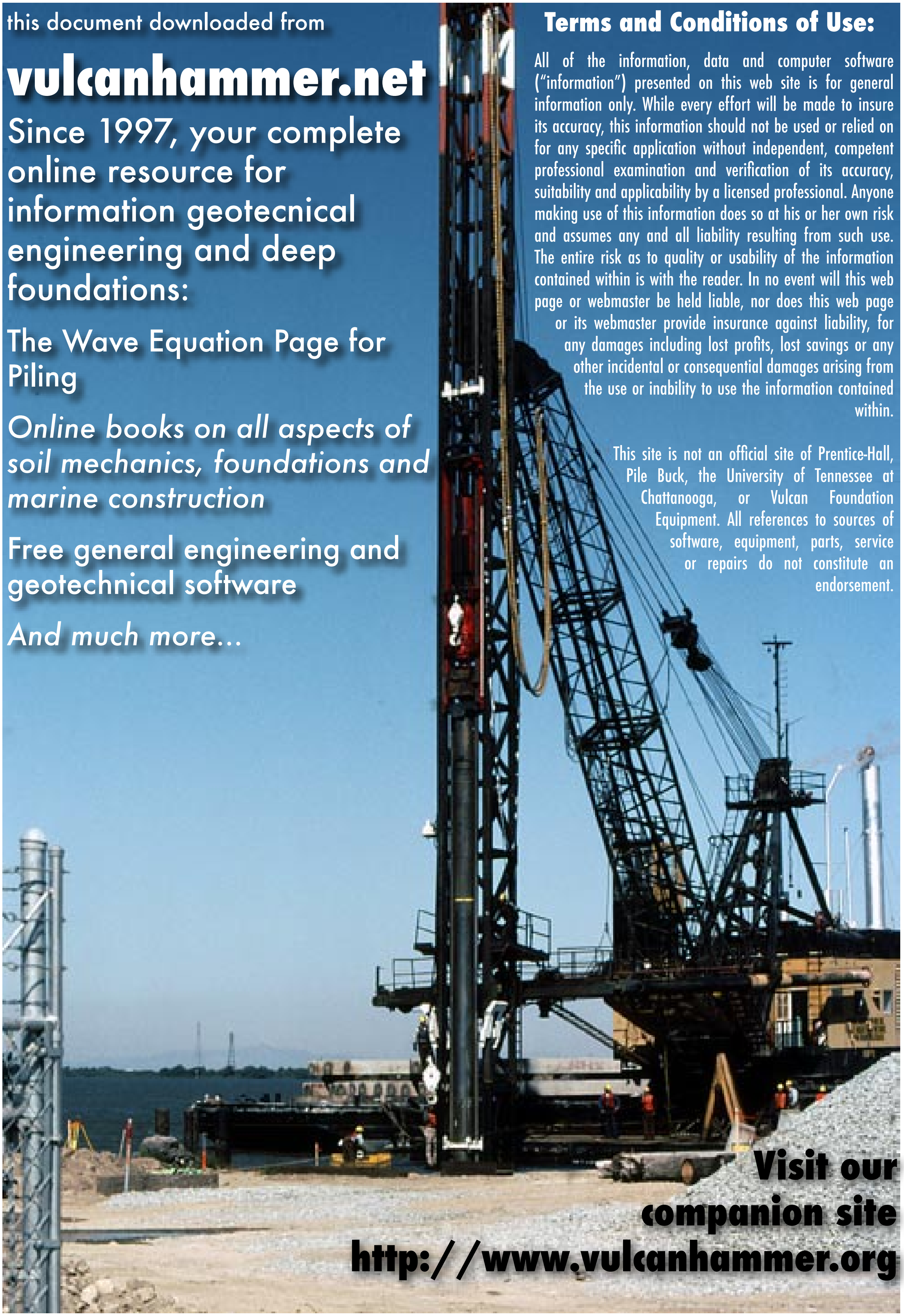

SHEAR MODULUS AND DAMPING RATIO VALUES OF SOILS FOUND IN ADAMA

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By

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SCHOOL OF GRADUATE STUDIES

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LISTS OF SYMBOLS AND ABBREVIATIONS

Symbols	Description	Unit
A	Area	mm
AAIT	Addis Ababa Institute of Technology	
A_{loop}	Area of loop	mm
A	area of triangle	mm
a	a parameter that depends on the plasticity index of soil	--
ASTM	American society for Testing and Materials	---
Po	Axial consolidation pressure	MPa
CPU	Central Processing Unit	---
D	Damping ratio	%
e	Void ratio	---
G_{max}	Maximum shear modulus	MPa
G	Shear modulus	MPa
LI	liquidity index	%
LL	Liquid Limit	%
CL	Low plasticity index	---
OCR	Over consolidation ratio	---
PL	Plasticity Limit	%
PI	Plasticity Index	%
UCS	Unified Classification System	---
w	Natural water content	%
σ'_m	Mean principal stress	MPa
ρ_d	density of soil	g/cm^3
ρ_w	Density of water	g/cm^3

ABSTRACT

In this study an attempt was done to determine shear modulus and damping ratio of soils found in Adama city. The city is located in Main Ethiopian Rift where occurrence of earthquake is expected. The response of soils for incoming earthquake is measured with the dynamic properties of soils (shear modulus and damping ratio) which are important parameters to study ground motion, site response of soil deposits under cyclic loading and soil -structure interaction. These parameters are also important for design of machine foundation. Therefore it is essential to study dynamic properties of soils under cyclic loading condition using cyclic simple shear machine.

The values of normalized shear modulus and damping ratio are compared with already known curves in literature. The study showed that the values of normalized shear modulus, G/G_{max} plotted against shear strain, show scatter when compared with curves of Seed and idriss. For sand the scattered of results are observed. For saturated clay, all the measured points are close to the known curves. The values of damping ratio are also compared with curves given by Seed and Idriss. For strain less than 1% most of the measured points are located within range of the curves given for sand and clay soils. For strain greater than and equal to 1%, the points lay within the range for clays and outside the range for sand.

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

The earthquakes cause extensive damages to dams, embankments, ports, bridges, buildings and life-lines and lose of life. To prevent destruction of the structures and also lose of life, geotechnical engineers have to deal with the effects of earthquake during design and construction.

Adama is one of the cities located in the Main Ethiopian Rift (MER). The city is categorized under region four based on seismicity [10]. At present there is dramatic increase in urbanization in Ethiopia associated with increased population. This increase in urban population has been accompanied by an equally strong growth in the number of high-rise buildings, residential houses, schools, bridges, water supply pipes, and other infrastructure constructions. The proximity of significant earthquakes to the major population centers such as Adama, Hawassa and Addis Ababa, obviously leads to the question of how much damage will be sustained by the structures

Therefore, it is essential to know the ground response of soil deposits in addition to the requirement of strict structural earthquake design guidelines. In order to study problems involving soil -structure interactions, site responses of soil deposits, and prediction of the ground motion it is important to know the dynamic properties (shear modulus and damping ratio) of natural soil deposits.

The nature and distribution of earthquake damage is strongly affected by response of soil deposits and earth structures under seismic loading conditions. Research had been done on Koka sand [12], Kolfe Keranio area of Addis Ababa on red clay soils [17] and Gulelle area red brown clay soils [1]. However, research on soils found in Adama city which need characterization and determination of shear modulus and damping ratio has not been undertaken.

A wide variety of field and laboratory techniques are available, each with different advantages and limitation with respect to different problems. Laboratory tests generally provide the most direct means of evaluating dynamic soil parameters for seismic analyses [14]. These laboratory tests are classified as large strain range, medium range and small strain range test. Since the soil is non linear material it could be tested under wide range of strain. It is possible to test the soils using cyclic simple shear test as it classified under large strain range.

The accurate determination of the shear modulus and damping ratio of soils would be an important contribution for conducting dynamic analysis.

1.2 OBJECTIVE OF THE STUDY

The main objective of this research is the determination of the dynamic soil property, namely shear modulus and damping ratio of soil found in Adama city. In addition to determination of dynamic property of soil the study also specifically include determination of index property, collection of information about geology and formation of soil and classification of the soil.

1.3 SCOPE AND LIMITATION OF THE THESIS

The dynamic soil properties are influenced by soil type and location of soil profile. The samples collected were not totally representing all soil at in Adama. In addition the samples are retrived from depth of three meter (3m). In addition to sampling limitation the test is preformed using simple cyclic shear test subject to limitations on the recovery and testing of representative samples. This have been demonstrated by Seed and Peacrock for uniform medium sand in which field values are about 20% higher than the laboratory values.

1.4 ORGANIZATION OF THE STUDY

The study consists of six Chapters. The background information is presented under Chapter one which mainly focus on introduction, objective, and scope and limitation of the thesis. Literature review is mainly presented in second Chapter which includes index property and dynamic properties of soils. In third Chapter description of study area, geology of area, formation of soil found in Adama, sample collection, sample preparation cyclic simple shear apparatus and stage of cyclic simple shear test are presented. The fourth Chapter consists of field and laboratory test results and analysis of the results. Discussion of test results is presented in Chapter five. The sixth Chapter is conclusion and recommendation of the thesis.

CHAPTER TWO

LITERATURE REVIEW

Even though the study of earthquake dates back many centuries, the analysis of earthquake effect on structures based on the dynamic soil property is a recent phenomenon. The nature and distribution of earthquake damage is strongly affected by response of soil deposits and earth structures under seismic loading conditions. The evaluation of the dynamic properties of natural soil deposits is of prior importance in order to solve problems involving soil - structure interactions, to study the site response, to predict the ground motion and to proceed to seismic zonation [16]. Ground motion under earthquake loading is influenced by the soil condition, but the non-linearity of the soil behavior makes it difficult to estimate the site response. The values of dynamic properties of soils; shear modulus and damping ratio are influenced by plasticity index, void ratio, relative density, number of cycles, grain size distribution, type of soils, over burden pressure, location of ground water and amplitude of earthquake (amplitude of cyclic loading). The shear modulus and damping ratio are obtained from laboratory and field tests. In literature review basic physical properties of soils and soil response under cyclic loading are examined.

2.1 BASIC PHYSICAL PROPERTY OF SOILS

A dynamic analysis requires the same parameters used to describe soil properties for static analyses of earth structures and foundations. These soil properties include specific gravity, plasticity index, grain size distribution, and soil structure.

2.2 SOIL RESPONSE UNDER CYCLIC LOADING

Soil properties that influence wave propagation and other low- strain phenomena include shear modulus, damping, Poisson's ratio and density. From these soil properties shear modulus and damping ratio are the most important parameters. The Shear modulus and damping ratio of cyclically loaded soils are critical to the evaluation of many geotechnical earthquake engineering problem for low, intermediate and high strain range. At high strain levels, the influence of the rate number of cycles of loading on shear strength and volume change is important. The behavior of soil under cyclic loading is non-linear and depends on some factors including soil type, confining pressure, number of loading cycles, and amplitude of loading. Parameters describing the cyclic soil properties required for a dynamic analysis include the initial (small strain) damping ratio, D, the initial shear modulus at small shear strain, G_{max} and the modulus reduction and damping curves for the soil [14]. Non-linear hysteretic soil behavior is commonly characterized by a viscous damping and equivalent shear modulus

2.2.1 Shear modulus and damping ratio

Shear modulus is usually expressed as the secant modulus, G determined by the extreme points on the hysteresis loop [13] as shown in Fig 2.1. Its value depends on the amplitude of strain for which hysteresis loop is determined and it must be determined as functions of the induced strain in a soil specimen or soil deposit. This hysteresis loop is obtained from stress-strain values which are the results of laboratory test such as triaxial and cyclic direct simple shear test. The value of shear modulus decreases with increasing magnitude of cyclic shear strain as indicated on Fig 2.3.

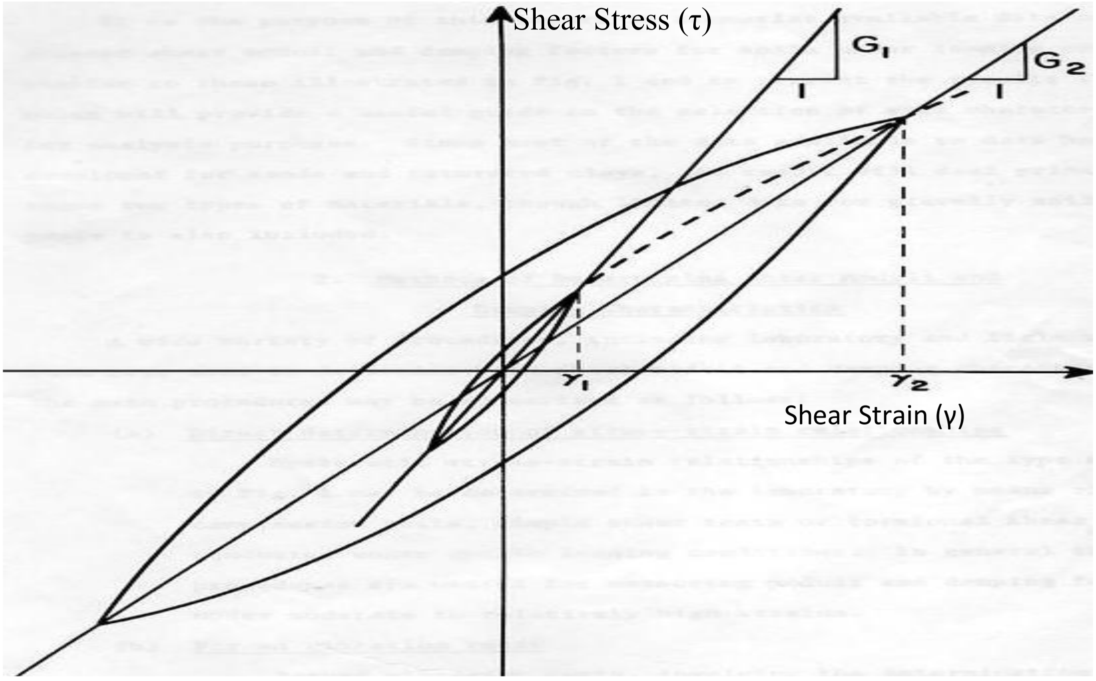


Fig 2.1 Hysteretic Stress-strain Relations at Different strain Amplitudes[13]

Damping ratio is a measure of energy dissipation and it increases with the increasing magnitude of cyclic shear strain as shown in Fig 2.3. It is also proportional to the area inside the hysteresis loop as shown in Fig 2.2. Damping curves for a numerous range of soil types have been developed by some investigators (e.g., Seed et al., 1986; Vucetic and Dobry, 1991) [14]. It is known that damping curves are within a relatively narrow range for most cohesionless soils, as the variation of dynamic curves with change in soil properties is small for such soils (e.g., Seed and Idriss, 1970) [14].

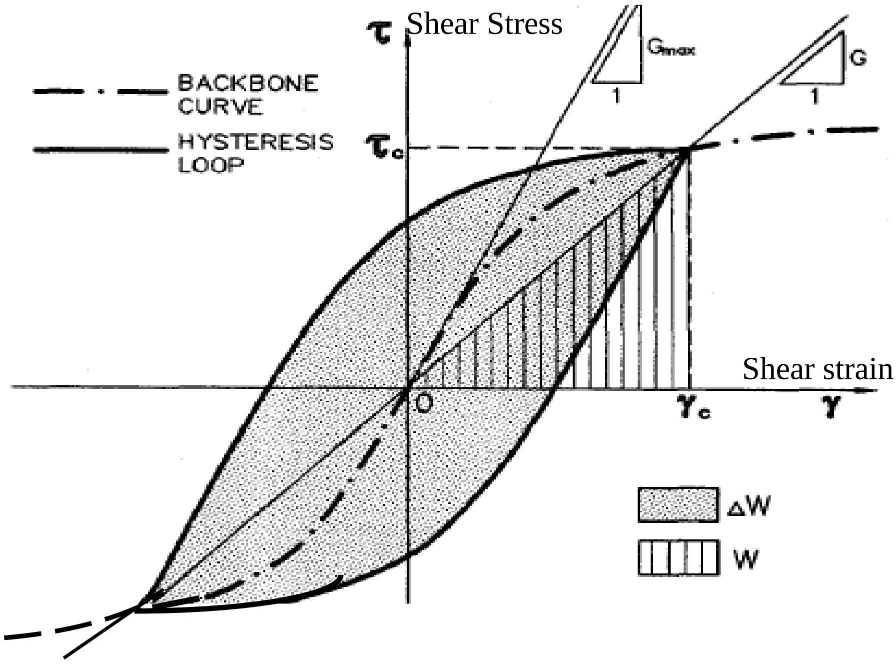


Fig 2.2 Stress-strain hysteresis loop to indicate the damping ratio [14]

Damping ratio of soil can be calculated from the following formula which is defined based on Fig 2.2

$$D = \frac{\Delta W}{4\pi W} \qquad (2.1)$$

Where

D = Damping ratio

W = The maximum stored energy and
ΔW = The energy loose per cycle represented by the area enclosed inside the hysteresis loop

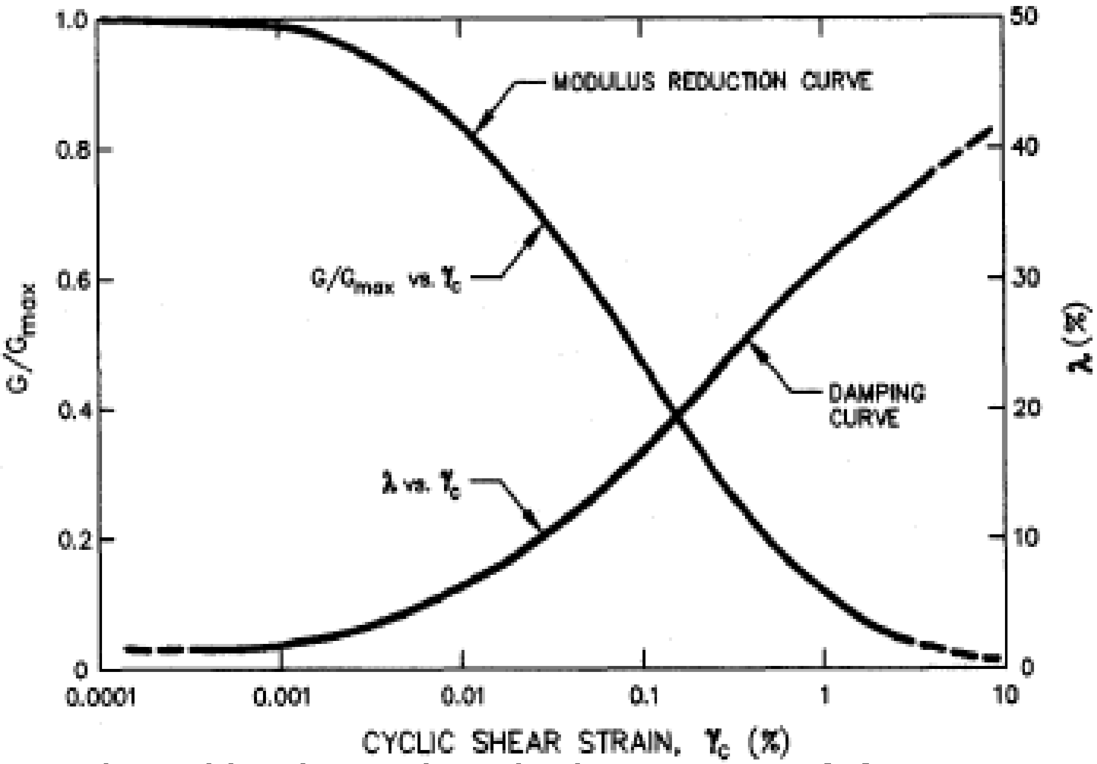


Fig 2.3 Shear modulus reduction and equivalent damping ratio curves [14]

2.2.2 Methods of determining of shear modulus and damping ratios

A wide variety of procedures, including field tests and laboratory have been used to determine both shear modulus and damping ratio. The main procedures are [9]:

1. Direct determination of stress strain relationships
2. Forced vibration tests
3. Free vibration tests
4. Field Measurement of wave velocities
5. Analysis of Ground response during earthquake

The approximate strain range are presented in Table 2.1

Table 2.1 Test procedures for measuring shear modulus and damping ratio [9]

General procedure	Test condition	Approximate strain range	Properties can be determined
Determination of hysteretic stress-strain relationships	Triaxial compression	$10^{-2} to\ 5\%$	Modulus : damping
	Simple shear	$\mathbf{10^{-2} to\ 5\%}$	**Modulus : damping**
	Torsional shear	$10^{-2} to\ 5\%$	Modulus : damping
Forced vibration	Longitudinal vibrations	$10^{-4} to\ 10^{-2}\%$	Modulus : damping
	Torsional vibrations	$10^{-4} to\ 10^{-2}\%$	Modulus : damping
	Shear vibration -Lab	$10^{-4} to\ 10^{-2}\%$	Modulus : damping
	Shear vibration -field	$10^{-4} to\ 10^{-2}\%$	Modulus : damping
Free vibration tests	Longitudinal vibrations	$10^{-3} to\ 1\%$	Modulus : damping
	Torsional vibrations	$10^{-3} to\ 1\%$	Modulus : damping
	Shear vibration -Lab	$10^{-3} to\ 1\%$	Modulus : damping
	Shear vibration -field	$10^{-3} to\ 1\%$	modulus
Field wave velocity measurements	Compression waves	$5x10^{-4}\%$	modulus
	Shear waves	$5x10^{-4}\%$	modulus

2.2.3 Factors affecting the values of shear modulus and damping ratio

Soils, in contrast to many structural materials, are highly non linear even at very low strains. This non linearity causes soil stiffness (can be expressed by shear modulus reduction curve) to decrease and damping ratio to increase with increasing shear strain amplitude [20] which is shown in Fig 2.3.

The shear modulus value strongly depends on confining pressure, (Fig 2.4) and the type of soil (plasticity index). Shear modulus values for sands are strongly influenced by the confining pressure, the strain amplitude and the void ratio (or relative density) whereas the shear modulus of clay is influenced by the effect of sample disturbance, effect of strain amplitude and plasticity of soils (Fig 2.5) [15].

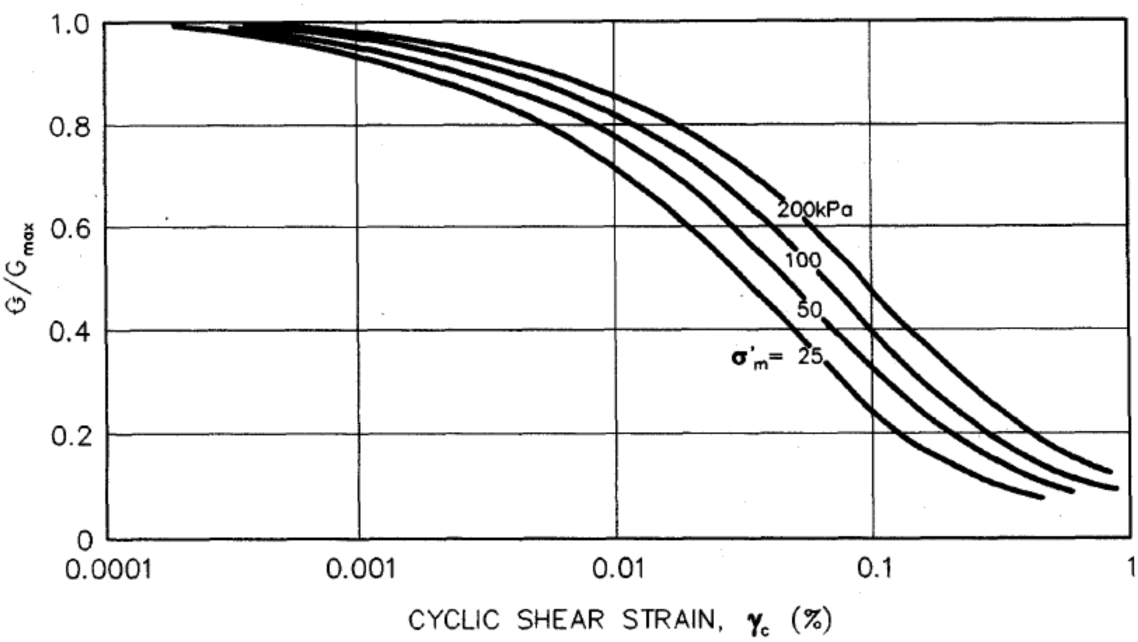


Fig. 2.4 Effect of confining pressure on shear modulus reduction curve for sandy soils [14]

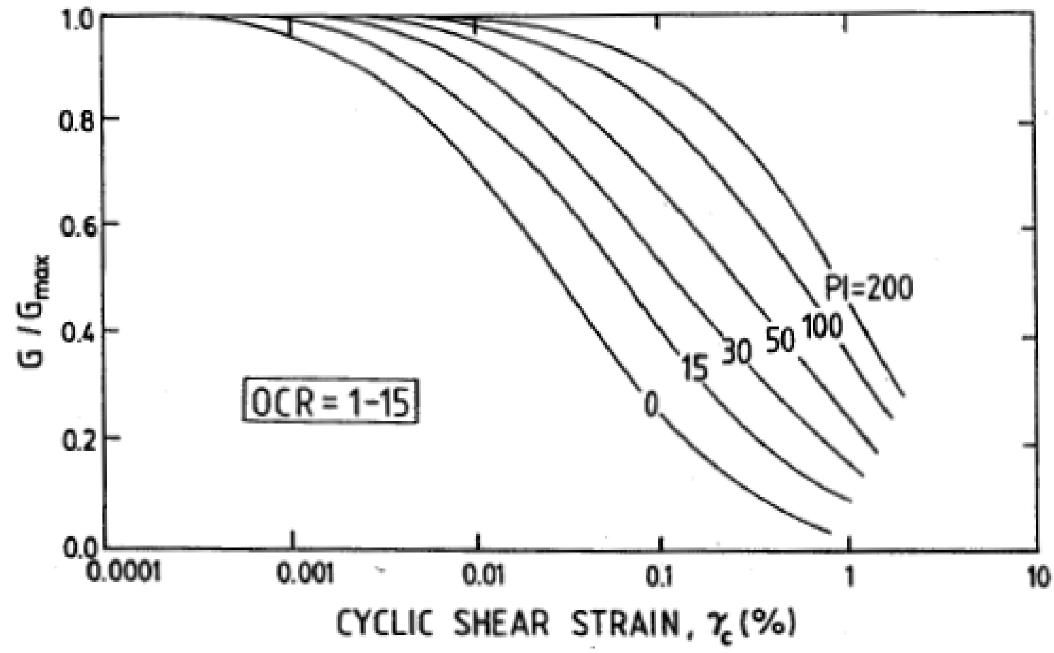


Fig 2.5 Effect of plasticity index on shear modulus reduction curve [20]

The factors which influence the value of damping ratio are effective confining pressure, plasticity index of soil and relative density. Different researchers had developed the relation between damping ratio and effective confining pressure (Fig 2.6) plasticity index and relative density for different types of soils as indicated in [13]. Damping ratio of highly plastic soil is lower than those of low plasticity soils at the same cyclic strain amplitude [14].

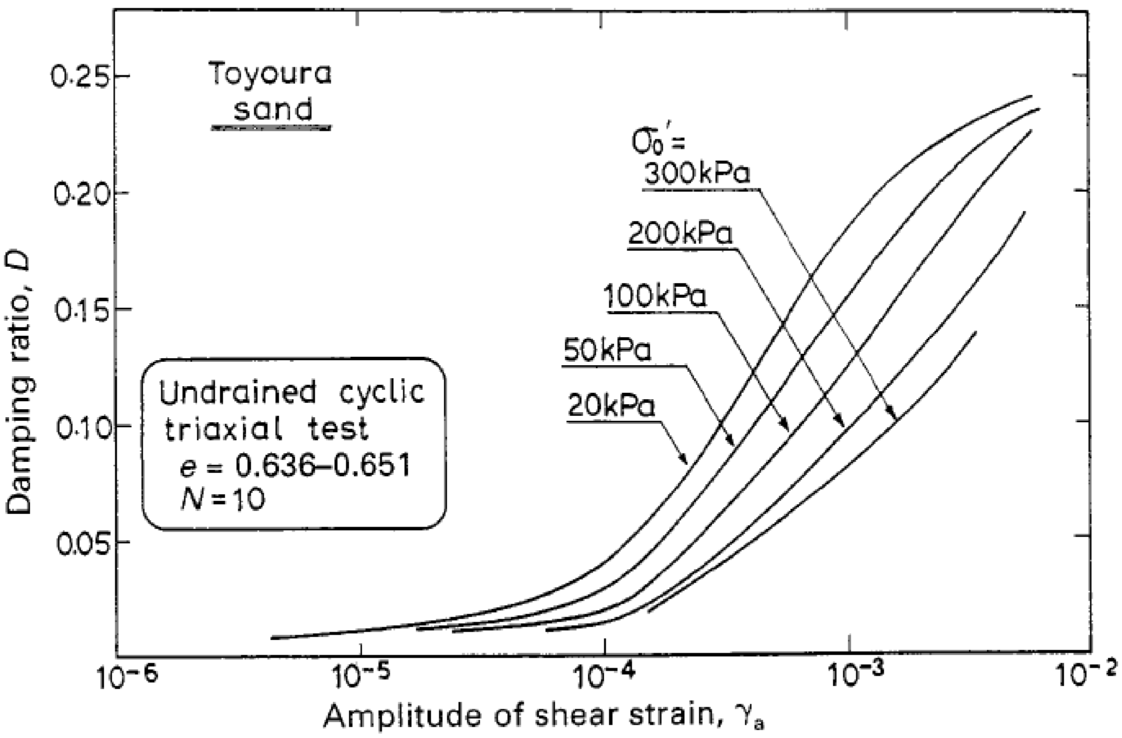


Fig 2.6 Effect of confining pressure on damping ratio of sand [15]

2.3 VALUES OF SHEAR MODULUS AND DAMPING RATIO OF CLAY AND SAND

Both response and ground failure are strongly influenced by properties of soil. Site response is primarily influenced by the properties that control wave propagation, particularly stiffness and damping. Ground failure is influenced by those properties but also by the shear strength of the soil. The properties of soil are influenced by types of soils namely; clay, sand, silt soil. But also dynamic properties of soils such as modulus reduction behavior is strongly dependent upon shear strain amplitude and plastic index; for cohesionless soils(clay and silt clay) and low plasticity soils(sandy soils) it is also influenced by mean effective stress. The influence of effective confining pressure is decreased with increasing plasticity index (PI) [20].

2.3.1 Shear modulus and damping ratio of sand

The shear modulus of sand determined by a number of investigators using different laboratory testing procedures under different factors is given in Fig 2.7 [13].

Aria, Amhara, Siver and Seed studied the effect of confining pressure for dry sand, Hardin and Drenvich for saturated sand [13]. In addition to confining pressure, other factors such as void ratio, degree of saturation and angle of friction were studied by a number of researchers. Based on these studies, Bolten and Indries presented the range of values of damping ratios as shown on Fig 2.8, [13].

