

# **SHEAR MODULUS AND DAMPING RATIO OF DRY KOKA SAND USING CYCLIC SIMPLE SHEAR TEST**

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## **SYMBOLS AND ABBREVIATIONS**

AASHTO	American Association of State Highway Transport Officials
ASTM	American Society for Testing and Materials
AAU	Addis Ababa University
$\gamma$	Strain amplitude
$\sigma'_m$	Effective mean principal stress
$e$	Void ratio
$N$	Number of cycles of loading
$S$	Degree of saturation
$C'$	Effective cohesion
$\Phi'$	Effective angle of friction
OCR	Overconsolidation ratio
$G_{max}$	Maximum shear modulus
$\sigma'_v$	Vertical effective stress
OMC	Optimum Moisture Content
PI	Plasticity Index
PL	Plastic Limit
$D$	Damping ratio
$G$	Shear modulus
$D_r$	Relative density

## **ABSTRACT**

The nature and distribution of earthquake damage is strongly influenced by the response of soils to cyclic loading, and the behavior of soils subjected to dynamic loading is influenced by dynamic soil properties. The determination of these dynamic soil properties is invaluable in the response analysis of soils to cyclic loading. Of these dynamic soil properties, shear modulus and damping ratio are the most important; and this paper is concerned with the determination of the shear modulus and damping ratio of sand.

In this research the shear modulus and damping ratio of Koka sand is determined using the cyclic simple shear test. The results have shown that the obtained normalized shear modulus values are located lower than those suggested in literature, especially at lower strains. For higher strains the obtained normalized shear modulus values agree with those suggested in literature. The obtained damping values are almost within the range suggested in literature.

## **1. INTRODUCTION**

### **1.1. Background**

The nature and distribution of earthquake damage is strongly influenced by the response of soils to cyclic loading. Different soil properties influence the behavior of the soil for different problems. The behavior of soils subjected to dynamic loading is influenced by dynamic soil properties [1].

The measurement of dynamic soil properties is a critical task in the solution of geotechnical earthquake engineering problems. A wide variety of field and laboratory techniques are available, each with different advantages and limitations with respect to different problems. Many are oriented towards measurement of low-strain properties and many others towards properties mobilized at large strains. The selection of testing techniques for measurement of dynamic soil properties requires careful consideration and understanding of the specific problem at hand.

The shear modulus and damping characteristics of cyclically loaded soils are critical to the evaluation of many geotechnical earthquake engineering problems not only at low-strains but because soils are nonlinear materials, also at intermediate and high strains [1]. These soil properties can be determined using empirical relations [4] or experimentally.

Even though Ethiopia is susceptible to earthquake, no experiment is done in the determination of the shear modulus and damping ratio of sand in our country. Our Geotechnical engineers have been using

charts from literature for the determination of these parameters for design. In this research the shear modulus and damping ratio of Koka sand is determined in the laboratory using the cyclic simple shear test.

## **1.2. Objective of the Study**

The main objective of this research is to determine the stiffness and damping values of a particular cohesionless soil viz., sand using the cyclic simple shear test and to provide additional useful guide in the selection of soil characteristics for analysis purposes.

## **1.3. Scope of the Investigation**

The scope of this study is limited to the determination of shear modulus and damping ratio of sand that is collected from Koka town. Koka sand is chosen because many tests were done with this sand. The method used in the determination of these parameters is limited to the cyclic simple shear test.

## **1.4. Methodology**

To meet the above-mentioned objectives, sand sample was collected from Koka town for the investigation. The sample of the sand was taken from downstream of the Koka River. The clay content was determined. Since the clay content was found to be high, all other tests were performed on the washed and air dried sample. Using the washed sample of sand specific gravity and particle size distribution of the sand sample were determined. Then cyclic simple shear test was performed, and, the stiffness and damping of the sand sample determined.

## **1.5. Organization of the Thesis**

This research is organized in five chapters. The first chapter gives a brief description of the thesis background, objectives, scope, and the methodology employed. The second chapter presents a brief literature review on dynamic soil characteristics of soils, and stiffness and damping values of sand. In the third chapter the cyclic simple shear system is explained. The fourth chapter presents laboratory test results. The last chapter gives the conclusions drawn and the recommendations made regarding the test results.

## **2. LITERATURE REVIEW**

### **2.1. Introduction**

Much progress has been made in recent years in the development of analytical procedures for evaluating the response of soil deposits under seismic loading conditions. Successful application of such procedures for determining ground response in specific cases, however, is essentially dependent on the incorporation of representative soil properties in the analysis. Thus, considerable effort has also been directed toward the determination of soil properties for use in these analytical procedures.

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

### **2.2. Physical properties and structure**

To date the laboratory testing of sands has been focused almost exclusively on the reconstituted sands. Much less emphasis was placed on the testing of natural sands due to the difficulty in sampling and its complicated nature. It has been well established that the mechanical behavior of reconstituted sands is governed by a few material properties. Examples are mineralogy, grain size distribution, grain shape, specific gravity and true friction angle.

#### **2.2.1. Physical properties**

The physical characteristics of sands are normally determined by the particle size, shape, surface texture and size distribution. The mineral

composition determines the hardness, cleavage, and resistance to physical and chemical breakdown.

### **Particle size and distribution**

The range of particle sizes in engineering soils is very large. Based on M.I.T classification [6], the commonly used particle ranges are shown in Figure 2-1. As can be seen from the figure, the particle size for clean sand ranges from 0.06–2 mm. Generally speaking, individual sand sized particles are visible to the naked eye. However, silts and clays can be seen only with optical or electron microscopes. The distribution of particle of sands is conveniently shown as a grading curve on a particle size distribution chart. If the grading curve is flat and the sand specimen contains a wide variety of particle sizes, it is said to be well graded. If the curve is steep and one size predominates, the specimen is said to be poorly graded.

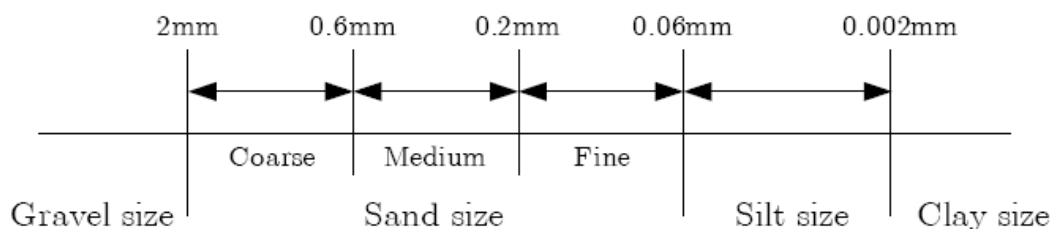
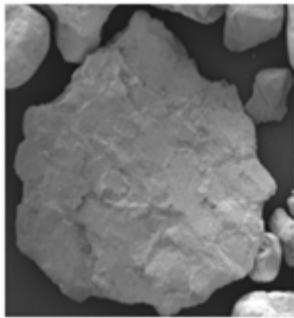


Figure 2-1: Range of particle sizes in soils.

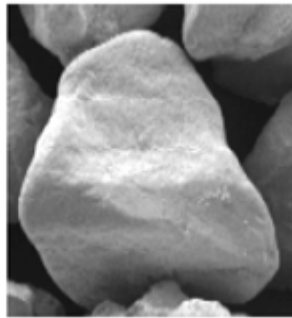
### **Particle shape**

The particle shape is normally described in terms of angularity and roundness. Elongated and platy particles can develop preferred orientations, which may be responsible for anisotropic properties of the specimen. The stress-strain and strength properties are also influenced by the surface texture of the particles of sands. Figure 2-2

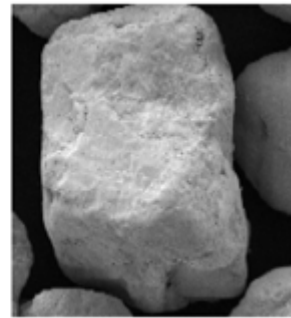
illustrates the different particle shapes found in sand together with clay platelets [15].



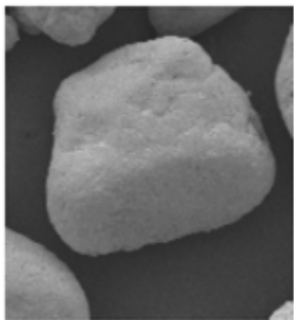
Angular



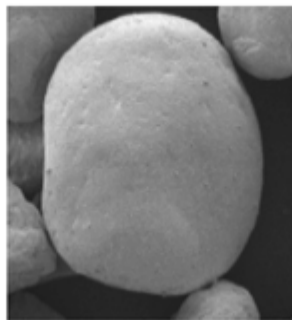
Subangular



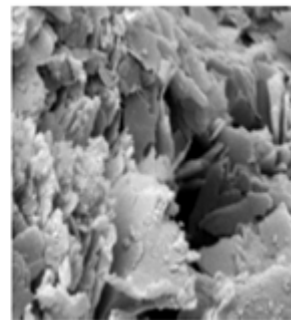
Subrounded



Rounded



Well rounded



Clay

Figure 2-2: Characterization of particle shapes of sands and flake shapes of clays [15]

### **Mineralogy**

Sands are predominantly rock fragments or mineral grains of common rock-forming minerals. The most abundant mineral is quartz. Calcareous (or carbonate) sediments are widely distributed in

oceans and in the tropical and temperate regions of the world. They can occur as bulky particles, shells, precipitates or in solution.

### **2.2.2. Structure**

It is well known that the matrix structure is an important controlling factor for the mechanical behavior of sands. The structure of sands can be defined as being the arrangement of sand grains on a particulate scale. This includes a description of particle contacts, their orientations and distribution, and cementation at the contacts.

## **2.3. Dynamic Soil Properties**

### **2.3.1. Shear Modulus**

Most soils have curvilinear stress-strain relationships as shown in Fig.2-3 below [3]. The shear modulus is expressed as the secant modulus determined by extreme points on the hysteretic loop.

### **2.3.2. Damping Ratio**

Damping is the dissipation of strain energy during cyclic loading [3]. Referring to Fig.2-3 the damping factor is proportional to the area inside the hysteretic loop.

