.00	13.43	17.32	21.24
39	8.48	5.46	2.80	1.31	0.56	4.73	7.98	13.43	17.27	21.24
40	8.49	5.46	2.83	1.62	0.78	4.27	7.88	13.43	17.29	21.24

Table A.2 Shear modulus and damping ration values of MD at 200kPa

Test Pit	**Modjo Dry Port at 200kPa axial stress**									
Strain (%)	**0.01**	**0.1**	**1**	**3**	**5**	**0.01**	**0.1**	**1**	**3**	**5**
Cycle No.	**Shear modulus, G (MPa)**					**Damping Ratio, D (%)**				
1	8.95	5.77	2.83	1.68	1.33	4.00	7.44	13.11	16.74	19.57
2	9.23	5.82	3.15	1.99	1.55	3.85	6.67	13.10	16.37	18.93
3	9.24	5.91	3.15	2.09	1.55	3.80	6.62	13.10	16.17	18.91
4	9.33	5.93	3.15	2.13	1.56	3.62	6.60	12.65	16.01	18.87
5	9.41	6.28	3.47	2.29	1.73	3.44	6.57	12.39	15.91	18.85
6	9.49	6.37	3.65	2.30	1.56	3.01	6.57	12.39	15.83	18.81
7	9.69	6.42	3.65	2.30	1.56	2.99	6.33	12.39	15.69	18.77
8	9.81	6.42	3.72	2.31	1.56	2.89	6.32	12.38	15.69	18.74
9	9.87	6.53	3.80	2.32	1.57	2.88	6.14	12.38	15.48	18.71
10	9.89	6.62	3.81	2.32	1.57	2.86	6.10	12.38	15.39	18.75
11	9.89	6.64	3.82	2.32	1.57	2.84	6.06	12.38	15.30	18.66
12	9.91	6.76	3.83	2.33	1.57	2.83	6.06	12.38	15.22	18.63
13	9.94	6.77	3.84	2.34	1.57	2.82	6.00	12.37	14.91	18.60
14	9.95	6.82	3.85	2.34	1.57	2.82	6.00	12.37	14.87	18.57
15	9.96	6.88	3.85	2.35	1.57	2.70	5.97	12.36	14.71	18.54
16	9.99	6.89	3.87	2.36	1.58	2.70	5.88	12.36	14.49	18.52
17	10.00	6.90	3.88	2.37	1.58	2.58	5.82	12.22	14.37	18.49
18	10.00	6.93	3.88	2.37	1.58	2.56	5.77	12.01	14.05	18.45
19	10.01	6.94	3.88	2.37	1.59	2.55	5.71	11.54	14.02	18.42
20	10.02	6.94	3.89	2.65	2.15	2.54	5.56	11.23	14.02	18.27
21	10.03	7.03	3.90	2.39	1.59	2.51	5.54	11.23	13.63	18.26
22	10.05	7.04	3.90	2.40	1.60	2.40	5.46	11.22	13.23	18.26
23	10.06	7.06	3.90	2.41	1.60	2.39	5.38	11.22	13.14	18.26
24	10.10	7.06	3.90	2.41	1.61	2.36	5.29	11.22	12.88	18.23
25	10.10	7.09	3.90	2.42	1.62	2.35	5.29	11.13	12.60	18.21
26	10.10	7.10	3.91	2.42	1.62	2.31	5.21	10.84	12.43	18.17
27	10.10	7.16	3.91	2.44	1.63	2.30	5.21	10.81	12.38	18.15
28	10.12	7.17	3.91	2.45	1.64	2.21	5.20	10.59	12.35	18.12
29	10.12	7.19	3.93	2.45	1.65	2.17	5.17	10.09	12.11	18.10
30	10.16	7.24	3.93	2.46	1.67	2.14	5.16	9.92	12.10	18.08
31	10.17	7.25	3.93	2.48	1.69	2.09	5.11	9.86	11.80	18.04
32	10.17	7.26	3.93	2.49	1.70	2.04	5.10	9.66	11.51	18.00
33	10.18	7.26	3.93	2.50	1.71	2.00	5.03	9.37	11.47	17.97
34	10.18	7.27	3.93	2.50	1.73	1.99	5.01	9.25	11.46	17.93
35	10.20	7.28	3.94	2.51	1.78	1.97	4.98	9.23	11.43	17.90
36	10.21	7.31	3.94	2.52	1.80	1.97	4.78	9.20	11.43	17.86
37	10.21	7.34	3.98	2.53	1.81	1.97	4.35	9.13	11.43	17.83
38	10.24	7.34	3.99	2.53	1.82	1.97	4.29	9.11	11.43	17.80
39	10.27	7.34	3.99	2.54	2.11	1.96	4.28	9.10	11.43	17.76
40	10.35	7.34	4.22	3.01	2.41	1.86	4.28	9.10	11.96	17.25