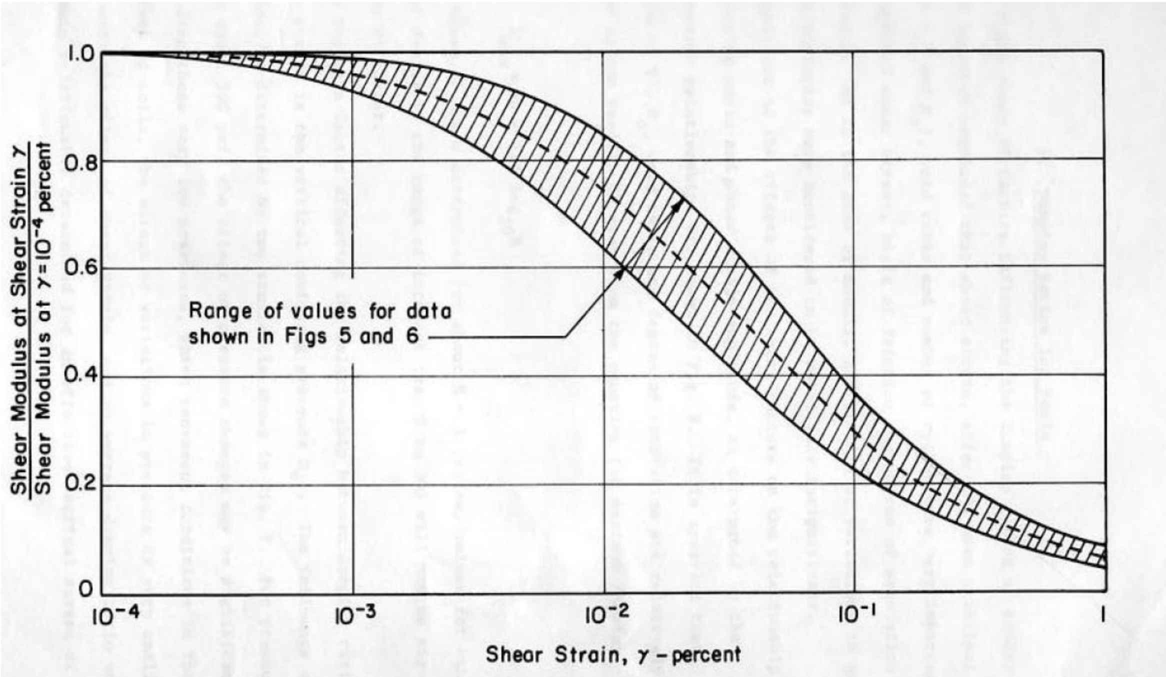


Fig.2.7 Variation of shear modulus with shear strain for sand [13]

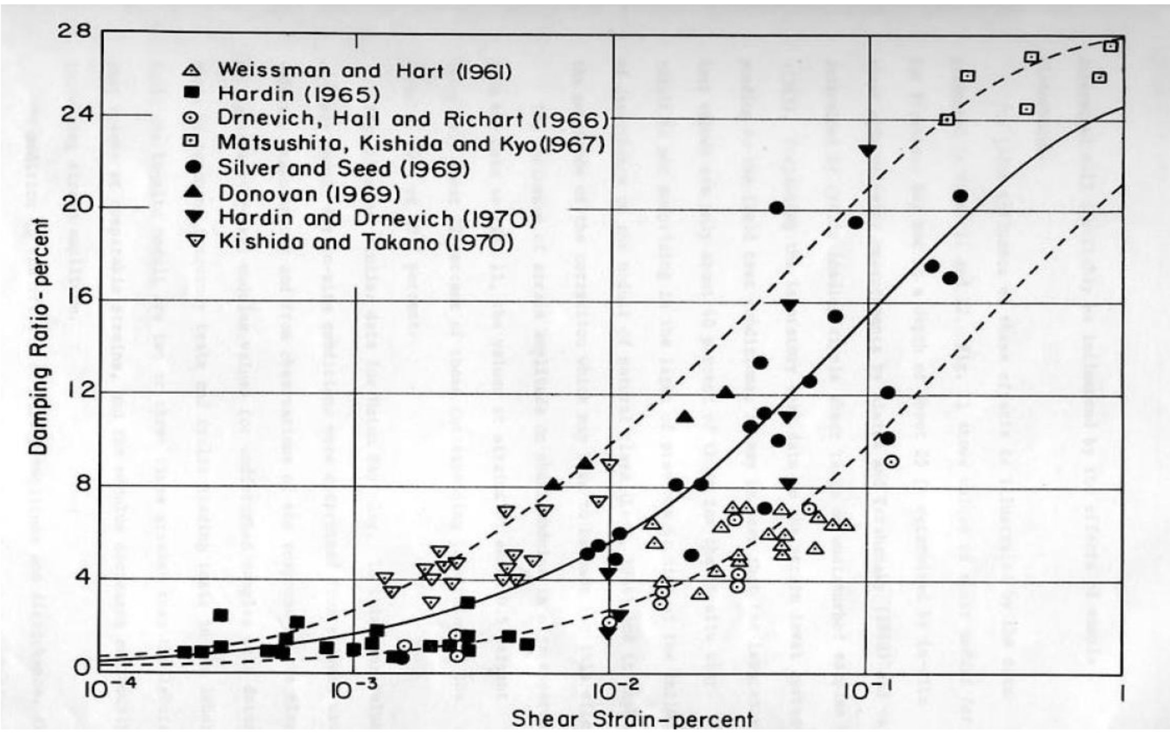


Fig. 2.8 Variation of damping ratios with shear strain for sand [13]

2.3.2 Shear Modulus and Damping Ratio of clay

The value of shear modulus of clay is strongly influenced by strain amplitude and disturbance of sample. Even though the in-situ measurement eliminates the problems of sample disturbance of specimen, no techniques have been developed for including large controlled strain amplitude. For this reason, the shear modulus is determined at very small strain level. In laboratory, samples may be tested under wide range of strain but for test specimens from natural deposits, the shear modulus determined will be inevitably be influenced by the effect of sample disturbance [13]. In addition to sample disturbance and effect of large strain amplitude, the shear modulus is influenced by effective mean principal stress, void ratio, over consolidation ratio and effective stress strength parameters.

Fig 2.9 shows the typical values of normalized shear modulus of saturated clay soils tested under different ranges of shear strain amplitude [13].

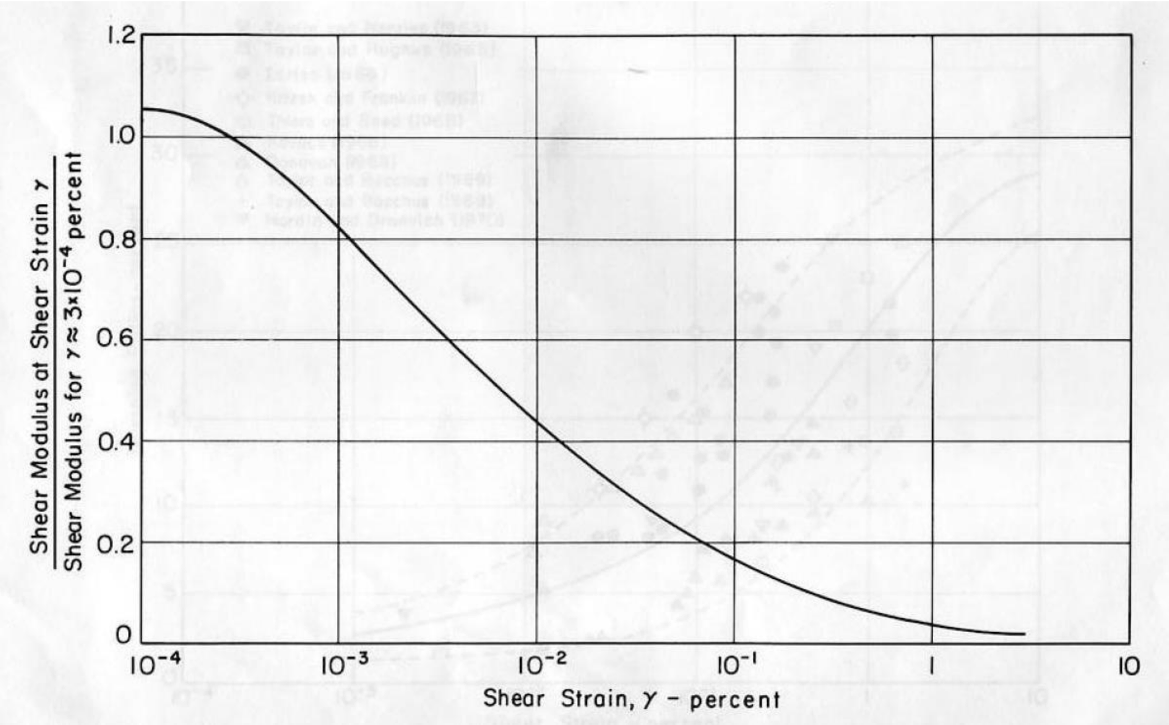


Fig 2.9 Typical reduction of shear modulus with shear strain for saturated clays [13]

Damping ratio of saturated clay soils is difficult to determine the main influencing factors as there is limitation of test data and variation of results to much extent.

Fig 2.10 below shows the approximate upper and lower bound relationships (dashed line) between damping ratio and shear strain and representative average relationships (solid line). This average relationship may well provide values of damping ratio with sufficient accuracy for many practical purposes.

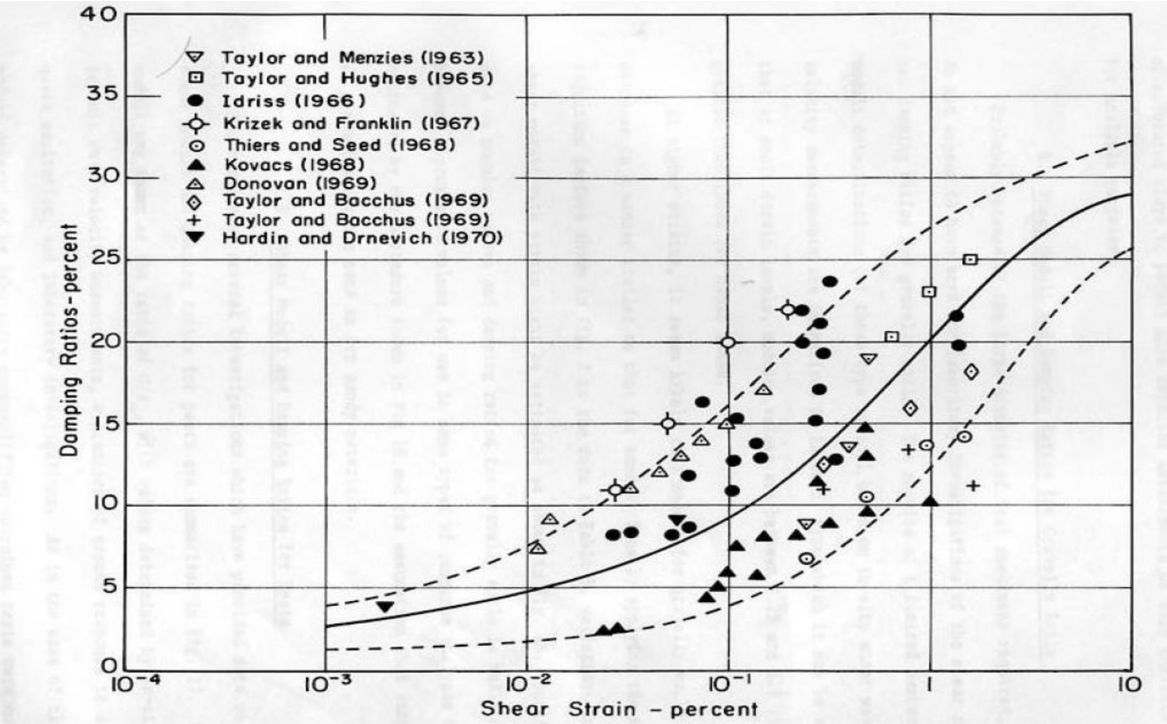


Fig. 2.10 Damping ratio for saturated clays [13]

2.4 DETERMINATION OF INITIAL SHEAR MODULUS

The small strain shear modulus, commonly referred to as the maximum shear modulus, G_{max} can be obtained from site-specific investigations (Table 2.2) or by using empirical correlations with index soil properties (Table 2.3).

2.4.1 Correlations of initial shear modulus with types of soils

Table 2.2 Typical value of initial shear modulus [14]

Type of soil	Initial shear modulus, G_{max} **(**kPa**)**
Soft clay	2,750 - 13,750
Firm clays	6,900 - 34,500
Silt Sands	27,600 - 13,800
Dense sands and gravel	69,000 - 34,500

2.4.2 Empirical correlations of shear modulus with Index properties of soils

Table 2.3 contains correlation proposed by different authors

Table 2.3 Correlations for estimating initial shear modulus [14].

Reference	Correlation	Units	Limitation
Seed et al. (1984)	$200(K_2) * (\sigma'_m)^{1/2}$ $(K_2)_{max} = 20(N_1)^{601/3}$	kPa	$(K_2)_{max}$= 30 for very loose sands and 75 for dense sands ; 80-180 for dense well graded gravels. Limited to cohesionless soils
Imai and Tonouchi (1982)	$G_{max} = 15560(N_{60})^{0.68}$	kPa	Limited to cohesionless soils
Hardin (1978)	$G_{max} = \frac{625(P_a*\sigma'_m)^{0.5*OCR*K}}{0.3+0.7e^2}$	kPa	Limited to cohesive soils P_a =atmospheric Pressure
Jarniolkowski et al. (1991)	$G_{max} = \frac{625(P_a*\sigma'_m)^{0.5*OCR*K}}{e^{1.3}}$	kPa	Limited to cohesive soils P_a = atmospheric Pressure
Mayne and Rix (1993)	$G_{max} = \frac{99.5(P_a) * 0.305 * (q_c)^{0695*OCR*K}}{e^{1.13}}$	kPa	Limited to cohesive soils P_a = atmospheric Pressure

The symbols indicated in Table 2.3 are defined as follow:-

$(K_2)_{max} =$ parameter which is the function of relative density and soil type

σ'_m = Mean normal effective stress

q_c = End resistance of cone penetration test

OCR = Over Consolidation Ratio

P_a = Atmospheric pressure

e = Void ratio of soil

N_{60} = Standard penetration number, corrected for field conditions

$N_1 = C_v * N_{60}$

Where C_v = Correction factor for effective over burden pressure

k = Power factor

Hardin and Drnevich presented the factors which influence the dynamic properties of soils and derived expression to determine initial (maximum) shear modulus (at essentially zero strain) based on soil properties for all types of soils [13].

Equation 2.1 is applied to determine maximum shear modulus for all types of soils.

$$G_{max} = 14760 * \frac{(2.973-e)^2 * (OCR)^a * (\sigma'_m)^{1/2}}{1+e} \qquad (2.2)$$

$e = Void\ ratio$

OCR = Over Consolidation Ratio = $\frac{P_r}{P_o}$

P_r= Pre-consolidation pressure of a specimen

P_o = Present effective vertical pressure

a = Parameter that depends on the plasticity index of soil

σ'_m = Mean principal effective stress

The value of "a" can be obtained from the following table

PI	**a**
0	0.0
20	0.18
40	0.30
60	0.41
80	0.48
100	0.50

CHAPTER THREE

DESCRIPTION OF STUDY AREA AND EXPERIMENTAL TECHNIQUES

3.1 AREA OF STUDY

The site where samples were collected is located in Adama city, 99km from Addis Ababa. Adama is one of the largest and most populated cities in Oromia National Regional State. It is located in the Misraq Shewa Zone of Oromia at 8^{o}33`35``N - 8$^{o}$36`46`` N latitude and 39^{o}11`57`` E – 39$^{o}$ 21`15`` E longitude. The altitude of the city is 1,712 m above mean sea level [2]. Adama has a total area of about 13,000 hectares, which has been subdivided into 14 urban kebele (least administrative structure) administrations. The name of Adama was replaced with Nezerath by Emperor Haile Selassie after Biblical Nazareth, and this name was used throughout the twentieth century. In 2000, the city officially reverted to its original Oromo language name, Adama, though "Nazareth" is still widely used.

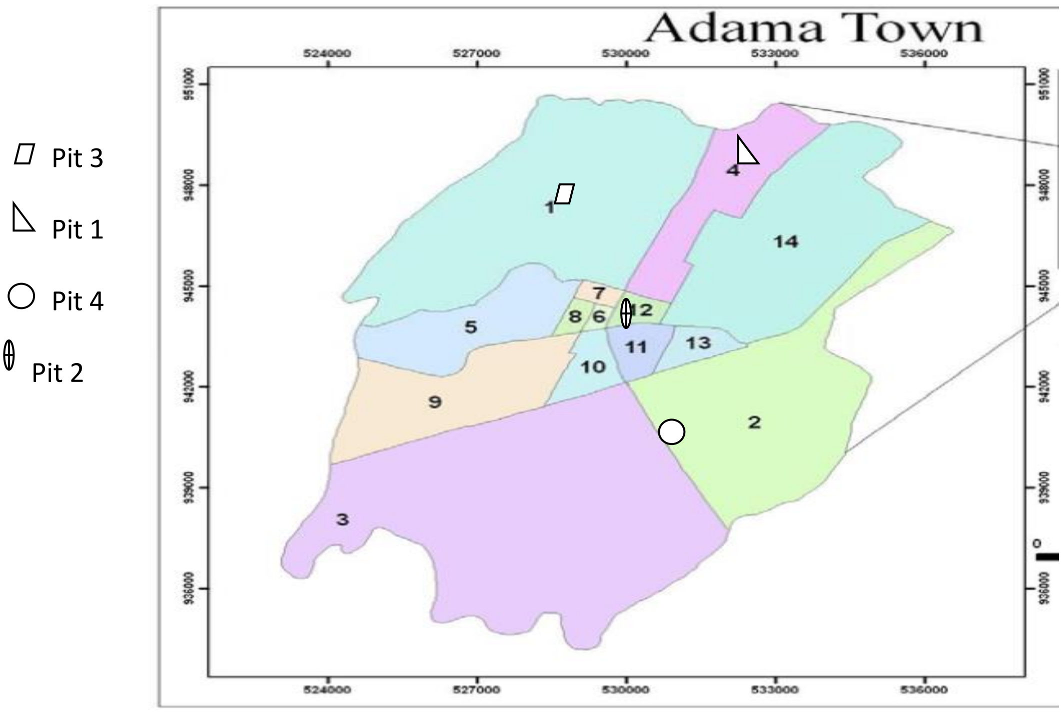


Fig 3.1 Adama city national and reginal setting

3.1.1 Precipitation and Temperature Conditions

According to Adama Master Plan (1995) reveals that the mean annual precipitation depth recorded for Adama is 82.25cm for the period of 1952 to 1991. The mean annual rainfall for the period of 1998 to 2006 was computed to be 72.67cm as indicated in Table 3.1. This figure is a little bit lower than the average total annual rainfall for most highland areas of Ethiopia (Alemneh, 1990; Messay, 2001).

Table3.1: Mean Annual Rainfall in centimetre (cm)-1998-2006

Year	Jan.	Feb.	March	April	May	June	July	Aug.	Sept	Oct	Nov	Dec	Ave.
1998	11.8	25.6	105.2	19.8	49	55.3	196.5	220.6	144.7	132.8	0	0	80.13
1999	9.2	0	34.6	1.2	19	74	283.2	194.4	66.3	164.7	3.1	0	70.78
2000	0	0	20.2	16.1	52	60.8	355.1	269	133.6	85.7	57.8	12.9	88.56
2001	0	6.2	108.3	28.7	177	51.2	216.9	145.3	107.8	1.7	0	6.6	70.8
2002	20.9	11.1	*	51.3	23	50.2	235.6	205.7	65.3	1.1	0	34.5	53.86
2003	46.5	69.1	151.2	88.9	3.6	75.2	114.4	279.7	122.8	0	5.3	48.8	93.89
2004	28.8	3.3	77.4	53.1	1.9	63.3	144.3	227.3	77.1	58.6	12.8	1.6	59.97
2005	72.5	6.3	90.1	41.3	71	50.2	173.5	165	68.4	6	5.3	0	60.04
2006	17.6	88.4	64.6	88.7	28	58.7	205.5	225	128.8	10.1	0.5	28.5	76.02
Ave.	23.1	23.3	81.5	43.2	47	59.9		214.7	101.6	51.2	9.4	14.8	72.7

Source : national Metrological service Agency (Computed)

Table 3.2 gives the monthly temperature variation

Table 3.2 Monthly mean temperature maximum, minimum and average temperature in Adama city(1998-2007)

	Jan	Feb	Mar	Apr	may	Jun	Jul	Aug	Sep	Oct	Nov	Dec	yearly
Mean max	26.7	28.9	29.3	29.9	31.1	29.8	26.2	25.7	27.1	27.6	27	25.9	26.7
Mean min	13.1	14.4	15	15.9	16.6	17.6	16.3	16.2	15.2	13.9	13.1	12.3	13.1
Ave.	19.9	21.7	22.2	22.9	23.9	23.7	21.3	21	21.2	20.8	20.1	19.1	19.9

Source : National Metrological Service Agency (Computed)

3.1.2 Geology

Adama city is located between the base of escarpment to the west and the Main Ethiopian Rift (MER). Its physiographic condition is, therefore, mainly the result of volcano-tectonic activities that occurred in the past and also partly the result of the deposition of sediments, which are considered largely of fluvial and lacustrine origin. It is regarded as seismically active area with expected earthquake hazards having probability occurrence of 0.99 in every 100 years (NUPI, 1995) [18]. MER may be geographically subdivided into three sectors. These sectors are: Northern (location of Adama city), Central and Southern. The MER of northern sector includes 7 00' – 8 40' latitude to the north. In this range of latitude four successive periods of volcanic activity have been identified [18].

According to others studies, there are two main volcanic units in the northern part of the rift system, namely Nazret series and Wonji series. Nazret series is represented by ignimbrites, basaltic and rhyolitic lava flows, trachyte flows and ash flows.

It is well known that Adama city is Subdivided into 14 Kebele as shown in Fig 3.1. The geological formation of each kebele of Adama is not identical in terms of time of formation and geological events throughout the area. For instant Kechema ridge represented by upper aphanitic basalt, middle pumice, ash deposits and lower intensely welded ignimbrite (light green) which has an absolute age of 1.7 million whereas Boku ridge is rhyolitic lava flows, obsidian interlayerings, fiamme ignimbrite,thin ash flow and pumice layers in some places.

3.1.3 Soil Formation

Soil formation in Adama city is mainly governed with the topographical feature of the area. Normally for the formation of the soils, physical and chemical agents are involved. Therefore the soil is formed by weathering process such as erosion by water and chemical reaction. That is erosion of material from the ridge and deposition of these eroded materials in lower area such as Kebele 09, 01, 02, 03, 12. For instance top soil (up to 3m depth) around Kebele 01 (Pit 03) and Kebele 09 are formed by erosion of the material from Kechema ridge, whereas soil around Kebele 02 (Pit 04) and Kebele 03 is eroded from Boku ridge. This is mainly true for others area of the city in the range of 3m up to ground level. The effects of weathering and transportation largely determine the basic nature of the soil (i.e. the size, shape, composition and distribution of the grains). The environment into which deposition takes place, and subsequent geological events that took place there, largely determine the state of the soil, (i.e. density, moisture content) and the structure or fabric of the soil (i.e. bedding, stratification, occurrence of joints or fissures, tree roots, voids, etc.). The soil in Adama is fine grained soil up to a depth of 3m.

3.2 EXPERIMENTAL TECHNIQUES

3.2.1 Sample collection and Methods

All soil samples were taken from four selected test pits which are located in Kebele 01, 02, 04, and 12 as shown on Fig. 3.1.The field density is determined using core cutter method [6]. To study the response of the soil at natural condition the field density is preferable to maximum dry density. The dynamic test is performed by compacting sample at field density and natural moisture content. Grain size distribution and index property of soil are determined.

3.2.2 Sample Preparation

Samples were pulverized and sieved on sieve No 4(4.75mm), and then known weight of soil is taken and mixed with water that equal to percentage of natural water content. The specimen is then remolded in a mould to attain field density and natural moisture content. From this remolded specimen, 20mm height and 70mm diameter of sample is prepared; and then placed in rubber membrane which is mounted on bottom plate of cyclic direct simple shear machine which is confined by brass rings (Fig 3.2) to control lateral deformation of sample during consolidation stage.

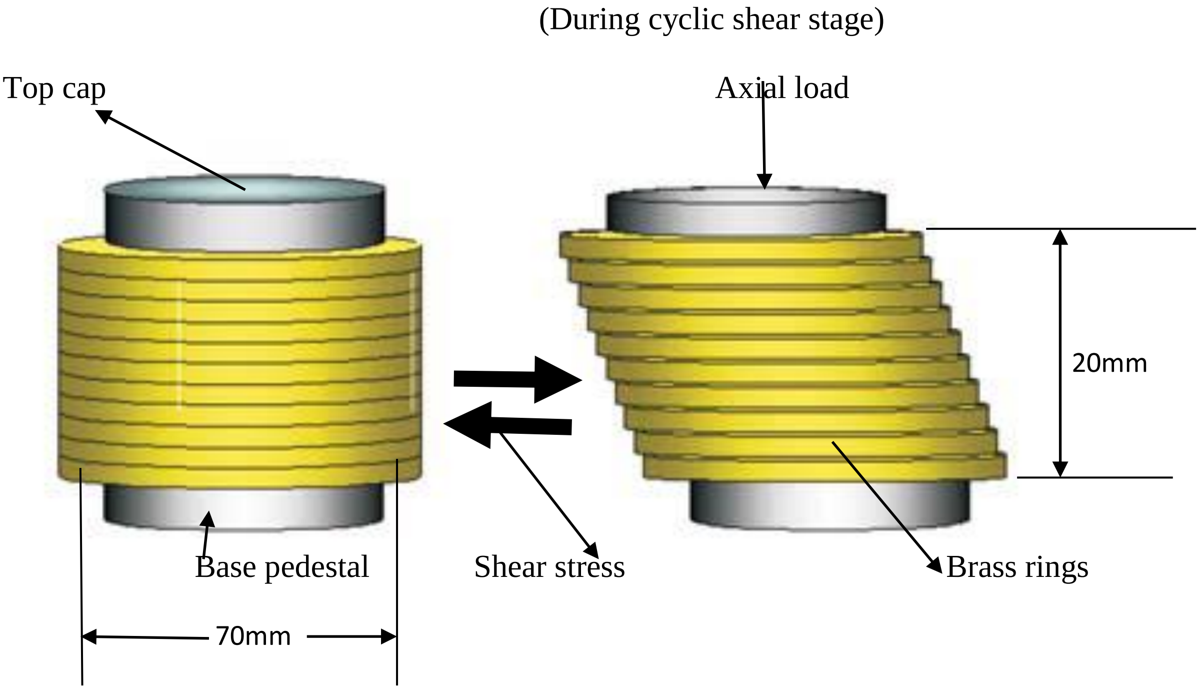


Fig 3.2 Simplified representation of lateral constrain of specimen under cyclic shear test

3.3 APPARATUS

To determine dynamic property of any type of soils various kind of machines are available. These include cyclic triaxial, resonant column, ultrasonic pulse, piezoelectric bender element, cyclic simple shear and cyclic torsional shear apparatuses [16]. Among these machines cyclic direct simple shear is used for this research.

3.3.1 Cyclic Direct Simple Shear Test

The simple shear device consists either of a rectangle box made of hinged plates or a cylindrical wire-reinforced membrane which surrounds the sample and restrains the sample from expanding laterally in all direction during consolidation stage, but allows the sample to deform horizontally during the cyclic loading test. It is connected to an electronic reading system [19]. The electronic reading system records lateral force and displacement, axial displacement and force. This electronic reading system is governed by UTS004 software application program that incorporates the functionality to perform consolidation, cyclic simple shear and linear displacement rate shear. In addition to wire-reinforced membrane and electronic reading system, the simple shear device consists of the features is arranged for applying a constant vertical load or for maintaining a constant sample height while measuring the vertical load and a mechanism for applying a horizontal cyclic shear load as shown in Fig 3.3.

The cyclic direct simple shear test may provide the most accurate representation of the stress state resulting from a vertically propagating shear wave in a horizontally layered soil deposit of any laboratory test; and also the sample is consolidated in K_o state. [9] By applying cyclic horizontal shear stresses to the bottom of the specimen, the test specimen is deformed in much the same way as an element of soil subjected to vertically propagating S-waves. At the top and bottom of the specimen the supporting platens are rough which assist to minimize the non uniformity of stress conditions. The effects of non-uniformity of stresses can also be reduced by increasing the diameter/ height ratio of the specimen: such effects are small at diameter/ height ratios greater than about 8:1(Kovacs and Leo, 1981) [16]. Since the diameter/ height ratio of the cyclic simple shear machine present in AAIT is 7:2 there is the effect of non uniformity stress condition. But the plate is rough enough to control the non uniformity of the stress condition.

In addition to accurate representation of natural condition of stress state, cyclic direct simple shear test can measure dynamic soils properties over wide ranges of strain (that is 10^{-2} % up to 5 %.) [9].

The general set up of the equipment is presented in Fig 3.3

Fig 3.3 Cyclic shear apparatus and its general features

Consolidation Stage

The consolidation stage is simply the application of static axial loading stress to the specimen while the lateral loading (shear) axis is held stationary. . In this thesis the axial stresses applied for consolidation are selected and their values are 100kPa, 250kPa and 400kPa. Axial stress and specimen displacements (axial and lateral) data are measured over time and logged by the system.

The consolidation stage is manually terminated once consolidation of the specimen is completed.

Cyclic Simple shear stage

The cyclic shear stage of the test is conducted by applying a lateral cyclic shear force under specified amplitude to the specimen, while the vertical height of the specimen is maintained at constant height. The lateral cyclic shear force tends to slide the rings over each other though the volume of the specimen is unchanged.

Since the lower and upper bounder of shear strain to be used for cyclic simple shear testing are 10^{-2} % and 5 % respectively, one can select the stains between these bounders for cyclic simple shear test as presented in Table 3.3.

Table3.3 Selected amplitude and corresponding shear strain for cyclic test

Amplitude(mm)	Shear strain (%)
0.002	0.01
0.02	0.1
0.2	1
0.5	2.5
1	5

Both axial and lateral force and specimen displacements are measured for each loading cycle. Measured data is obtained from 50 sample points captured over the cycle period.

CHAPTER FOUR

PRESENTATION AND ANALYSIS OF TEST RESULTS

The physical properties of soil are expressed by density, water content, specific gravity, Atterberg's limit, void ratio and behavior of soils under compaction. These physical properties are equally important both under static and dynamic loading condition. Therefore, before going to determine the dynamic soil properties, it is essential to determine index properties of soils. Index properties of soil were determined both in the field and laboratory. Summary of these test results are presented in Table 4.1 (field test result), Table 4.2 (laboratory test result, index properties of soil).

3.1 FIELD TEST RESULT

The test result of field test is presented in Table 4.1 which include field density and natural water content

Table 4.1 Field test result

Location	Sample from	Field Density –Bulk (g/cm^3)	Field density-Dry Density (g/cm^3)	Natural water content (%)
Kebele 04	Pit 1	1.36	1.14	19.3
Kebele 12	Pit 2	1.34	1.05	27.62
Kebele 01	Pit 4	1.38	1.14	21.16
Kebele 02	Pit 5	1.34	1.01	32.54

3.2 LABORATORY TESTS

4.2.1 Index properties

Table 4.2 shows the laboratory test result of index properties of sample collected from Pit 1, Pit 2, Pit 3 and Pit 4. The state of soils is also indicated in Table which is based on liquidity index of soil.

Table 4.2 Laboratory test (Index Properties)

Sample from	Specific gravity	Liquid limit (LL)	Plastic Limit (PL)	Plasticity Index (PI=LL-PL)	Liquidity Index $LI = \frac{w-PL}{PI}$	State Of Soil
Pit 1	2.70	35.9	25.9	10.0	-0.66	Semisolid state
Pit 2	2.61	48.8	37.4	11.4	-0.86	Semisolid state
Pit 3	2.67	39.5	28.7	10.8	-0.70	Semisolid state
Pit 4	2.65	49.4	34.7	14.7	-0.15	Semisolid state

4.2.2 Classification soil according to UCS

The soil sample is classified based on the ASTM D 2487. Table 4.3 shows classification of soils which is based on plasticity chart and grain size distribution. As in ASTM D 2487 the soils classified as fine grained if percentages of particle passing sieve No 200 greater than 50% else coarse grained soils.

Table 4.3 Classification according to UCS

Sample from	% of particle passing No 200	Type of soil	Characteristics of soil passing sieve No 40			On plasticity Chart	soil type
			Liquid Limit	Plastic Limit	Plasticity Index		
Pit 1	43.75	Coarse Grained	35.92	25.91	10	Blow A-line	Silty Sand
Pit 2	93	Fine Grained	48.81	37.41	11.4	Blow A-line	Silt
Pit 3	69	Fine Grained	39.5	28.71	10.79	Blow A-line	Silt
Pit 4	75.5	Fine Grained	49.4	34.68	14.72	Blow A-line	Silt

Sieve analysis and Hydrometer test results are presented on appendix A percentage of each type of soils in given sample is indicated in Table 4.4

According to UCS, the soil sample from Pit 1 is classified as silty sandy soil. Whereas the soil sample of Pit 2, Pit 3, and Pit 4 are classified as sandy silt (ML or OL) soil.

The results of compaction test are presented in Table 4.4

Table 4.4 Compaction Test result

Sample from	Maximum Dry Density(gm/cm3)	Optimum water Content (%)	Natural Water content (%)
Pit 1	1.53	25.3	19.29
Pit 2	1.48	25	27.62
Pit 3	1.52	24.5	21.16
Pit 4	1.33	30.5	32.54

4.2.3 Test result from cyclic simple shear test

The data obtained from cyclic simple direct shear test is simply raw data which include Axial Lvdt, Axial Force, Ext Axial Lvdt, Lateral Lvdt and Lateral Force of 50 data point for single cyclic loading in the form Microsoft excel. Since the number of cycle ordered to be done by cyclic machine is 40, for complete test of any selected amplitude 2000 data points are recorded. From Lateral Lvdt and Lateral force test results, shear stresses and shear strains are evaluated, and then dynamic soil parameters are calculated. Once shear modulus and damping ratio are calculated, shear modulus and damping ratio versus shear strain can be drawn.

4.2.4 Determination of shear modulus and damping ratio

The values of shear modulus and damping ratio can be determined from stress- strain relationships which are based on raw data obtained from cyclic shear test which is indicated on Fig 4.1.