It is readily apparent that each of these properties will depend on the magnitude of the strain for which the hysteresis loop is determined (see Fig.2-3) and thus both shear moduli and damping factors must be determined as functions of the induced strain in a soil specimen or soil deposit. [1]

The purpose of this study is to determine the dynamic shear moduli and damping factors for sand under loading conditions similar to those illustrated in Fig.2-3 and to present the results in a form which will provide a useful guide in the selection of soil characteristics for analysis purposes

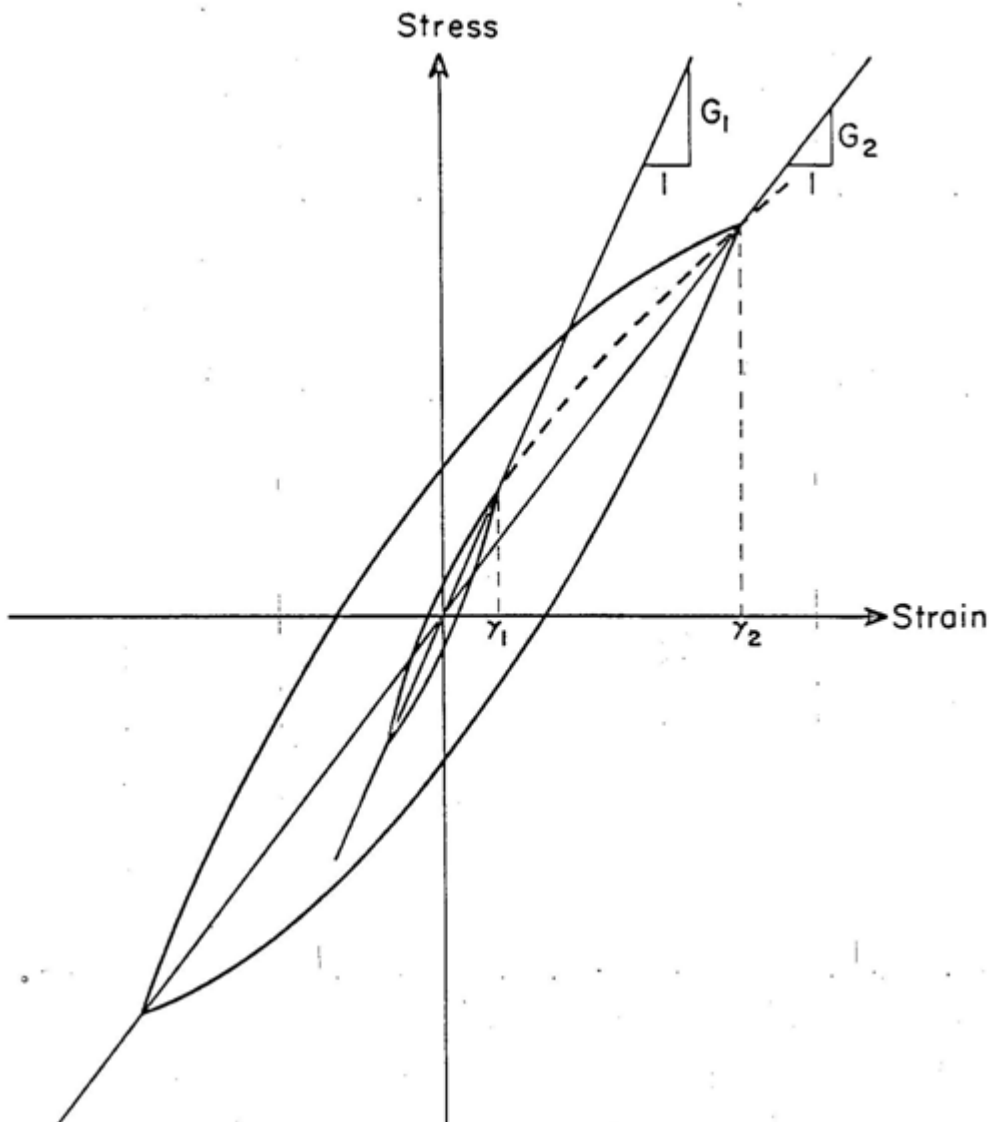


Figure 2-3: Hysteretic stress-strain relationships at different strain amplitudes

## **2.4. Methods of Determining Shear Moduli and Damping Characteristics**

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

### **2.4.1. Direct determination of stress-strain relationships**

Hysteretic stress-strain relationships of the type shown in Fig.2-3 may be determined in the laboratory by means of triaxial compression tests, simple shear tests or torsional shear tests conducted under cyclic loading conditions. In general these procedures are useful for measuring shear moduli and damping factors under moderate to relatively high strains.

As this paper is concerned in the determination of shear moduli and damping factors using the cyclic simple shear test, this test is discussed in detail in the next chapter.

### **2.4.2. Forced vibration tests**

Forced vibration tests, involving the determination of resonant frequencies and measurement of response at other frequencies have been used to determine both shear moduli and damping factors. Test conditions in the laboratory have included the application of longitudinal vibrations and torsional vibrations to cylindrical samples or shear vibrations to layers of soil placed on a shaking table. In general these procedures are useful for determining properties at relatively low to moderate strain levels.

### **2.4.3. Free vibration tests**

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

### **2.4.4. Field measurement of wave velocities**

Field tests have been used to measure the velocity of propagation of compression waves, shear wave, and Rayleigh waves from which values of soil modulus can readily be determined for low strain conditions. These procedures have not provided values of damping factors however.

### **2.4.5. Analysis of ground response during earthquakes**

In a few cases where motions have been determined at different depths in a soil profile during earthquakes, computations have been made to determine the effective moduli and damping factors affecting the response of the deposit.

The different test procedures for measuring moduli and damping characteristics and the approximate ranges of strain within which they have been used are summarized below in Table 2-1[4].

Table 2.1 Test Procedure for Measuring Moduli and Damping Characteristics [4]

General procedure	Test Condition	Approximate Strain Range	Properties Determined
Determination of hysteretic stress-strain relationships	Triaxial compression	10 <sup>-2</sup> to 5%	Modulus;damping
	Simple Shear	10 <sup>-2</sup> to 5%	Modulus;damping
	Torsional Shear	10 <sup>-2</sup> to 5%	Modulus;damping
Forced vibration	Longitudinal vibrations	10 <sup>-4</sup> to 10 <sup>-2</sup> %	Modulus;damping
	Torsional vibrations	10 <sup>-4</sup> to 10 <sup>-2</sup> %	Modulus;damping
	Shear vibrations-lab	10 <sup>-4</sup> to 10 <sup>-2</sup> %	Modulus;damping
	Shear vibrations-field		Modulus
Free vibration tests	Longitudinal vibrations	10 <sup>-3</sup> to 1%	Modulus;damping
	Torsional vibrations	10 <sup>-3</sup> to 1%	Modulus;damping
	Shear vibrations-lab	10 <sup>-3</sup> to 1%	Modulus;damping
	Shear vibrations-field	10 <sup>-3</sup> to 1%	Modulus
Field wave velocity measurements	Compression waves	≈5*10 <sup>-4</sup>	Modulus
	Shear waves	≈5*10 <sup>-4</sup>	Modulus
	Rayleigh waves	≈5*10 <sup>-4</sup>	Modulus
Field seismic response	Measurement of motions at different levels in depth		Modulus;damping

## 2.5. Shear Modulus Values and Damping Ratios for Sands

### 2.5.1. Previous studies

The factors affecting the shear moduli and damping factors of soils and expressions for determining these properties have been studied by Hardin and Drnevich (1970) [4]. In this study it was suggested that the primary factors affecting moduli and damping factors are:

- Strain amplitude,  $\gamma$
- Effective mean principal stress,  $\sigma'_m$
- Void ratio,  $e$
- Number of cycles of loading,  $N$
- Degree of saturation for cohesive soils,  $S$

and that less important factors include:

- Overconsolidation ratio, OCR
- Effective stress strength parameters,  $c'$  and  $\Phi'$
- Time effects

### 2.5.2. Shear modulus values for sands

All investigation have shown that modulus values for sands are strongly influenced by the confining pressure, the strain amplitude and the void ratio( or relative density) but not significantly by variations in grain size characteristics. It has been found that in general, the shear modulus and confining pressure are related by the equation [4]:

$$G=1000K_2(\sigma'_m)^{0.5} \dots\dots\dots(2.1)$$

so that the influence of void ratio and strain amplitude can be expressed through their influence on the parameter  $K_2$ .

It is found that at very low strains ( $\gamma < 10^{-3}$  percent),  $K_2$  depends only on the void ratio,  $e$ . At intermediate strains ( $10^{-3} < \gamma < 10^{-1}$  percent), the variation of  $K_2$  with strain is only slightly influenced by the vertical stress, and very slightly by variations in  $\phi'$  and  $K_0$ . The values of  $K_2$  are still influenced strongly by the void ratio, however. At very high strains ( $\gamma > 10^{-1}$  percent), the values of  $K_2$  are slightly influenced by the vertical stress, but they are essentially independent of  $\phi'$ ,  $K_0$  and  $e$ .

Thus, for practical purposes, values of  $K_2$  may be considered to be determined mainly by the void ratio or relative density and the strain amplitude of the motions.

It is shown that the variation of the ratio of shear modulus at strain  $\gamma$  to shear modulus at shear strain of  $10^{-4}$  percent with shear strain falls within the relatively narrow band shown in Fig.2-4 [4]. Thus, a close approximation to the shear modulus vs. shear strain relationship for any sand can be obtained by determining the modulus at a very low strain level, and then reducing this value for other strain levels in accordance with the results indicated by the dashed (average) line in Fig.2-4. There is also a good general agreement between the results of laboratory and in-situ investigations [4].