Table A.3 Shear modulus and damping ration values of MD at 400kPa

Test Pit	**Modjo Dry Port at 400kPa axial stress**									
Strain (%)	**0.01**	**0.1**	**1**	**3**	**5**	**0.01**	**0.1**	**1**	**3**	**5**
Cycle No.	**Shear Modulus, G (MPa)**					**Damping Ratio, D (%)**				
1	11.62	7.72	4.27	3.02	2.43	1.75	3.36	6.83	9.35	11.38
2	12.12	8.15	4.28	3.25	2.50	1.39	3.32	6.71	9.10	10.98
3	12.26	8.15	4.32	3.27	2.57	1.38	3.32	6.10	9.09	10.98
4	12.38	8.15	4.37	3.33	2.58	1.36	3.31	6.09	8.63	10.94
5	12.40	8.15	4.72	3.34	2.66	1.24	2.79	5.78	8.02	10.79
6	12.96	8.53	5.06	3.54	2.87	1.21	2.79	5.55	8.02	10.79
7	12.98	8.54	5.06	3.54	2.88	0.93	2.78	5.55	8.01	10.79
8	12.99	8.61	5.06	3.54	2.89	0.90	2.58	5.55	8.01	10.50
9	13.03	8.64	5.06	3.55	2.90	0.89	2.58	5.54	7.55	10.42
10	13.22	8.70	5.07	3.55	2.96	0.89	2.57	5.54	7.55	10.34
11	13.22	8.70	5.07	3.55	2.98	0.87	2.55	5.46	6.86	10.28
12	13.26	8.71	5.07	3.55	2.99	0.86	2.49	5.43	6.83	10.24
13	13.30	8.71	5.13	3.55	3.00	0.84	2.46	5.27	6.83	10.20
14	13.35	8.72	5.13	3.55	3.01	0.79	2.41	5.16	6.80	10.18
15	13.35	8.72	5.15	3.55	3.01	0.74	2.36	5.11	6.78	10.08
16	13.37	8.72	5.16	3.55	3.03	0.70	2.32	4.94	6.77	10.00
17	13.39	8.75	5.18	3.56	3.05	0.67	2.29	4.91	6.78	9.97
18	13.44	8.75	5.20	3.57	3.06	0.68	2.30	4.89	6.77	9.83
19	13.44	8.78	5.21	3.78	3.12	0.67	2.30	4.89	6.76	9.82
20	13.45	8.78	5.21	3.88	3.17	0.64	2.27	4.99	7.00	9.78
21	13.53	8.78	5.21	3.88	3.17	0.66	2.29	4.65	6.21	9.78
22	13.57	8.79	5.21	3.89	3.17	0.64	2.27	4.47	6.15	9.75
23	13.57	8.79	5.21	3.89	3.17	0.65	2.27	4.34	6.14	9.67
24	13.59	8.79	5.22	3.89	3.17	0.65	2.27	4.20	6.16	9.67
25	13.60	8.79	5.23	3.90	3.17	0.65	2.27	4.15	6.23	9.67
26	13.64	8.79	5.25	3.94	3.18	0.60	2.22	4.65	6.11	9.67
27	13.66	8.79	5.25	3.94	3.18	0.61	2.23	4.62	6.36	9.67
28	13.69	8.80	5.26	3.94	3.18	0.60	2.22	4.59	6.22	9.66
29	13.71	8.80	5.26	3.94	3.19	0.49	2.12	4.63	6.16	9.66
30	13.74	8.80	5.28	3.94	3.20	0.49	2.12	4.62	6.15	9.66
31	13.77	8.83	5.29	3.95	3.23	0.49	2.12	4.62	6.15	9.65
32	13.79	8.84	5.30	3.95	3.25	0.49	2.12	4.62	6.15	9.65
33	13.81	8.85	5.30	3.96	3.32	0.50	2.12	4.62	6.15	9.64
34	13.85	8.85	5.32	3.97	3.35	0.53	2.15	4.62	6.15	9.64
35	13.88	8.85	5.33	4.02	3.38	0.49	2.11	4.62	6.14	9.64
36	13.91	8.86	5.33	4.03	3.44	0.39	2.01	4.62	6.14	9.64
37	13.94	8.86	5.34	4.06	3.51	0.29	1.91	4.61	6.14	9.62
38	13.96	8.90	5.35	4.06	3.53	0.27	1.89	4.61	6.14	9.54
39	13.98	8.90	5.36	4.07	3.58	0.28	1.91	4.61	6.14	9.54
40	13.98	9.23	5.62	4.37	3.59	0.25	1.81	4.61	6.14	8.93