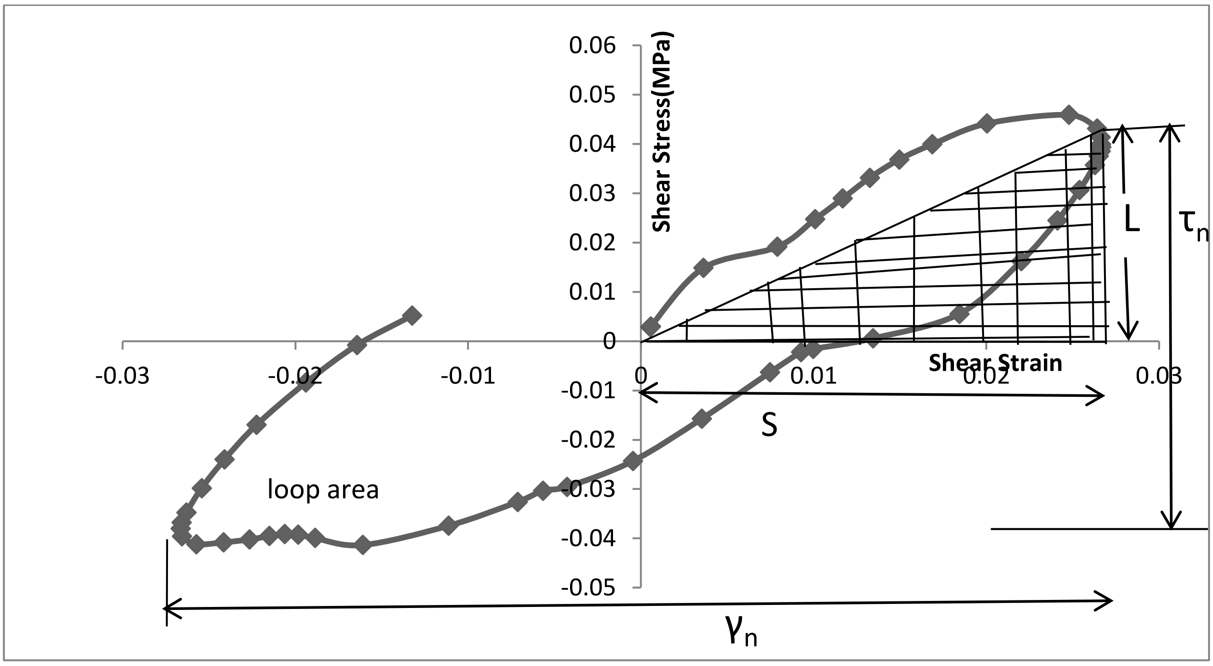


Fig 4.1 Shear stress versus shear strain to indicate hysteresis loop and energy dissipation with triangular area

As shown in Fig 4.1 there are 50 data points for single cycle. Using these data points the hysteresis loop can be drawn. Appling equations 4.1 to 4.4, the values of both damping ratio and shear modulus are calculated. A typical calculation is presented in Table 4.5. The calculation is based on shear stress and shear strain that obtain from shear force and cyclic amplitude which are the results of cyclic simple shear test. Normally there are 40 cycle for single amplitude (cyclic shear strain) and similar calculation is applied to obtain dynamic soil parameters, shear modulus and damping ratio of soil.

Notice that the symbols used in equation 4.3 and 4.4 are indicated on Fig 4.1

$$Shear\ stress(\tau) = \frac{shear\ Force}{area\ of\ sample} = \frac{F}{A} \qquad 4.1$$

$$Area\ of\ sample\ (A) = \pi * 35^2 = 3848.45cm^2$$

$$shear\ strain\ (\gamma) = \frac{Lateral\ Lvdt}{Height\ of\ the\ sample} \qquad 4.2$$

$$\text{Height of the sample} = 20\text{mm}$$

Shear modulus can be calculated from equation 4.3

$$\text{Shear Modulus}(G) = \frac{\tau_n}{\gamma_n} \qquad 4.3$$

τ_n − The difference between the maximum and the minimum values of shear stress

γ_n - The difference between the maximum and the minimum values of shear strain

Damping ratio is also calculated from equation 4.4

$$D(\%) = \frac{A_{Loop}}{4\pi * A_{\Delta}} * 100 \qquad 4.4$$

A_{Loop} - Area of loop

$$A_{Loop} = 0.5 * \sum(\tau_i - \tau_{i+1}) * (\gamma_i - \gamma_{i+1})$$

$$A_{\Delta} = 0.5 * (L * S)$$

A_{Δ} - Triangular area as shown in Fig 4.1 with shaded part

Table 4.5 Typical calculation of shear modulus and damping ratio

Calculation of shear modulus		Calculation of damping ratio	
τ_{max}	0.0605	$A_{Loop} = 0.5 * \sum(\tau_i - \tau_{i+1}) * (\gamma_i - \gamma_{i+1})$	0.0054
τ_{min}	-0.0605	$A_{\Delta} = 0.5 * (L * S)$	0.00168
τ_{max}-τ_{min}= τ_n	0.121		
γ_{max}	-0.0571		
γ_{min}	-0.0541		
γ_{max}-γ_{min}= γ_n	0.111		
$\text{Shear modulus}(G) = \frac{\tau_n}{\gamma_n}$	**1.09**	$D(\%) = \frac{A_{Loop}}{4\pi * A_{\Delta}} * 100$	**25.60**

Table 4.6 shows the values of shear modulus and damping ratio of sample from Pit 4 for 100kPa consolidation pressure and 0.01%, 0.1%, 1%, 2.5% and 5% cyclic shear strain.

Table 4.6 Values of shear modulus and damping ratio of sample from Pit 4 at 100kPa

Pit 4	Shear modulus for 100kPa						Damping ratio for 100kPa				
Strain (%)	0.01	0.1	1	2.5	5		0.01	0.1	1	2.5	5
No of cycle											
1	5.41	4.77	2.47	1.63	**1.09**		6.79	9.106	12.07	21.47	**25.6**
2	6.52	6.567	2.42	1.45	0.91		4.96	9.188	12.54	19.17	23.67
3	6.27	6.08	2.38	1.36	0.84		6.84	9.317	11.76	18.23	22.14
4	7.41	6.025	2.33	1.3	0.77		7.33	6.583	12	17.8	21.05
5	7.16	5.479	2.29	1.26	0.78		7.25	8.073	12.55	17.7	20.47
6	6.89	5.401	2.28	1.24	0.73		7.2	7.982	10.8	17.12	19.2
7	6.67	5.358	2.24	1.22	0.72		6.6	7.787	11.48	16.74	19.21
8	6.48	5.202	2.23	1.2	0.69		6.84	7.702	10.07	16.66	18.78
9	6.2	5.119	2.21	1.18	0.68		5.23	7.449	11.3	16.29	18.85
10	5.39	5.164	2.19	1.17	0.64		4.94	6.888	10.06	16.5	18.73
11	6.3	5.12	2.19	1.16	0.64		6.24	6.708	10.86	15.84	17.85
12	6.45	5.143	2.17	1.15	0.61		6.01	6.556	9.82	16.24	18.94
13	6.34	5.156	2.17	1.13	0.6		5.67	6.935	10.88	15.96	17.97
14	6.38	5.145	2.15	1.12	0.6		5.53	6.292	9.207	16.09	18.33
15	6.37	5.169	2.15	1.11	0.59		5.26	5.813	10.24	15.74	17.75
16	6.29	5.173	2.13	1.11	0.58		5.29	6.384	11.11	15.56	17.56
17	6.24	5.078	2.13	1.1	0.56		5.01	6.161	10.18	15.75	17.62
18	6.3	5.111	2.12	1.09	0.56		5.27	6.007	10.95	15.61	17.66
19	6.34	5.188	2.11	1.08	0.56		5.14	5.619	9.656	15.57	17.43
20	6.23	5.197	2.1	1.08	0.55		5.1	6.119	10.59	15.47	17.47
21	6.13	5.193	2.1	1.07	0.54		4.94	6.359	9.565	15.54	17.91

22	6.19	5.09	2.1	1.07	0.54		4.89	6.952	10.49	15.28	16.71
23	6.18	5.086	2.08	1.06	0.54		4.99	7.357	9.222	15.56	17.78
24	6.11	5.041	2.08	1.06	0.53		4.85	7.065	10.14	15.29	16.61
25	6.07	5.071	2.07	1.05	0.52		4.9	6.969	9.238	15.64	17.32
26	6.06	5.085	2.06	1.05	0.52		4.92	6.935	10.78	15.4	16.99
27	6.08	5.095	2.06	1.05	0.51		4.91	7.178	10.78	15.11	16.62
28	6.04	5.111	2.07	1.04	0.51		4.93	6.962	9.699	15.27	16.77
29	6	4.996	2.05	1.04	0.5		4.78	7.298	10.61	15.27	16.57
30	5.93	5.017	2.05	1.03	0.5		4.82	6.96	9.585	15.57	17.18
31	5.93	5.056	2.05	1.03	0.49		4.83	7.06	10.38	15.32	16.89
32	5.94	5.098	2.04	1.02	0.49		4.63	7.027	9.341	15.61	17.25
33	5.83	4.998	2.04	1.02	0.49		4.72	7.482	10.17	15.49	16.71
34	5.9	5.057	2.04	1.02	0.48		4.75	7.319	9.174	15.72	17.38
35	5.84	5.075	2.03	1.01	0.48		4.71	7.137	9.905	15.59	16.68
36	5.85	5.052	2.04	1.01	0.47		4.7	7.42	9.042	15.87	14.66
37	5.79	4.999	2.03	1.01	0.47		4.78	7.352	9.813	15.59	16.73
38	5.83	5.031	2.03	1.01	0.47		4.67	7.593	10.48	15.37	16.4
39	5.81	5.032	2.02	1	0.46		6.85	7.381	9.488	15.87	16.82
40	5.73	5.068	2.01	1	0.46		6.59	7.454	10.35	15.57	16.3

The values of shear modulus and damping ratio of all other pits and for various conditions are presented under appendix B in tabular form of Table 4.6.

4.3 SHEAR MODULUS AND DAMPING RATIO CURVES

To examine the influence of different factors, the values of shear stress, shear modulus and damping ratio are plotted versus shear strain. These curves are hysteresis loop, shear modulus versus shear strains, shear modulus reduction curves (G/G_{max} versus shear strains), damping ratio versus shear strains. Therefore, under this sub-section presentation of test result is focused by plotting the values of shear stress, shear modulus and damping ratio of soil collected from Pit 4. However, the curves of sample from other test pits are presented in appendix C.

4.3.1 Hysteresis loops

To determine the dynamic properties of soils, the graphs of shear stress versus shear strain, is commonly known as hysteresis loop are plotted. Fig 4.2 shows the hysteresis loop of sample from Pit 4 at axial pressure of 100kPa for 0.01%, 0.1%, 1%, 2.5% and 5% shear strains.

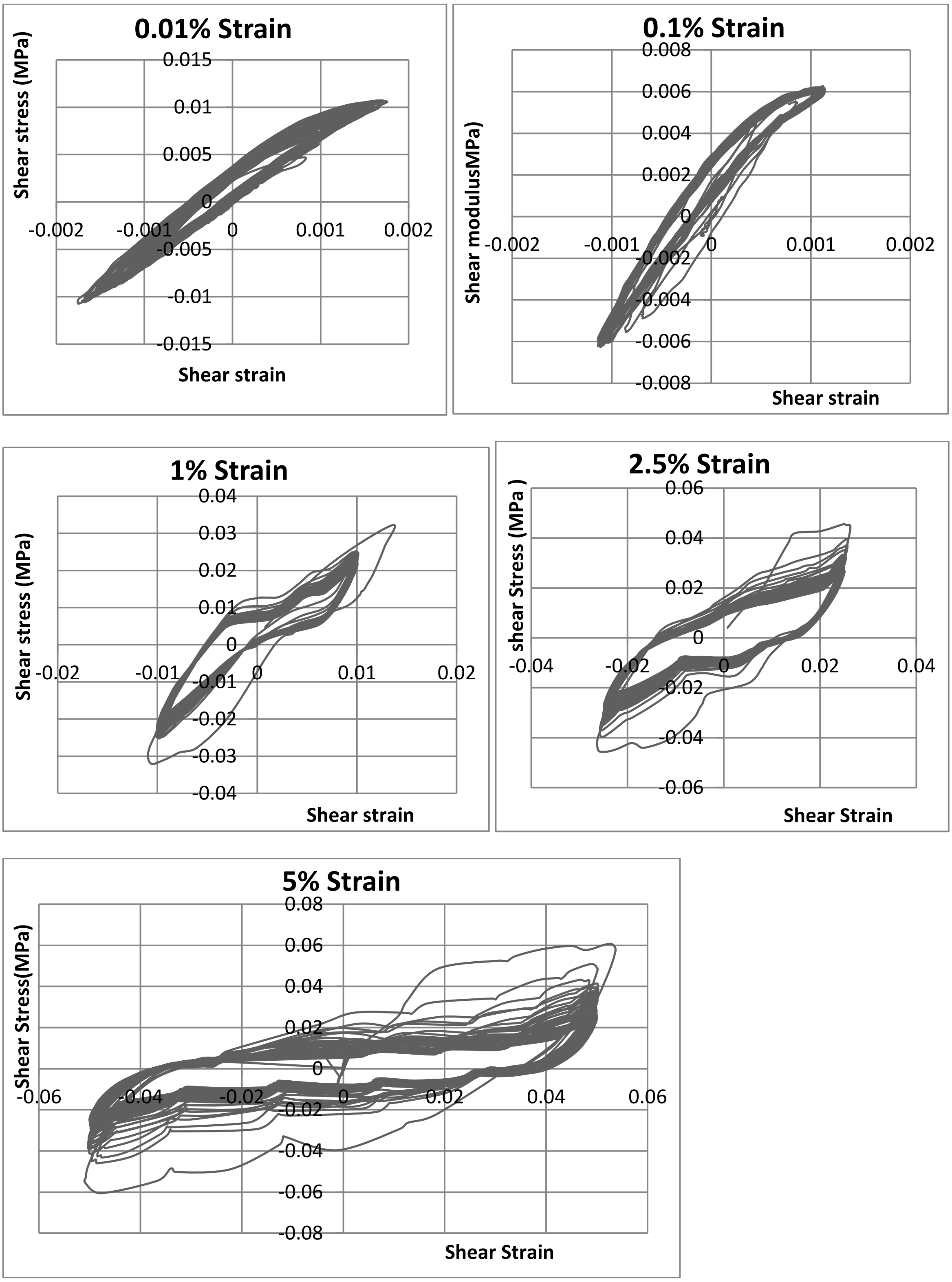


Fig 4.2 Hysteresis loop of sample from Pit 4 at axial stress of 100kPa for 0.01%, 0.1%, 15, 2.5% and 5% strains

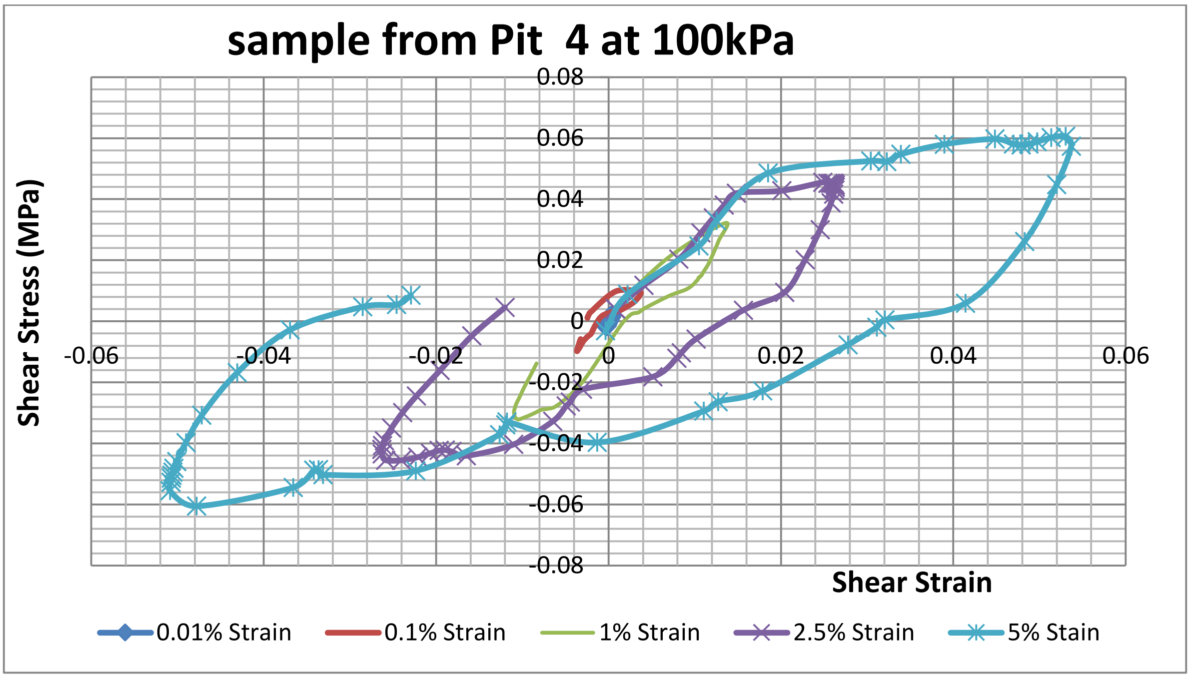


Fig 4.3 Hysteresis loop showing the effect of shear strain amplitude on the hysteresis loop at 100kPa of axial stress

Fig 4.3 is drawn by taking the results obtained from cyclic simple shear test of shear stress and shear strain of first cycle of sample from Pit 4 for 100kPa confining pressure. The curves indicate the influence of shear strain on the hysteresis loop. The biggest loop corresponds to 5% shear strain and the smallest loop for 0.01% strain.

4.3.2 Dependency of shear modulus and damping ratio on number of cycle

Fig 4.4 and Fig 4.5 indicate the variation of the values of shear modulus and damping ratio with the number of cycles.

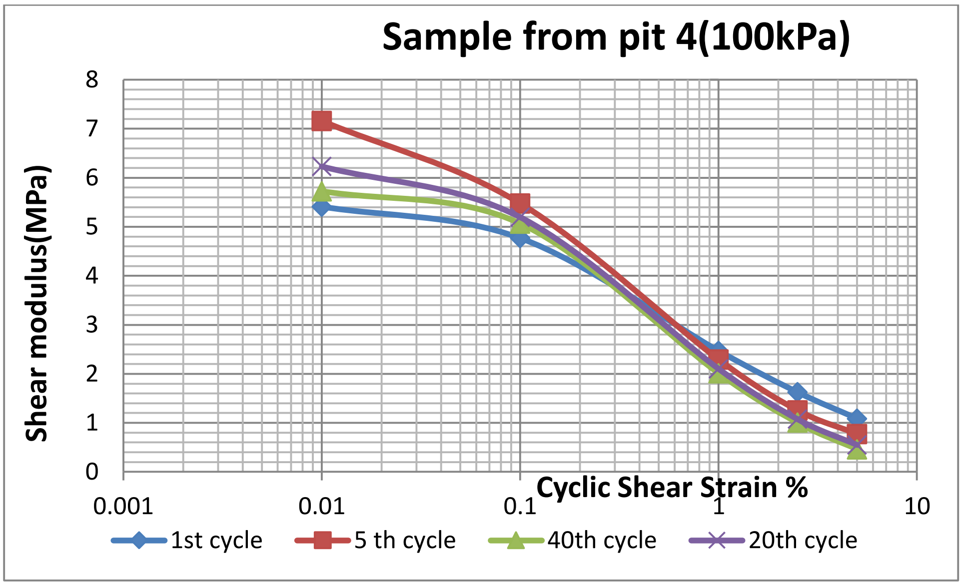


Fig 4.4 Effect of number of cycles on shear modulus of soil

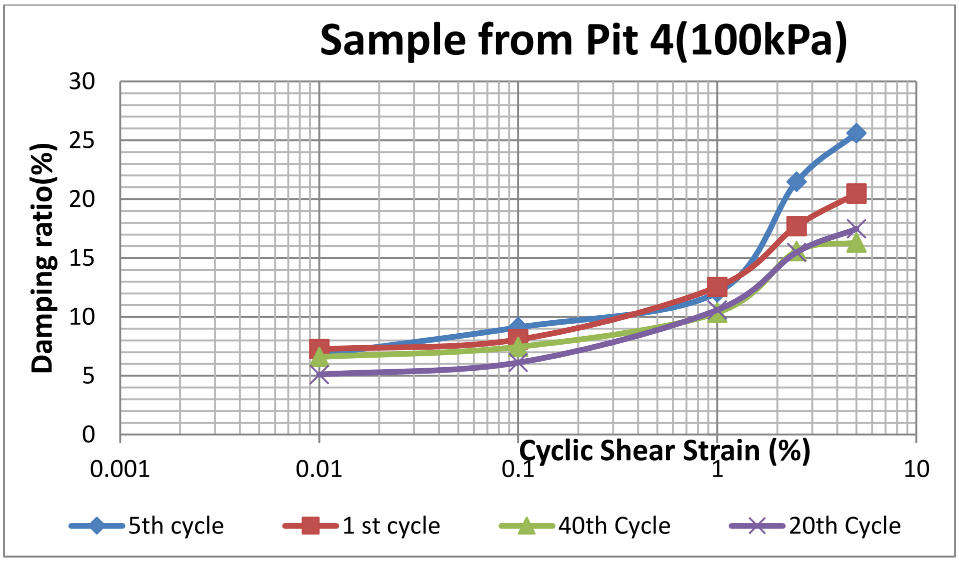


Fig 4.5 Effect of number of cycles on damping ratio of soil

As indicated in Fig 4.4 and Fig 4.5 the variation of both shear modulus and damping ratio for different cycle is almost the same. ASTM D3999 indicates that the values determined at 5th cycle are likely to provide reasonable values for all practical purposes [3]. Thus, in this research the values determined at 5th cycle is considered for analysis purpose.

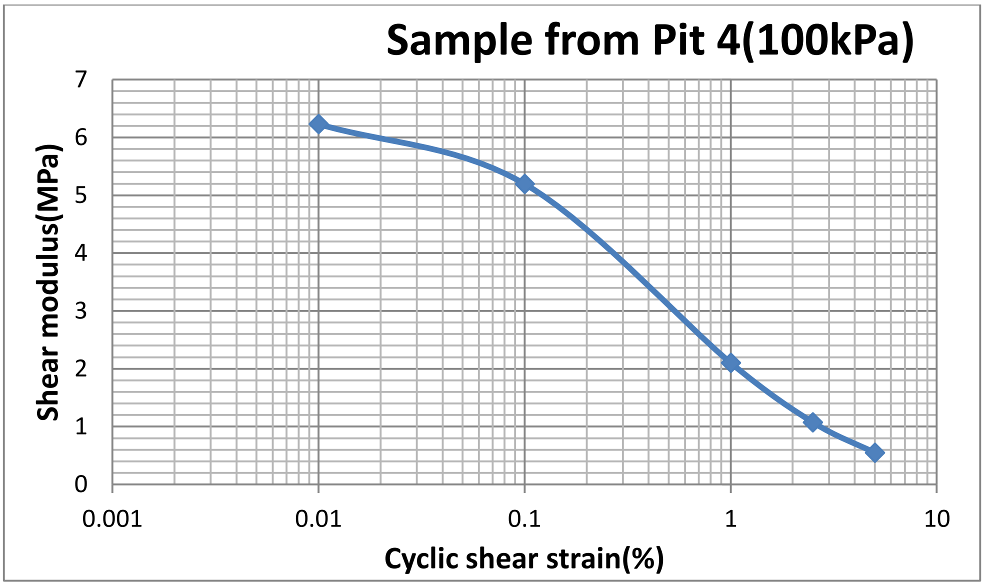
Table 4.6 contains the values of shear modulus and damping ratio of all pits for strain 0.01%, 0.1%, 1%, 2.5% and 5% under axial consolidation pressures of 100kPa, 250kPa and 400kPa.

Table 4.7 values of shear modulus and damping ratio at 5th cycle and their average

Pit 1						
	shear modulus			Damping Ratio		
Axial stress (kN)	100	250	400	100	250	400
Shear strain (%)						
0.01	7.11	9.58	12.54	7.75	5.75	3.06
0.1	3.22	6.67	7.256	11.7	7.31	6.05
1	1.93	3.98	5.3	16.1	11	9.48
2.5	0.72	1.55	2.521	23.1	20.1	17.7
5	0.33	0.62	0.995	26.9	23.7	21.6
Pit 2						
0.01	6.08	10.4	13.81	4.8	4.21	2.17
0.1	4.12	7.9	8.889	10.7	7.02	5.87
1	2.88	3.77	5.79	11.8	9.52	8.15
2.5	1.15	2.1	4.213	17.8	15.8	13.3
5	0.71	1.39	1.931	27.3	22.6	21.2
Pit 3						
0.01	9.43	11.4	12.05	5.5	4.17	2.86
0.1	4.58	8.16	9.026	8.08	6.31	5.44
1	2.59	4.34	5.502	12.3	9.46	9.11
2.5	0.86	2.31	3.13	18.2	14.4	12.3
5	0.46	1	1.665	23.1	18.2	17.3
Pit 4						
0.01	7.16	10.4	14.56	7.25	4.49	1.9
0.1	5.48	6.18	11.26	8.07	7.41	3.05
1	2.29	3.56	5.483	12.5	10.9	10.1
2.5	1.26	2.09	3.381	17.7	17	16.6
5	0.78	1.08	1.413	20.5	20.1	18.5
Average values						
0.01	8.47	11.7	15.21	9.86	6.71	2.89
0.1	4.67	7.94	10.19	11.7	7.47	5.1
1	2.6	4.57	6.172	16.1	10.9	9.21
2.5	1.07	2.22	3.698	23.6	17.2	15
5	0.61	1.12	1.678	29.6	21.1	19.6

4.3.3 Dependency of shear modulus and damping ratio on shear strain amplitude

It is well known that the deformation characteristics of soils are highly non linear and this is manifested by the shear modulus and damping ratio which vary significantly with the amplitude of shear strain under cyclic loading. Fig 4.6 shows the variation of shear modulus and damping ratio with shear strain.



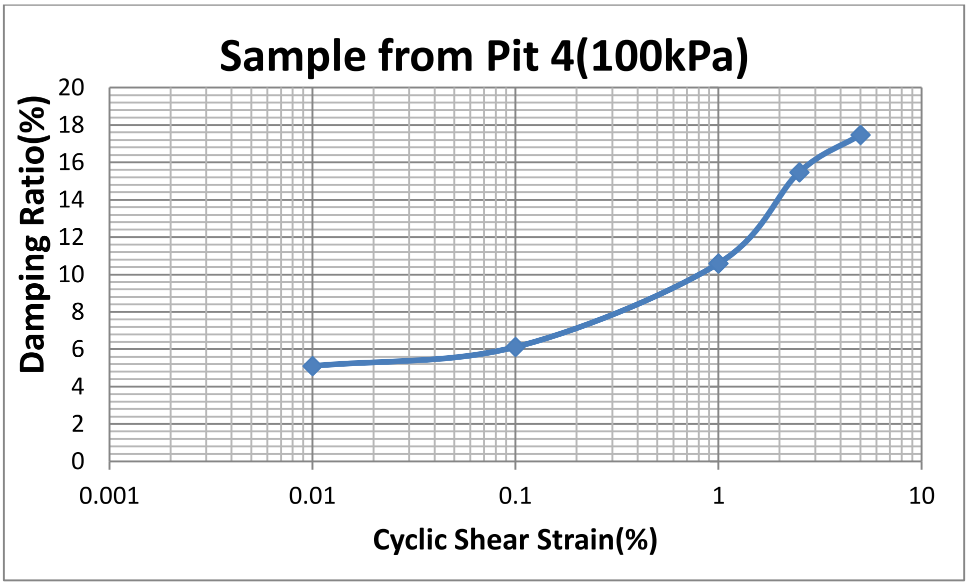
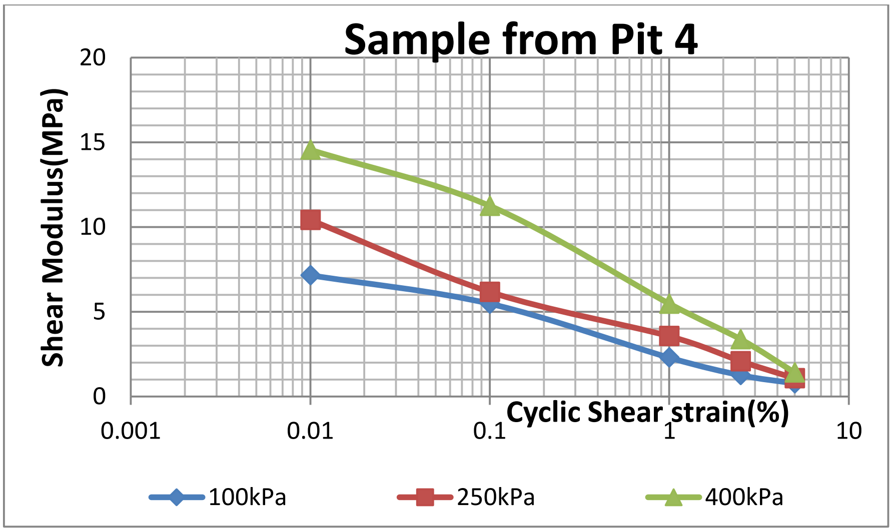


Fig 4.6 Shear modulus and damping ratio versus shear strain for sample of Pit 4 at 100kPa axial stress

4.3.4 Dependency of shear modulus and damping ratio on axial stresses

One of the factors which are expected to influence the values of shear modulus and damping ratio of soils is axial consolidation pressure. Fig 4.7 indicates the influence of axial pressure of 100kPa, 250kPa, 400kPa for strain range from 0.01% to 5%.



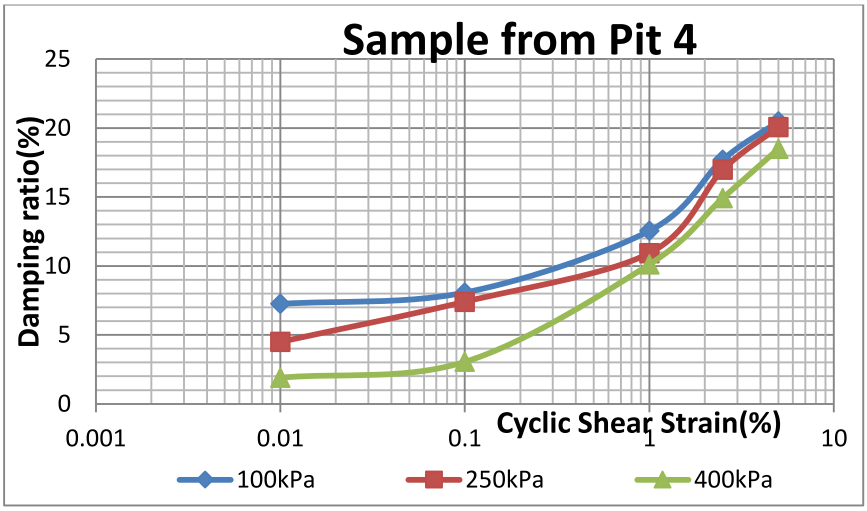
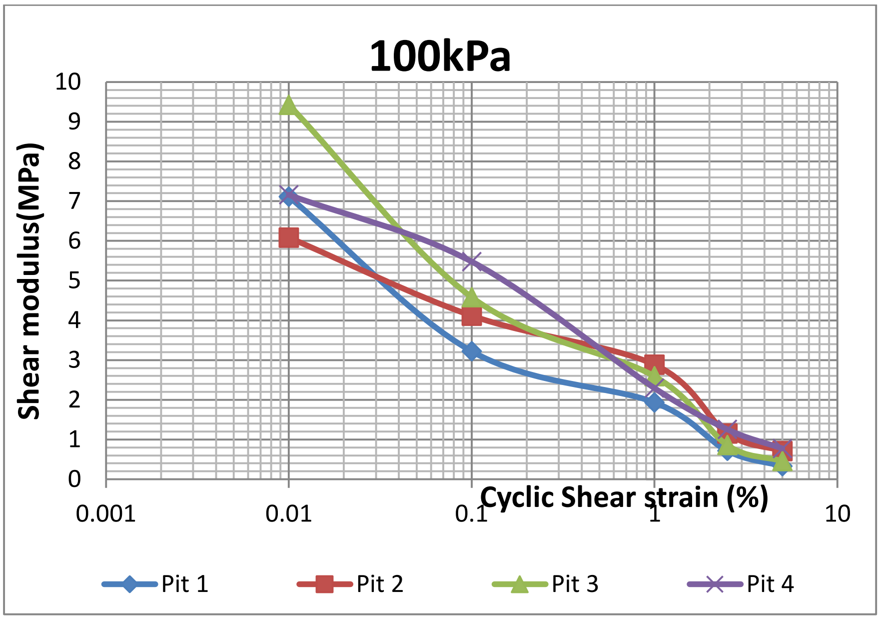


Fig 4.7 Comparison of values of shear modulus and damping ratio with indicated axial stress

4.3.5 Dependency of shear modulus and damping ratio on types of soils

The values of shear modulus and damping ratio are influenced by the physical properties of soils such as plasticity index, void ratio or relative density of soils. Fig 4.8 shows, the values of shear modulus and damping ratio versus shear strain for samples from Pit 1, Pit 2, Pit 3 and Pit 4 at axial consolidation pressure of 100kPa. As indicated in the figure, the curves are almost identical special at higher strain. The PI of sample from Pit 1=10%, Pit 2=11.4%, Pit 3=10.79%, and Pit 4=14.52% in which except sample from Pit 4 others have approximately the same PI value.