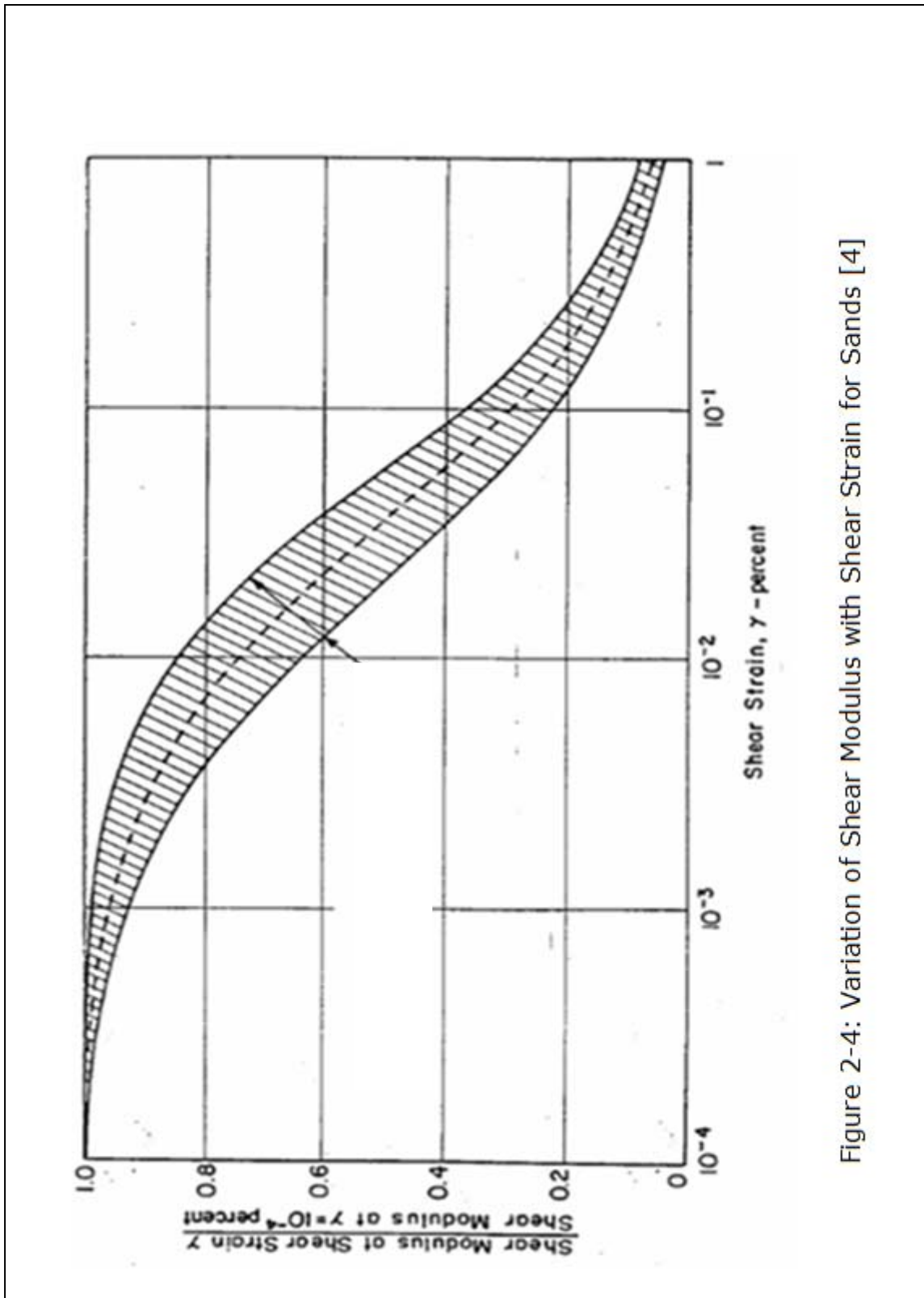


Figure 2-4: Variation of Shear Modulus with Shear Strain for Sands [4]

Seed and Idriss [10] have shown that for sands and gravels the maximum shear modulus may be calculated by the following equation:

$$G_{\max}/p_a = 22K_2(\sigma'_o/p_a)^{0.5} \dots\dots\dots (2.2)$$

where  $K_2$  is an empirical constant (different from that expressed in equation 2.1) which may be related to the soil type and relative density as shown in Table 2-2 [10];  $\sigma'_o$  is the effective mean normal stress;  $p_a$  is atmospheric pressure in the same units as  $\sigma'_o$ .

*Table 2-2 Values of constant used with equation 2.2 to estimate cyclic shear modulus at low strains for sands [10]*

Relative Density	$K_2$
90	70
75	61
60	52
45	42
40	40
30	33

### **2.5.3. Damping Ratio for Sands**

Hardin and Drnevich [4] have studied the factors influencing the damping ratio of sands. From their study, they concluded that shear strain, effective mean principal stress (or  $\sigma_v'$  and  $K_o$ ), void ratio and number of cycles were very important, while octahedral shear stress, angle of friction and degree of saturation had lesser effects. As in the case of moduli, the effects of variations in grain size characteristics were considered to be relatively insignificant.

It is observed that the effects of  $\Phi'$ ,  $K_o$ , void ratio and degree of saturation are relatively minor. Thus, the main factor affecting the relationship between damping ratio and shear strain is the vertical confining pressure  $\sigma_v'$ .

Approximate upper and lower bound relationships between damping ratio and shear strain are shown by the dashed lines in Fig.2-5 [4] and a representative average relationship is shown by the solid line.

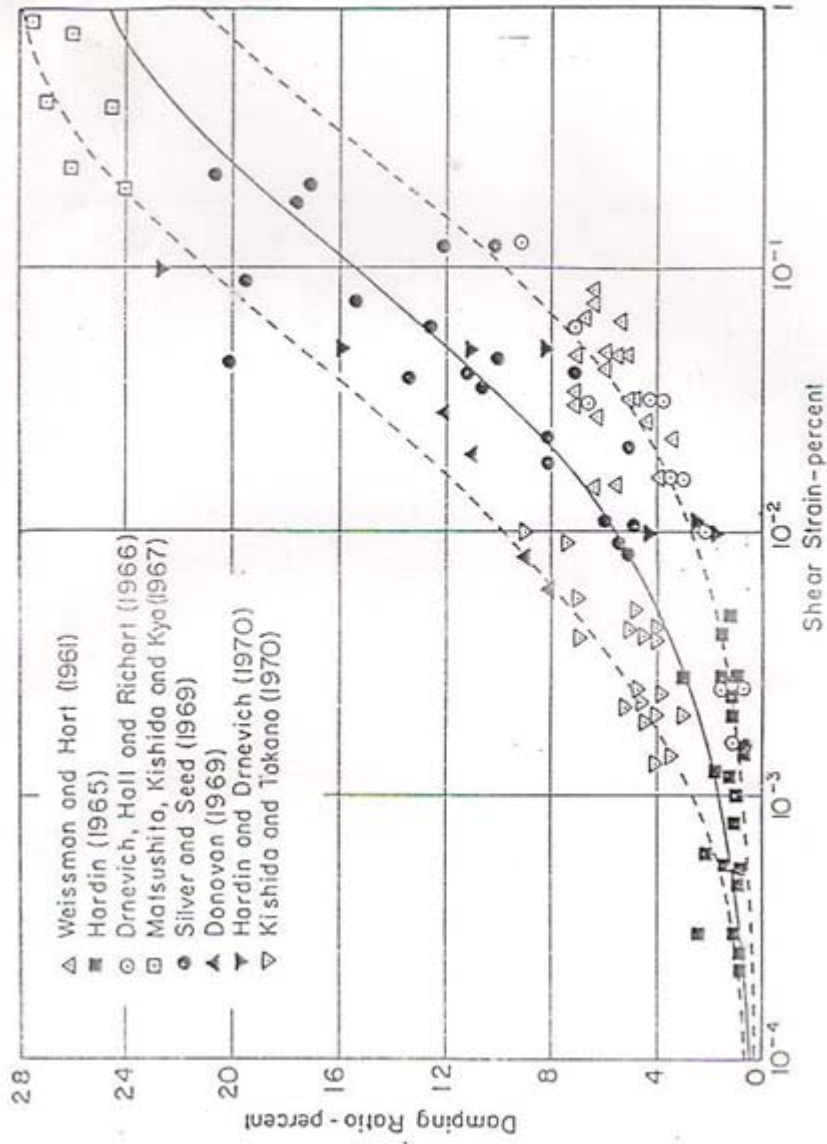


Figure 2-5: Damping ratios for sands [4]

### **3. DESCRIPTION OF EXPERIMENTAL TECHNIQUES**

#### **3.1. Cyclic Simple Shear Testing System**

##### **3.1.1 Introduction**

The cyclic simple shear apparatus is generally used for research into the dynamic field of soil behavior. Nowadays there are different types of cyclic simple shear apparatuses in use. In this research the type of apparatus used is *31-WF7500* cyclic simple shear machine which is developed by the Controls Group. The complete system is controlled by the UTS004 software application program.

In the cyclic simple shear device, the shear strain is induced by horizontal movement at the bottom of the sample relative to the top. The horizontal diameter of the sample remains constant [13]. The system is designed to allow a sample to be consolidated, drained and then sheared.

##### **3.1.2 General Description**

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

The sample is supported by a rubber membrane placed and secured with O-rings. To maintain a constant diameter throughout the test the sample is supported by a series of slip rings.

During shear the rings slide across each other as shown below in Fig. 3-1. During the shearing stage of the test the vertical height of the

sample is maintained at a constant height by the vertical actuator in a closed control loop with the vertical displacement transducer. The rings maintain a constant sample diameter.