Table A.4 Shear modulus and damping ration values of TK at 200kPa

Test Pit	**Teklehaymanot Church at 200kPa axial stress**									
Strain (%)	**0.01**	**0.1**	**1**	**3**	**5**	**0.01**	**0.1**	**1**	**3**	**5**
Cycle No.	**Shear modulus, G (MPa)**					**Damping Ratio, D (%)**				
1	12.25	8.79	5.27	3.96	3.542	3.15	7.3	12.59	16.43	19.619
2	12.76	9.55	5.74	4.29	3.952	3.13	7.16	11.88	16.38	19.089
3	12.86	9.56	5.77	4.32	3.962	3.01	7.15	11.86	15.46	19.149
4	12.96	9.59	5.81	4.37	3.972	2.97	6.44	11.84	15.26	19.049
5	12.98	9.62	5.84	4.45	3.982	2.58	6.43	11.82	15.25	18.809
6	12.99	9.68	6.04	4.74	4.092	2.56	6.11	11.72	15.04	18.759
7	12.99	9.74	6.14	4.75	4.102	2.43	6.08	11.63	14.36	18.649
8	13.01	9.79	6.24	4.76	4.112	2.17	6.07	11.03	14.34	18.529
9	13.02	9.8	6.24	4.78	4.122	2.14	5.94	11.03	14.31	18.519
10	13.03	9.81	6.25	4.8	4.132	2.12	5.91	10.98	14.28	18.469
11	13.05	9.81	6.27	4.8	4.142	2.09	5.86	10.96	14.22	18.459
12	13.06	9.82	6.28	4.82	4.152	2.04	5.81	10.94	14.21	18.449
13	13.08	9.82	6.31	4.84	4.152	1.99	5.77	10.92	14.19	18.429
14	13.11	9.83	6.34	4.85	4.152	1.98	5.74	10.91	14.19	18.389
15	13.12	9.83	6.37	4.85	4.162	1.99	5.75	10.84	14.18	18.349
16	13.14	9.85	6.38	4.85	4.182	2.02	5.74	10.84	14.17	18.289
17	13.16	9.86	6.41	4.86	4.202	1.98	5.71	10.83	14.17	18.249
18	13.21	9.88	6.43	4.88	4.222	1.98	5.73	10.83	14.16	18.219
19	13.25	9.89	6.45	4.89	4.232	1.97	5.71	10.83	14.16	18.099
20	13.65	10.09	6.47	4.9	4.242	1.95	5.7	10.82	14.15	18.019
21	13.68	10.12	6.49	4.92	4.252	1.94	5.68	10.81	14.15	18.009
22	13.72	10.13	6.51	4.92	4.262	1.92	5.67	10.8	14.14	17.999
23	13.75	10.15	6.54	4.93	4.272	1.89	5.65	10.79	14.13	17.989
24	13.79	10.17	6.58	4.94	4.282	1.88	5.63	10.76	14.13	17.979
25	14.02	10.19	6.58	4.95	4.282	1.88	5.6	10.72	14.12	17.949
26	14.05	10.21	6.59	4.96	4.292	1.87	5.58	10.72	14.11	17.939
27	14.07	10.22	6.61	4.96	4.302	1.85	5.54	10.71	14.11	17.789
28	14.09	10.23	6.62	4.97	4.322	1.84	5.44	10.7	14.11	17.749
29	14.12	10.24	6.64	4.98	4.322	1.83	5.34	10.68	14.11	17.699
30	14.14	10.25	6.67	4.99	4.322	1.84	5.32	10.67	14.11	17.579
31	14.15	10.26	6.69	5.01	4.342	1.81	5.33	10.66	14.09	17.549
32	14.17	10.28	6.71	5.03	4.352	1.78	5.28	10.64	14.08	17.519
33	14.19	10.32	6.73	5.04	4.362	1.77	5.27	10.62	14.06	17.479
34	14.2	10.36	6.73	5.05	4.382	1.77	5.26	10.56	14.05	17.469
35	14.23	10.39	6.74	5.05	4.392	1.76	5.24	10.54	14.03	17.449
36	14.24	10.43	6.75	5.08	4.402	1.75	5.2	10.49	14.03	17.379
37	14.26	10.47	6.76	5.1	4.422	1.73	5.2	10.45	14.01	17.379
38	14.28	10.59	7.12	5.16	4.462	1.67	5.19	10.45	13.99	17.359
39	14.29	10.67	7.15	5.19	4.512	1.64	5.18	10.38	13.85	17.339
40	14.31	10.79	7.22	5.63	4.852	1.41	4.95	9.93	13.03	16.619

Table A.5 Shear modulus and damping ration values of TK at 400kPa

Test Pit	**Teklehaymanot Church at 400kPa axial stress**									
Strain (%)	**0.01**	**0.1**	**1**	**3**	**5**	**0.01**	**0.1**	**1**	**3**	**5**
Cycle No.	**Shear Modulus, G (MPa)**					**Damping Ratio, D (%)**				
1	15.57	11.24	7.73	6.29	5.35	1.69	4.94	9.87	12.73	15.48
2	15.64	11.79	8.19	6.61	5.57	1.29	4.53	9.5	11.91	14.94
3	15.84	12.05	8.29	6.71	5.70	1.27	4.43	9.46	11.89	14.89
4	16.04	12.06	8.38	6.77	5.73	1.24	4.29	9.3	11.85	14.88
5	16.31	12.08	8.21	6.81	5.75	1.22	4.29	9.18	11.69	14.77
6	16.33	12.33	8.63	6.86	5.96	1.2	4.27	9.16	11.65	14.71
7	16.68	12.35	8.66	6.91	5.96	1.17	4.27	9.13	11.54	14.62
8	16.69	12.41	8.67	6.97	5.97	1.15	4.21	8.96	11.39	14.56
9	16.73	12.45	8.68	7.02	5.96	1.14	4.23	9.03	11.44	14.59
10	16.76	12.64	8.80	7.16	5.97	1.13	4.21	8.98	11.41	14.58
11	16.90	12.66	8.67	7.18	6.03	1.11	4.19	8.94	11.38	14.56
12	17.00	12.66	8.64	7.19	6.06	1.09	4.12	8.9	11.37	14.53
13	17.07	12.76	8.64	7.20	6.09	1.08	4.12	8.8	11.35	14.51
14	17.11	12.84	8.65	7.21	6.10	1.07	4.18	8.97	11.41	14.57
15	17.15	12.84	8.67	7.22	6.11	1.05	4.09	8.79	11.31	14.49
16	17.19	12.89	8.69	7.23	6.12	1.03	4.08	8.77	11.29	14.48
17	17.20	12.92	8.70	7.24	6.12	0.99	4.06	8.76	11.29	14.46
18	17.22	12.93	8.70	7.27	6.13	0.96	4.06	8.75	11.27	14.45
19	17.26	12.95	8.71	7.29	6.19	0.95	4.03	8.72	11.25	14.43
20	17.29	12.96	8.72	7.30	6.25	0.84	3.89	8.66	11.15	14.27
21	17.39	13.06	8.72	7.32	6.35	0.93	3.89	8.7	11.14	14.41
22	17.50	12.99	8.72	7.31	6.32	0.93	3.99	8.68	11.13	14.38
23	17.52	13.08	8.73	7.34	6.37	0.92	3.98	8.64	11.12	14.28
24	17.53	13.10	8.75	7.35	6.39	0.88	3.97	8.62	11.11	14.25
25	17.55	13.16	8.80	7.47	6.40	0.87	3.96	8.61	11.1	14.24
26	17.59	13.18	8.80	7.49	6.42	0.86	3.96	8.6	11.09	14.21
27	17.60	13.19	8.81	7.51	6.46	0.83	3.9	8.58	11.08	14.21
28	17.66	13.22	8.82	7.53	6.53	0.83	3.89	8.56	11.07	14.19
29	17.68	13.24	8.82	7.55	6.59	0.77	3.88	8.54	11.06	14.18
30	17.73	13.27	8.82	7.61	6.63	0.76	3.86	8.53	11.05	14.18
31	17.76	13.28	8.83	7.67	6.65	0.75	3.84	8.5	11.04	14.17
32	17.78	13.30	8.84	7.68	6.67	0.74	3.83	8.5	11.03	14.16
33	17.80	13.32	8.90	7.69	6.69	0.72	3.82	8.48	11.02	14.15
34	17.81	13.36	8.92	7.71	6.69	0.71	3.81	8.41	11.01	14.16
35	17.83	13.38	8.94	7.74	6.72	0.61	3.8	8.38	11.01	14.14
36	17.83	13.37	8.94	7.72	6.71	0.59	3.78	8.4	10.99	14.11
37	17.83	13.41	8.95	7.75	6.72	0.58	3.76	8.36	10.99	14.09
38	17.85	13.44	9.00	7.77	6.73	0.56	3.74	8.34	10.98	14.07
39	17.85	13.71	9.03	7.78	6.75	0.55	3.7	8.21	10.96	13.79
40	17.86	13.80	9.39	7.79	6.82	0.41	3.17	7.57	10.08	13.12