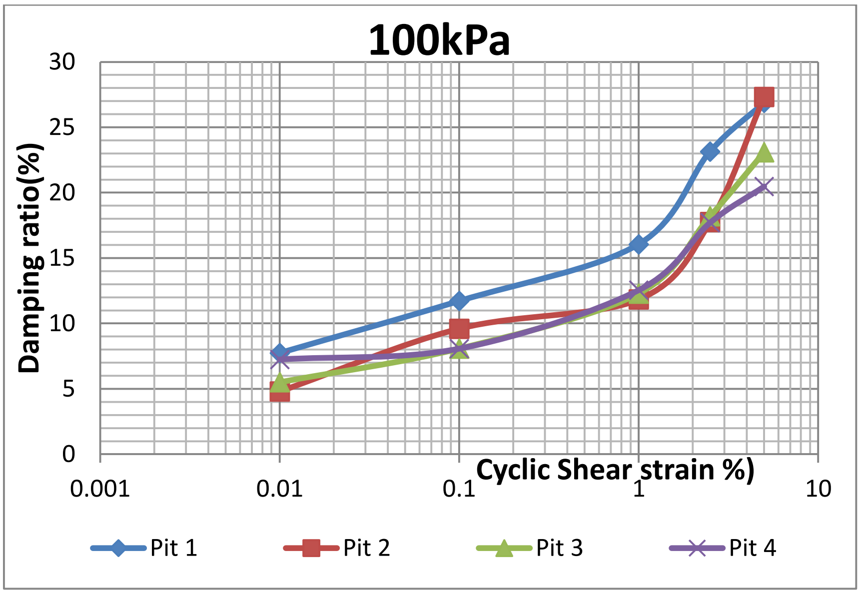
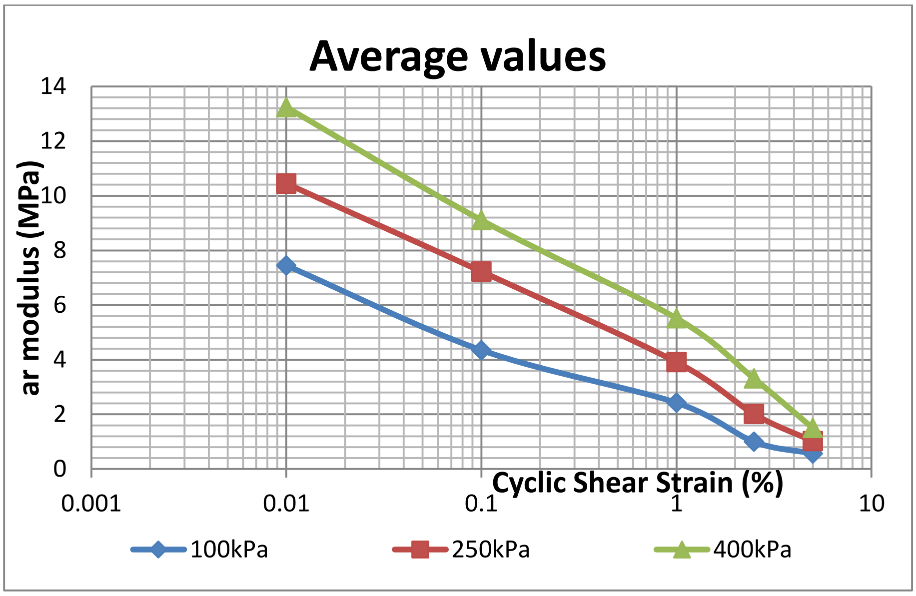


Fig 4.8 Comparisons of values of shear modulus and damping ratio of sample collected from different test pits

From Fig 4.8, on can observes that it is possible to draw average values of shear modulus and damping ratio. Fig 4.9 shows the average values of shear modulus and damping ratio of under axial pressure of 100kPa, 250kPa and 400kPa.



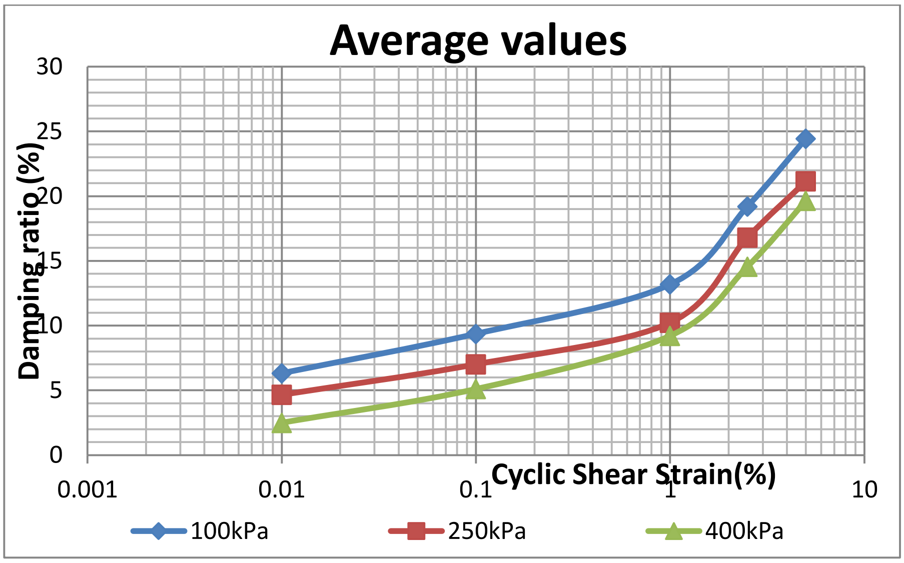


Fig 4.9 Average values of shear modulus and damping ratio soils of four test pits

4.4 DETERMINATION OF INITIAL SHEAR MODULUS

Maximum shear modulus of any type of soil can be determined using equation 4.5 which is derived by Hardin and Drnevich [13].

$$G_{max} = 14760 * \frac{(2.973-e)^2*(OCR)^a*(\sigma'_m)^{1/2}}{1+e} \qquad 4.5$$

Where

$$e = \frac{G*\rho_w}{\rho_d} - 1$$

G = specific gravity

ρ_d = Dry density of soil

ρ_w =Density of water

$$\sigma'_m = \frac{\sigma'_1+\sigma'_2+\sigma'_3}{3}$$

σ'_m = Effective vertical stress

For the condition

$$\sigma'_3 = \sigma'_2$$

$$K_O = \frac{\sigma_3}{\sigma_1}$$

For at rest condition $K_o = 0.5$, σ'_m=2/3*σ'_1

Over consolidation ratio (OCR) for a soils can be defined as [8]

$$OCR = \frac{P_r}{P_o}$$

P_r= Pre-consolidation pressure of a specimen

Dagnachew Debebe has done thesis on investigation into some of the engineering characteristics of soils in Adama town. The samples were taken from test pit 1-5 are similar with the sample used to done this research in both location and depth. Thus the value of pre-consolidation pressure is taken from Dagnachew Debeba laboratory test result, which is equal to 50kPa.

P_o = Present effective vertical pressure

Based on equation 4.5, the values of G_{max} can be calculated and presented in Table 4.8 and summary of the values of G_{max} is presented in Table 4.9.

Table 4.8 Calculation of initial shear modulus

Parameter	symbol	Sample from Pit			
		1	2	3	4
Effective vertical pressure	P_o	100kPa			
Specific gravity	G	2.7	2.61	2.67	2.65
Void ratio	e	1.4	1.5	1.3	1.6
	a	0.09	0.15	0.1	0.14
Over Consolidation Ratio	OCR	0.5	0.5	0.5	0.5
Mean principal effective stress	σ'_m	1392.4	1392.4	1392.4	1392.4
Maximum shear modulus	G_{max}(Pfs)	563,020.1	457,016.9	585,324.50	354,110.70
	G_{max}(kPa)	26,957.40	21,881.97	28,025.33	16,954.82
Effective vertical pressure	P_o	250kPa			
Specific gravity	G	2.7	2.61	2.67	2.65
Void ratio	e	1.4	1.5	1.3	1.6
	a	0.09	0.15	0.1	0.14
Over Consolidation Ratio	OCR	0.2	0.2	0.2	0.2
Mean principal effective stress	σ'_m	3480.9	3480.9	3480.9	3480.9
Maximum shear modulus	G_{max}(Pfs)	819,719.0	657,769.5	846,693.60	501,488.3
	G_{max}(kPa)	39,248.1	31,494.0	40,539.7	24,011.3
Effective vertical pressure	P_o	400kPa			
Specific gravity	G	2.7	2.61	2.67	2.65
Void ratio	e	1.4	1.5	1.3	1.6
	a	0.09	0.15	0.1	0.14
Over Consolidation Ratio	OCR	0.13	0.13	0.13	0.13
Mean principal effective stress	σ'_m	5569.5	5569.5	5569.5	5569.5
Maximum shear modulus	G_{max}(Pfs)	993,909.5	792,849.9	1,023,213.0	599,483.7
	G_{max}(kPa)	47,588.4	37,961.7	48,991.4	28,703.3

Table 4.9 Summary of maximum shear modulus

symbol	Sample from Pit			
	1	2	3	4
P_o	100kPa			
G_{max} (kPa)	26,957.4	21,882	28,025.3	16,954.8
P_o	250kPa			
G_{max} (kPa)	39,248.1	31,494.	40,539.7	24,011.3
P_o	400kPa			
G_{max} (kPa)	47,588.4	37,961.7	48,991.4	28,703.3

Once the values of G_{max} are calculated, one can calculate G/G_{max}. Depending on the values of G/G_{max} and shear strain amplitude, one can draw normalized shear modulus reduction curves to indicate the influence of confining pressure and types of soils (Plasticity index). Fig 4.10 shows that the influence of consolidation pressure while Fig 4.11 shows the influence of plasticity of soils for indicated test pits.

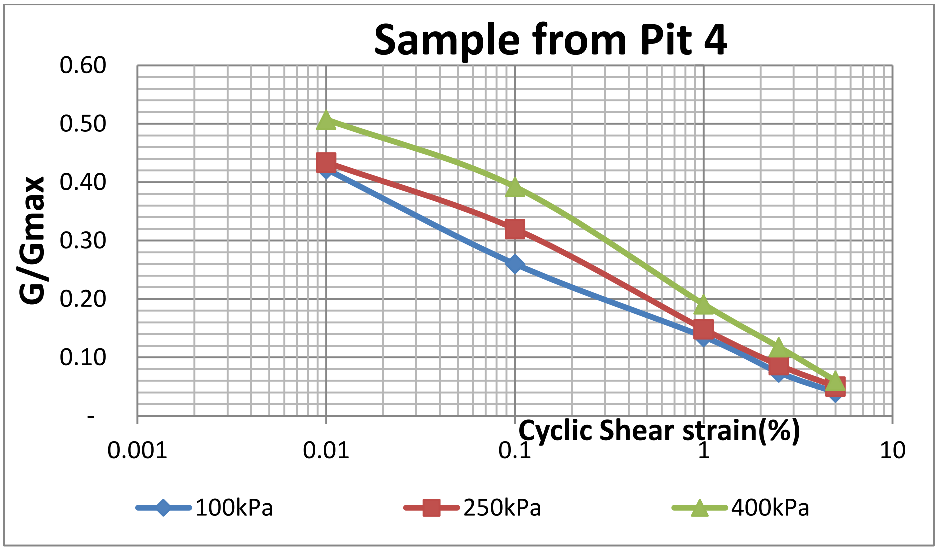


Fig 4.10 G/G_{max} versus shear strain amplitude at axial consolidation pressure of 100kPa, 250kPa and 400kPa

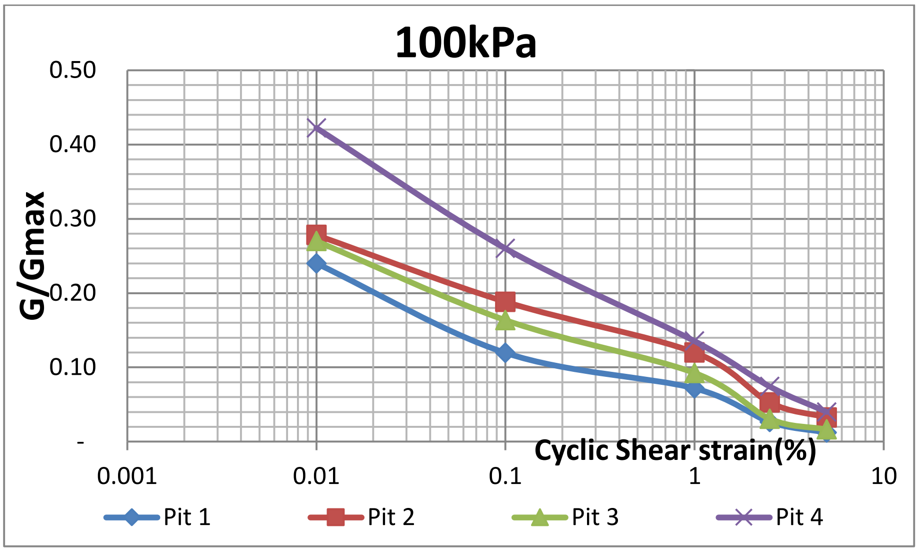


Fig 4.11 G/G_{max} versus shear strain while comparing the values of G/G_{max} for soils of different pits at 100kPa consolidation pressure

As illustrated in Fig 4.11, there is significant difference between curves for sample from Pit 1, Pit 2, Pit 3, and Pit 4 not observed in Fig 4.8.

4.5 COMPARISON OF TEST RESULT WITH PREVIOUS STUDIES

The values of normalized shear modulus and damping ratio are compared with previous report of Seed and Idriss [13]. Fig 4.12 shows the location of values of G/G_{max} of soil for sample from Pit 4 in relation to sandy soil whereas Fig 4.13 shows the values of G/G_{max} in relation to saturated clay soil. These curves are presented by Seed and Idriss [13]

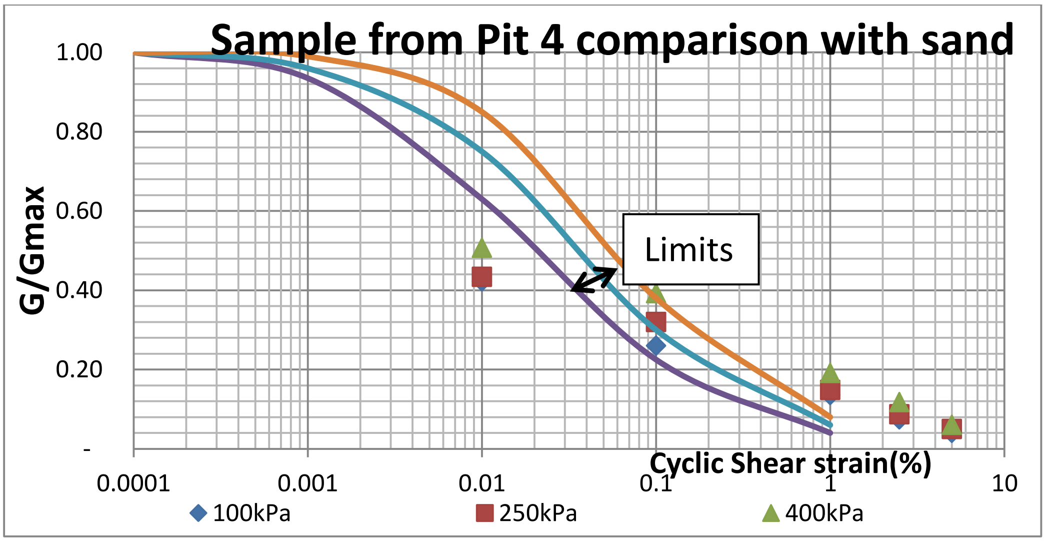


Fig 4.12 Comparison of value of G/G_{max} of sample from Pit 4 with the curves of Seed and Idriss for sand

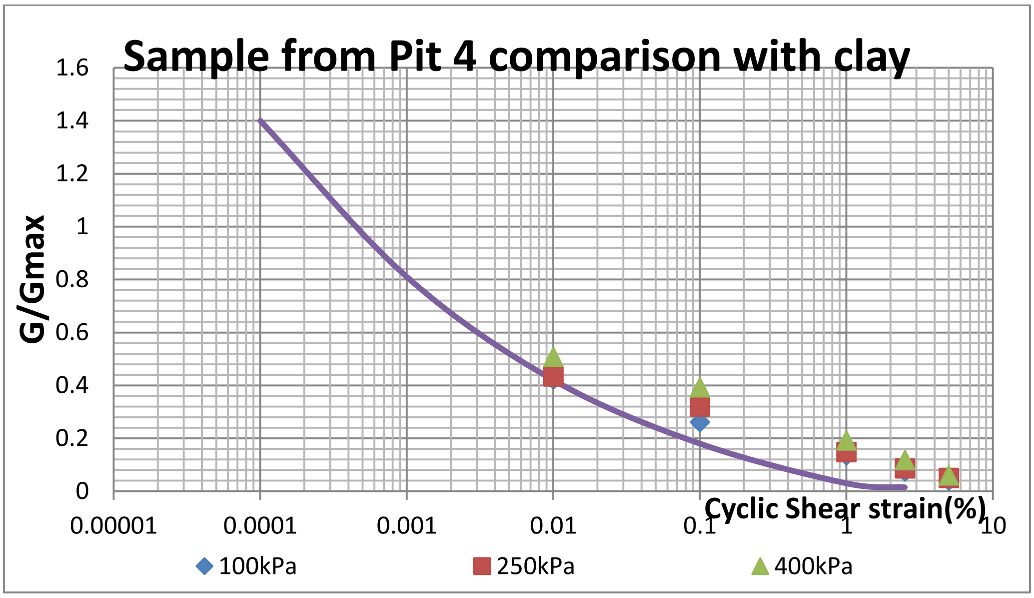


Fig 4.13 Comparison of value of G/G_{max} of sample from Pit 4 with the curves of Seed and Idriss for saturated clay

Fig 4.14 and 4.15 also show the location of values of damping ratio Pit 4 when compared with the curve presented by Seed and Idriss for sand and saturated clay respectively.

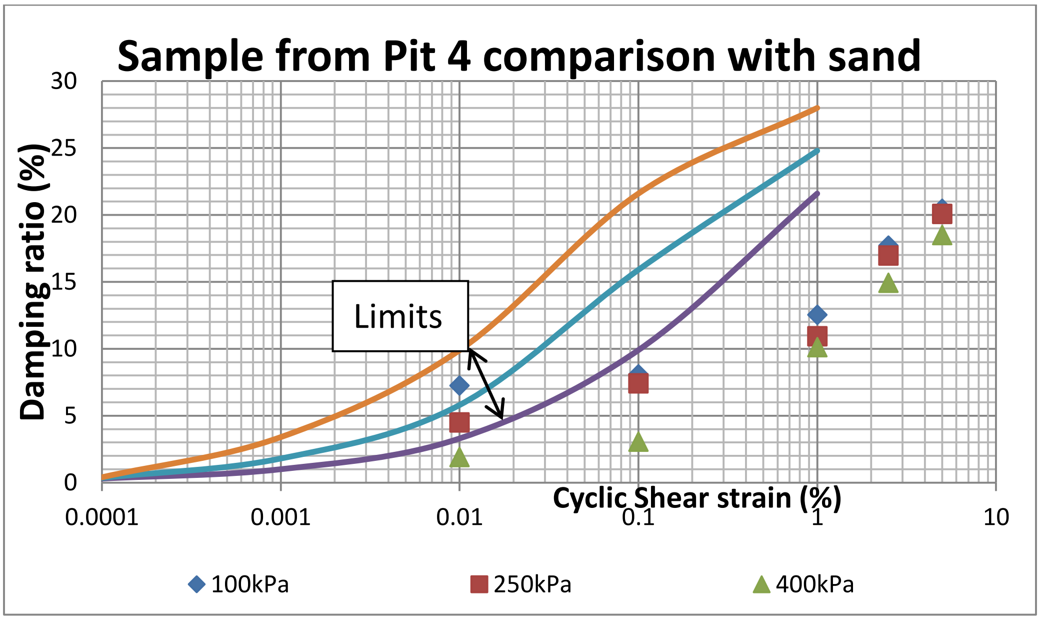


Fig 4.14 Comparison of value of damping ratio of sample from Pit 4 with the curves of Seed and Idriss for sand

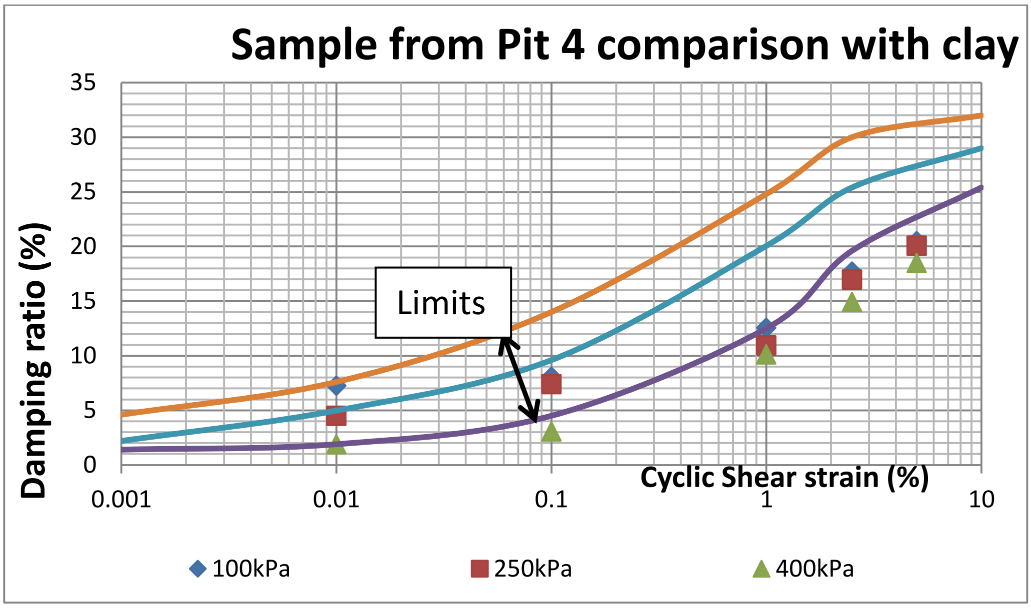


Fig 4.15 Comparison of value of damping ratio of sample from Pit 4 with the curves of Seed and Idriss for saturated clay

CHAPTER FIVE

DISCUSSION OF TEST RESULTS

To identify the effect of different factors which influence the values of both shear modulus and damping ratio, the results were analyzed. These effects are: - number of cycles confining pressure, strain amplitude and soil type (Plasticity index).

5.1 Influence of number of cycle on shear modulus and damping ratio

The test result show that the shear modulus values obtained for specified axial stress at the 5^{th} and 10^{th} cycles differ at most by 20% when the shear strain is minimum(0.01% strain) and the same percentage of difference was noted also in the damping ratio of soils. It was also observed that the effect of the number of cycles disappears when the stress application is repeated for more than 10 cycles. (Fig 4.4 and Fig 4.5)

5.2 Influence of confining pressure on shear modulus and damping ratio

As indicated on Fig 4.7 the values of dynamic properties strongly depend on the values of axial consolidation stresses. The values shear modulus is higher at higher effective axial consolidation stress having the same values of shear strain and vice versa. However, in case of damping ratio of smaller values are obtained at higher values of effective axial consolidation stress.

5.3 Influence of shear strain amplitude on shear modulus and damping ratio

The influence of shear strain amplitude on shear modulus and damping ratio of soils are shown on Fig 4.6. As it observed from the figure the shear modulus tends to decrease as shear strain increases. However, the value of damping ratio increases as shear strain amplitude increases. This is because of at higher values of shear strain the strength of soils is become smaller to resist deformation and more energy is released to yield high deformation.

5.4 Influence of type of soils on shear modulus and damping ratio

As mentioned in previous section the physical properties of soils are one of the factors which influence the values of dynamic property of soils. Especially plasticity index for fine grained soils and relative density for coarse grained soils have significant influence on the values of shear modulus and damping ratio of soil. Fig 4.8 it does not indicate the influence of plasticity index on values of shear modulus but Fig 4.11 shows that the soils which has higher PI, has higher values of G/G_{max}. Based on the both curves, one can expect that there is another factor which influences these values. These factors may be testing condition; complexity to recover the soil samples which are identical to its natural state and the least sensitivity of cyclic simple shear apparatus for lower strain.

5.5 Comparison of the test results with previous studies

Even though the soils obtained from Adama city are silty sand and silty soil, the test results were compared with previous studies made by Seed and Indris [13].

For sand, for the strain greater than and equal to 1%, all measured points of G/G_{max} lay close to the extended curves given by Seed and Idriss. For strain of 0.1%, the measured points of G/G_{max} close to the curve or within boundery. For strain value of 0.01%, the measured points are below the range given by Seed and Idriss. For saturated clay, the measured points of G/G_{max} are close to the curve of Seed and Idriss (Fig 4.12, Fig4.13 and appendix C).

Comparisons were also done for damping ratio values with curves given by Seed and Idriss for sand and saturated clay soils. From these comparisons it is observed that for strain less than 1%, the measured points are located within range of either the curves given for sand or clay soils. For strain greater than and equal to 1% the points lay within range for clay and outside for sand (Fig 4.14 and Fig 4.15 and appendix C).

The values of G/G_{max} and damping ratio obtained by this research, it is observed that there is slightly variation on some measured points from the range given by Seed and Idriss for clay and sand. This variation is occurred due to testing condition and the testing method

The results of this research are also compared with other researches which were done in our country by Abera Bedada on Addis Ababa red brown clay soils of Gulelle area

From the comparison, it is observed that the values of G/G_{max} are less than the values obtained by Abera. The values of damping ratio are higher than the values obtained by Abera for sample from Pit II under axial pressure of 300kPa and 350kPa and lower than the values of Pit I obtained by Abera (Appendix C).

CHAPTER SIX

CONCLUSION AND RECOMMENDATION

6.1 CONCLUSION

Based on the investigations obtained from this research the following conclusions may be drawn.

1. From comparison of shear modulus and damping ratio curves based on consolidation pressure, it is observed that the confining pressure has less influence on the values of shear modulus and damping ratio at 2.5% and 5% strain than smaller strains.
2. The sample collected from test pit 4 has higher values of G/G_{max} and damping ratio than sample of another test pit for strain 0.01% -5%.
3. Based on the comparison with sand; for the strain greater than 1%, all measured points of G/G_{max} lay close to the extended curve given by Seed and Idriss. For stain of 0.1%, the measured points of G/G_{max} close to curve within boundary. For strain value of 0.01%, the measured points are below the curve given by Seed and Idriss. For saturated clay, the measured points are close to the curve of Seed and Idriss.
4. Values of damping ratio obtained for strain less than 1% are located within the range of either the curves given by Seed and Idriss for sand or clay soils. For strain greater than and equal to 1% the points lay within range for clay.
5. Almost all curves illustrated in this research follow the trend of the curves given in available literature.

Based on the comparison of test results of this research with the test result obtained by Abera the following conclusions are made

1. The values of G/G_{max} are lower than the result obtained by Abera at all measured points.
2. The values of damping ratio of this research compared with result obtained by Abera, shows scatter in which some of the points lie above and some points below the curves.

6.2 RECOMMENDATION

In this research an attempt was made to determine the values of shear modulus and damping ratio of soils found in Adama city. Based on this investigation the following recommendations are made:

- ✓ In this research the values of shear modulus and damping ratio are determined at natural moisture content and not at saturation. To compare this test result with previous studies and observe the effect of degree of saturation and other factors which influence their values, the test need to be done by saturating sample.
- ✓ Because of lack of time and resource the samples in this study is collected from four test pits only. A better and comprehensive picture would be obtained if more samples are tested.

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APPENDIX

APPENDIX A

TEST RESULTS OF INDEX PROPERTIES OF SOILS

FIELD DENSITY AND WATER CONTENT OF SOILS

Field Density and Moisture Content

Sample from Pit 1			Sample from Pit 2	
Depth (m) 2.0			Depth (m) 2.5	
Weight of (Wt) mold 406.8 Wt of Mold +soil 816.9			Mass (Wt) mold 461 Wt of Mold +soil 1506.1	
diameter of mold 9.5cm		height 11cm		
Mass (wt) of the specimen(g) 356.1			Mass (wt) of the specimen(g) 1045.1	
Moisture content of soils				
Can No	A8/80	C31/103	D22/A	A17/C2
Wt of can	21.6	21	22	22
Wt of can +Wt of Moist soil(g)	76.5	84.5	75.4	95.4
Wt of can +Wt of dry soil(g)	68	73.8	64	79.3
Wt of Dry soil(g)	46.4	52.8	42	57.3
Wt of pore water (g)	8.5	10.7	11.4	16.1
Water content (%)	18.319	20.265	27.143	28.098
Average water content (%)	19.29		27.62	
Bulk Density (g/cm3)	1.36		1.34	
Dry Density (g/cm3)	1.14		1.05	

Field Density and Moisture Content

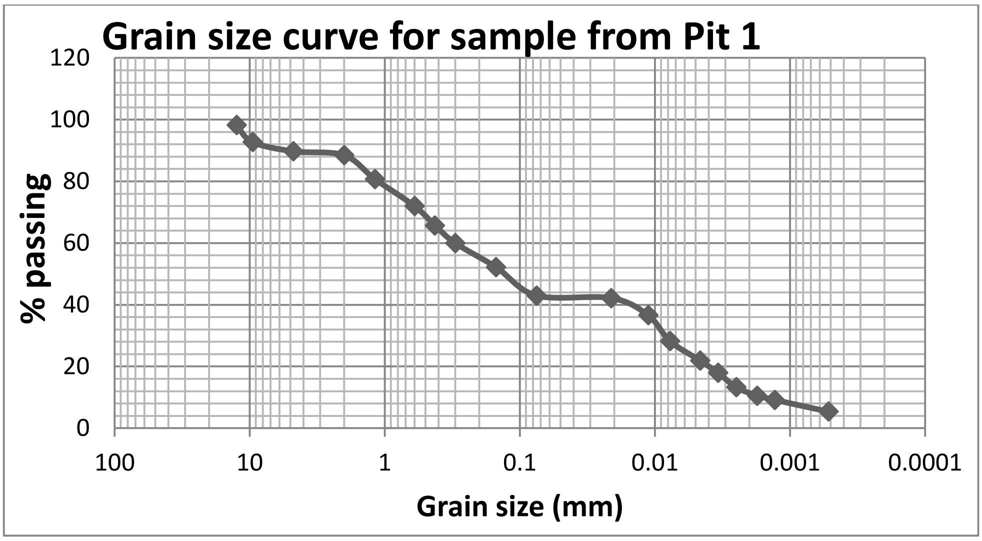
Sample from Pit 4			Sample from Pit 3	
Depth (m) 2.8			Depth (m) 2.7	
Mass (Wt) mould 406.8 Wt of Mould +soil 1506.3			Mass (Wt) mould 461 Wt of Mould +soil 1538.1	
Mass (wt) of the specimen(g) 1045.3			Mass (wt) of the specimen(g) 1077.2	
Moisture content of soils			Moisture content of soils	
Can No	80/A8	A10/16	C15/D9	86
Wt of can	22.4	22.3	21.6	21.9
Wt of can +Wt of Moist soil(g)	70.7	67	62.5	82.5
Wt of can +Wt of dry soil(g)	59.2	55.7	56	71
Wt of Dry soil(g)	36.8	33.4	34.4	49.1
Wt of pore water (g)	11.5	11.3	6.5	11.5
Water content (%)	31.25	33.83	18.90	23.42
Average water content (%)	32.54		21.16	
Bulk Density (g/cm3)	1.340		1.382	
Dry Density (g/cm3)	1.01		1.14	

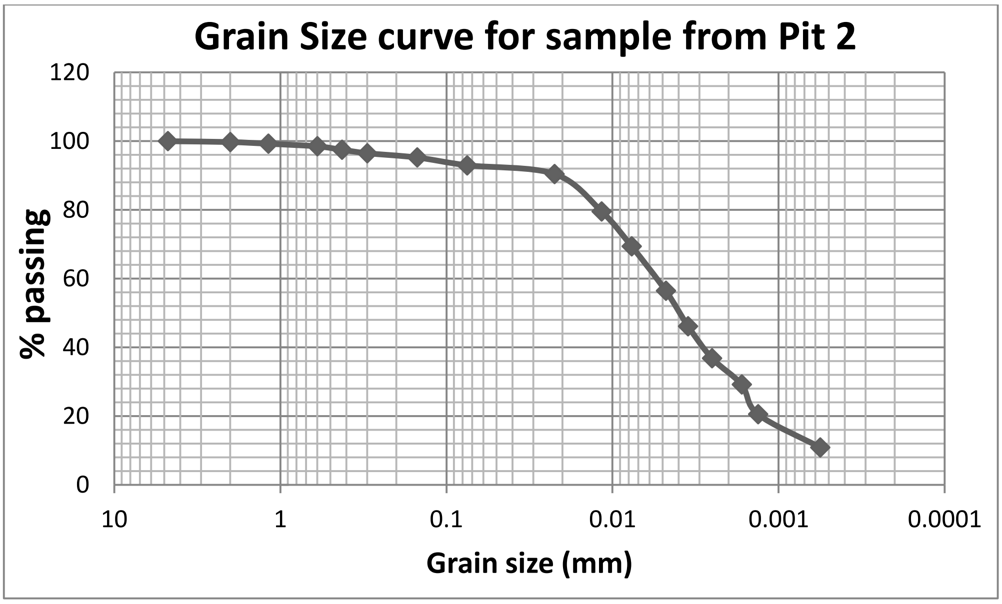
Specific gravity test results for sample from Pit 1, 2, 3 and Pit 4