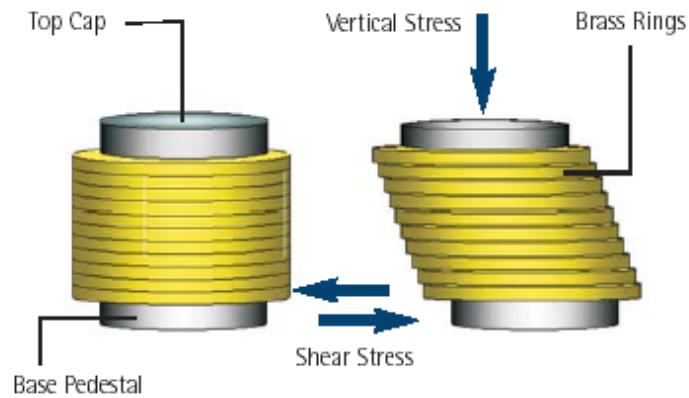


Figure 3-1: The Shearing Stage



Figure 3-2: 31-WF750 cyclic simple shear machine

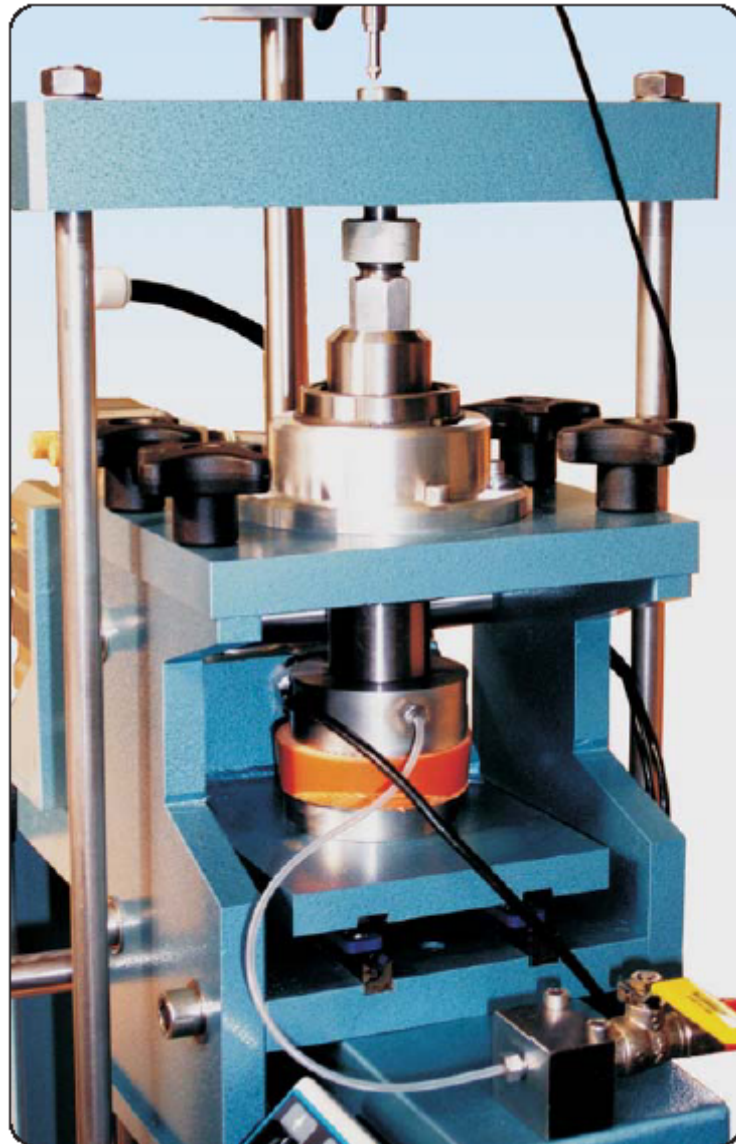


Figure 3-3: Samples in the 31-WF7500 cyclic simple shear machine

### **3.1.3 Data Acquisition and Monitoring**

#### **Consolidation Stage**

The consolidation stage is simply the application of a static axial loading stress to the specimen while the lateral loading (shear) axis is held stationary. Axial stress and specimen displacements (axial and lateral) data are measured over time and logged by the system. Logged data is also displayed to the operator in the form of charts and tables as the test stage proceeds. The consolidation stage is manually terminated by the operator once consolidation of the specimen is determined to be complete.

#### **Cyclic Simple Shear Stage**

This stage of the test applies a lateral cyclic shear force, or optionally a displacement, to the specimen, while the axial axis is either maintained at the specified stress, or optionally, the specimen height is maintained. Both axial and lateral force and specimen displacements are measured over time and logged by the system. Measured data is obtained from 50 sample points captured over the cycle period [14]. This data is displayed to the operator in the form of wave shapes, charts and tables and also logged by the system to an archive data file. The loading cycle shape is operator selectable from predefined functions but may also be a user generated shape.

## **3.2. Overview of the Testing Method**

Cyclic simple shear testing is used in this research work to determine the shear modulus and damping ratio of sand. It has long been recognized, however, that there is no standard procedure to characterize the cyclic behavior of sands within the geotechnical engineering community. It is found that there are three factors that

are more critical than others when trying to reproduce meaningful and comparable results [15]:

- Specimen preparation method;
- Shape of the loading pattern;
- Initial state of sand tested.

### **Specimen preparation method**

The method of reconstituting samples has a strong effect on dynamic test results, and it is important to consider this effect in the interpretation of test data. In this experimental work, the tamping specimen preparation technique was used for the cyclic testing programs. Particles larger than 2cm were removed from the sample before preparing specimen for test [12].

### **Shape of the loading pattern**

Three wave forms are commonly used in geotechnical research laboratories including triangular, square-shaped and sinusoidal. Square-wave loading produces more severe conditions than sinusoidal loading and consequently may produce an apparently lower cyclic shear strength. At the other extreme, triangular wave loading produces less severe conditions than sinusoidal loading and consequently may produce an apparently higher cyclic shear strength [16]. The sinusoidal wave form was recommended [15] and has been used in all tests conducted in this research work.

### **Initial state of sand tested**

According to the literature on characterizing the behavior of saturated sands under cyclic loading, the main influencing factors have been identified as the initial effective confining pressure  $\sigma'_0$  and density [15]. For this reason, in this study, specimens are tested under different confining pressures and densities.

### **Loading rate**

Information available at the present time indicates that the dynamic behavior of soils is relatively insensitive to the frequency of applied cyclic loading within the range of 0.5 to 2 Hz. It is therefore common practice to carry out laboratory cyclic tests at a frequency in the neighborhood of 1 Hz [16]. A frequency of 1 Hz has been used in most tests conducted in this research work.

## **4. LABORATORY TESTS AND ANALYSIS OF RESULTS**

### **4.1. Laboratory Tests for Index Properties**

#### **4.1.1. General**

Even though the country has abundant sand deposits [7], due to financial limitations and time constraints sand samples are collected from one site located at the central Ethiopia. The sand samples for laboratory investigation are collected from eastern Showa. The samples are collected from the riverbed of the Koka River just downstream of the dam.

To conduct the different laboratory tests, about 200Kg of sand sample was collected in bulk randomly from the site. From the visual inspection of the sand sample, it was observed that the color of the sample is whitish blue. Before conducting any of the laboratory tests, the clay content of the sample was determined, and it was found that it has high clay content. Therefore all the laboratory tests were conducted on the washed and air-dried sand sample.

The following laboratory tests are conducted and the results are presented and analyzed in the next chapters:

- Clay content
- Particle size Analysis
- Specific gravity test
- Maximum and minimum dry densities
- cyclic shear tests

#### **4.1.2. Test Results**

##### **4.1.2.1. Clay Content**

Since this paper is concerned in the properties of the pure sand, the sand to be tested should be free from impurities. So, the clay content of the sample was determined as per the specification of AASHTO 11-91 [8] and the results are shown in Table A-1 in the appendix.

The average clay content of the sample is determined to be 8%, which is higher than the acceptable i.e. 1% [7]. Thus, washing of the sand sample is imperative before conducting tests on the sample.

##### **4.1.2.2. Particle Size Analysis**

Particle size analysis is widely used in engineering classification of soils. The purpose of this test is to determine the distribution of grain sizes in a given soil sample. The result of Particle size analysis performed on the sand sample is shown in Table A-2 and the Particle size distribution curve is shown in Fig. A-1 in the appendix.

##### **4.1.2.3. Soil Classification**

According to ASTM D 2487, Standard Test Method for Classification of soils for Engineering Purposes, which is based on the Unified Soil Classification System [9], the soil sample is classified as poorly graded sand (SP). It has a coefficient of uniformity of 3.91 and with a mean grain size  $D_{50}$  of 0.97mm.

##### **4.1.2.4. Specific Gravity**

The specific gravity of solid matter in a soil particle may be defined as the ratio of the unit weight of solid matter to the unit weight of water [6]. The specific gravity was determined in the laboratory according

to ASTM D854-92 [5]. According to ASTM D854-92, specific gravity of soils is determined by means of a pycnometer. The results of the test are shown in Table A-3 in the appendix. The specific gravity of the sand sample is found to be 2.65.

#### **4.1.2.5. Maximum Dry Density**

In this study the standard used for determining the maximum density of the sample was ASTM D698. The result is summarized in Table A-4. The maximum dry density of the sample was found to be 1.972g/cm<sup>3</sup>. See Fig. A-2 in the appendix.

#### **4.1.2.6. Minimum Dry Density**

The minimum dry unit weight is determined according to ASTM D4254 [5]. The dry sand is shaken in a glass cylinder and allowed to fall freely, thereby entrapping air and forming a grain structure enclosing the maximum possible volume of voids. Using this method the minimum dry density of the sample was found to be 1.092g/cm<sup>3</sup>.

#### **4.1.2.7. Relative Density**

Relative density can be used to define the state conditions in cohesionless soils. It can be defined as follows [9]:

$$D_r = ((\gamma_n - \gamma_{min}) / (\gamma_{max} - \gamma_{min})) (\gamma_{max} / \gamma_{min}) \quad \dots\dots\dots (4-1)$$

Where  $D_r$  is the relative density,

$\gamma_n$ ,  $\gamma_{max}$ ,  $\gamma_{min}$  are the natural, maximum and minimum unit weights respectively.

Using this equation the relative densities of the specimens in this research are calculated.

## **4.2. Test Results Using the Cyclic Simple Shear Test**

In this section, the determination of the shear modulus and damping ratio on sand samples using the cyclic simple shear apparatus is presented.

### **4.2.1. Sample Preparation**

Cylindrical soil specimens of size 70 mm diameter and 20mm height were prepared by tamping in three layers. Loose sand samples (of relative densities 15-35%) and medium dense sand samples (of relative densities 35-65%) [6] are considered in the air dry state in this study. Each layer is compacted by hand tamping to the required density.

### **4.2.2. Cyclic Simple Shear Test results**

#### **4.2.2.1. The Consolidation Stage**

The consolidation stage was continued until the rate of vertical strain becomes less than 0.05% per hour [11]. Because the consolidation pressure is the main factor affecting the shear modulus of sands, the specimens were consolidated under different pressures.