Table A.6 Shear modulus and damping ration values of SH at 100kPa

Test Pit	**Shashemane Road Exit at 100kPa axial stress**									
Strain (%)	**0.01**	**0.1**	**1**	**3**	**5**	**0.01**	**0.1**	**1**	**3**	**5**
Cycle No.	**Shear modulus, G (MPa)**					**Damping Ratio, D (%)**				
1	6.15	3.71	1.71	0.79	0.34	6.52	10.76	16.324	20.386	23.09
2	6.21	3.78	1.85	0.98	0.37	5.91	10.36	15.704	19.696	22.95
3	6.29	3.82	1.89	0.99	0.47	5.89	10.25	15.564	19.666	22.75
4	6.45	3.85	2.01	1.01	0.56	5.78	10.15	15.454	19.606	22.65
5	6.48	4.17	2.05	1.04	0.64	5.68	9.96	15.434	19.546	22.27
6	6.61	4.18	2.15	1.06	0.75	5.58	9.8	15.344	19.526	22.25
7	6.68	4.22	2.17	1.09	0.76	5.55	9.79	14.664	19.276	22.15
8	6.69	4.24	2.18	1.09	0.78	5.51	9.73	14.204	18.816	22.04
9	6.72	4.26	2.21	1.11	0.79	5.48	9.67	14.114	18.676	22.01
10	6.73	4.27	2.25	1.15	0.81	5.18	9.51	13.994	18.016	21.85
11	6.75	4.29	2.26	1.17	0.83	5.17	9.5	13.894	18.016	21.84
12	6.75	4.32	2.26	1.18	0.85	5.15	9.48	13.874	17.946	21.83
13	6.77	4.34	2.27	1.21	0.87	5.12	9.45	13.864	17.846	21.81
14	6.78	4.35	2.28	1.23	0.88	5.11	9.44	13.844	17.826	21.65
15	6.8	4.37	2.29	1.24	0.89	4.87	9.44	13.754	17.826	21.53
16	6.87	4.39	2.3	1.25	0.91	4.86	9.42	13.634	17.796	21.36
17	6.9	4.42	2.31	1.26	0.93	4.85	9.42	13.614	17.726	21.26
18	6.91	4.45	2.32	1.27	0.94	4.84	9.42	13.614	17.726	21.12
19	6.91	4.48	2.33	1.29	0.96	4.83	9.42	13.613	17.725	20.59
20	6.93	4.61	2.34	1.31	0.98	4.82	9.22	13.992	17.924	20.58
21	6.95	4.62	2.35	1.33	0.99	4.74	9.42	13.574	17.556	20.46
22	6.99	4.63	2.35	1.35	1.01	4.67	9.42	13.554	17.526	20.42
23	6.99	4.68	2.35	1.37	1.02	4.64	9.42	13.544	17.526	20.35
24	7.01	4.74	2.36	1.38	1.03	4.59	9.41	13.524	17.526	20.28
25	7.03	4.78	2.37	1.4	1.05	4.57	9.4	13.524	17.526	20.25
26	7.05	4.81	2.41	1.42	1.07	4.49	9.39	13.514	17.526	20.24
27	7.08	4.85	2.43	1.44	1.09	4.43	9.38	13.494	17.526	20.21
28	7.15	4.89	2.45	1.45	1.1	4.37	9.37	13.494	17.266	20.15
29	7.16	4.91	2.46	1.47	1.11	4.33	9.35	13.464	17.266	20.11
30	7.17	4.96	2.47	1.48	1.12	4.28	9.34	13.454	17.256	20.05
31	7.18	4.98	2.48	1.49	1.13	4.24	9.32	13.454	17.256	20.01
32	7.21	5.01	2.51	1.51	1.14	4.16	9.3	13.404	17.246	19.98
33	7.22	5.05	2.52	1.53	1.15	4.15	9.27	13.354	17.236	19.95
34	7.25	5.08	2.54	1.54	1.16	4.14	9.25	13.354	17.236	19.93
35	7.27	5.09	2.55	1.56	1.17	4.18	9.23	13.024	17.126	19.92
36	7.29	5.11	2.57	1.57	1.18	4.16	9.2	12.914	16.826	19.91
37	7.32	5.12	2.59	1.59	1.19	4.62	9.1	12.874	16.606	19.9
38	7.34	5.13	2.63	1.62	1.21	4.61	9.04	12.834	16.566	19.89
39	7.35	5.15	2.65	1.63	1.22	4.58	8.76	12.754	16.496	19.87
40	7.37	5.17	2.68	1.65	1.25	4.29	8.48	12.714	16.486	19.55