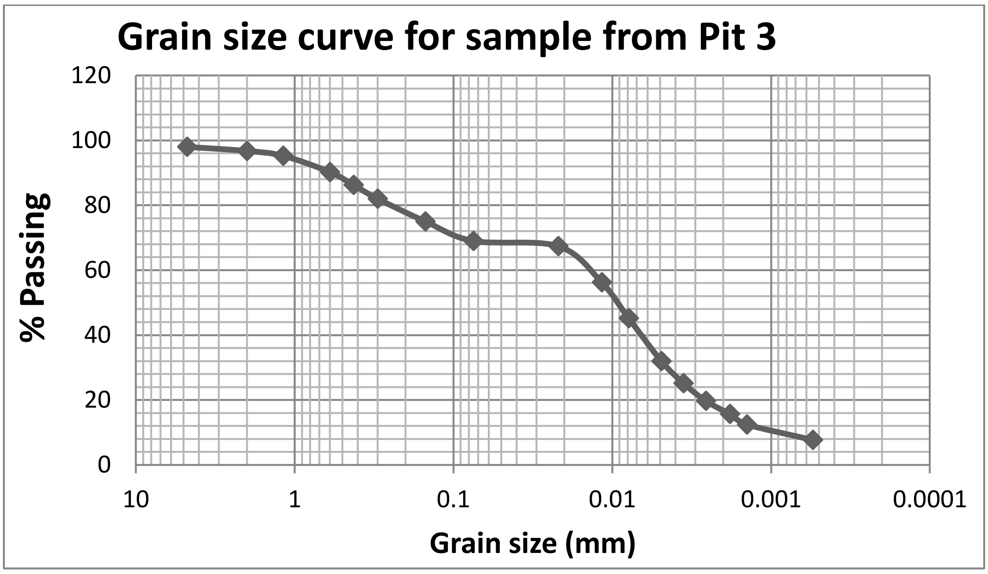
	Sample from Pit 1		Sample from Pit 2	
Trial No	1	2	1	2
Pycnometer No	P52	P2	p13	P10
Weight of dry soil (Ms),g	25	25	25	25
Weight of pycnometer +water + soil (M1),g	165.354	165.082	164.748	163.97
Test temperature ^{0} C	21.7	22.4	21.6	22.3
Weight of pycnometer +water(M2),g	149.678	149.255	149.225	148.613
specific gravity of soil at test temperature (G at T)	2.6813	2.72539	2.637966	2.592554
correction factor, K	0.99966	0.998788	0.99968	0.998991
specific gravity of soil at 20 ^{0}C	2.68	2.722	2.637	2.590
Average specific gravity of soil at 20 ^{0}C	2.70		2.61	

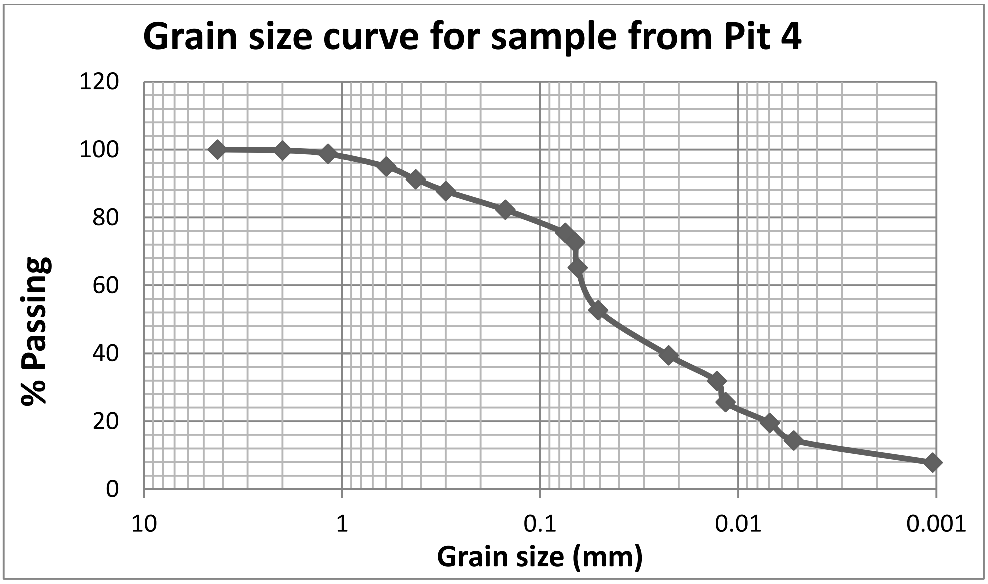
	sample from Pit 3		sample from Pit 4	
Trial No	1	2	1	2
Pycnometer No	PA	P6	P3	P20
Weight of dry soil (Ms),g	25	25	25	25
Weight of pycnometer +water+soil (M1),g	163.951	164.685	163.429	159.261
Test temperature ^{0} C	21.4	22.5	22.4	22.5
Weight of pycnometer +water(M2),g	148.291	149.071	147.895	143.615
specific gravity of soil at test temperature (G at T)	2.677	2.664	2.641	2.673
correction factor, K	0.99972	0.998585	0.998788	0.998585
specific gravity of soil at 20 ^{0}C	2.68	2.66	2.638	2.669
Average specific gravity of soil at 20 ^{0}C	2.67		2.65	

Grain size analysis test result for sample from Pit1, 2, 3, Pit 4

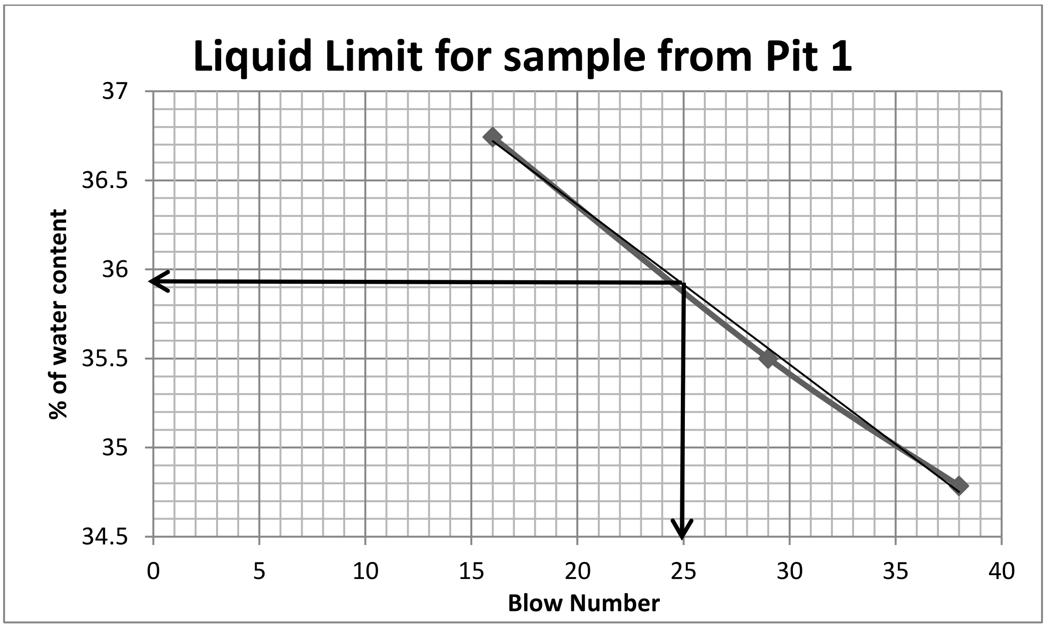


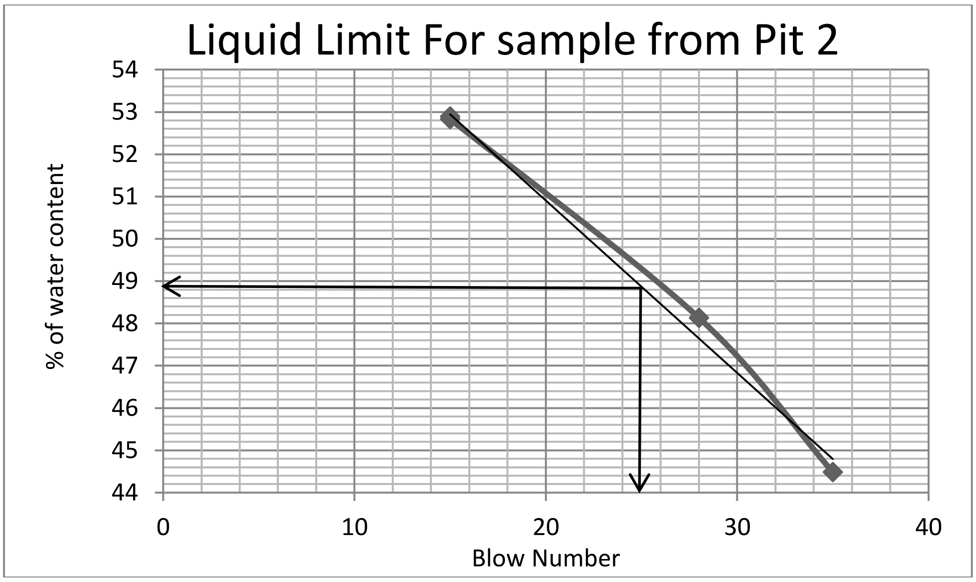


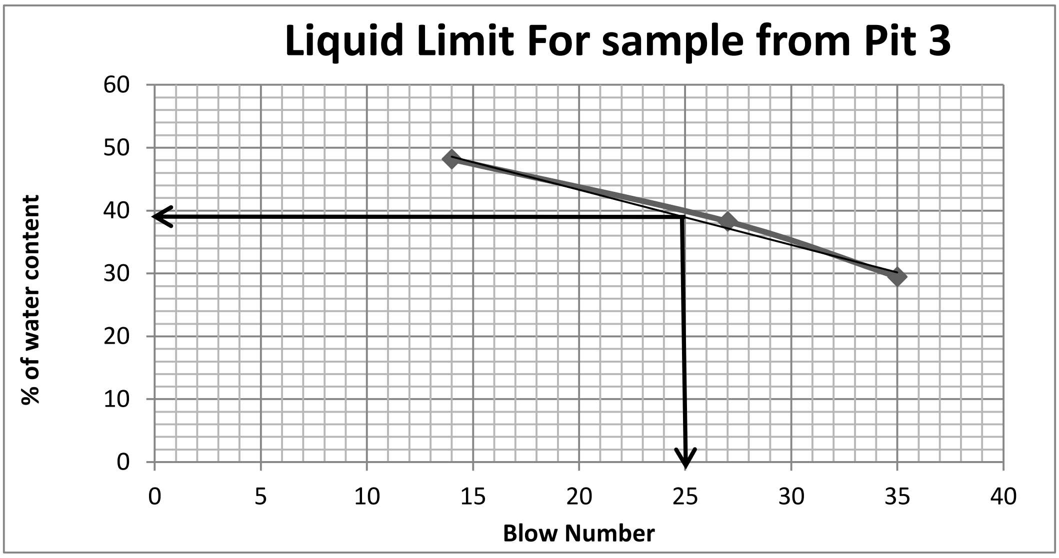

Grain size curve for sample from Pit 3
120
100
80
60
40
20
0
% Passing
10
1
0.1
0.01
0.001
0.0001
Grain size (mm)

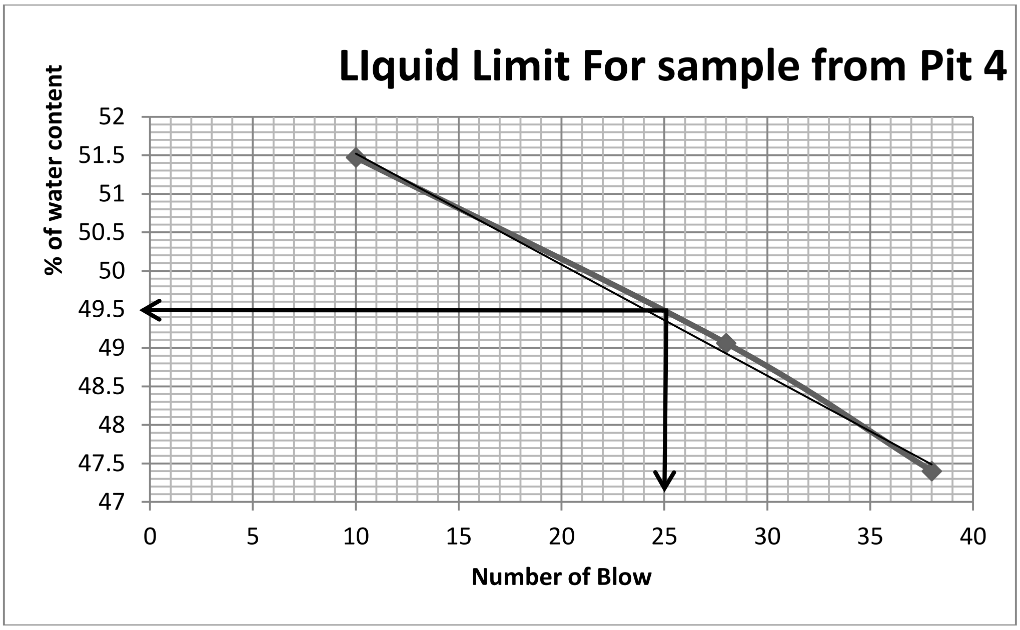

Grain size curve for sample from Pit 4
120
100
80
60
40
20
0
% Passing
10
1
0.1
0.01
0.001
Grain size (mm)

Atterberg's limit -test results for sample from Pit1, 2, 3 and Pit 4

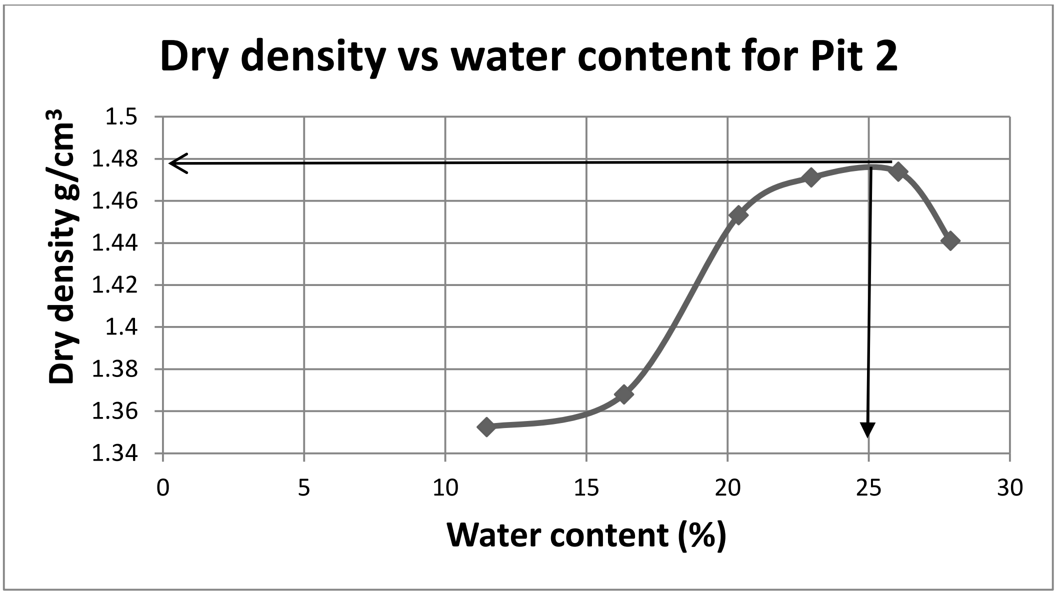


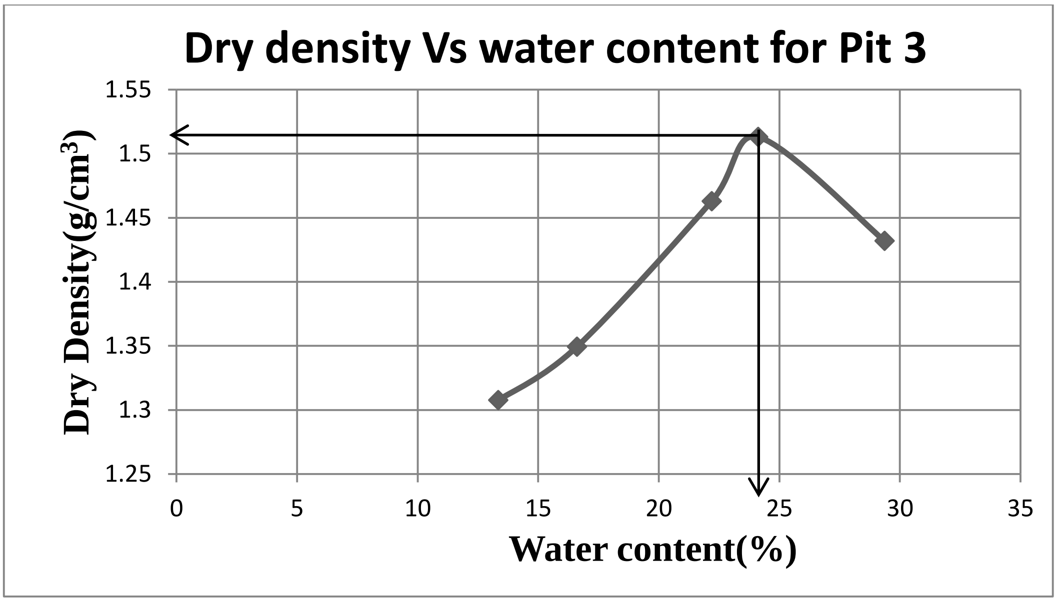


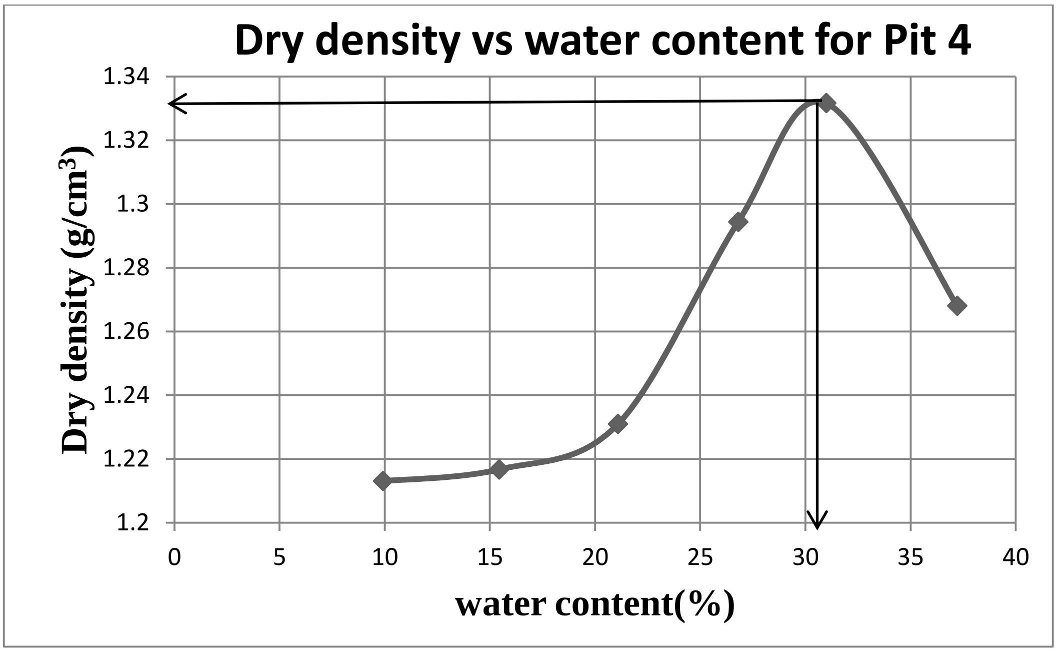

Liquid Limit For sample from Pit 3
% of water content
60
50
40
30
20
10
0
0
5
10
15
20
25
30
35
40
Blow Number


LIquid Limit For sample from Pit 4
% of water content
52
51.5
51
50.5
50
49.5
49
48.5
48
47.5
47
0
5
10
15
20
25
30
35
40
Number of Blow

Compaction test results for sample from Pit 2, 3, Pit 4






Dry density vs water content for Pit 4
Dry density (g/cm3)
1.34
1.32
1.3
1.28
1.26
1.24
1.22
1.2
0
5
10
15
20
25
30
35
40
water content(%)

APPENDIX B Values of shear modulus and damping ratio

Pit 1	Shear modulus for 100kPa						Damping ratio for 100kPa				
Strain (%)	0.01	0.1	1	2.5	5		0.01	0.1	1	2.5	5
No of cycle											
1	4.89	2.923	2.17	1.25	0.64		7.97	13.36	15.67	23.43	39.52
2	7.66	3.041	2.12	1	0.44		7.67	13.11	16.16	22.58	32.13
3	5.72	3.123	2.04	0.9	0.38		7.69	11.43	15.1	21.37	29.56
4	8.01	3.21	1.97	0.85	0.35		7.38	11.29	14.6	21.35	27.51
5	7.11	3.222	1.93	0.72	0.33		7.75	11.72	16.06	23.15	26.89
6	9.79	3.087	1.89	0.67	0.31		2.6	11.8	14.18	24.02	26.43
7	7.08	3.323	1.86	0.67	0.3		5.81	8.563	14.28	23.25	26.05
8	7.41	3.16	1.82	0.67	0.29		7.39	11.34	14.07	22.54	25.57
9	7.34	3.111	1.8	0.66	0.27		7.55	10.84	14.09	22.3	25.71
10	5.83	3.211	1.77	0.65	0.27		7.88	11.14	13.85	22.83	24.89
11	6.46	3.148	1.75	0.67	0.26		8.46	12.18	13.71	21.62	24.93
12	5.46	3.301	1.74	0.67	0.25		7.84	8.771	13.77	19.56	25.19
13	5.63	3.161	1.72	0.65	0.24		3.74	10.97	13.75	20.6	25.03
14	5.43	3.185	1.71	0.64	0.24		4.81	10.34	13.67	20.78	24.58
15	5.36	3.216	1.69	0.63	0.24		5.66	11.51	13.54	20.58	24.4
16	5.54	3.08	1.68	0.62	0.23		5.01	11.05	13.9	21	24.34
17	5.69	3.288	1.66	0.62	0.23		6.42	9.758	13.52	20.52	24.72
18	5.39	3.262	1.65	0.61	0.22		6.63	10.44	13.8	20.77	23.94
19	5.42	3.225	1.64	0.61	0.22		6.61	11.33	13.41	20.68	24.06
20	5.34	3.119	1.64	0.6	0.22		6.59	10.6	13.54	20.65	23.78
21	5.61	3.281	1.62	0.6	0.22		5.87	9.728	13.4	20.88	23.93
22	5.35	3.234	1.62	0.59	0.21		5.47	10.2	13.53	20.44	23.88
23	5.35	3.183	1.61	0.59	0.21		5.89	11.19	13.26	20.3	23.88
24	5.11	3.12	1.6	0.58	0.21		4.99	10.64	13.6	20.3	23.4
25	5.11	3.266	1.59	0.59	0.2		5.87	9.881	13.3	19.78	23.79
26	5.03	3.191	1.58	0.58	0.2		5.36	9.385	13.36	20.06	23.66
27	5.02	3.173	1.58	0.58	0.2		6.07	11.51	13.36	19.8	24.03
28	4.87	3.117	1.57	0.57	0.2		5.3	10.54	13.47	19.66	23.47
29	4.85	3.251	1.57	0.57	0.19		5.56	10.94	13.34	19.66	23.77
30	4.69	3.144	1.56	0.57	0.19		5.25	10.37	13.43	19.84	23.81
31	4.66	3.269	1.56	0.56	0.19		5.24	9.696	13.3	19.82	23.47
32	4.63	3.227	1.55	0.56	0.19		5.07	9.608	13.41	19.7	23.52
33	4.54	3.201	1.55	0.56	0.19		4.88	11.83	13.35	19.65	23.28
34	4.45	3.116	1.54	0.55	0.18		4.83	11.2	13.28	19.31	24.2
35	4.37	3.295	1.54	0.55	0.18		4.86	8.925	13.34	19.93	23.3
36	4.27	3.25	1.53	0.55	0.18		4.72	9.75	13.28	19.17	22.14

37	4.18	3.181	1.53	0.55	0.17		5.06	12.05	13.4	19.61	23.22
38	4.06	3.094	1.53	0.55	0.17		5.19	10.99	13.2	19.25	23.81
39	3.99	3.297	1.52	0.54	0.17		5.19	8.83	13.31	19.36	22.92
40	3.92	3.216	1.51	0.54	0.17		5.25	10.2	13.18	19.35	22.87

Pit 1	Shear modulus for 250kPa						Damping ratio for 250kPa				
Strain (%)	0.01	0.1	1	2.5	5		0.01	0.1	1	2.5	5
No of cycle											
1	8.76	5.95	4.45	2.74	1.38		5.61	3.73	7.66	21.45	34.31
2	9.46	6.66	4.27	2.01	0.89		9.89	10.1	11.6	23.45	28.5
3	8.83	6.55	4.17	1.76	0.73		5.75	8.03	11	21.17	27.25
4	9.7	6.59	4.1	1.64	0.7		12.8	7.27	11	20.87	24.15
5	9.58	6.67	4.03	1.55	0.62		5.75	7.31	11	20.06	23.71
6	9.42	6.55	3.98	1.49	0.59		7.43	7.14	10.3	19.51	22.27
7	9.46	6.64	3.93	1.43	0.58		7.66	7.27	11	19.21	21.51
8	8.82	6.64	3.88	1.4	0.56		8.6	7.19	9.87	18.74	21.66
9	8.45	6.67	3.85	1.37	0.53		12.1	6.96	10.8	18.42	21.57
10	8.33	6.64	3.81	1.35	0.51		9.37	7.15	9.56	17.97	21.33
11	8.32	6.65	3.78	1.33	0.5		9.16	7.05	10.5	17.19	21.2
12	8.18	6.68	3.75	1.31	0.49		8.91	7.21	9.32	17.09	20.92
13	8.16	6.67	3.73	1.28	0.47		9	6.97	10.1	16.35	20.81
14	8.32	6.64	3.7	1.27	0.46		8.6	7.09	8.93	16.56	20.76
15	8.24	6.7	3.68	1.21	0.45		8.4	6.95	9.86	16.19	20.92
16	8.39	6.67	3.65	1.23	0.44		8.5	7.06	10.8	17.13	20.6
17	8.3	6.62	3.64	1.17	0.43		8.67	6.97	9.58	15.69	20.78
18	8.37	6.77	3.62	1.18	0.43		7.9	6.99	10.4	17.26	20.37
19	8.41	6.64	3.6	1.11	0.42		7.58	6.91	9.46	16.12	20.5
20	8.35	6.64	3.58	1.16	0.41		7.72	7.1	10.3	17.11	20.36
21	8.48	6.7	3.57	1.07	0.41		8.1	6.77	9.13	16.43	20.39
22	8.56	6.67	3.56	1.12	0.4		7.82	6.89	9.95	16.67	20.24
23	8.47	6.63	3.54	1.08	0.4		7.44	6.81	8.91	16.11	20.2
24	8.46	6.62	3.52	1.12	0.4		7.26	6.98	9.76	16.84	20.05
25	8.45	6.72	3.52	1.04	0.39		7.61	7.05	8.58	16.19	20.38
26	8.4	6.65	3.49	1.07	0.39		7.16	6.96	10.6	16.17	20.2
27	8.46	6.72	3.49	1.05	0.38		6.94	6.79	10.6	16.09	19.78
28	8.39	6.69	3.47	1.08	0.38		6.9	6.73	9.39	16.13	19.91
29	8.44	6.71	3.46	1.03	0.38		7.03	6.79	10.2	16.13	19.65
30	8.5	6.73	3.45	1.03	0.37		7.02	7.05	9.09	16.09	20.01
31	8.41	6.67	3.44	1.01	0.37		6.42	6.66	10.1	16.26	19.6
32	8.5	6.59	3.43	1.01	0.36		6.75	7.05	8.88	16	19.88

33	8.48	6.66	3.42	1	0.36		6.77	6.92	9.77	16.2	19.83
34	8.51	6.69	3.41	0.99	0.36		6.77	7.07	8.56	16.15	20
35	8.6	6.62	3.4	0.98	0.35		6.63	6.76	9.66	16.24	19.68
36	8.45	6.68	3.39	0.97	0.35		6.64	6.74	8.52	16.42	18.02
37	8.42	6.67	3.38	0.97	0.35		6.6	6.82	9.35	16.63	20
38	8.46	6.71	3.38	0.97	0.35		6.44	6.88	10.3	16.15	19.34
39	8.48	6.7	3.37	0.98	0.34		6.5	6.82	9.16	16.96	19.72
40	8.41	6.62	3.36	0.97	0.34		6.32	6.94	10.2	16.21	19.27

Pit 1	Shear modulus for 400kPa						Damping ratio for 400kPa				
Strain (%)	0.01	0.1	1	2.5	5		0.01	0.1	1	2.5	5
No of cycle											
1	10.99	6.31	5.76	3.72	2.01		8.25	4.76	8.1	20.21	28.71
2	12.52	7.55	5.62	3.18	1.44		0.94	8.94	10.7	17.01	25.28
3	13.89	7.23	5.49	2.87	1.22		14.7	7.17	9.69	18.19	23.09
4	11.73	7.17	5.39	2.66	1.1		2.01	6.49	9.51	17.98	21.72
5	12.54	7.26	5.3	2.52	0.99		3.06	6.05	9.48	17.69	21.61
6	10.82	7.1	5.23	2.4	0.92		6.34	6.74	9.06	17.68	21.31
7	12.97	7.16	5.16	2.31	0.86		11.1	6.35	9.26	17.38	21.12
8	12.14	7.16	5.11	2.22	0.81		4.52	6.71	8.66	17.42	21.03
9	11.6	7.2	5.07	2.16	0.77		1.24	6.37	8.91	17.24	20.96
10	10.91	7.19	5.02	2.1	0.74		4.33	6.84	8.45	17.22	20.91
11	9.832	7.18	4.99	2.03	0.7		11.5	6.48	8.81	17.4	20.92
12	12.82	7.25	4.96	1.99	0.68		7.61	6.8	8.18	16.92	21.52
13	11.61	7.32	4.94	1.95	0.66		3.75	6.61	8.57	17.04	21.17
14	11.65	7.18	4.9	1.91	0.64		2.15	6.95	8.06	16.83	21.04
15	11.03	7.15	4.88	1.87	0.62		4.04	6.76	8.5	16.95	21.32
16	9.675	7.22	4.87	1.83	0.61		7.87	6.11	8.89	17.02	20.8
17	12.4	7.28	4.84	1.81	0.61		8.9	6.74	8.3	16.7	21.02
18	11.69	7.29	4.81	1.79	0.57		4.29	6.3	8.83	16.67	20.86
19	11.66	7.24	4.79	1.76	0.57		4.72	6.88	8.24	16.6	21.37
20	11.7	7.26	4.79	1.74	0.57		4.89	6.33	8.69	16.45	20.21
21	11.07	7.22	4.77	1.72	0.56		6.03	6.72	8.04	16.4	20.43
22	11.59	7.19	4.75	1.7	0.53		4.95	6.57	8.62	16.3	22.11
23	10.3	7.16	4.73	1.68	0.54		7.08	6.77	7.96	16.31	22.32
24	9.91	7.19	4.72	1.67	0.54		10.7	6.37	8.43	16.03	20.94
25	9.8	7.22	4.71	1.65	0.53		7.97	6.87	7.77	16.07	21.39
26	9.554	7.09	4.68	1.64	0.54		7.54	6.53	8.82	15.86	20.37
27	9.384	7.1	4.68	1.63	0.53		7.97	6.35	8.82	16.23	20.74
28	9.398	7.25	4.67	1.61	0.51		7.71	6.46	8.15	15.79	20.87
29	9.38	7.17	4.66	1.61	0.5		7.78	6.16	8.71	15.79	21.23
30	9.192	7.15	4.65	1.59	0.5		7.85	6.6	8.11	15.4	21.96

31	9.317	7.19	4.64	1.58	0.5		8.28	6.43	8.64	15.62	20.36
32	9.244	7.25	4.62	1.57	0.49		7.87	6.71	7.91	15.16	20.84
33	9.088	7.24	4.61	1.57	0.49		7.63	6.36	8.56	15.31	19.71
34	9.141	7.17	4.6	1.55	0.48		7.71	6.86	7.87	14.91	21.02
35	9.153	7.18	4.6	1.55	0.48		8.02	6.69	8.47	15.11	20.74
36	9.022	7.21	4.59	1.53	0.48		7.89	6.63	7.65	14.72	20.17
37	8.927	7.28	4.58	1.52	0.46		7.76	6.47	8.32	14.96	22.11
38	8.984	7.2	4.57	1.51	0.47		7.75	6.13	8.75	15.09	20.03
39	8.913	7.14	4.56	1.49	0.46		8.16	6.81	8.2	14.95	20.68
40	8.861	7.2	4.56	1.49	0.46		7.73	6.05	8.62	14.99	20.37