#### **4.2.2.2. The Cyclic Shearing Stage**

The tests conducted for the evaluation of shear modulus and damping ratio are strain-controlled tests. A servo-system is used to apply cycles of controlled deformation. The specimen were cyclically loaded through 40 cycles [5] using 1 Hz sinusoidal deformation.

#### **4.2.2.3. Determination of Shear Modulus and Damping Ratio**

The hysteresis loop is achieved by plotting shear stress against shear strain. It is used for the calculation of shear modulus and damping ratio for each cycle. In order to illustrate this, cyclic shear test results of one specimen consolidated to a pressure of 300KPa and cyclically loaded to maximum single displacement amplitude of 0.095mm (corresponding to maximum single strain amplitude of 0.14%) are shown in Fig.4-1, Fig.4-2 and Fig.4-3. Additional cyclic shear test results are shown in appendix B.

The shear stress is calculated simply by dividing the shear force by the area of the specimen base ( $0.003848\text{m}^2$ ), and the shear strain is calculated by dividing the shear displacement by the diameter of the specimen circular base (70mm). Shear modulus and damping ratio are calculated using the following equations:

$$G = \zeta_{DA} / \gamma_{DA}$$
$$\text{and } D = A_{\text{loop}} / 4\pi A_{\Delta} \quad \text{..... (4-2)}$$

with variables as described in Fig.4-4. To obtain these two values from the hysteresis loop the recommendations of standard ASTM D3999 are followed. Since, in most seismic events, the number of significant cycles is likely to be less than 20, the values determined at 5 cycles are likely to provide reasonable values for all practical purposes [2]. Thus, in this research work the values determined at 5 cycles are considered for the analysis purpose.