Table A.7 Shear modulus and damping ration values of SH at 200kPa

Test Pit	**Shashemane Road Exit at 200kPa axial stress**									
Strain (%)	**0.01**	**0.1**	**1**	**3**	**5**	**0.01**	**0.1**	**1**	**3**	**5**
Cycles No.	**Shear modulus, G (MPa)**					**Damping Ratio, D (%)**				
1	8.92	5.74	3.18	2.22	2.01	4.18	7.71	11.88	14.66	17.12
2	8.94	5.77	3.33	2.59	2.32	4.08	7.69	11.66	13.72	17.09
3	9.26	5.78	3.46	2.63	2.34	3.48	7.68	10.85	13.69	16.85
4	9.31	6.32	3.51	2.65	2.35	3.46	7.67	10.84	13.67	16.74
5	9.45	6.41	3.68	2.66	2.31	3.45	6.55	10.83	13.45	16.17
6	9.46	6.42	3.85	2.86	2.39	3.28	6.54	10.18	13.35	16.56
7	9.47	6.43	3.88	2.96	2.41	3.2	6.33	10.08	13.28	16.55
8	9.49	6.45	3.92	2.98	2.43	3.17	6.32	10.03	13.18	16.53
9	9.56	6.47	3.93	3.01	2.44	3.12	6.29	10.02	13.16	16.51
10	9.68	6.48	4.07	3.02	2.47	2.97	6.18	9.95	13.05	16.39
11	9.69	6.49	4.08	3.03	2.48	3.06	6.17	9.94	13.03	16.38
12	9.73	6.52	4.19	3.04	2.49	3.05	6.16	9.82	13.02	16.06
13	9.76	6.62	4.2	3.05	2.52	3.03	6.15	9.80	13.01	15.96
14	9.82	6.75	4.22	3.06	2.52	3.02	6.14	9.75	12.92	15.82
15	9.84	6.82	4.21	3.07	2.54	3.01	6.13	9.75	12.90	15.29
16	9.91	6.89	4.2	3.08	2.55	2.98	6.09	9.74	12.89	15.21
17	10.02	6.95	4.19	3.09	2.56	2.73	5.92	9.74	12.86	15.16
18	10.12	7.05	4.28	3.1	2.57	2.7	5.71	9.73	12.84	15.12
19	10.3	7.14	4.32	3.12	2.58	2.66	5.62	9.72	12.80	15.08
20	10.35	7.29	4.36	3.13	2.59	2.63	5.56	9.71	12.78	14.98
21	10.39	7.37	4.35	3.14	2.6	2.52	5.5	9.71	12.76	14.95
22	10.46	7.38	4.44	3.15	2.61	2.48	5.46	9.71	12.73	14.94
23	10.5	7.45	4.43	3.16	2.62	2.39	5.41	9.71	12.72	14.91
24	10.54	7.45	4.42	3.17	2.63	2.27	5.37	9.70	12.67	14.85
25	10.56	7.47	4.41	3.18	2.64	2.27	5.29	9.68	12.66	14.81
26	10.62	7.47	4.41	3.2	2.65	2.26	5.28	9.65	12.66	14.75
27	10.66	7.47	4.4	3.22	2.66	2.23	5.27	9.64	12.65	14.71
28	10.72	7.48	4.39	3.24	2.67	2.19	5.2	9.63	12.63	14.65
29	10.75	7.48	4.39	3.26	2.68	2.1	5.06	9.62	12.62	14.65
30	10.77	7.48	4.38	3.28	2.69	2.04	4.95	9.59	12.61	14.61
31	10.79	7.49	4.38	3.29	2.7	2	4.91	9.58	12.58	14.51
32	10.8	7.5	4.38	3.31	2.71	1.99	4.82	9.58	12.54	14.51
33	10.82	7.5	4.38	3.33	2.72	1.99	4.67	9.56	12.51	14.41
34	10.84	7.5	4.4	3.35	2.73	1.95	4.67	9.55	12.47	14.39
35	10.86	7.5	4.42	3.37	2.74	1.92	4.66	9.52	12.42	14.38
36	10.88	7.52	4.45	3.39	2.75	1.91	4.65	9.48	12.38	14.31
37	10.9	7.52	4.45	3.4	2.76	1.89	4.64	9.45	12.31	14.31
38	10.92	7.54	4.48	3.42	2.77	1.88	4.63	9.41	12.27	14.31
39	10.93	7.59	4.53	3.43	2.78	1.87	4.61	9.36	12.22	14.28
40	10.95	7.95	4.98	3.65	3.02	1.85	4.6	9.01	12.06	14.26