Pit 2	Shear modulus for 100kPa						Damping ratio for 100kPa				
Strain (%)	0.01	0.1	1	2.5	5		0.01	0.1	1	2.5	5
No of cycle											
1	7.2	4.098	3.07	1.56	0.95		5.44	8.933	9.60	22.05	32.21
2	7.41	4.291	3.01	1.37	0.84		5.6	10.22	12.42	20.66	28.83
3	8.18	4.179	2.95	1.26	0.78		5.26	9.418	11.85	19.26	28.49
4	7.4	4.206	2.92	1.2	0.74		3.92	10.1	11.81	17.97	28.63
5	7.3	4.118	2.88	1.15	0.71		4.8	10.67	11.84	17.76	27.32
6	7.63	4.155	2.86	1.13	0.68		5.51	9.254	11.75	17.58	27.99
7	7.84	4.247	2.84	1.09	0.67		6.92	9.76	11.9	17.08	27.9
8	7.65	4.19	2.83	1.08	0.66		5.62	8.96	11.43	17.26	27.24
9	7.72	4.138	2.8	1.04	0.63		6.48	9.667	11.61	17.42	27.76
10	7.69	4.16	2.8	1.04	0.65		5.73	9.988	11.24	17.11	26.69
11	7.7	4.17	2.78	1.01	0.62		6.29	8.866	11.69	17.06	26.72
12	7.4	4.224	2.77	1.01	0.62		7.11	9.464	10.87	17.15	26.59
13	7.29	4.195	2.76	0.98	0.61		8.09	8.747	11.51	17.38	26.72
14	7.42	4.213	2.75	0.99	0.6		7.52	9.397	10.59	16.73	26.31
15	7.28	4.106	2.74	0.98	0.58		7.43	9.503	11.28	16.35	26.87
16	7.13	4.171	2.73	0.97	0.6		7.2	9.273	10.14	16.29	26.55
17	7.04	4.134	2.73	0.99	0.58		7.1	9.758	11.04	16.35	25.8
18	7.12	4.198	2.72	0.97	0.58		7.05	9.011	11.51	16.89	25.61
19	6.95	4.171	2.72	0.96	0.58		6.94	9.17	10.86	16.4	25.57
20	6.95	4.168	2.71	0.97	0.57		6.67	8.614	11.42	16.76	25.14
21	6.95	4.16	2.71	0.96	0.57		6.97	9.713	10.75	16.23	24.58
22	6.86	4.175	2.7	0.97	0.57		6.66	8.796	11.35	16.38	24.97
23	6.89	4.168	2.69	0.95	0.56		6.64	9.148	10.34	16.6	25.02
24	6.87	4.142	2.69	0.97	0.55		6.7	9.573	11.19	16.63	24.82
25	6.89	4.151	2.68	0.94	0.55		6.88	9.084	10.24	16.7	25
26	6.74	4.063	2.68	0.95	0.55		6.57	9.312	9.895	16.23	24.74
27	6.72	4.146	2.68	0.96	0.55		6.51	8.811	9.895	16.48	24.91
28	6.81	4.178	2.67	0.94	0.54		6.82	9.525	10.79	16.75	25.06

29	6.67	4.17	2.66	0.93	0.54		6.72	8.782	11.37	16.75	24.67
30	6.64	4.099	2.67	0.94	0.54		6.71	9.506	10.74	16.29	24.35
31	6.63	4.09	2.66	0.94	0.54		6.93	9.289	11.17	16.08	24.93
32	6.55	4.172	2.66	0.93	0.53		6.53	8.678	10.51	16.36	24.47
33	6.49	4.147	2.65	0.95	0.55		6.79	9.986	11.24	15.78	23.79
34	6.43	4.14	2.65	0.92	0.55		7.43	8.825	10.33	16.56	23.88
35	6.42	4.119	2.64	0.92	0.53		7.08	9.338	11.07	16.25	24.12
36	6.34	4.211	2.64	0.92	0.54		7.05	9.131	10.11	16.37	22.55
37	6.23	4.187	2.64	0.91	0.54		7.05	9.419	11.03	16.54	23.22
38	6.22	4.153	2.63	0.94	0.54		7.51	8.622	9.931	15.56	23.93
39	6.11	4.114	2.64	0.91	0.52		7.45	9.249	10.77	16.59	23.72
40	6.06	4.194	2.62	0.92	0.53		7.42	8.98	11.21	16.03	23.87

Pit 2	Shear modulus for 250kPa						Damping ratio for 250kPa				
Strain (%)	0.01	0.1	1	2.5	5		0.01	0.1	1	2.5	5
No of cycle											
1	10.4	6.02	4.07	2.43	1.89		2.68	7.54	9.04	20.34	24.24
2	11.5	7.14	3.97	2.19	1.63		6.04	11.1	9.78	15.45	23.74
3	11.8	7.55	3.89	2.16	1.51		4.4	8.56	9.57	15.09	22.83
4	11.3	7.75	3.83	2.11	1.45		4.49	7.18	9.18	15.59	22.24
5	10.4	7.9	3.8	2.1	1.39		4.21	7.02	9.52	15.82	22.63
6	11.1	7.9	3.77	2.09	1.37		4.84	6.82	9.21	15.68	21.56
7	11.6	8.25	3.75	2.07	1.34		5.35	6.6	9.33	16.28	22.01
8	9.81	8.11	3.73	2.07	1.32		4.27	6.54	9.08	15.74	21.23
9	11.5	8.05	3.72	2.06	1.29		3.61	6.54	9.26	16.07	21.52
10	11.3	7.99	3.71	2.05	1.28		4.05	6.51	8.99	15.5	21.35
11	11.4	8.17	3.7	2.05	1.26		6.18	6.48	9.19	16.05	21.5
12	11.2	8.06	3.69	2.05	1.24		5.77	6.32	8.85	15.57	21.49
13	11.5	7.96	3.68	2.04	1.23		5.05	6.3	9.15	16.47	21.45
14	11.4	8.11	3.67	2.04	1.22		4.65	6.28	8.76	15.83	21.67
15	11.2	8.13	3.66	2.02	1.21		4.78	6.27	9.02	16.27	21.26
16	11.3	8.03	3.66	2.04	1.21		4.52	6.14	9.21	16.72	21.52
17	11.1	8.01	3.65	2.02	1.18		4.11	6.17	9.01	16.32	21.55
18	11.5	8.1	3.65	2.02	1.18		4.06	6.28	9.14	16.76	21.56
19	11.1	8.25	3.64	2.01	1.18		4.72	6.1	8.84	16.2	21.32
20	11	8.08	3.63	2.01	1.17		4.49	7.08	9.08	14.62	21.28
21	11.1	8.03	3.63	1.99	1.16		4.68	6.99	8.77	14.27	21.65
22	11.2	8.02	3.62	1.99	1.15		4.5	7.13	9.05	14.51	21.26
23	11.1	8.14	3.62	1.98	1.15		4.58	7.01	8.67	14.03	21.73
24	11.3	8.01	3.61	1.97	1.14		4.36	7.06	9.02	14.55	21.58
25	11.3	8.04	3.61	1.96	1.14		4.38	6.67	8.65	14.11	21.77
26	11	8.07	3.59	1.96	1.13		4.34	6.75	8.61	14.6	21.36

27	11	8.19	3.59	1.95	1.12		4.14	6.97	8.61	14.94	21.54
28	11.3	8.01	3.59	1.95	1.12		4.42	6.81	8.91	14.94	21.58
29	11.2	7.96	3.59	1.95	1.11		4.57	6.9	9.08	14.94	21.69
30	11.7	8.04	3.59	1.95	1.11		5.18	6.72	8.82	14.61	21.75
31	11.1	8.1	3.58	1.94	1.1		4.84	6.89	9.02	14.94	21.66
32	11.2	8.02	3.58	1.94	1.1		4.77	6.67	8.71	14.44	21.9
33	11.1	7.93	3.57	1.94	1.1		4	6.82	9.02	14.96	21.58
34	11	7.99	3.58	1.93	1.09		4.48	7.02	8.7	14.46	22.15
35	11.5	8.23	3.56	1.93	1.09		4.41	6.94	8.97	15.03	21.82
36	11.4	8.12	3.57	1.92	1.08		4.43	6.93	8.65	14.3	20.5
37	11.1	7.95	3.57	1.91	1.08		4.51	6.97	8.91	15.07	21.93
38	11.1	7.98	3.57	1.91	1.08		3.62	7.29	8.65	15.22	21.86
39	11.4	8.05	3.56	1.9	1.08		4.46	6.84	8.84	15	22.07
40	11.2	8.07	3.56	1.91	1.07		4.73	6.91	9.09	15.24	21.92

Pit 2	Shear modulus for 400kPa						Damping ratio for 400kPa				
Strain (%)	0.01	0.1	1	2.5	5		0.01	0.1	1	2.5	5
No of cycle											
1	12.21	7.96	5.92	4.86	2.81		2.9	3.96	6.59	13.71	22.1
2	13.31	10.3	5.94	4.53	2.31		3.72	4.47	8.63	13.65	22.04
3	13.75	8.78	5.87	4.35	2.15		4.19	6.53	8.25	13.61	21.37
4	12.74	8.6	5.83	4.28	2.03		4.67	6.29	8.16	13.36	21.19
5	13.81	8.89	5.79	4.21	1.93		2.17	5.87	8.15	13.28	21.15
6	13.54	8.74	5.74	4.14	1.86		4.64	3.98	7.94	13.56	20.96
7	14.2	8.74	5.73	4.08	1.8		2.24	5.03	7.93	13.28	21.01
8	13.73	8.47	5.68	4.03	1.75		3.59	6.62	8.02	13.6	20.84
9	14	8.51	5.66	3.98	1.71		2.59	5.58	7.72	13.38	20.87
10	14.09	9.05	5.67	3.94	1.67		2.93	5.08	7.78	13.64	20.83
11	13.83	8.76	5.64	3.91	1.63		2.37	5.76	7.74	13.41	21.13
12	14	8.77	5.61	3.89	1.62		2.79	5.8	7.82	13.68	21.12
13	13.9	8.89	5.59	3.87	1.6		2.59	5.66	7.74	13.45	21.26
14	14.05	9.29	5.6	3.85	1.58		2.78	5.12	7.65	13.74	21.1
15	14.02	8.76	5.59	3.83	1.57		2.71	6.25	7.73	13.49	21.01
16	13.92	9.47	5.55	3.82	1.56		2.62	5.61	7.59	13.21	20.86
17	14.04	9.02	5.56	3.8	1.54		2.44	5.5	7.63	13.51	20.63
18	13.95	9.14	5.56	3.79	1.54		2.86	6.89	7.54	13.22	20.69
19	14.17	9.24	5.55	3.78	1.53		2.38	6.25	7.63	13.52	20.48
20	13.92	8.77	5.53	3.77	1.51		2.91	6.85	7.61	13.25	20.56
21	14.01	8.93	5.53	3.76	1.5		2.39	6.67	7.54	13.6	20.3
22	14.01	8.86	5.53	3.75	1.49		2.8	3.83	7.55	13.32	20.31
23	14.08	9.29	5.51	3.74	1.48		2.54	7.97	7.59	13.63	20.2
24	14.09	8.54	5.51	3.73	1.47		2.77	6.28	7.66	13.32	20.15

25	14.18	8.97	5.5	3.72	1.46		2.43	5.74	7.57	13.63	20.15
26	14.07	8.84	5.48	3.71	1.45		2.83	5.5	7.57	13.42	20.04
27	13.93	9.14	5.48	3.7	1.45		2.47	4.78	7.57	13.14	19.96
28	14.02	8.84	5.48	3.69	1.44		2.73	4.47	7.59	13.18	19.92
29	13.95	8.58	5.48	3.69	1.43		2.6	5.63	7.61	13.18	19.91
30	14.15	9.07	5.47	3.67	1.43		2.58	5.46	7.48	13.55	19.78
31	14.01	9.05	5.47	3.67	1.42		2.56	5.54	7.56	13.21	19.77
32	13.93	8.7	5.47	3.67	1.41		2.57	4.6	7.51	13.58	19.77
33	14.02	8.84	5.46	3.66	1.4		2.6	5.52	7.63	13.24	19.67
34	14.23	9.23	5.47	3.65	1.39		2.67	5.58	7.55	13.61	19.75
35	13.9	8.77	5.46	3.65	1.38		2.6	4.71	7.52	13.3	19.64
36	14.11	8.84	5.45	3.64	1.38		2.71	5.52	7.52	13.61	16.83
37	14.26	8.95	5.44	3.64	1.37		2.51	6.02	7.58	13.35	19.58
38	14.09	9.18	5.43	3.63	1.37		2.51	4.76	7.51	13.15	19.62
39	13.93	9.13	5.44	3.62	1.36		2.63	4.57	7.51	13.44	19.46
40	13.99	9.37	5.42	3.61	1.36		2.59	5.86	7.52	13.14	19.46

Pit 3	Shear modulus for 100kPa						Damping ratio for 100kPa				
Strain (%)	0.01	0.1	1	2.5	5		0.01	0.1	1	2.5	5
No of cycle											
1	4.47	4.563	2.78	1.32	0.69		4.33	4.98	11.61	24.5	33
2	9.12	4.584	2.73	1.09	0.57		5.21	9.096	11.92	21.18	24.42
3	7.75	4.577	2.65	0.96	0.52		0.38	7.601	10.86	20.16	22.25
4	8.24	4.589	2.62	0.89	0.49		9.26	7.674	11.19	19.72	21.04
5	9.43	4.583	2.59	0.86	0.46		5.5	8.075	12.29	18.2	23.09
6	6.99	4.62	2.56	0.86	0.44		5.73	7.712	10.83	17.37	22.46
7	9.2	4.592	2.53	0.84	0.42		5.05	8.204	11.5	16.76	22.6
8	7.86	4.595	2.51	0.84	0.42		3.88	7.717	10.45	16.59	21.48
9	7.72	4.641	2.49	0.83	0.39		2.01	8.278	10.88	15.49	21.28
10	7.52	4.545	2.47	0.82	0.38		0.4	7.799	10.04	15.12	22.54
11	6.28	4.668	2.46	0.81	0.38		0.13	7.87	10.57	14.89	22.52
12	5.27	4.636	2.45	0.81	0.37		5.08	7.797	9.789	14.54	21.56
13	6.25	4.631	2.43	0.8	0.36		6.45	7.802	10.3	14.11	22.46
14	7.02	4.615	2.42	0.79	0.35		5.23	7.429	9.443	14.39	22.39
15	7.18	4.63	2.4	0.79	0.35		4.09	7.599	9.95	13.96	22.19
16	6.99	4.576	2.4	0.77	0.34		3.18	8.006	10.66	13.96	21.88
17	7.19	4.636	2.39	0.77	0.34		3.15	7.929	9.765	13.75	22.23
18	6.96	4.633	2.38	0.76	0.34		2.84	7.781	10.3	13.77	21
19	7	4.598	2.37	0.76	0.34		3.31	7.56	9.512	13.46	21.03
20	6.28	4.636	2.36	0.75	0.35		3.03	7.818	10.18	13.63	22.22
21	6.26	4.683	2.35	0.75	0.33		4.04	7.894	9.395	13.21	21.09
22	6.07	4.631	2.35	0.74	0.33		3.7	7.659	9.87	13.46	21.84

23	5.87	4.615	2.34	0.74	0.33		3.5	7.167	9.154	13.09	20.53
24	5.76	4.672	2.33	0.74	0.33		3.8	7.798	9.742	13.31	21.25
25	5.63	4.659	2.32	0.73	0.32		3.28	7.46	9.145	13	21.35
26	5.61	4.642	2.31	0.73	0.33		3.11	7.759	10.12	13.15	20.28
27	5.61	4.621	2.31	0.73	0.33		3.37	7.569	10.12	13.06	21.38
28	5.59	4.687	2.31	0.72	0.32		3.11	7.514	9.442	13.08	20.71
29	5.52	4.641	2.3	0.72	0.32		2.98	7.765	10.08	13.08	20.72
30	5.54	4.615	2.29	0.72	0.31		3.03	7.366	9.296	12.85	20.7
31	5.49	4.653	2.3	0.72	0.32		3.33	7.438	9.84	12.96	21.38
32	5.44	4.647	2.28	0.72	0.31		2.86	7.51	9.12	12.73	20.64
33	5.38	4.673	2.28	0.71	0.31		2.85	7.769	9.741	12.95	20.64
34	5.39	4.681	2.28	0.71	0.31		2.75	7.52	9.028	12.58	20.35
35	5.38	4.639	2.28	0.71	0.31		2.96	7.463	9.465	12.8	20.51
36	5.38	4.675	2.27	0.71	0.31		2.81	7.597	8.891	12.52	18.1
37	5.31	4.651	2.27	0.71	0.31		2.74	7.456	9.457	12.72	20.45
38	5.33	4.662	2.27	0.7	0.31		2.75	8.054	9.961	12.71	20.2
39	5.27	4.663	2.26	0.71	0.31		2.79	7.452	9.277	12.59	20.42
40	5.28	4.626	2.26	0.7	0.31		2.83	7.875	9.919	12.71	20.5

Pit 3	Shear modulus for 250kPa						Damping ratio for 250kPa				
Strain (%)	0.01	0.1	1	2.5	5		0.01	0.1	1	2.5	5
No of cycle											
1	10.1	6.57	4.6	3.04	1.55		3.77	4.97	9.45	16.84	26.83
2	11.9	8.7	4.47	2.65	1.22		1.55	6.69	9.03	16.37	22.66
3	15.3	7.89	4.43	2.49	1.13		3.1	7.24	8.45	15.73	19.81
4	13.5	8	4.39	2.38	1.06		3.88	6.91	9.01	14.83	18.79
5	11.4	8.16	4.38	2.31	1		4.17	6.31	9.46	14.37	18.17
6	15.5	8.22	4.34	2.25	0.96		2.6	6.79	8.32	14.27	17.58
7	10.3	8.13	4.31	2.21	0.93		2.84	6.44	9.12	13.8	16.96
8	14	8.21	4.29	2.17	0.9		0.92	6.22	8.36	14.02	16.63
9	12.8	8.22	4.26	2.13	0.88		0.32	6.22	8.61	13.51	16.24
10	12.4	8.34	4.24	2.1	0.87		3.62	6.8	8.4	13.84	15.92
11	14.3	8.15	4.24	2.08	0.86		3.61	6.74	8.17	13.32	15.55
12	10.7	8.31	4.21	2.05	0.84		4.62	6.42	8.45	13.59	15.48
13	13.5	8.33	4.21	2.03	0.83		2.83	6.22	7.98	13.19	15.14
14	11.7	8.27	4.19	2	0.82		3.16	6.56	8.32	13.43	15.09
15	9.12	8.16	4.18	1.99	0.81		0.77	6.42	8.01	13.19	14.73
16	13.9	8.27	4.16	1.97	0.8		3.33	6.4	8.61	12.81	14.73
17	12.3	8.29	4.16	1.94	0.8		1.45	6.32	8.11	13.18	14.64
18	10.9	8.24	4.15	1.93	0.79		3.42	6.28	8.23	12.85	14.55
19	17.3	8.14	4.13	1.91	0.78		1.93	6.47	8.17	13.09	14.41
20	9.83	8.17	4.13	1.9	0.77		1.23	6.34	8.07	12.8	14.28
21	14.4	8.28	4.12	1.88	0.77		0.76	6.4	8.14	13	14.19
22	13	8.35	4.11	1.87	0.76		1.4	6.34	7.95	12.73	14.14
23	11.2	8.23	4.09	1.86	0.76		5.4	6.38	8.06	12.85	14.08
24	13.1	8.19	4.09	1.84	0.75		4.01	6.48	7.99	12.66	13.8
25	12.2	8.29	4.09	1.84	0.74		4.03	6.23	7.98	12.69	14
26	10.8	8.37	4.07	1.83	0.74		3.44	6.41	8.24	12.6	13.79
27	13.7	8.28	4.07	1.81	0.74		2.25	6.17	8.24	12.23	13.62
28	12.9	8.26	4.07	1.8	0.73		3.22	6.2	8.06	12.27	13.72
29	11.9	8.29	4.06	1.8	0.72		4.07	6.27	8.01	12.27	13.72
30	12	8.37	4.06	1.79	0.72		6.01	6.4	7.99	12.49	13.33
31	12	8.25	4.05	1.78	0.72		0.29	6.41	7.96	12.29	13.51
32	13.6	8.3	4.05	1.77	0.72		1.39	6.25	8.01	12.41	13.13
33	13.2	8.29	4.04	1.77	0.71		2.14	6.46	7.87	12.24	13.3
34	13.3	8.28	4.03	1.75	0.71		3.91	6.07	7.87	12.38	13.2
35	13.6	8.13	4.03	1.75	0.7		4.32	6.49	7.97	12.23	13.13
36	13	8.22	4.02	1.75	0.71		1.95	6.44	7.8	12.15	11.23

37	13.9	8.3	4.02	1.74	0.7		4.18	6.26	7.94	12.22	12.81
38	13.7	8.31	4.01	1.73	0.7		1.63	6.09	8.04	11.9	13.06
39	13.7	8.15	4.01	1.72	0.7		5.91	6.3	8	12.23	12.77
40	11.4	8.17	4.01	1.73	0.69		3.3	6.23	8	11.92	12.87

Pit 3	Shear modulus for 400kPa						Damping ratio for 400kPa				
Strain (%)	0.01	0.1	1	2.5	5		0.01	0.1	1	2.5	5
No of cycle											
1	10.58	7.63	5.67	3.75	2.38		2.29	4.11	6.55	13.28	23.05
2	10.36	9.18	5.59	3.28	1.97		1.95	5.53	10.3	14.24	20.12
3	11.86	9.06	5.56	3.23	1.85		3.26	5.83	9.18	13.47	18.38
4	9.908	8.93	5.53	3.17	1.75		1.79	6.51	9.2	12.72	17.57
5	12.05	9.03	5.5	3.13	1.67		2.86	5.44	9.11	12.34	17.3
6	11.09	8.94	5.47	3.09	1.62		1.21	6.07	8.45	12.41	16.57
7	10.67	8.92	5.44	3.06	1.59		2.5	6.53	8.72	11.98	16.22
8	11.09	8.63	5.42	3.03	1.56		1.5	5.64	8.17	12.25	15.8
9	10.07	8.92	5.41	3	1.53		1.85	7.56	8.52	11.87	15.65
10	10.89	8.73	5.38	2.98	1.5		3.36	5.67	7.88	12.13	15.53
11	10.82	8.91	5.36	2.95	1.48		1.12	7.29	8.33	11.75	15.37
12	10.57	8.73	5.33	2.93	1.45		2.72	5.98	7.78	12.1	15.27
13	10.51	8.92	5.34	2.92	1.43		1.19	6.53	8.16	11.75	15.18
14	10.64	8.79	5.33	2.89	1.41		2.37	5.84	7.38	12.11	15.08
15	10.39	8.72	5.31	2.87	1.4		1.41	6.66	7.97	11.79	15.02
16	10.53	8.74	5.3	2.85	1.38		2.01	5.6	8.39	11.58	14.92
17	10.3	8.83	5.3	2.84	1.37		1.19	6.16	7.94	11.86	14.89
18	10.35	8.88	5.28	2.83	1.35		1.94	5.54	8.24	11.55	14.86
19	10.34	8.88	5.27	2.82	1.34		1.36	6.53	7.79	11.82	14.82
20	10.4	8.76	5.26	2.8	1.33		2.08	5.82	8.14	11.55	14.82
21	10.24	8.91	5.25	2.8	1.32		1.2	5.99	7.7	11.82	14.68
22	10.29	8.79	5.25	2.79	1.31		1.91	5.86	7.99	11.59	14.62
23	10.22	8.84	5.24	2.78	1.31		1.52	6.27	7.39	11.82	14.57
24	10.53	8.79	5.23	2.77	1.3		1.91	5.95	7.9	11.57	14.62
25	10.17	8.83	5.22	2.76	1.29		1.4	5.88	7.24	11.86	14.5
26	10.29	8.78	5.21	2.76	1.28		1.78	5.87	8.15	11.65	14.56
27	10.33	8.87	5.21	2.76	1.26		1.25	5.82	8.15	11.27	14.63
28	10.38	8.8	5.21	2.75	1.27		1.92	5.87	7.69	11.27	14.45
29	10.28	8.8	5.21	2.74	1.26		1.3	5.74	8.12	11.27	14.29
30	10.35	8.82	5.2	2.74	1.25		1.79	5.9	7.64	11.57	14.47
31	10.14	8.88	5.19	2.74	1.24		1.29	5.75	7.91	11.22	14.43
32	10.35	8.78	5.19	2.73	1.24		1.8	6.03	7.42	11.59	14.35
33	10.21	8.76	5.18	2.73	1.23		1.4	5.7	7.9	11.24	14.45
34	10.4	8.88	5.18	2.72	1.23		1.85	5.72	7.31	11.55	14.32
35	10.32	8.83	5.18	2.72	1.22		1.44	5.82	7.76	11.28	14.24

36	10.4	8.81	5.16	2.71	1.22		1.77	5.97	7.12	11.54	12.51
37	10.22	8.81	5.17	2.71	1.22		1.37	5.75	7.69	11.27	14.29
38	10.3	8.89	5.16	2.7	1.21		1.76	5.77	8.16	11.01	14.14
39	10.13	8.91	5.16	2.7	1.21		1.52	6.04	7.6	11.29	14.2
40	10.32	8.83	5.15	2.7	1.2		1.62	5.85	7.94	10.96	14.13

Pit 4	Shear modulus for 250kPa						Damping ratio for 250kPa				
Strain (%)	0.01	0.1	1	2.5	5		0.01	0.1	1	2.5	5
No of cycle											
1	6.93	5.54	3.71	2.82	1.71		6.07	7.87	10.6	18.79	23.79
2	7.52	6.72	3.69	2.31	1.35		3.82	7.23	11	18.34	24.15
3	7.56	6.36	3.65	2.2	1.25		4.93	7.65	9.73	18.08	21.48
4	6.64	6.21	3.61	2.15	1.13		3.35	7.49	10.4	17.35	21.17
5	10.4	6.18	3.6	2.09	1.08		4.49	7.41	10.9	16.97	20.06
6	8.41	6.13	3.56	2.02	1.02		2.73	7.32	9.59	17.09	19.59
7	6.71	6.17	3.55	1.96	0.96		1.55	7.54	10.3	16.81	19.99
8	6.46	6.16	3.53	1.94	0.92		1.22	7.55	9.4	16.74	19.69
9	9.46	6.22	3.52	1.9	0.89		2.71	7.38	9.88	16.64	19.44
10	8.68	6.27	3.51	1.86	0.87		3.51	7.38	9.09	16.87	19.45
11	8.75	6.2	3.5	1.85	0.84		0.53	7.54	9.54	16.3	19.31
12	7	6.21	3.49	1.8	0.8		1.89	7.47	9	16.67	20.97
13	9.3	6.24	3.48	1.8	0.79		5.95	7.39	9.39	16.38	19.77
14	8.28	6.28	3.47	1.76	0.77		5.2	7.39	8.83	16.58	20.55
15	8.2	6.2	3.46	1.76	0.76		1.15	7.52	9.18	16.35	19.74
16	7.11	6.23	3.45	1.73	0.74		1.8	7.42	9.64	16.08	20.31
17	7.98	6.22	3.45	1.72	0.73		5.52	7.31	9.07	16.3	19.4
18	8.05	6.24	3.44	1.7	0.73		5.37	7.28	9.5	16.07	20.35
19	8.66	6.25	3.43	1.69	0.72		0.39	7.36	8.98	16.24	19.68
20	8.7	6.16	3.43	1.66	0.7		1.6	7.3	9.3	16.16	20.43
21	7.3	6.24	3.43	1.66	0.71		5.49	7.28	8.85	16.08	18.95
22	7.82	6.23	3.42	1.65	0.7		5.85	7.21	9.29	16.12	20.1
23	8.79	6.18	3.41	1.63	0.69		1.63	7.37	8.75	16.05	19.08
24	7.9	6.23	3.41	1.63	0.7		2.33	7.4	9.06	16.03	18.94
25	6.87	6.27	3.41	1.61	0.69		1.5	7.15	8.71	16.01	18.37
26	7.24	6.29	3.4	1.62	0.66		5.91	7.42	9.42	16.14	19.54
27	7.58	6.12	3.4	1.59	0.68		4.98	7.3	9.42	15.76	18.11
28	8.11	6.21	3.39	1.61	0.67		2.48	7.4	8.88	15.65	18.3
29	7.25	6.2	3.39	1.6	0.65		0.38	7.15	9.31	15.65	18.74
30	7.23	6.24	3.39	1.57	0.67		3.07	7.14	8.81	16.03	17.85
31	7.83	6.14	3.38	1.59	0.66		6.05	7.17	9.15	15.88	18.53
32	9.12	6.18	3.38	1.58	0.64		1.37	7.38	8.66	16.12	18.53
33	8.33	6.22	3.38	1.56	0.64		1.46	7.15	9.1	15.88	18.96
34	6.73	6.28	3.37	1.57	0.65		1.46	7.18	8.69	16.02	17.97

35	6.82	6.15	3.37	1.56	0.63		5.09	7.28	8.93	15.91	17.88
36	8.3	6.18	3.37	1.55	0.63		4.69	7.21	8.6	15.78	16.34
37	8.67	6.23	3.37	1.55	0.63		1.31	7.06	8.87	15.98	18.13
38	7.59	6.25	3.36	1.54	0.64		2.58	7.23	9.34	15.78	17.4
39	6.25	6.2	3.36	1.55	0.6		2.47	7.25	8.74	15.86	17.79
40	8.98	6.23	3.36	1.54	0.63		5.37	7.29	9.14	15.68	17.18

Pit 4	Shear modulus for 400kPa						Damping ratio for 400kPa				
Strain (%)	0.01	0.1	1	2.5	5		0.01	0.1	1	2.5	5
No of cycle											
1	10.21	9.45	5.68	4.19	2.39		2.47	3.4	6.6	16.1	23.45
2	10.97	11.5	5.58	3.79	1.88		4.11	4.74	10.7	15.41	20.21
3	11.14	11.2	5.53	3.55	1.65		2.9	3.62	10.3	15.61	19.16
4	13	11.1	5.52	3.46	1.5		3.35	3.95	10.1	15.06	18.81
5	14.56	11.3	5.48	3.38	1.41		1.9	3.05	10.1	14.92	18.49
6	12.14	11.2	5.44	3.34	1.32		2.12	3.73	9.88	14.96	18.26
7	11.58	11.2	5.41	3.28	1.25		3.78	3.13	9.85	14.76	18.21
8	10.8	11.1	5.41	3.24	1.19		0.17	4.19	9.63	14.9	18.1
9	11.48	11.2	5.37	3.19	1.12		6.66	3.32	9.83	14.82	18.47
10	11.8	11.2	5.34	3.14	1.08		3.67	3.6	9.55	14.89	18.18
11	12.23	11.1	5.34	3.1	1.04		2.63	3.43	9.7	14.97	18.6
12	11.98	11.1	5.32	3.06	1.01		2.37	4.09	9.26	14.98	18.73
13	12.09	11.2	5.3	3.02	0.97		2.66	3.4	9.63	15.1	19.01
14	11.93	11.1	5.28	3	0.96		2.52	3.68	9.13	15.07	18.84
15	12.13	11.2	5.27	2.97	0.93		2.31	3.43	9.53	15.16	18.93
16	12.01	11.1	5.27	2.94	0.9		3.16	3.24	9.65	14.91	19.48
17	11.72	11.1	5.25	2.92	0.89		4.17	3.56	9.46	15.18	19.08
18	11.44	11.1	5.23	2.9	0.87		5	3.25	9.74	15.01	19.43
19	11.95	11.1	5.24	2.88	0.85		3.47	3.69	9.24	15.23	19.45
20	11.67	11.1	5.23	2.86	0.83		3.79	3.4	9.58	15.2	19.96
21	11.98	11.1	5.21	2.84	0.82		3.68	3.72	9.14	15.23	19.79
22	12.02	11.2	5.2	2.82	0.81		3.53	3.31	9.58	15.23	20.08
23	11.7	11.2	5.2	2.8	0.8		3.83	3.5	8.96	15.27	20.05
24	11.81	11.2	5.2	2.79	0.77		3.62	3.55	9.4	15.37	20.6
25	12	11.2	5.17	2.77	0.77		3.73	4.07	8.83	15.3	20.35
26	11.92	11.2	5.16	2.76	0.76		3.24	3.55	9.66	15.4	20.55
27	11.85	11.2	5.16	2.74	0.76		3.02	3.21	9.66	15.11	20.36
28	11.73	11.1	5.17	2.73	0.74		3.9	3.66	9.17	15.25	20.77
29	11.78	11.1	5.15	2.72	0.72		3.25	3.28	9.63	15.25	21.01
30	11.84	11.2	5.14	2.71	0.73		3.81	3.58	9.12	15.56	20.8
31	11.67	11.2	5.14	2.69	0.72		3.34	3.22	9.51	15.4	20.97
32	11.75	11.1	5.14	2.68	0.7		3.64	3.79	8.93	15.57	21.28
33	11.87	11	5.13	2.67	0.7		3.33	3.62	9.43	15.51	21.28