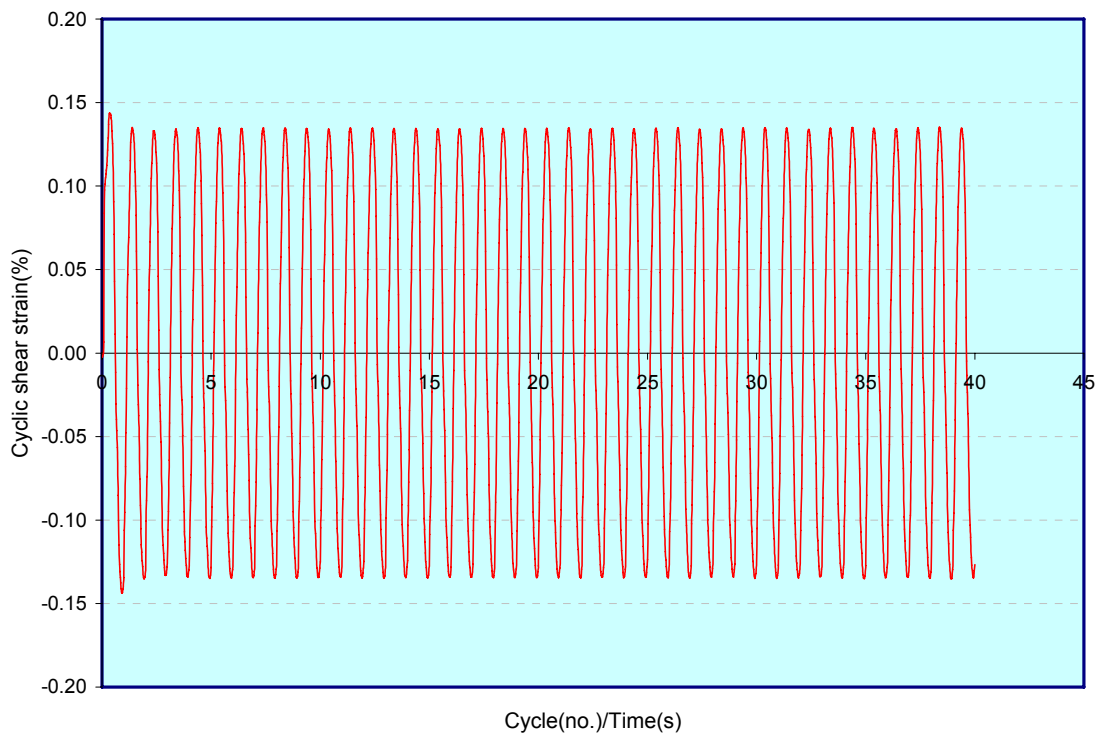


Figure 4-1: Graph of cyclic shear strain vs. cycle

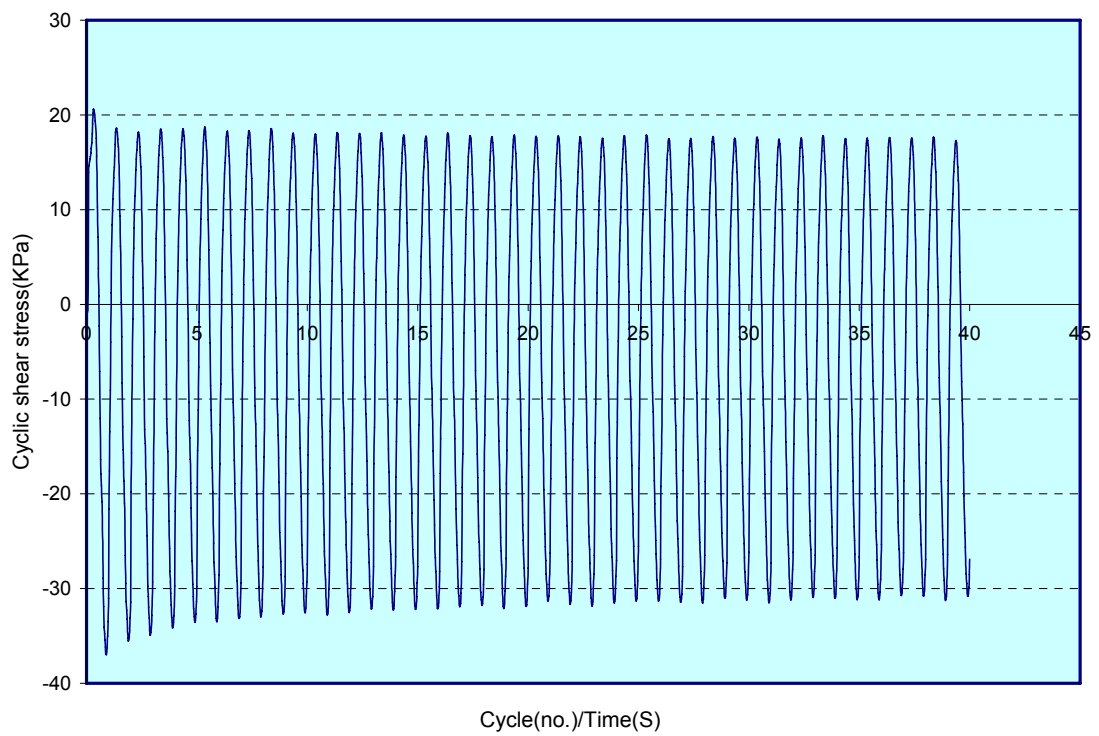


Figure 4-2: Graph of cyclic shear stress vs. cycle

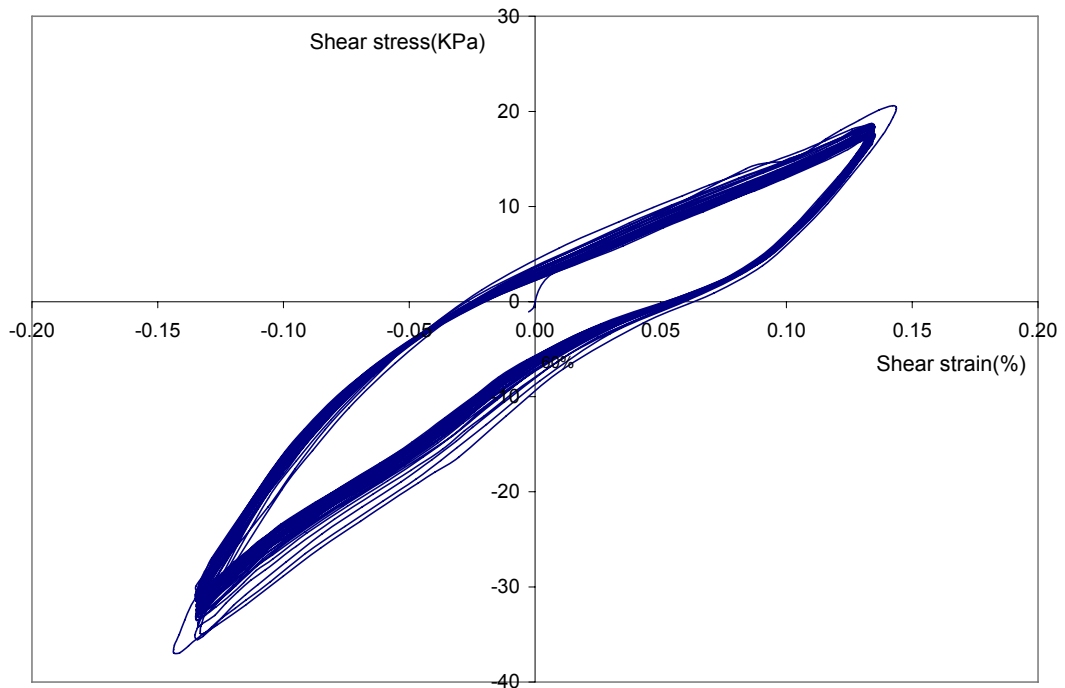


Figure 4-3: Graphs of hysteresis loops

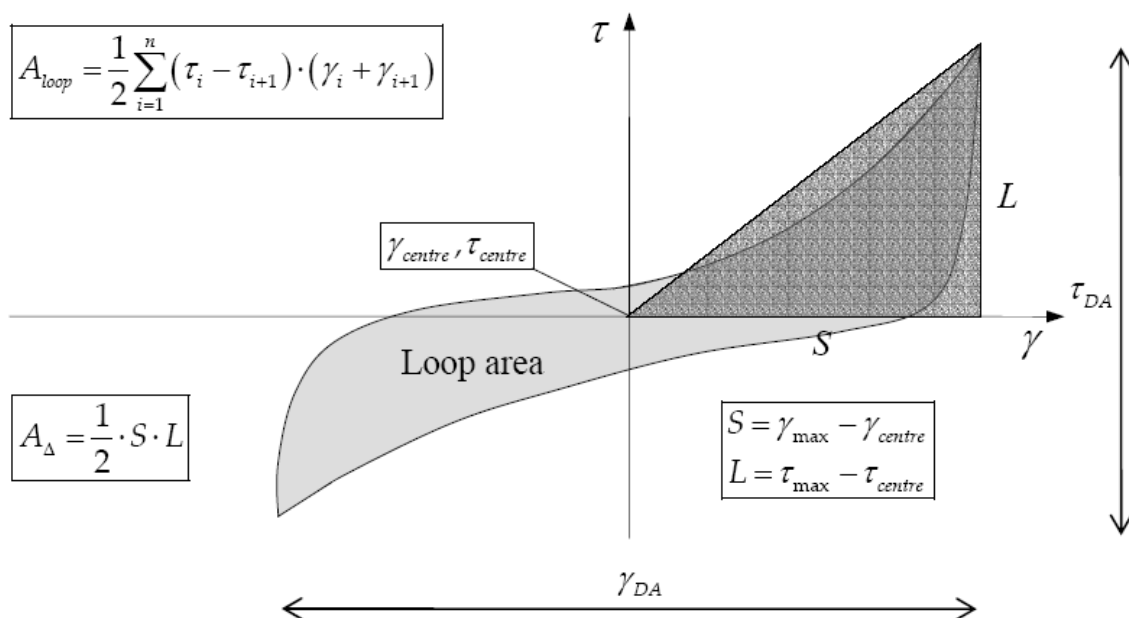


Figure 4-4: Hysteresis loop with triangle area

### 4.3. Discussion on Test Results

The influence of relative density and consolidation pressure on the shear modulus and damping values is studied.

#### 4.3.1. Influence of Relative Density on Shear Modulus

Because of small sample size and the sample is to be compacted on the pedestal of the apparatus, it was difficult to obtain a wide range of relative densities.

A change in relative density from 40% to 64% is reflected by a relatively modest change in the shear modulus degradation curves as demonstrated in Fig.4-5.

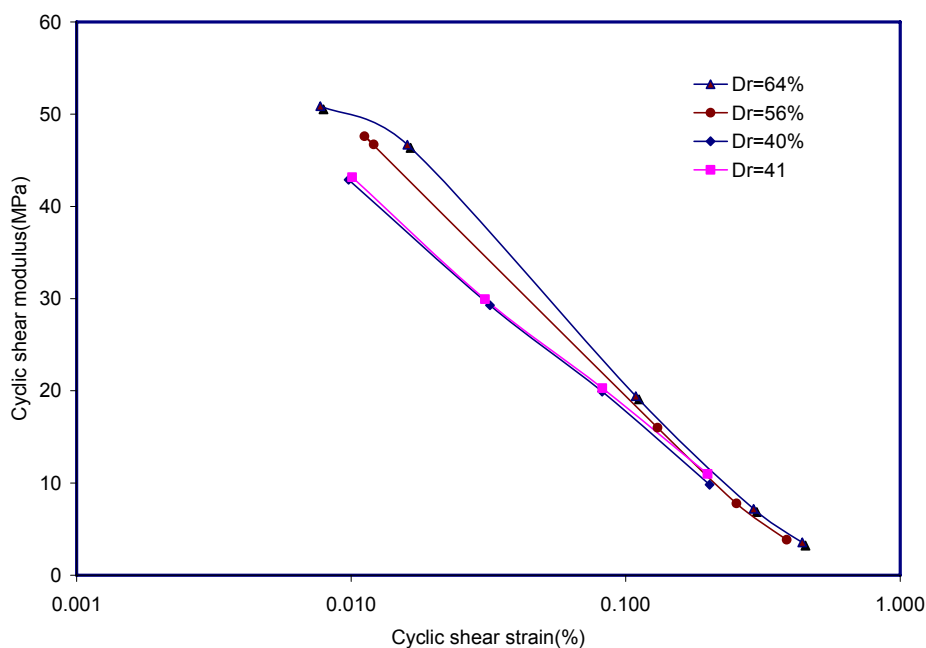


Figure 4-5: Influence of relative density on shear modulus-shear strain relationship

#### 4.3.2. Influence of Consolidation Stress on Shear Modulus and Damping Values

As mentioned in the previous sections it is the consolidation stress which has a major influence on shear modulus and damping values. In this research samples were consolidated under an axial stress of 100, 200, 300 and 400KPa in order to evaluate the influence of consolidation stress.

From Fig. 4-6 it can be seen that samples consolidated to a higher consolidation stress have higher shear modulus values.

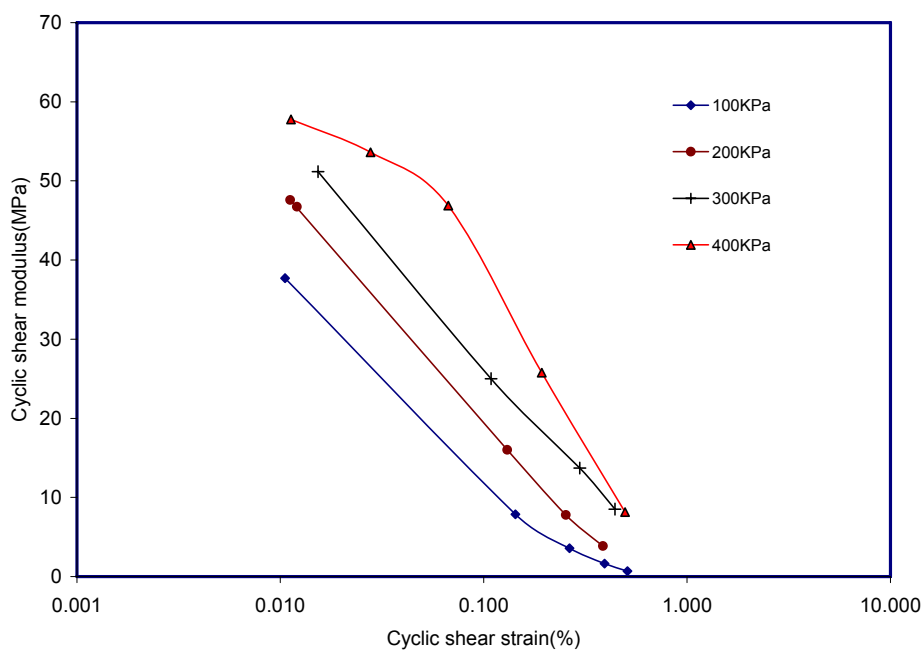


Figure 4-6: Influence of effective vertical stress on shear modulus at 40% relative density

Fig.4-7 shows the influence of effective vertical stress on the damping ratio. As it could be observed from the figure, the damping ratio decreases as the confining pressure increases.

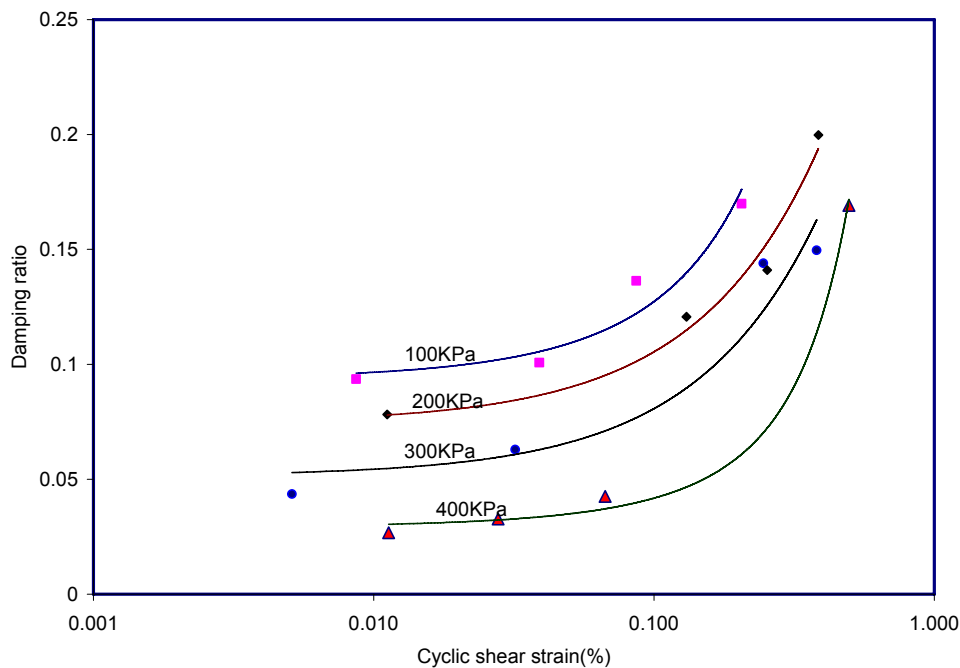


Figure 4-7: Influence of effective vertical stress on damping ratio at 40% relative density

#### 4.3.3. Comparison of Test Results with Previous Findings

##### Shear modulus values

Since cyclic simple shear tests are high strain tests (0.01 to 5%) one cannot measure shear modulus and damping values at low strain levels. So, the maximum shear modulus,  $G_{max}$  which corresponds to very low strain levels cannot be determined from such tests. For the sake of comparison the maximum shear modulus,  $G_{max}$  of each specimen is determined using equation 2.2 rewritten below, and the

calculated  $G_{max}$  is used to obtain the normalized shear modulus which is then compared with those obtained from literature [4].

$$G_{max}/p_a = 22K_2(\sigma'_o/p_a)^{0.5} \dots\dots\dots(4.3)$$

Where  $K_2$  is a constant which depends on the relative density and it can be obtained from Table 2-2.  $\sigma'_o$  is the effective mean normal stress;  $p_a$  is atmospheric pressure in the same units as  $\sigma'_o$ . For this study the atmospheric pressure is taken to be 101KPa.