Table A.8 Shear modulus and damping ration values of SH at 400kPa

Test Pit	**Shashemane Road Exit at 400kPa axial stress**									
Strain (%)	**0.01**	**0.1**	**1**	**3**	**5**	**0.01**	**0.1**	**1**	**3**	**5**
Cycles No.	**Shear Modulus, G (MPa)**					**Damping Ratio, D (%)**				
1	11.82	8.54	5.09	3.74	3.21	1.81	4.59	8.66	10.82	12.57
2	11.89	8.65	5.53	4.18	3.62	1.62	4.19	8.69	10.18	11.98
3	12.08	8.85	5.61	4.21	3.67	1.59	4.17	8.66	9.88	11.96
4	12.27	9.03	5.62	4.32	3.69	1.57	4.05	8.57	9.86	11.89
5	12.55	9.04	5.63	4.33	3.7	1.53	3.75	7.59	9.84	11.78
6	12.56	9.07	5.85	4.35	3.76	1.5	3.74	7.54	9.84	11.77
7	12.57	9.09	5.87	4.36	3.77	1.47	3.69	7.53	9.75	11.76
8	12.58	9.11	5.88	4.37	3.78	1.46	3.59	7.51	9.75	11.75
9	12.72	9.2	5.88	4.37	3.84	1.22	3.53	7.09	9.74	11.74
10	12.88	9.4	5.89	4.38	3.95	1.2	3.43	7.07	9.75	11.73
11	12.89	9.41	5.92	4.39	3.97	1.19	3.16	6.95	9.73	11.71
12	13.16	9.45	5.93	4.41	4.02	1.18	2.99	6.92	9.59	11.64
13	13.26	9.49	5.94	4.42	4.03	1.17	2.77	6.91	9.54	11.62
14	13.32	9.54	5.95	4.44	4.05	1.16	2.79	6.63	9.48	11.57
15	13.44	9.54	5.98	4.47	4.07	1.15	2.78	6.62	9.48	11.55
16	13.51	9.59	6.01	4.51	4.08	1.14	2.82	6.62	9.45	11.51
17	13.61	9.71	6.03	4.52	4.1	1.13	2.75	6.59	9.44	11.5
18	13.62	9.74	6.04	4.53	4.11	1.12	2.74	6.55	9.39	11.48
19	13.63	9.77	6.16	4.65	4.12	0.99	2.73	6.51	9.29	11.51
20	13.64	9.77	6.18	4.67	4.13	0.96	2.74	6.5	9.19	11.15
21	13.86	9.82	6.21	4.7	4.16	0.79	2.58	6.46	9.09	11.44
22	13.86	9.84	6.28	4.77	4.18	0.53	2.57	6.44	9.08	11.43
23	13.89	9.85	6.37	4.86	4.19	0.49	2.5	6.39	9.07	11.42
24	13.89	9.85	6.49	4.98	4.21	0.47	2.49	6.38	9.06	11.4
25	14	9.85	6.53	5.02	4.22	0.43	2.39	6.32	9.05	11.39
26	14.01	9.95	6.54	5.03	4.22	0.42	2.33	6.32	9.04	11.37
27	14.02	9.95	6.55	5.04	4.23	0.42	2.33	6.3	9.03	11.35
28	14.04	10	6.55	5.05	4.23	0.41	2.25	6.27	9.02	11.28
29	14.06	10.05	6.56	5.06	4.23	0.4	2.23	6.24	9.01	11.28
30	14.07	10.12	6.56	5.06	4.24	0.39	2.16	6.24	9	11.24
31	14.14	10.32	6.56	5.05	4.25	0.38	2.13	6.23	8.99	11.14
32	14.15	10.38	6.56	5.06	4.29	0.37	2.12	6.19	8.98	11.14
33	14.17	10.4	6.56	5.05	4.29	0.36	2.11	6.19	8.96	11
34	14.28	10.41	6.57	5.05	4.3	0.35	2.08	6.13	8.93	11.01
35	14.28	10.41	6.57	5.04	4.32	0.34	2.04	6.13	8.88	10.93
36	14.29	10.45	6.57	5.05	4.33	0.33	2.02	6.11	8.86	10.94
37	14.30	10.45	6.57	5.06	4.34	0.32	1.95	6.11	8.84	10.93
38	14.36	10.47	6.57	5.06	4.42	0.31	1.93	6.08	8.84	10.91
39	14.38	10.55	6.57	5.06	4.43	0.29	1.85	6.07	8.82	10.9
40	14.38	10.58	6.59	5.08	4.44	0.281	1.82	5.59	8.34	10.43