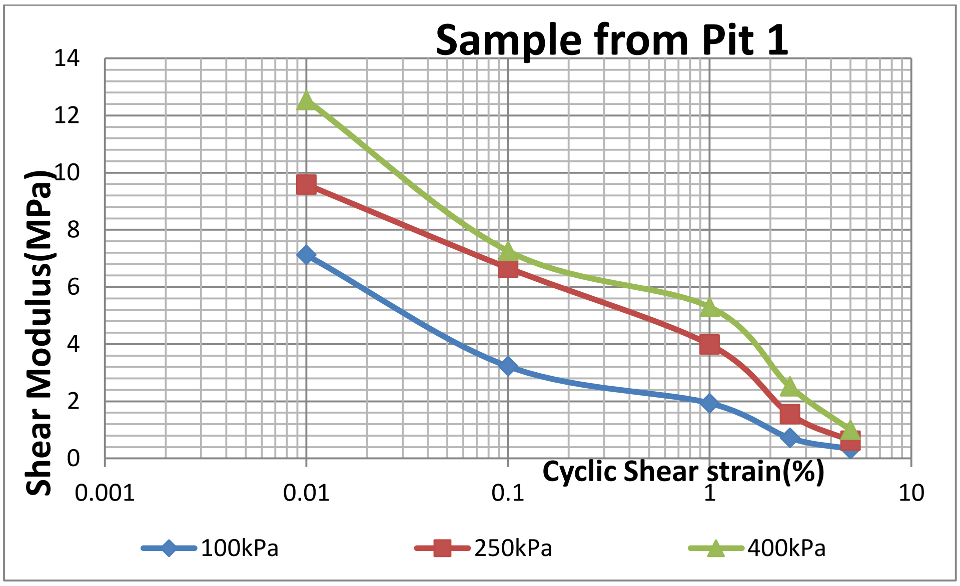
34	11.71	11.2	5.13	2.66	0.69		3.81	3.87	8.8	15.5	21.24
35	11.78	11.2	5.13	2.65	0.67		3.58	3.35	9.25	15.58	21.6
36	11.86	11.1	5.11	2.64	0.67		4.03	4.11	8.67	15.49	19.23
37	11.74	11.1	5.12	2.64	0.69		3.56	3.57	9.16	15.62	20.52
38	11.72	11.2	5.11	2.63	0.69		2.98	3.32	9.67	15.18	19.04
39	11.74	11.1	5.1	2.62	0.68		3.52	3.66	9.01	15.61	18.07
40	11.78	11.1	5.09	2.61	0.68		3.34	3.37	9.55	15.25	17.47

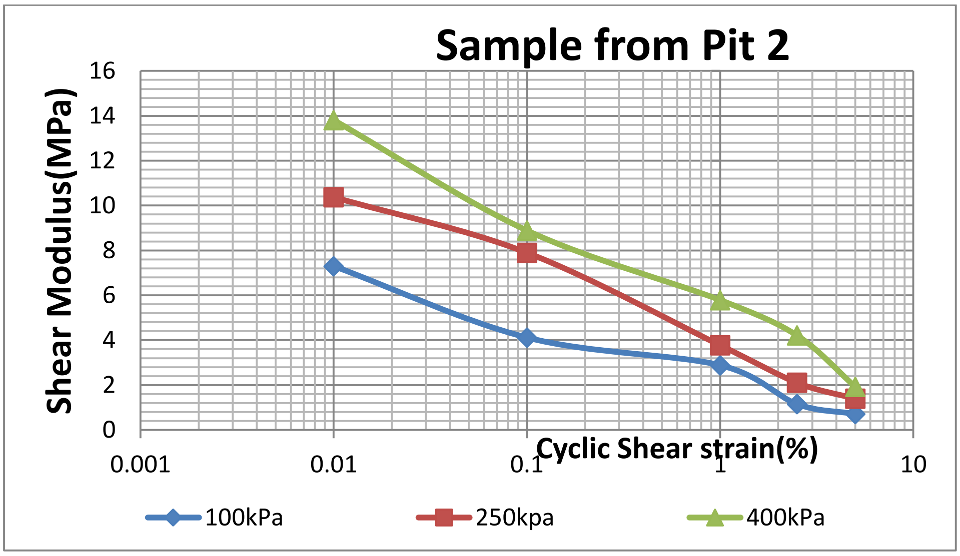
APPENDIX C

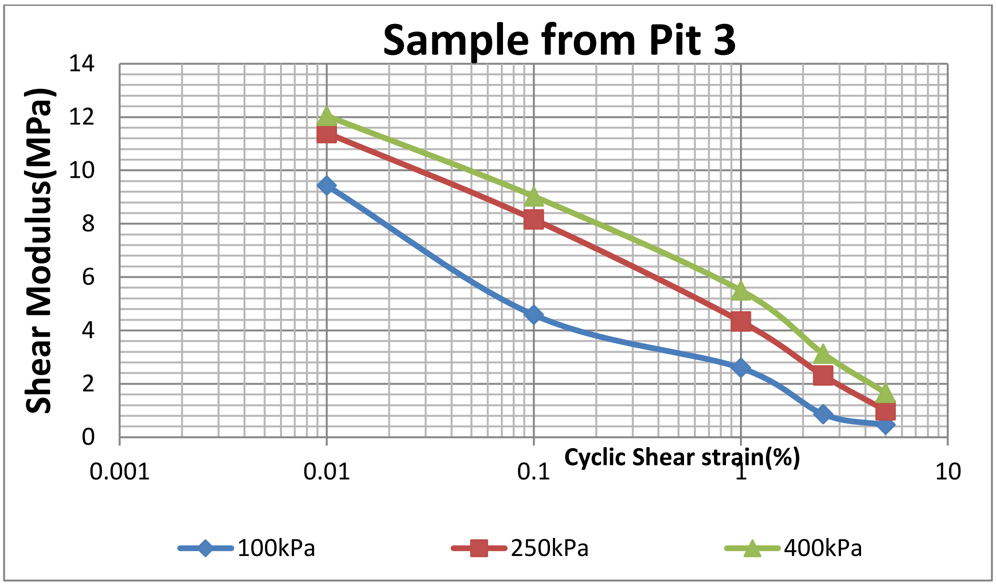
Comparison Curves

a. Comparison based on axial stress

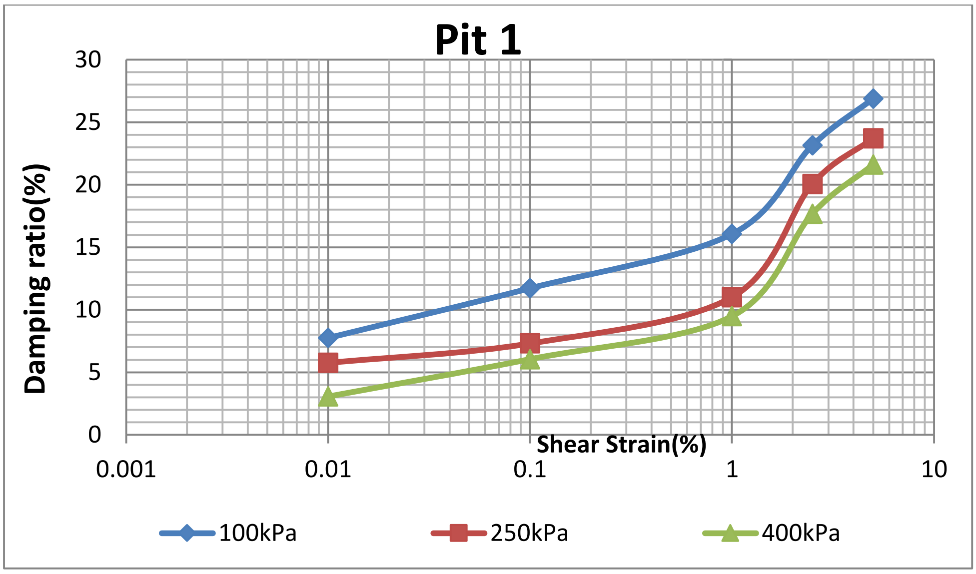
Shear modulus

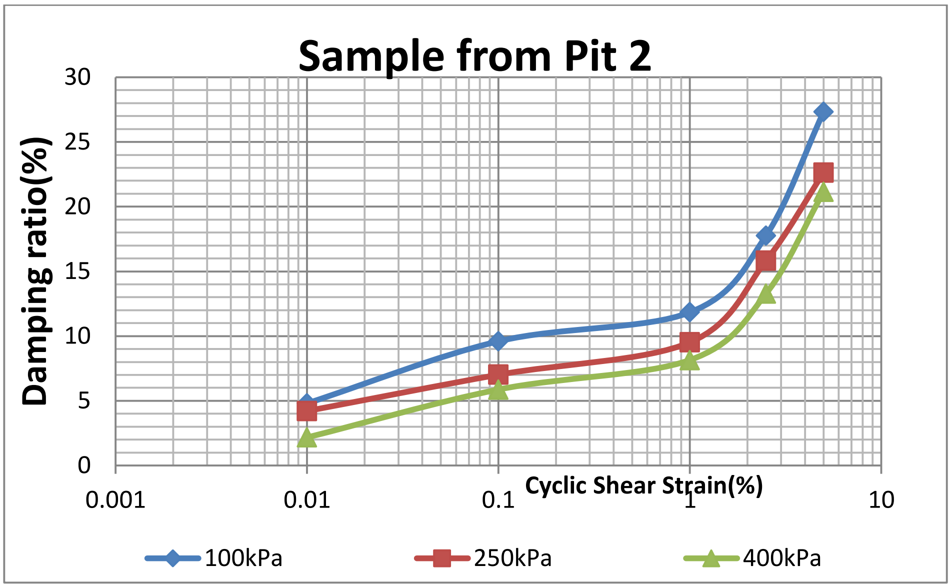


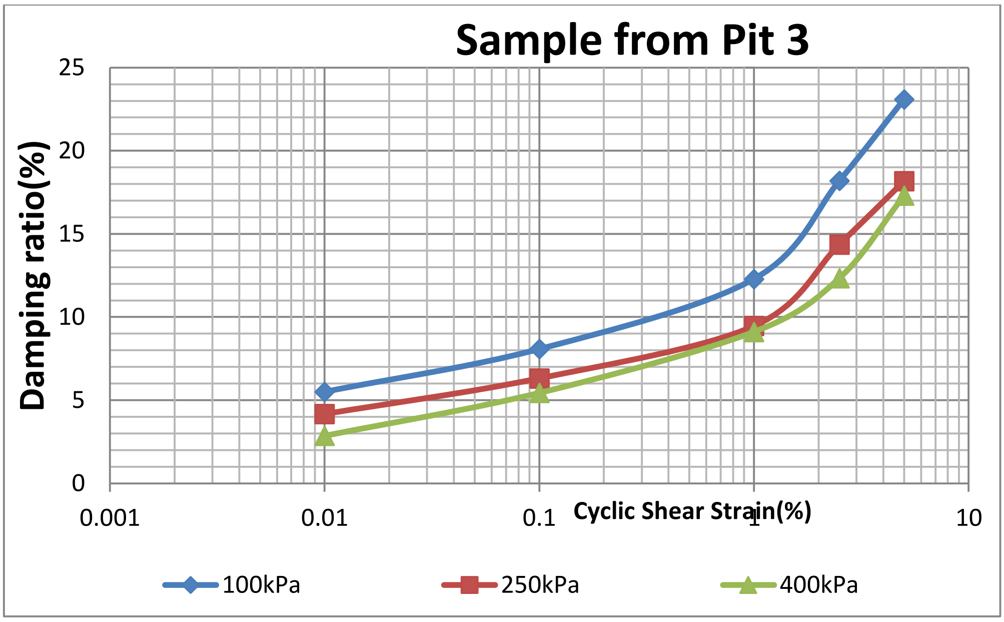




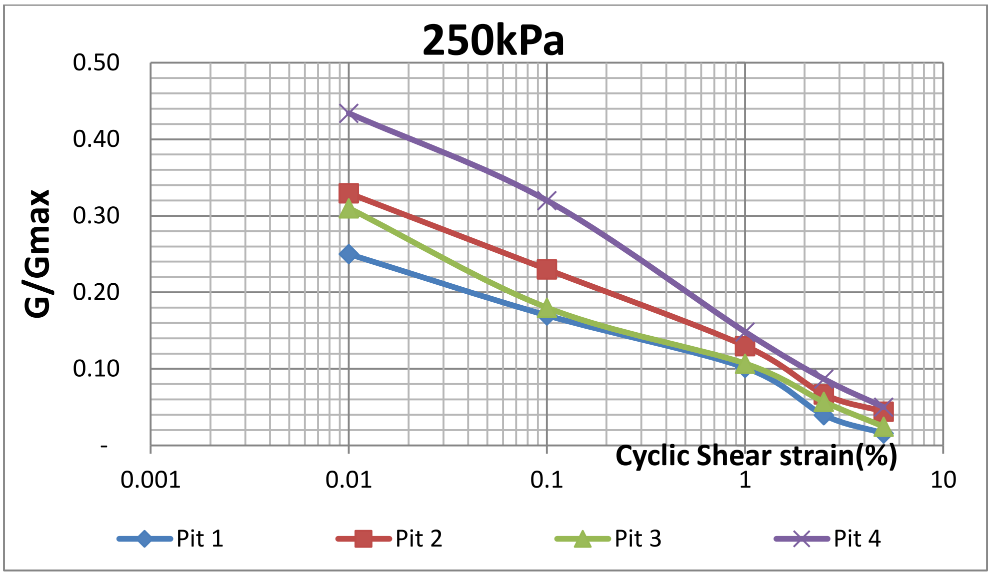
Damping ratio

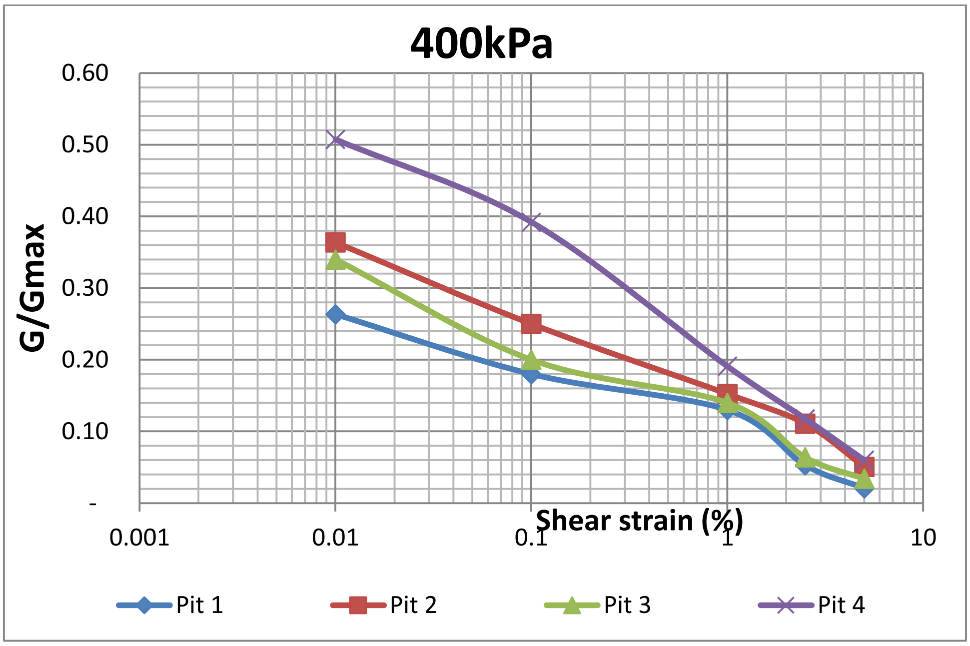



Sample from Pit 2
Damping ratio(%)
30
25
20
15
10
5
0
0.001
0.01
0.1
1
10
Cyclic Shear Strain(%)
100kPa
250kPa
400kPa

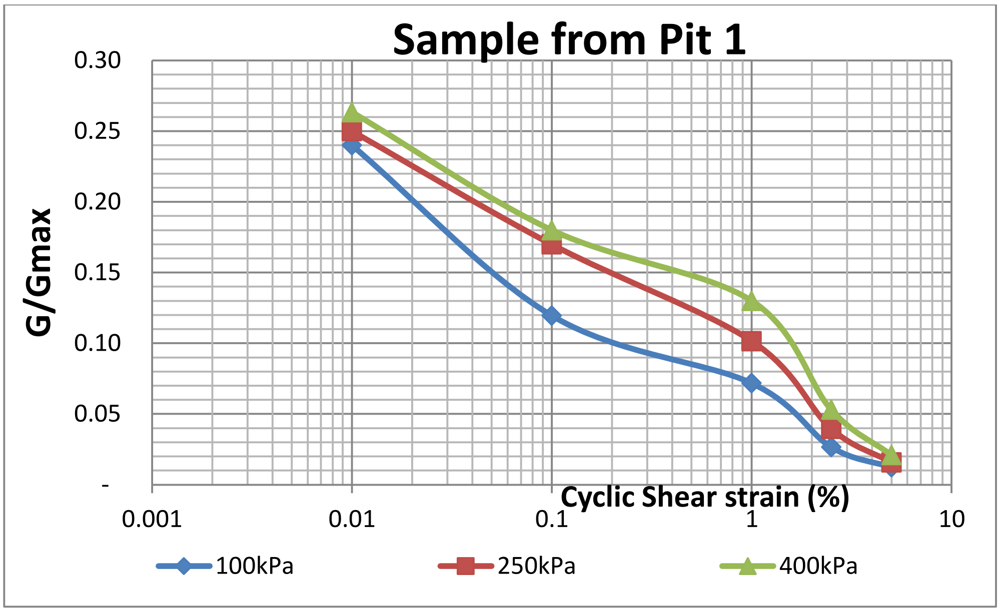

Sample from Pit 3
Damping ratio(%)
25
20
15
10
5
0
0.001
0.01
0.1
1
10
Cyclic Shear Strain(%)
100kPa
250kPa
400kPa

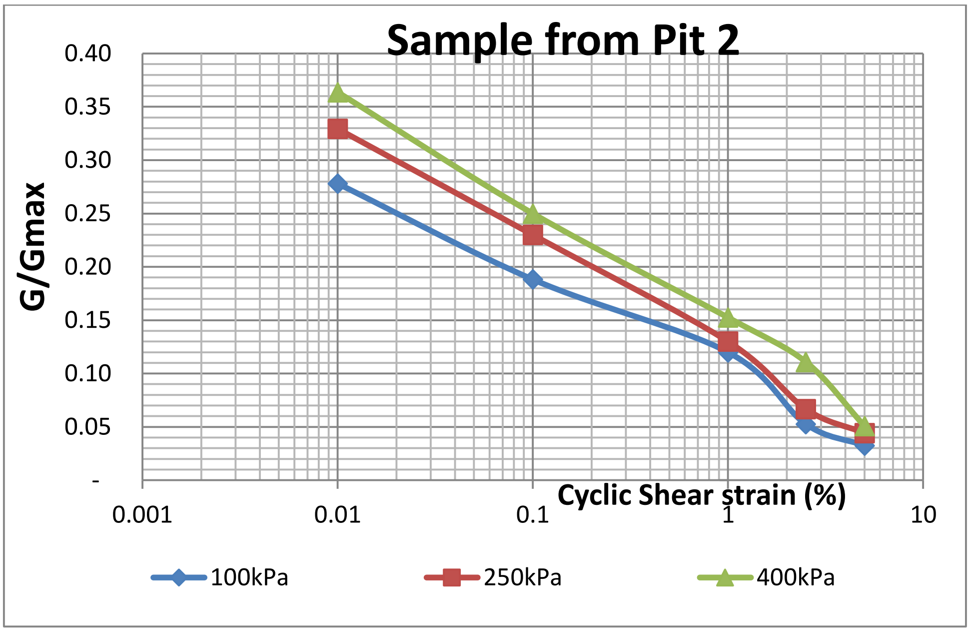
Graph of G/G_{max} versus shear strain amplitude for comparison of test result of pit 1, 2, 3 and Pit 4

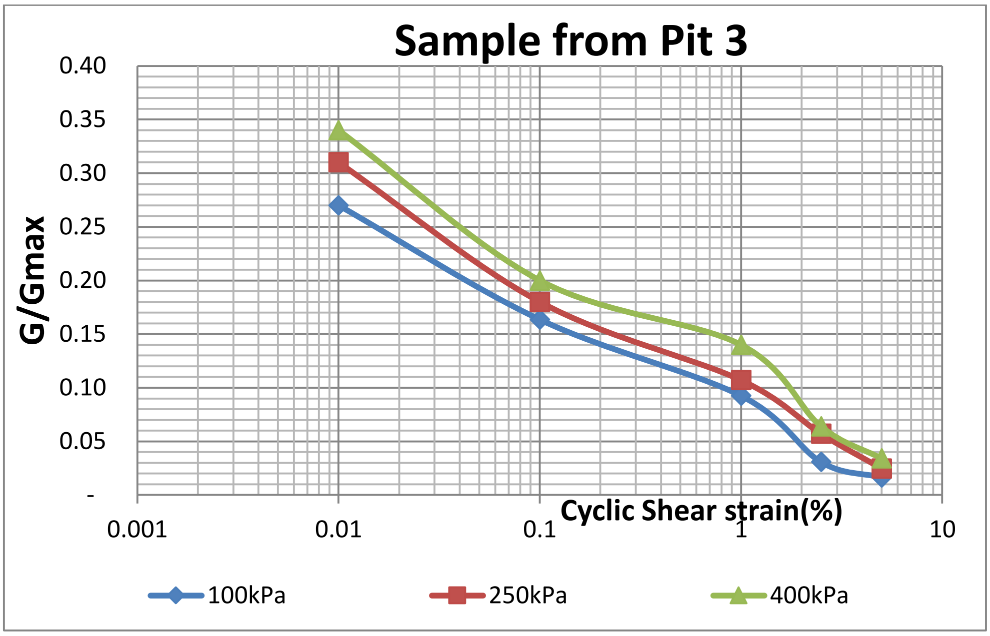




Graph of G/Gmax versus shear strain amplitude based on axial stresses

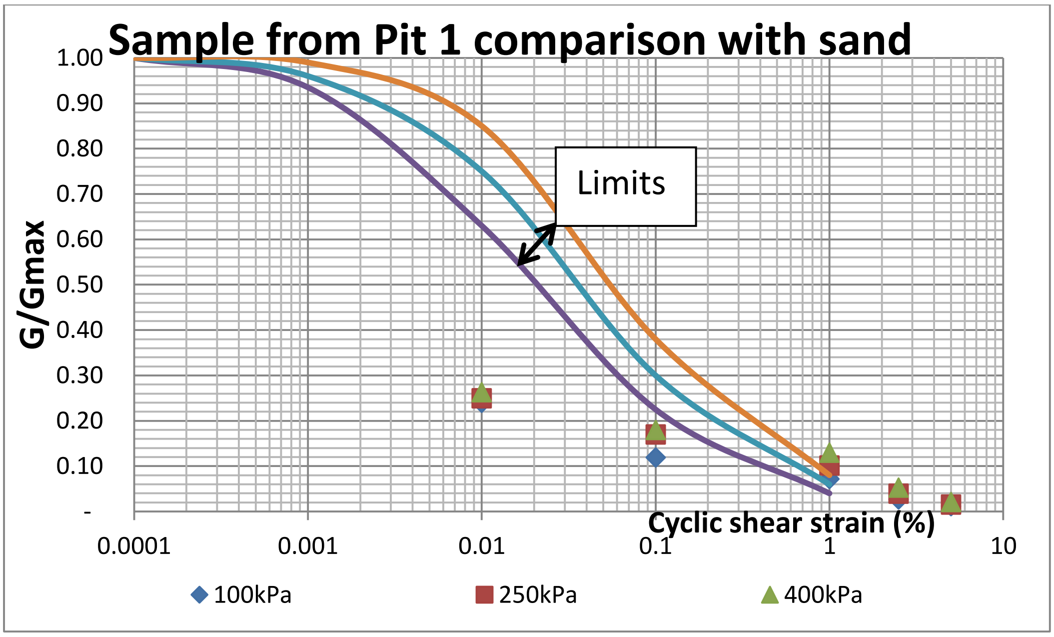


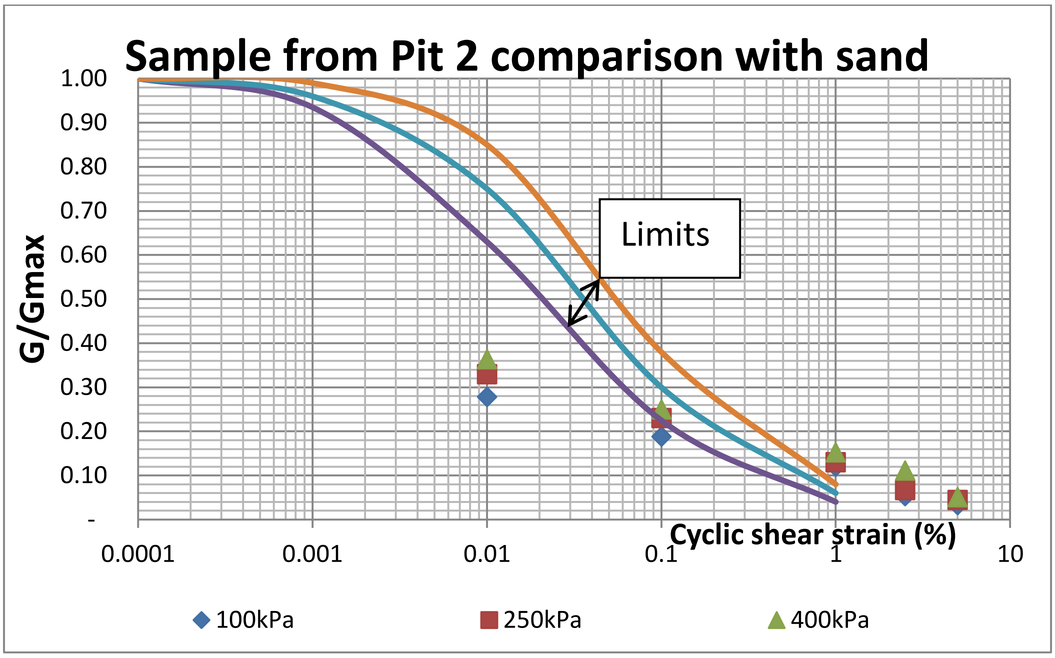


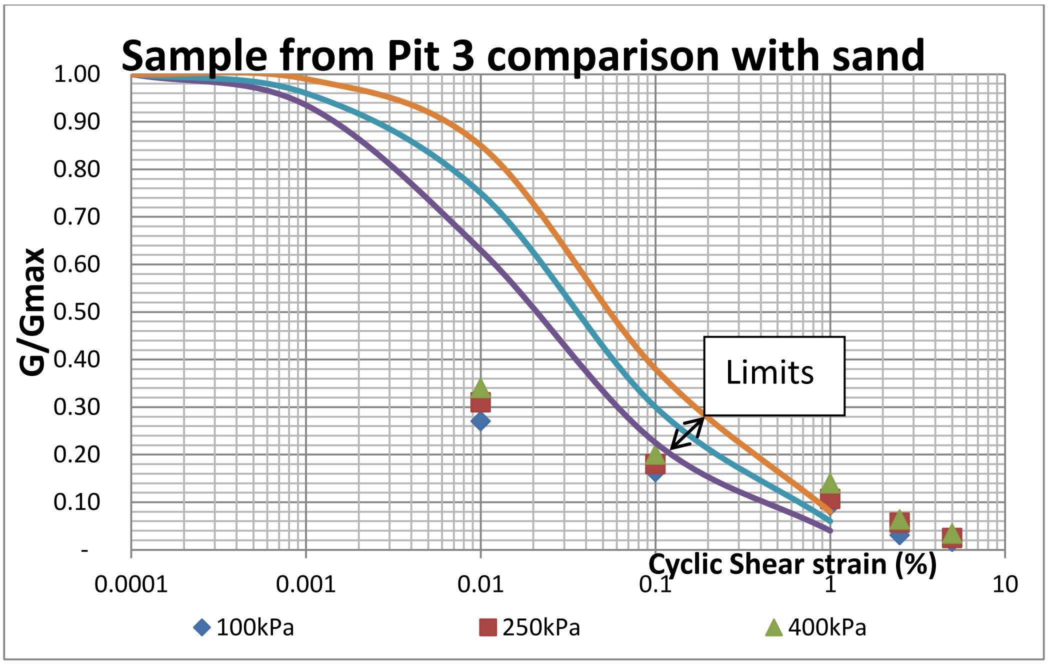


Curves for comparison values of G/Gmax and Damping ratio with previous studies

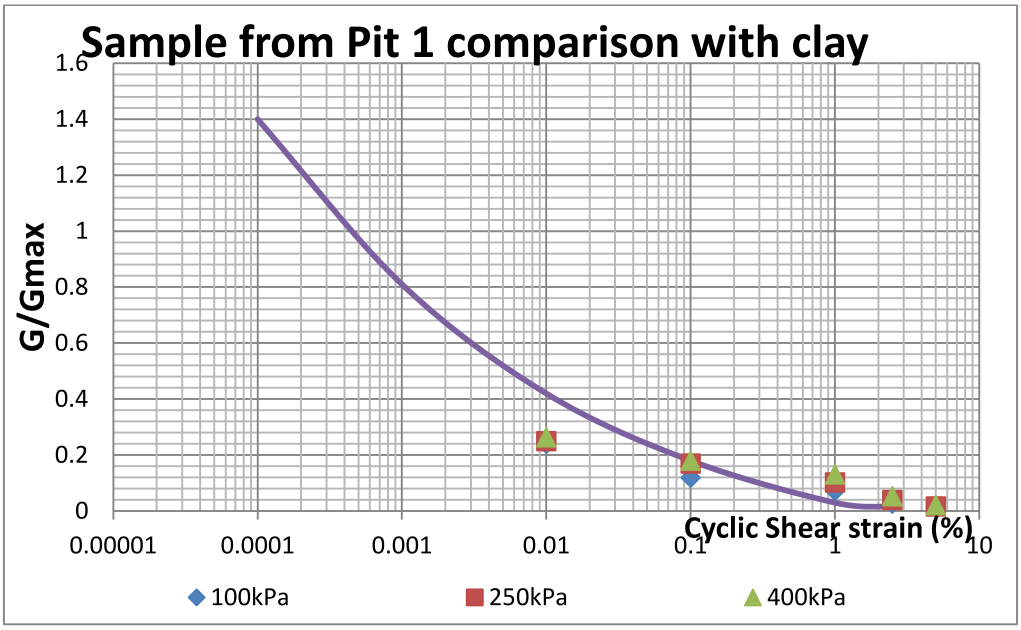
a. **Comparison values of G/G_{max} with sand**

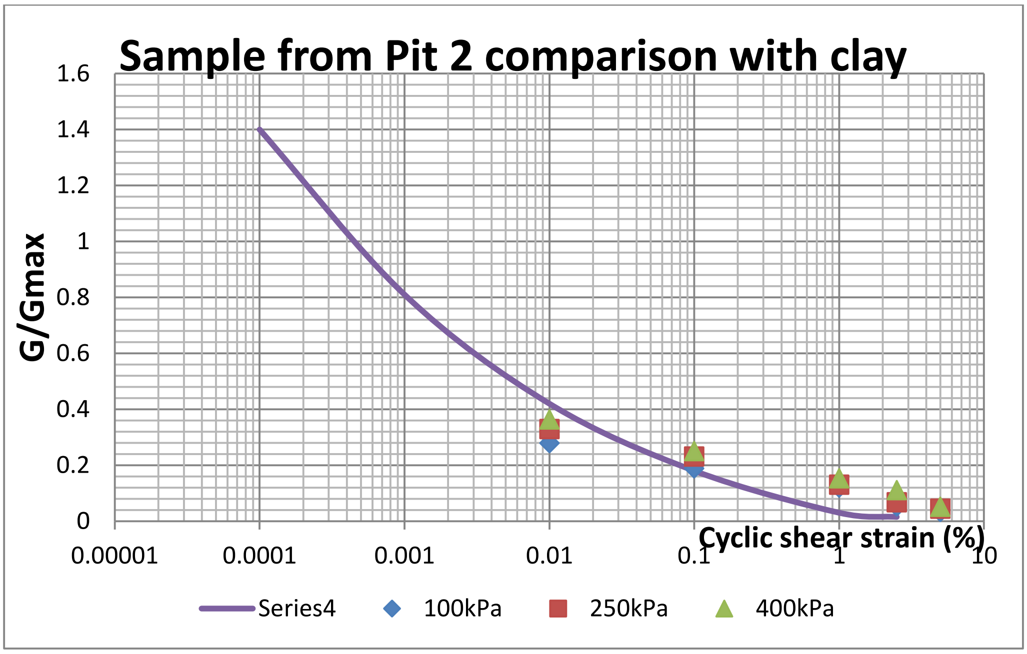


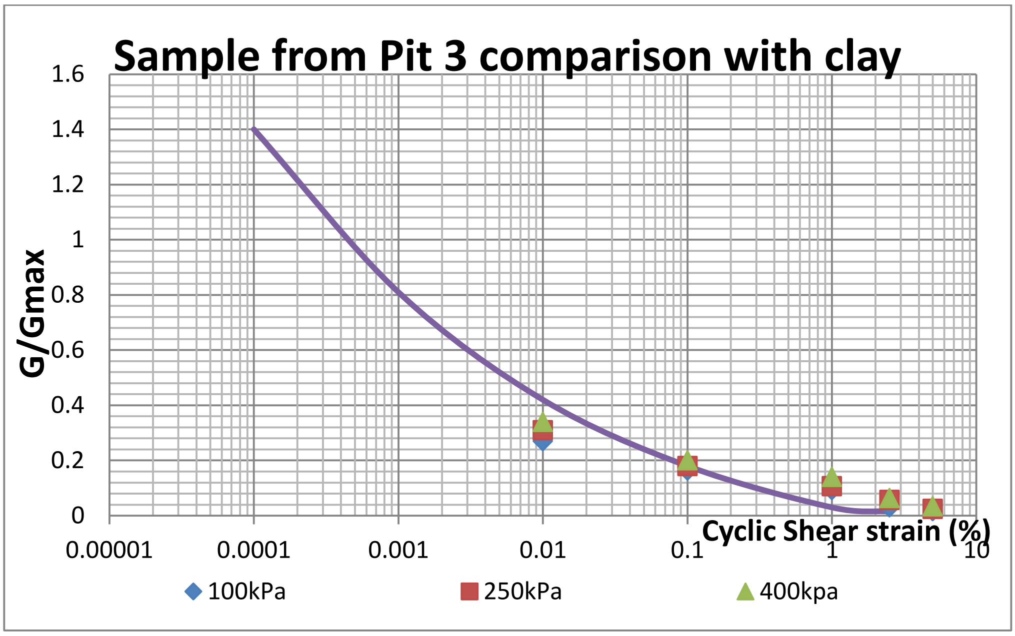

Sample from Pit 2 comparison with sand
G/Gmax
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
-
Limits
Cyclic shear strain (%)
0.0001
0.001
0.01
0.1
1
10
100kPa
250kPa
400kPa