For example, for the specimen mentioned in section 4.2.2.3, the effective mean normal stress,  $\sigma'_o = (\sigma'_v + 2\sigma'_h)/3$  and  $\sigma'_h = K_o\sigma'_v$ . where  $\sigma'_v$  is the effective vertical stress;  $\sigma'_h$  is the effective horizontal stress and  $K_o$  is the coefficient of lateral pressure at rest. For cohesionless soils  $K_o$  is often taken to be 0.5[9]. The relative density of the specimen is calculated using Eq.4-1 rewritten below:

$$D_r = ((\gamma_n - \gamma_{min}) / (\gamma_{max} - \gamma_{min})) (\gamma_{max} / \gamma_{min})$$

Since  $\gamma_{min} = 1.09g/cm^3$ ,  $\gamma_{max} = 1.97g/cm^3$  and the sample unit weight  $\gamma_n = 1.41g/cm^3$ , it follows that:

$$D_r = ((1.41 - 1.09) / (1.97 - 1.09)) (1.97 / 1.09) * 100\% \\ = 51\%$$

For a specimen having a relative density of 51%, from Table 2-2, by interpolation  $K_2 = 46$ .

$$\text{So, } \sigma'_o = (300 + 2 * 0.5 * 300) / 3 \\ = 200\text{KPa.}$$

$$G_{max}/p_a = 22K_2(\sigma'_o/p_a)^{0.5} \\ G_{max}/101 = 22 * 46 * (200/101)^{0.5}$$

Thus,  $G_{max} = 143,832\text{KPa}$

For this specimen the fifth cycle cyclic shear modulus is 19,210KPa.

$$\text{So, } G/G_{max} = 19,210\text{KPa} / 143,832\text{KPa} \\ = 0.134$$

Similarly,  $G_{\max}$  for each specimen is calculated and the normalized shear modulus ( $G/G_{\max}$ ) is plotted against shear strain and is compared with findings from literature [4] as shown in Fig. 4-8.

From the figure it can be seen that the obtained normalized shear values are located lower than those suggested by literature, especially at lower strains. For higher strains the obtained normalized shear values agree with those suggested by literature [4].

It would be appropriate at this stage to mention some of the factors that have influenced the test results.

1. In this study, the standard used for determining the maximum dry density of the sample was ASTM D698. This method may not give a well defined maximum unit weight for cohesionless soils, and the result may be less than that obtained by other test methods. This has a great influence in calculating the maximum shear modulus, because the term  $K_2$  in equation 4.1, used to calculate the maximum shear modulus, is dependent on the relative density of the specimen.
2. The rings are supposed to be frictionless but practically one cannot avoid friction. So, the small friction induced in the rings may affect the results obtained.
3. There is sufficient experimental evidence to suggest that by adopting different specimen preparation methods, the stress-strain curves may show marked differences. So, due to the specimen preparation method employed in this study, there might be a deviation of the results from those obtained from literature.

4. Scalping (the removal of the coarse fraction of a sample) is also known to influence test results particularly in dynamic testing, but the nature of the influence is not well understood. Therefore, the influence of scalping should be considered whenever interpreting the test results.
5. It is assumed that there is uniform distribution of void ratio and particles in the specimen. But in reality the distribution is not uniform, thus, affecting the test results.

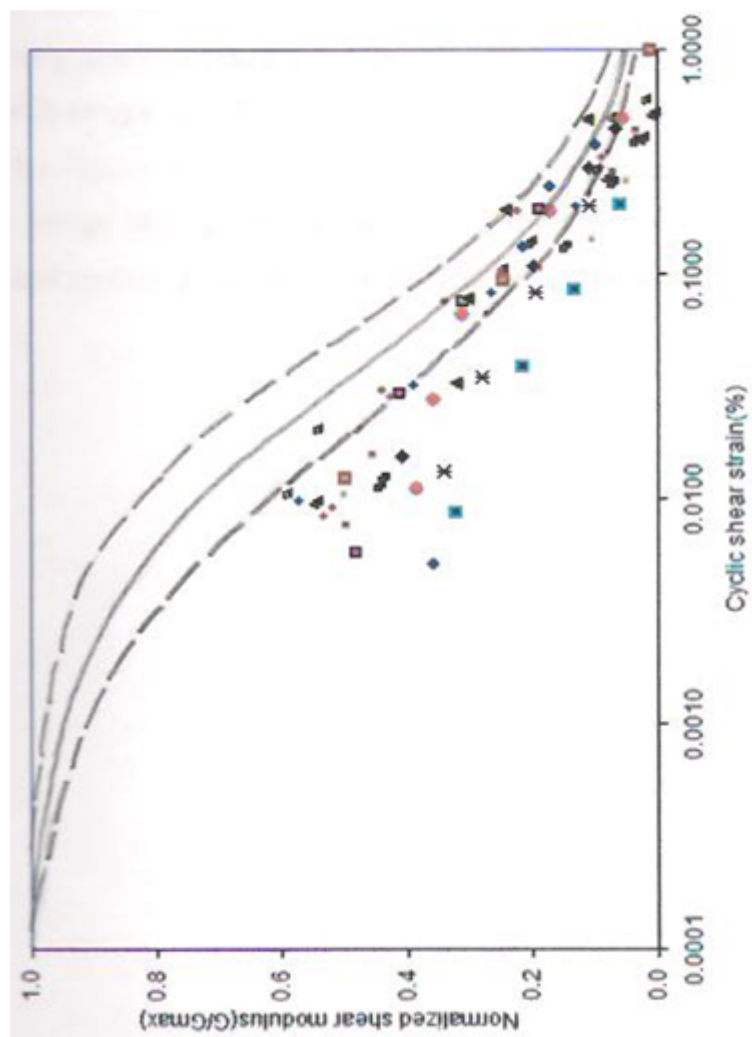


Figure 4-8: Comparison of shear modulus values with previous findings.

### Damping Ratio Values

As discussed in chapter two, the main factor affecting the relationship between damping ratio and shear strain is the vertical confining pressure  $\sigma_v'$ .

For the sake of comparison the damping values obtained from the laboratory are replotted on a graph showing the variation of damping ratio with single amplitude shear strain [4]. This is shown in Fig.4-9. From the figure it can be seen that the obtained damping values are almost within the range suggested by literature. Scatter of the data is attributed to the difficulty in reconstituting the sand sample and the factors that affect the shear modulus results mentioned above will also affect the damping values obtained.

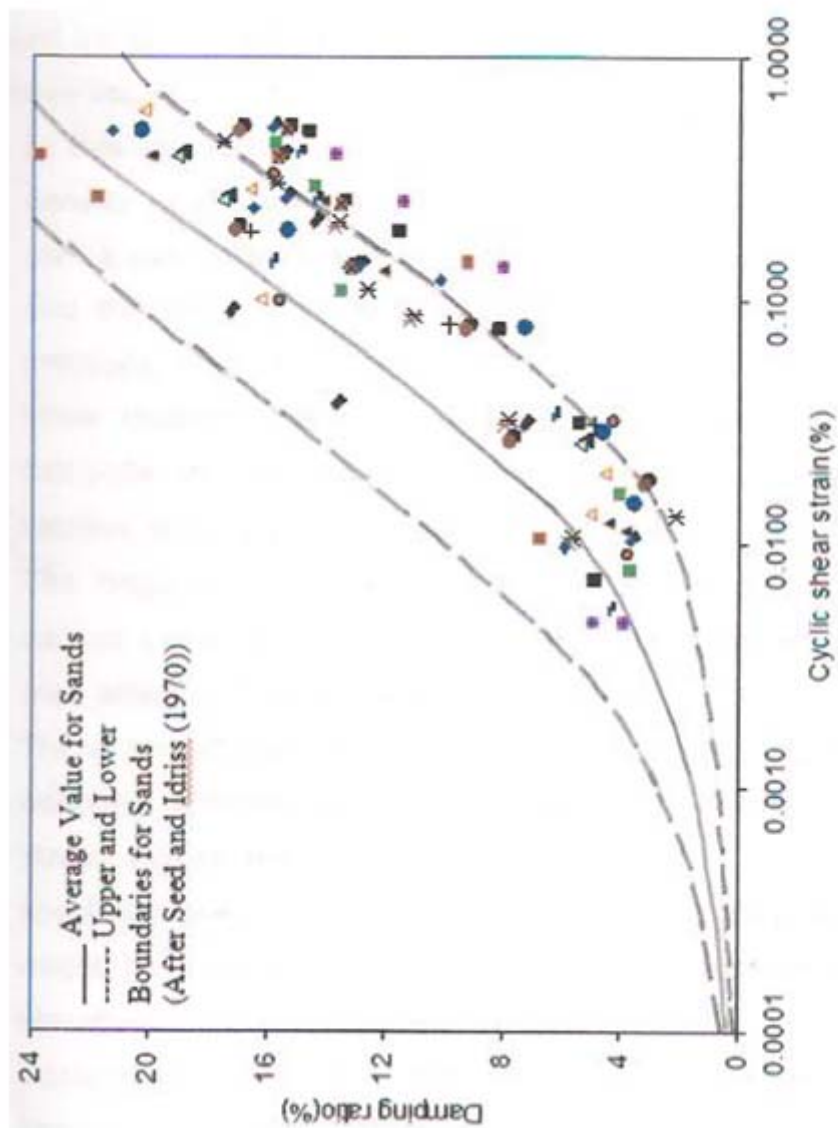


Figure 4-9: Comparison of damping values with previous findings.

## **5. CONCLUSIONS AND RECOMMENDATIONS**

In this study, investigations are conducted to determine the shear modulus and damping values of Koka sand using one of the advanced soil testing apparatuses: the cyclic simple shear test apparatus. Based on the results, it is possible to draw conclusions and to make recommendations as given below.

### **5.1. Conclusions**

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

1. The obtained normalized shear modulus values are located lower than those suggested in literature, especially at lower strains. For higher strains the obtained normalized shear values agree with those suggested in literature [4].
2. The obtained damping values are almost within the range suggested in literature.

## **5.2. Recommendations for Future Work**

The present work has attempted to determine the shear modulus and damping ratio of sands using the cyclic simple shear system. From the findings of the study on the determination of shear modulus and damping factors of sands using the cyclic simple shear apparatus the following recommendations are made:

1. Even though, there are abundant sand deposits in our country, samples are taken from one site only for this research due to financial and time constraints. A more reliable result would be obtained by taking sand samples from several other sites.
2. The present investigation studied the cyclic soil parameters under air dry condition but it is also necessary to determine these cyclic properties under saturated condition.
3. This study is performed using the cyclic simple shear apparatus only. It is important to supplement these results by cyclic triaxial test results.