Table A.9 Shear modulus and damping ration values of NMR at 100kPa

Test Pit	**Near Minjar Road Exit at 100kPa axial stress**									
Strain (%)	**0.01**	**0.1**	**1**	**3**	**5**	**0.01**	**0.1**	**1**	**3**	**5**
Cycle No.	**Shear modulus, G (MPa)**					**Damping Ratio, D (%)**				
1	11.91	7.91	4.17	2.68	1.85	7.57	12.17	19.01	22.63	25.06
2	12.3	8.22	4.49	3.14	2.21	7.21	11.94	18.58	22.36	24.54
3	12.39	8.53	4.62	3.15	2.42	7.13	11.49	17.81	21.98	24.52
4	12.43	8.55	4.67	3.19	2.43	7.04	11.45	17.77	21.76	24.47
5	12.56	8.57	4.84	3.21	2.46	6.89	11.09	17.76	21.54	24.21
6	12.84	9.04	5.01	3.24	2.53	6.88	11.08	17.14	21.13	24.19
7	12.86	9.05	5.04	3.24	2.57	6.83	11.06	17.04	21.03	24.17
8	12.89	9.21	5.06	3.26	2.57	6.79	11.04	16.99	20.93	24.14
9	12.97	9.25	5.09	3.28	2.59	6.73	11.03	16.98	20.91	24.13
10	13.09	9.29	5.23	3.28	2.59	6.53	10.81	16.94	20.91	24.02
11	13.11	9.31	5.24	3.29	2.59	6.5	10.79	16.9	20.88	23.95
12	13.12	9.32	5.35	3.29	2.6	6.46	10.74	16.78	20.81	23.93
13	13.13	9.37	5.35	3.3	2.6	6.41	10.35	16.76	20.81	23.84
14	13.15	9.38	5.36	3.31	2.61	6.35	10.16	16.71	20.67	23.64
15	13.19	9.39	5.36	3.31	2.61	6.34	9.95	16.71	20.65	23.11
16	13.19	9.41	5.37	3.32	2.61	6.31	9.88	16.7	20.64	23.03
17	13.21	9.42	5.38	3.34	2.61	6.06	9.87	16.7	20.61	23.01
18	13.22	9.43	5.44	3.35	2.61	6.03	9.85	16.69	20.59	22.94
19	13.23	9.44	5.48	3.36	2.61	5.99	9.83	16.68	20.55	22.87
20	13.24	9.45	5.51	3.73	2.87	5.96	9.81	16.67	20.53	22.83
21	13.25	10.12	5.52	3.82	2.62	5.85	9.21	16.67	20.51	22.77
22	13.26	10.13	5.54	3.83	2.63	5.81	9.17	16.67	20.48	22.76
23	13.27	10.2	5.54	3.85	2.63	5.72	9.12	16.67	20.47	22.73
24	13.29	10.2	5.54	3.88	2.63	5.6	9.08	16.66	20.42	22.67
25	13.33	10.22	5.54	3.9	2.63	5.6	9.04	16.64	20.41	22.63
26	13.43	10.22	5.55	3.9	2.63	5.59	8.99	16.61	20.41	22.57
27	13.51	10.22	5.55	3.92	2.64	5.56	8.98	16.6	20.4	22.53
28	13.52	10.23	5.56	3.92	2.65	5.52	8.91	16.59	20.38	22.47
29	13.58	10.23	5.56	3.92	2.65	5.43	8.77	16.58	20.37	22.47
30	13.59	10.23	5.57	3.92	2.66	5.37	8.66	16.55	20.36	22.43
31	13.61	10.24	5.57	3.93	2.67	5.33	8.64	16.54	20.36	22.33
32	13.62	10.25	5.58	3.93	2.67	5.32	8.63	16.54	20.35	22.33
33	13.63	10.25	5.58	3.94	2.68	5.32	8.61	16.52	20.35	22.23
34	13.64	10.25	5.59	3.95	2.69	5.28	8.58	16.51	20.34	22.21
35	13.66	10.25	5.6	3.95	2.7	5.25	8.58	16.5	20.34	22.2
36	13.68	10.27	5.61	3.96	2.72	5.24	8.56	16.47	20.33	22.19
37	13.69	10.27	5.61	3.98	2.74	5.17	8.56	16.45	20.32	22.16
38	13.71	10.29	5.64	4.01	2.76	5.15	8.55	16.35	20.32	22.12
39	13.78	10.36	5.69	4.06	2.78	5.14	8.55	16.31	20.29	22.1
40	13.98	10.38	6.24	4.55	3.57	5.12	8.53	15.48	19.67	21.76

Table A.10 Shear modulus and damping ration values of NMR at 200kPa

Test Pit	**Near Minjar Road Exit at 200kPa axial stress**									
Strain (%)	**0.01**	**0.1**	**1**	**3**	**5**	**0.01**	**0.1**	**1**	**3**	**5**
Cycles No.	**Shear modulus, G (MPa)**					**Damping Ratio, D (%)**				
1	15.06	10.81	6.62	4.61	3.65	4.93	8.47	15.12	18.78	20.84
2	15.43	11.14	7.12	4.84	3.91	4.52	8.01	15.09	17.98	20.23
3	15.62	11.16	7.14	4.95	3.96	4.49	7.99	14.97	17.68	20.12
4	15.73	11.3	7.15	5.01	3.98	4.43	7.87	14.49	17.66	20.08
5	15.9	11.31	7.16	5.04	4.01	4.39	7.77	13.89	17.64	20.05
6	16.01	11.34	7.18	5.05	4.02	4.36	7.57	13.85	17.64	19.98
7	16.03	11.35	7.2	5.06	4.02	4.35	7.51	13.48	17.55	19.78
8	16.12	11.35	7.21	5.07	4.07	4.32	7.41	13.46	17.55	19.74
9	16.26	11.36	7.21	5.09	4.13	4.31	7.35	13.07	17.55	19.71
10	16.28	11.48	7.22	5.11	4.18	4.25	7.25	13.04	17.54	19.68
11	16.43	11.58	7.22	5.12	4.26	4.23	6.98	12.9	17.53	19.67
12	16.7	11.66	7.24	5.13	4.31	4.19	6.81	12.87	17.39	19.61
13	16.8	11.76	7.26	5.14	4.32	4.18	6.64	12.86	17.31	19.59
14	16.86	11.81	7.28	5.15	4.34	4.17	6.61	12.58	17.28	19.54
15	16.98	11.81	7.31	5.16	4.36	4.16	6.6	12.57	17.28	19.52
16	17	11.86	7.34	5.17	4.37	4.13	6.59	12.57	17.25	19.48
17	17.02	11.98	7.36	5.18	4.39	3.99	6.57	12.54	17.24	19.48
18	17.06	12.01	7.37	5.19	4.39	3.98	6.56	12.53	17.23	19.47
19	17.08	12.04	7.49	5.2	4.41	3.85	6.56	12.52	17.22	19.45
20	17.09	12.04	7.61	5.52	4.52	3.82	6.75	12.55	16.73	19.18
21	17.24	12.09	7.64	5.22	4.45	3.65	6.4	12.41	16.99	19.44
22	17.4	12.11	7.68	5.23	4.47	3.33	6.38	12.39	16.95	19.44
23	17.44	12.12	7.7	5.26	4.48	3.31	6.32	12.34	16.89	19.41
24	17.46	12.12	7.82	5.34	4.49	3.3	6.31	12.33	16.89	19.37
25	17.54	12.12	7.86	5.34	4.51	3.29	6.21	12.27	16.88	19.36
26	17.55	12.22	7.87	5.34	4.51	3.28	6.15	12.27	16.87	19.34
27	17.56	12.22	7.88	5.35	4.52	3.28	6.15	12.25	16.86	19.32
28	17.58	12.27	7.88	5.36	4.52	3.26	6.07	12.22	16.84	19.25
29	17.6	12.32	7.89	5.37	4.52	3.25	6.05	12.19	16.83	19.25
30	17.61	12.39	7.89	5.37	4.53	3.25	5.98	12.19	16.82	19.21
31	17.68	12.59	7.89	5.37	4.54	3.23	5.95	12.18	16.79	19.11
32	17.69	12.65	7.89	5.38	4.58	3.21	5.94	12.14	16.78	19.11
33	17.71	12.67	7.89	5.38	4.58	3.19	5.91	12.14	16.76	18.98
34	17.82	12.68	7.9	5.39	4.59	3.17	5.85	12.08	16.73	18.97
35	17.82	12.68	7.9	5.44	4.61	3.15	5.84	12.08	16.68	18.91
36	17.83	12.72	7.9	5.44	4.62	3.15	5.82	12.06	16.66	18.9
37	17.84	12.72	7.9	5.45	4.63	3.06	5.74	12.06	16.64	18.9
38	17.9	12.74	7.9	5.49	4.65	3.05	5.72	12.04	16.64	18.88
39	17.92	12.82	7.9	5.49	4.67	3.03	5.7	12.03	16.62	18.87
40	17.92	12.85	8.23	6.21	5.12	3.03	5.68	11.58	15.55	17.89