Sample from Pit 3 comparison with sand
G/Gmax
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
-
Limits
Cyclic Shear strain (%)
0.0001
0.001
0.01
0.1
1
10
100kPa
250kPa
400kPa

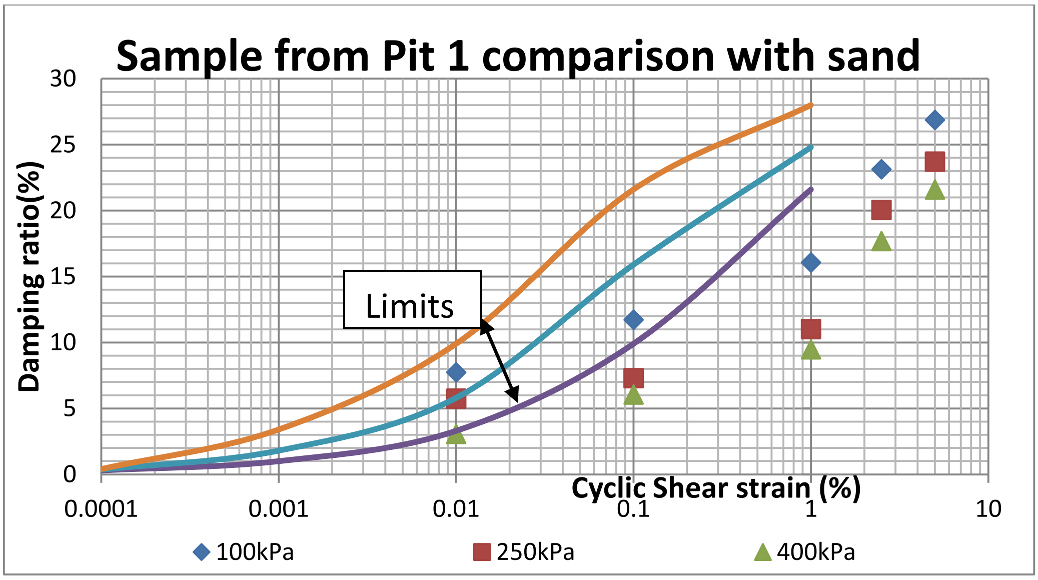
b. Comparison values of G/G_{max} with clay

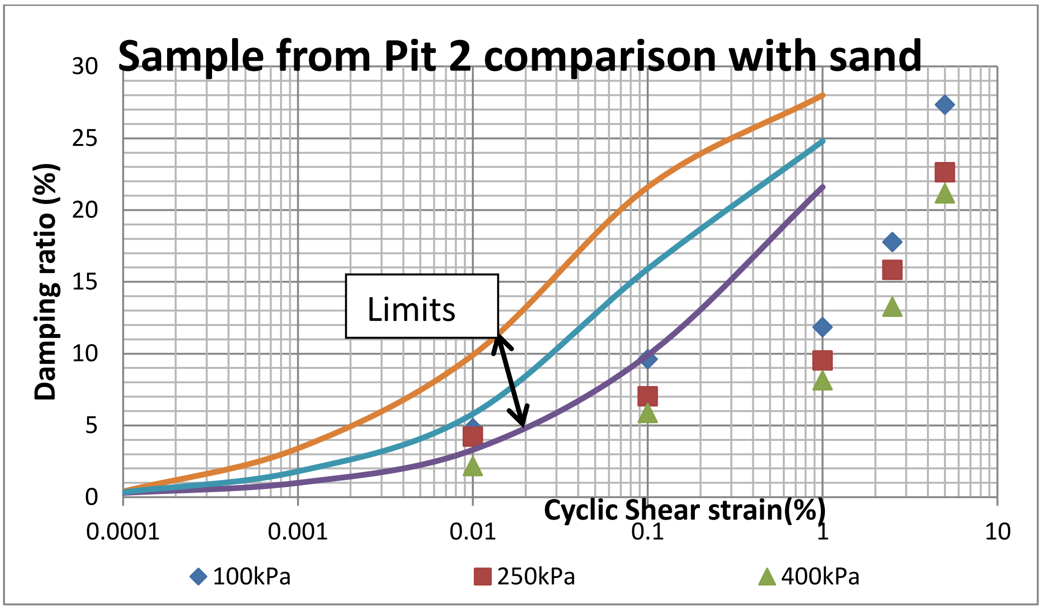


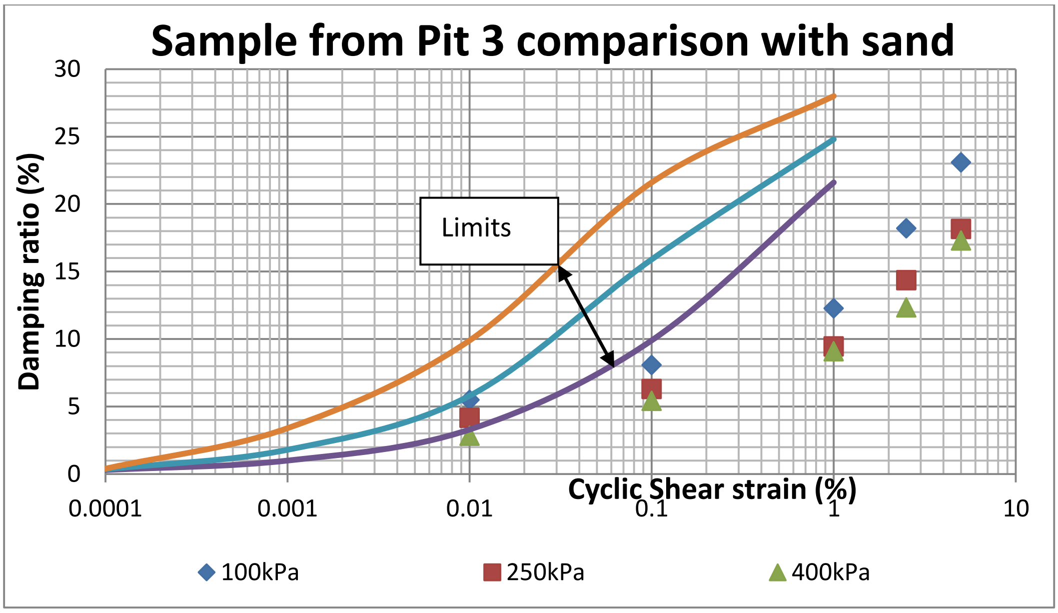




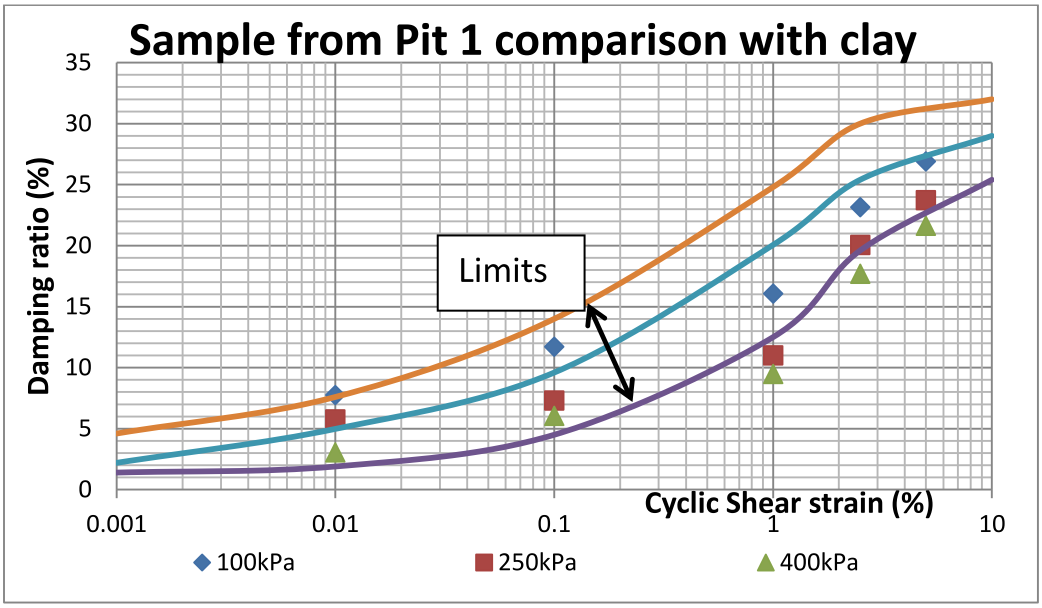
c. Comparison values of damping ratio with sand

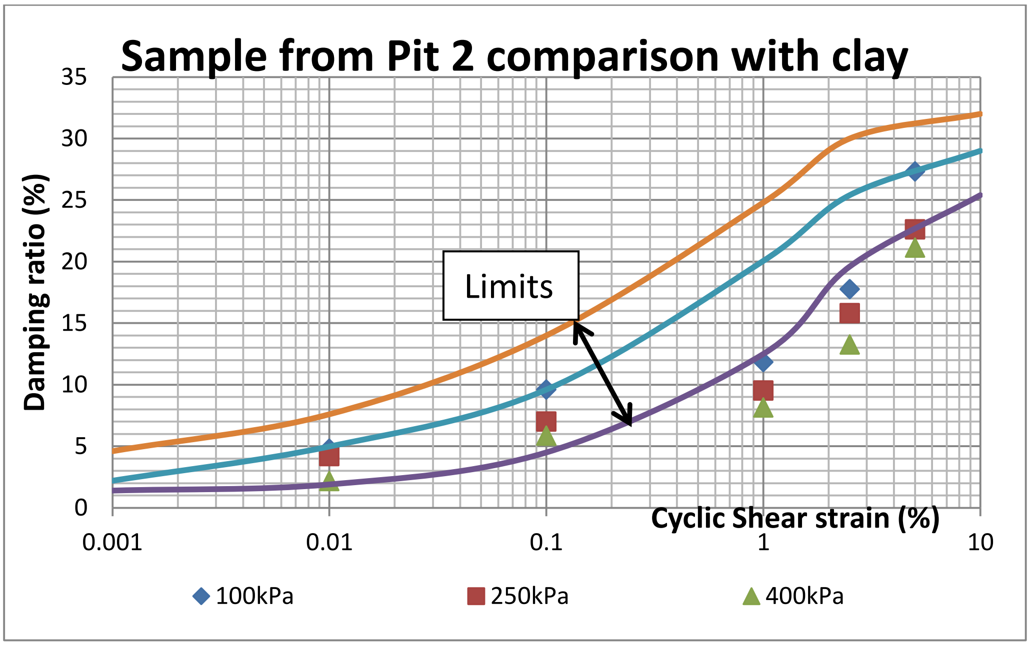


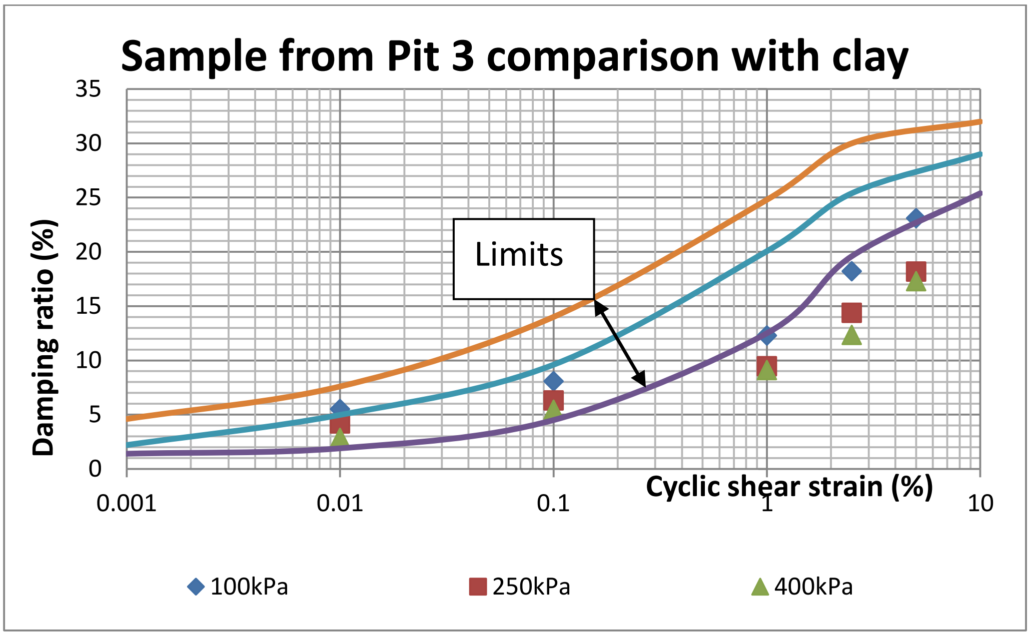

Sample from Pit 2 comparison with sand
Damping ratio (%)
30
25
20
15
10
5
0
Limits
Cyclic Shear strain(%)
0.0001
0.001
0.01
0.1
1
10
100kPa
250kPa
400kPa


Sample from Pit 3 comparison with sand
Damping ratio (%)
30
25
20
15
10
5
0
Limits
Cyclic Shear strain (%)
0.0001
0.001
0.01
0.1
1
10
100kPa
250kPa
400kPa

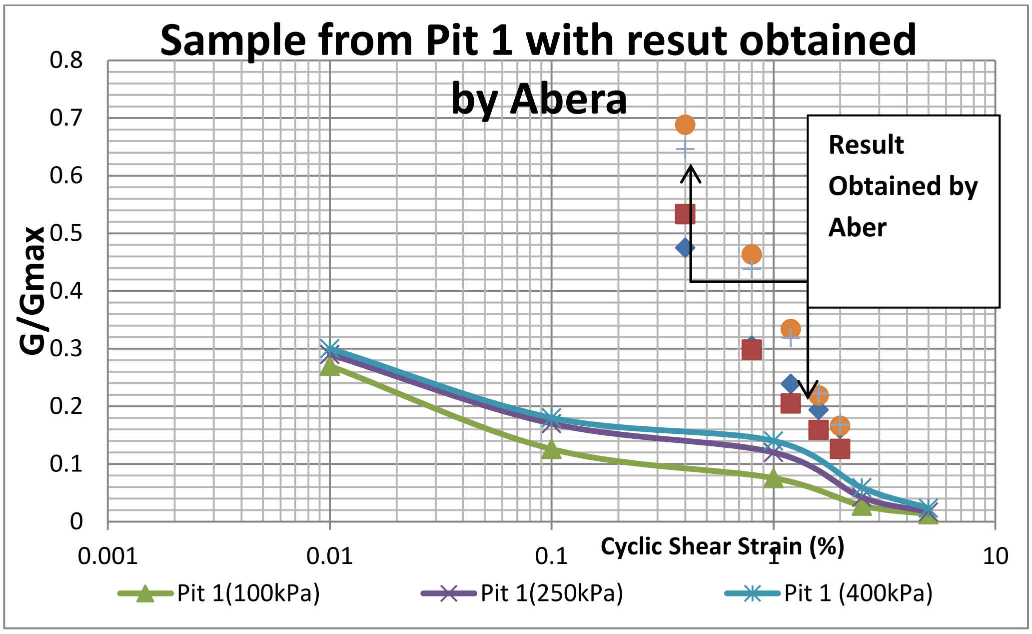
d. Comparison values of damping ratio with clay

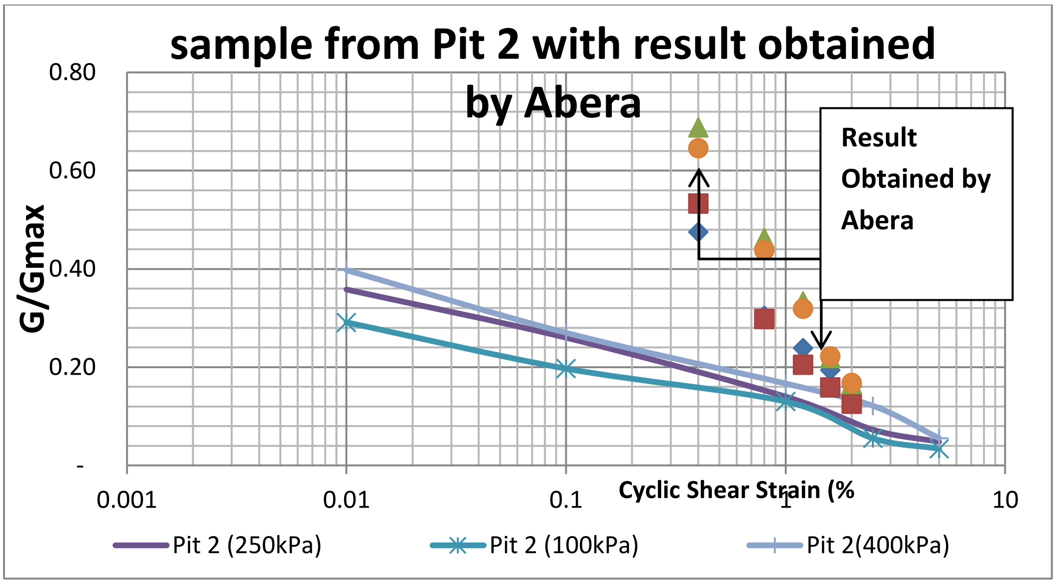


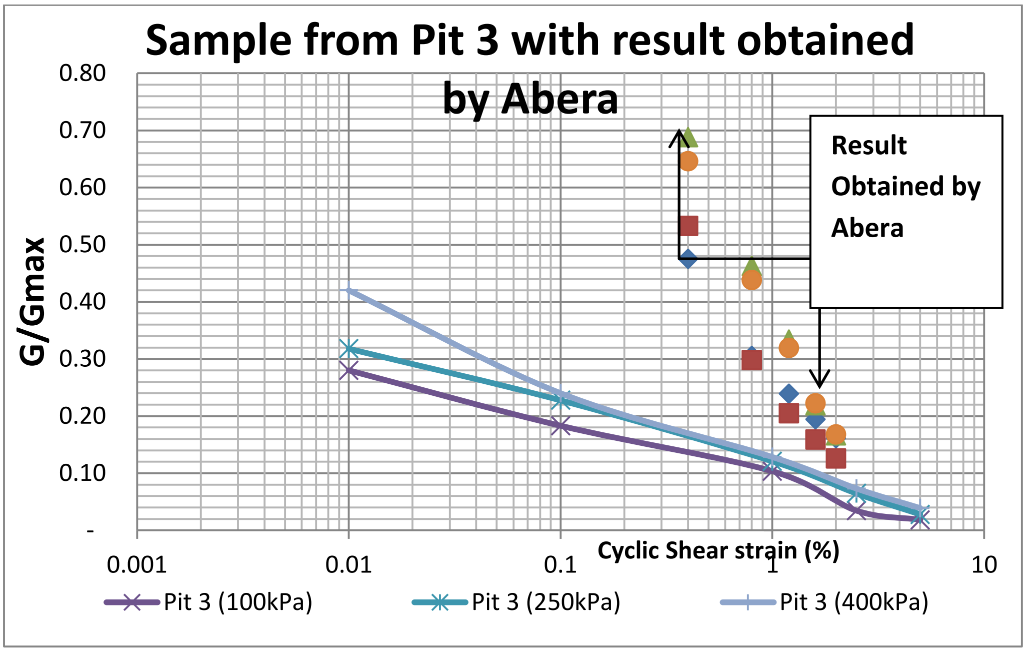


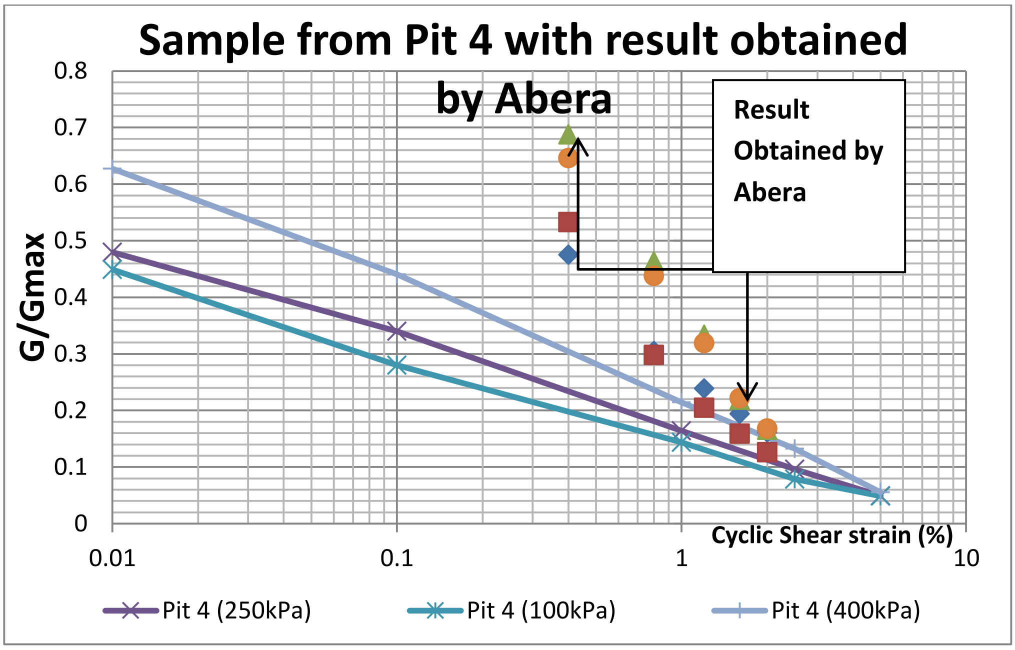

Sample from Pit 3 comparison with clay
Damping ratio (%)
35
30
25
20
15
10
5
0
Limits
Cyclic shear strain (%)
0.001
0.01
0.1
1
10
100kPa
250kPa
400kPa

e. Comparison values of G/G_{max} with result obtained by Abera Bedada

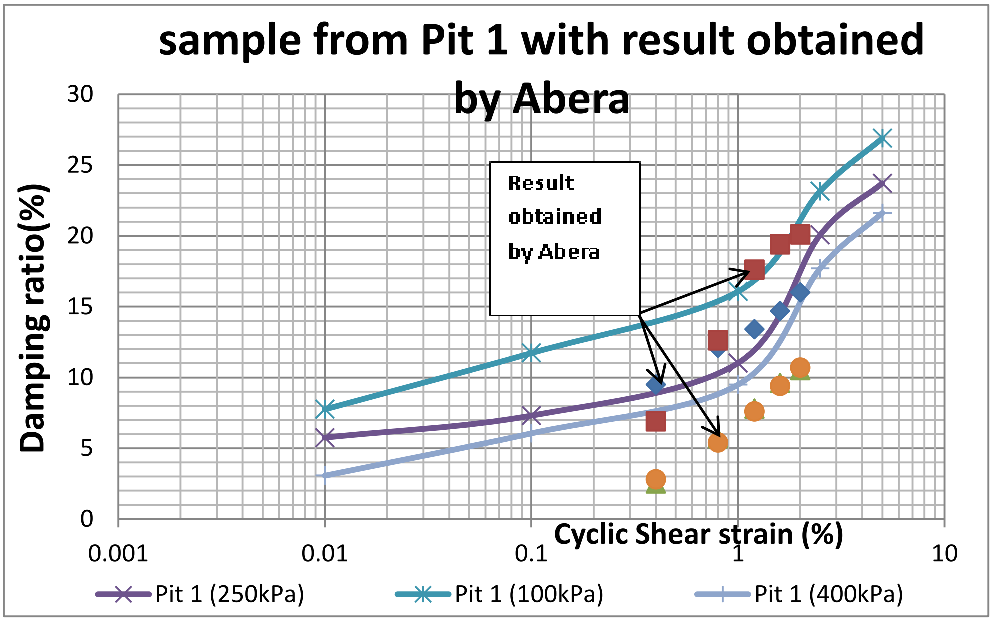


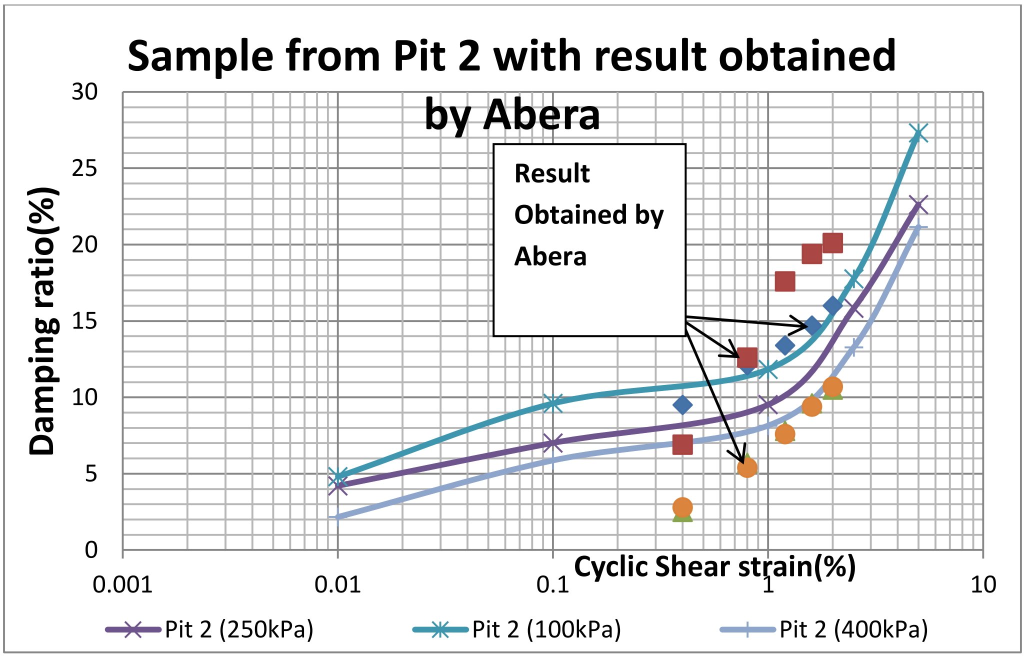


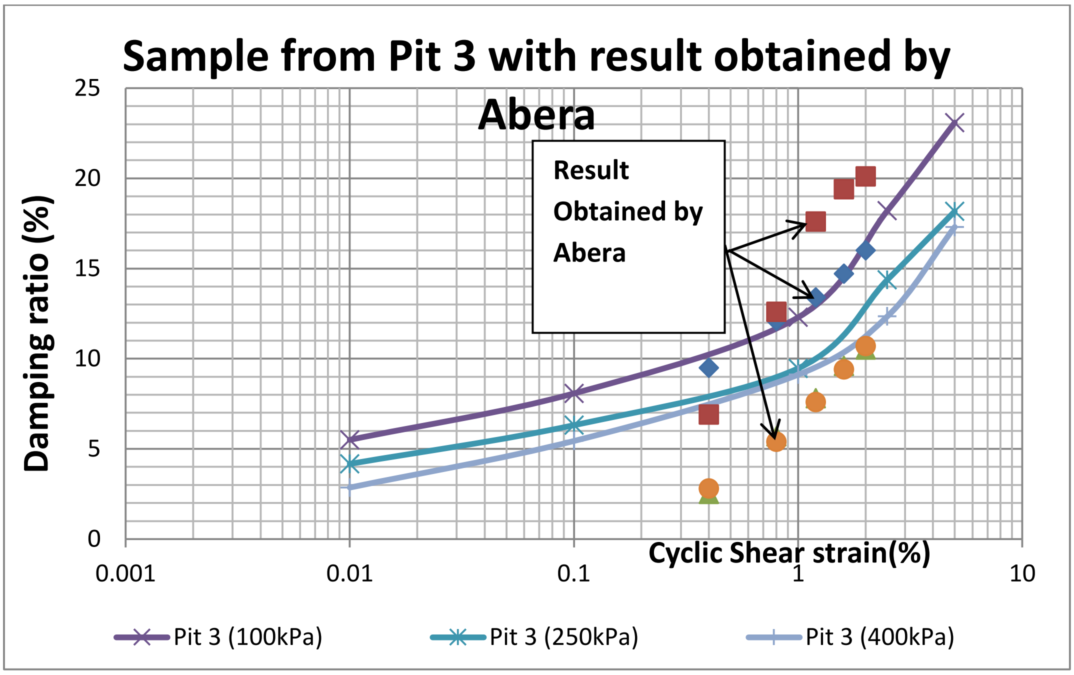

Sample from Pit 3 with result obtained by Abera
G/Gmax
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
-
0.001
0.01
0.1
1
10
Cyclic Shear strain (%)
Result Obtained by Abera
Pit 3 (100kPa)
Pit 3 (250kPa)
Pit 3 (400kPa)

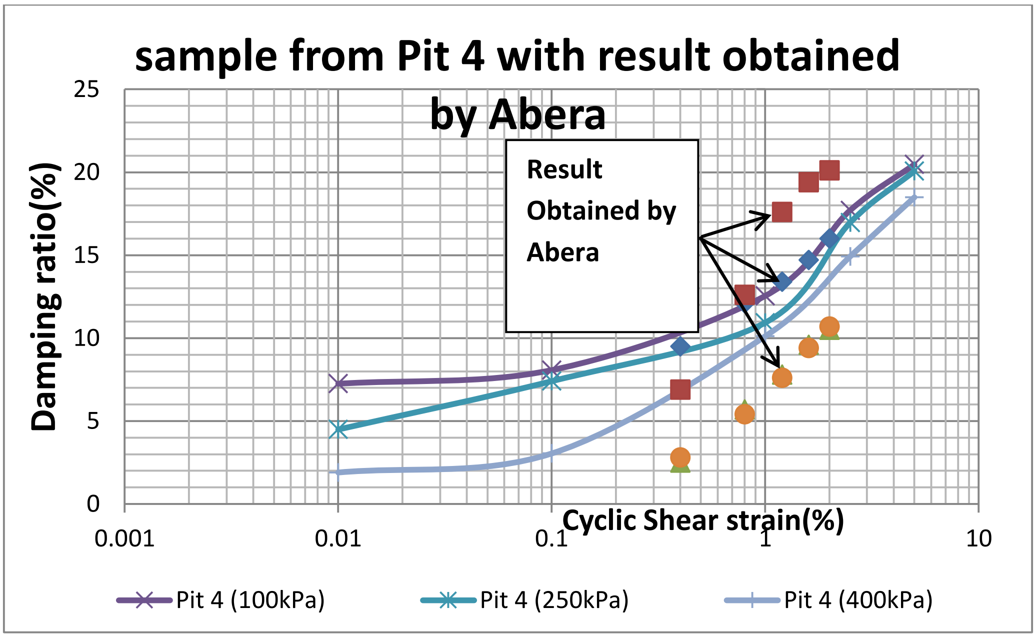

Sample from Pit 4 with result obtained by Abera
G/Gmax
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.01
0.1
1
10
Cyclic Shear strain (%)
Result Obtained by Abera
Pit 4 (250kPa)
Pit 4 (100kPa)
Pit 4 (400kPa)

f. Comparison values of Damping ratio with result obtained by Abera Bedada






Sample from Pit 3 with result obtained by Abera
Damping ratio (%)
25
20
15
10
5
0
0.001
0.01
0.1
1
10
Cyclic Shear strain(%)
Result Obtained by Abera
Pit 3 (100kPa)
Pit 3 (250kPa)
Pit 3 (400kPa)


sample from Pit 4 with result obtained by Abera
Damping ratio(%)
25
20
15
10
5
0
0.001
0.01
0.1
1
10
Cyclic Shear strain(%)
Result Obtained by Abera
Pit 4 (100kPa)
Pit 4 (250kPa)
Pit 4 (400kPa)

DECLARATIONS

I, undersigned, declare that this thesis is based on my original work and that has not been presented for a degree in any other University. All sources of materials used for this thesis has been fully acknowledged.

ABU GEMECHU FEYISSA

Signature--Date---------------------------------