Table A.11 Shear modulus and damping ration values of NMR at 400kPa

Test Pit	**Near Minjar Road Exit at 400kPa axial stress**									
Strain (%)	**0.01**	**0.1**	**1**	**3**	**5**	**0.01**	**0.1**	**1**	**3**	**5**
Cycles No.	**Shear Modulus, G (MPa)**					**Damping Ratio, D (%)**				
1	19.14	14.26	9.57	7.13	6.01	2.79	5.11	10.69	14.77	16.89
2	19.94	14.84	9.87	7.55	6.51	2.26	5.07	9.95	13.75	16.28
3	20.14	15.14	10.11	7.59	6.56	2.23	4.38	9.91	13.73	16.23
4	20.35	15.25	10.18	7.67	6.64	2.21	4.34	9.85	13.69	16.22
5	20.42	15.28	10.21	7.75	6.67	2.22	4.43	9.83	13.83	16.21
6	20.64	15.35	10.72	8.15	6.79	2.15	4.28	9.61	13.53	16.05
7	20.99	15.41	10.78	8.16	6.84	2.12	4.25	9.58	13.38	15.96
8	21.02	15.43	10.85	8.17	6.89	2.12	4.18	9.48	13.28	15.93
9	21.04	15.44	10.89	8.19	6.92	2.11	4.16	9.43	13.25	15.92
10	21.07	15.5	10.91	8.21	6.95	2.11	4.13	9.42	13.25	15.91
11	21.21	15.5	10.91	8.23	6.99	2.11	4.16	9.41	13.23	15.90
12	21.31	15.56	10.92	8.24	7.02	2.11	4.14	9.39	13.22	15.90
13	21.38	15.6	10.92	8.24	7.05	2.1	4.07	9.35	13.21	15.87
14	21.42	15.6	10.93	8.25	7.06	2.09	4.07	9.25	13.19	15.85
15	21.51	15.65	10.93	8.26	7.07	2.09	4.04	9.24	13.15	15.83
16	21.64	15.74	10.94	8.27	7.08	2.08	4.03	9.22	13.13	15.82
17	21.85	15.78	10.95	8.28	7.08	2.07	4.01	9.21	13.13	15.80
18	21.89	15.85	10.96	8.31	7.09	2.06	4.01	9.2	13.11	15.79
19	21.97	15.87	10.97	8.33	7.15	2.05	3.98	9.17	13.09	15.77
20	21.88	16.12	10.99	8.34	7.21	1.71	3.97	9.15	13.07	15.52
21	21.99	16.13	10.99	8.35	7.28	1.67	3.94	9.13	13.05	15.72
22	21.98	16.14	11	8.36	7.31	1.67	3.94	9.11	13.03	15.65
23	22.01	16.15	11	8.38	7.33	1.67	3.93	9.09	13.01	15.62
24	22.02	16.16	11.01	8.39	7.35	1.67	3.92	9.07	13.00	15.59
25	22.04	16.17	11.08	8.41	7.36	1.66	3.91	9.06	13.01	15.58
26	22.11	16.18	11.08	8.43	7.38	1.65	3.91	9.05	12.99	15.55
27	22.12	16.19	11.09	8.45	7.42	1.62	3.85	9.03	12.98	15.55
28	22.38	16.21	11.1	8.47	7.49	1.62	3.84	9.01	12.96	15.53
29	22.38	16.24	11.1	8.49	7.55	1.56	3.83	8.99	12.93	15.52
30	22.5	16.25	11.1	8.49	7.59	1.55	3.81	8.98	12.92	15.52
31	22.51	16.24	11.11	8.51	7.61	1.54	3.79	8.95	12.91	15.51
32	22.52	16.25	11.12	8.52	7.63	1.53	3.78	8.95	12.89	15.50
33	22.52	16.25	11.18	8.53	7.65	1.52	3.77	8.93	12.87	15.49
34	22.53	16.28	11.2	8.55	7.65	1.42	3.76	8.86	12.85	15.50
35	22.53	16.28	11.22	8.56	7.67	1.46	3.75	8.83	12.85	15.48
36	22.52	16.29	11.22	8.58	7.68	1.38	3.73	8.85	12.83	15.45
37	22.52	16.47	11.23	8.58	7.68	1.37	3.71	8.81	12.83	15.43
38	22.54	16.51	11.28	8.59	7.69	1.35	3.69	8.79	12.82	15.38
39	22.65	16.56	11.31	8.65	7.71	1.34	3.65	8.76	12.80	15.22
40	22.98	17.15	11.75	8.95	7.87	1.17	3.42	8.32	12.12	14.54