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## APPENDIX A- Laboratory Results for Index Properties

Table A-1: Clay content test result of the sand sample

mass of can(g)	248
mass of can & air dried sand(g)	1284
mass of can & oven dried sand before washing(g)	1264
mass of can & oven dried sand after washing(g)	1182
mass of oven dried sand before washing(g)	1016
mass of oven dried sand after washing(g)	934
mass of washed particles(g)	82
Clay content (%)	8

Table A-2: Sieve Analysis Test Results

Sieve size (mm)	Weight retained (gm)	Percentage retained (%)	Cumulative Percentage retained (%)
19	0	0.00	0
9.5	28	3.17	3.17
4.75	74	8.39	11.56
2.36	98	11.11	22.68
1.18	150	17.01	39.68
0.6	256	29.02	68.71
0.3	188	21.32	90.02
0.15	48	5.44	95.46
0.075	18	2.04	97.51
pan	22	2.49	100.00
sum	882		-

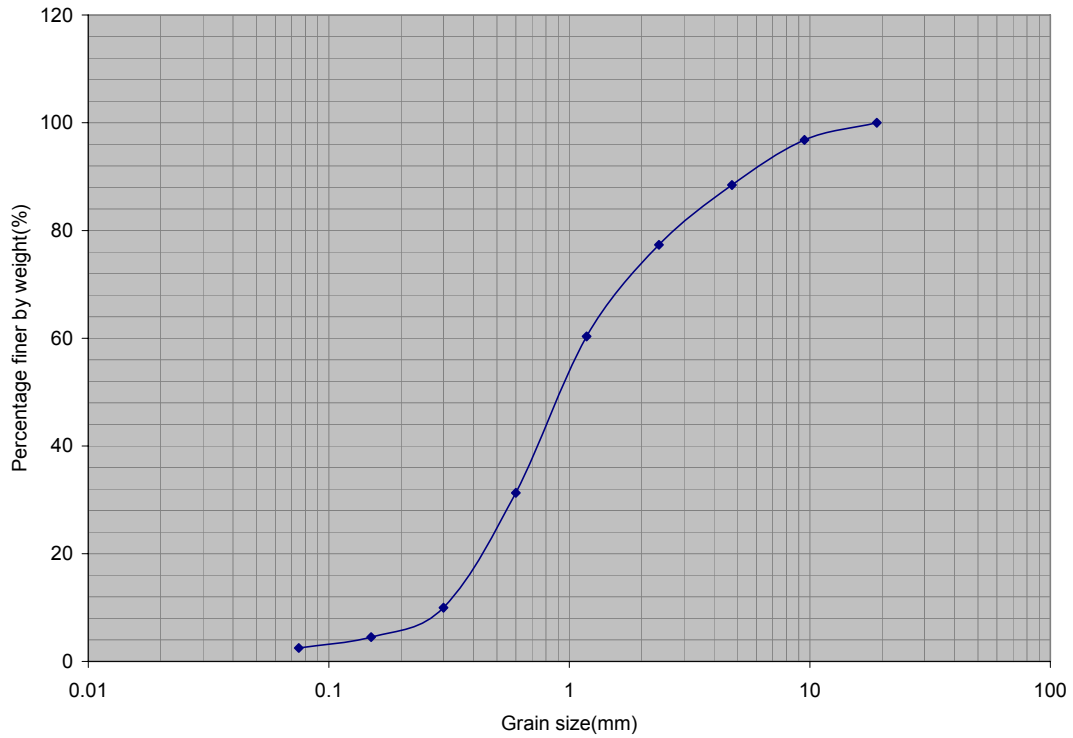


Figure A-1: Particle size distribution curve

Table A-3: Specific gravity test result of the sand sample

Description	sample number		
	1	2	3
mass of pycnometer, $M_f$	45	50	49.8
mass of sand, $M_o$	64.5	59.9	52.7
mass of pycnometer + water at $T_b$ , $M_a$	144.9	149.7	149.2
mass of pycnometer + sand + water, $M_b$	185.1	186.9	182
temperature, $T_b$	20.0	20.0	20
conversion factor, $K$	1.0	1.0	1
Specific gravity, $G_s$	2.65	2.64	2.65
average value of $G_s$	2.65		

Table A-4: Determination of maximum dry density

Description	Specimen number				
	1	2	3	4	5
mass of can(g)	5.1	5.2	5.1	15.8	15.8
mass of can + sample(g)	184	252	250	98	114
mass of can +oven dried sample(g)	178	232	222	84	90
mass of oven dried sample(g)	172.9	226.8	216.9	68.2	74.2
mass of water(g)	6	20	28	14	24
water content(%)	3.47	8.82	12.91	20.53	32.35
mass of compacting mold(g)	5640	5640	5640	5640	5640
mass of mold + sample(g)	7563	7665	7736	7854	7819.56
volume of mold(cm <sup>3</sup> )	944	944	944	944	944
mass of sample(g)	1922.8	2025.5	2096.1	2213.8	2179.56
bulk density of sample(g/cm <sup>3</sup> ),	2.04	2.15	2.22	2.35	2.31
dry density(g/cm <sup>3</sup> )	1.969	1.972	1.967	1.946	1.745

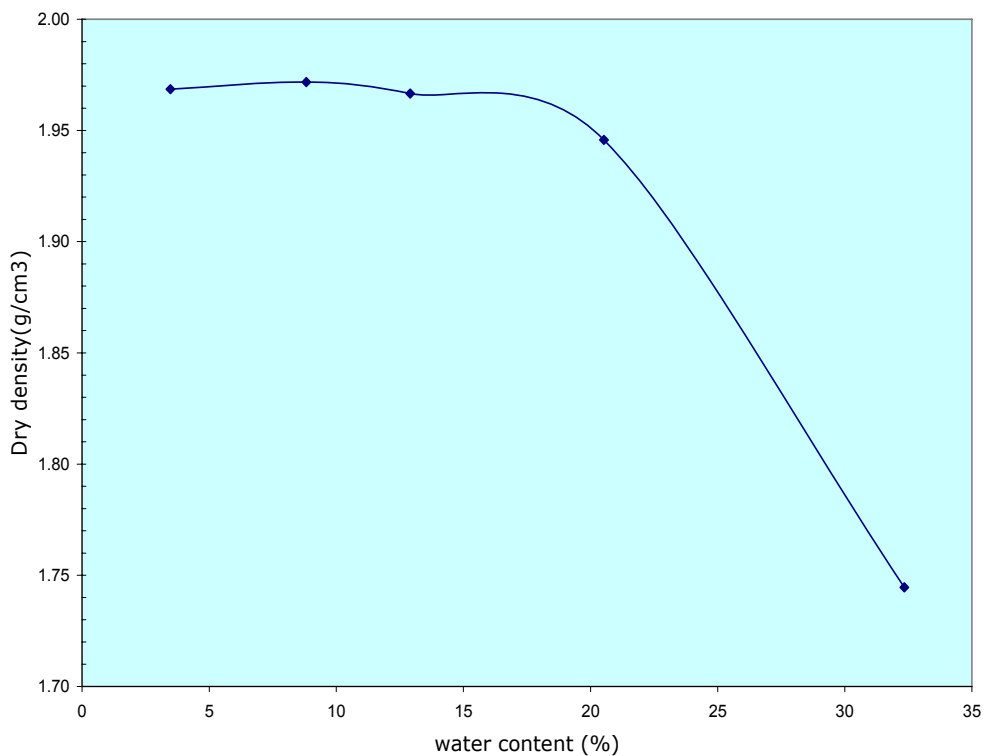


Figure A-2: Graph showing dry density vs. water content

## APPENDIX B- Cyclic Simple Shear Test Results

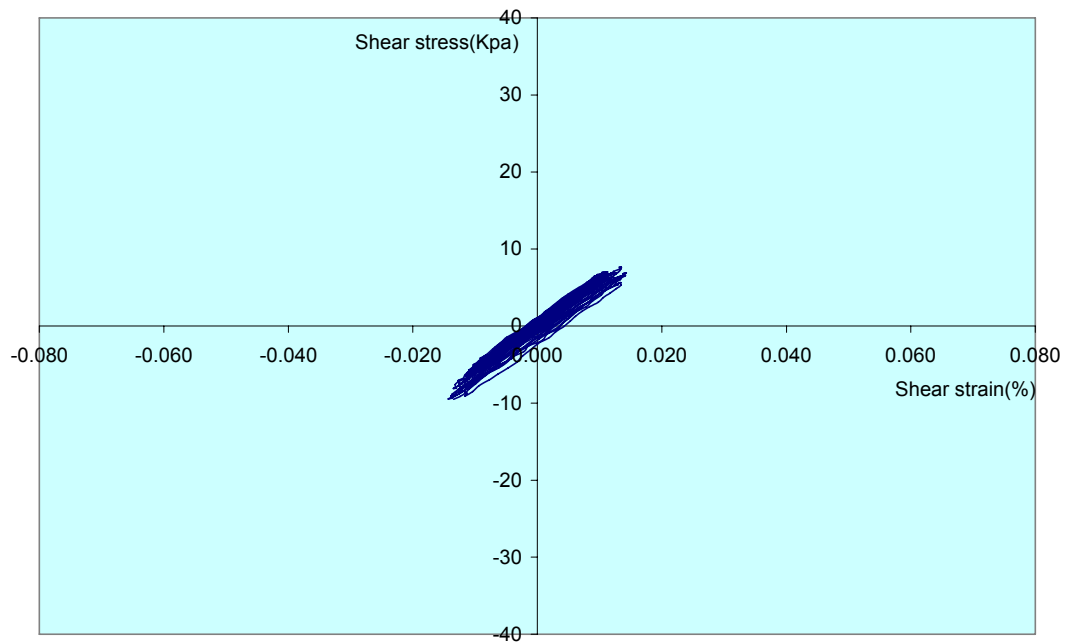


Figure B-1: Graphs of hysteresis loops for a maximum single amplitude strain of 0.01 % ( $\sigma'_v = 400\text{KPa}$ ,  $D_r = 46\%$ )

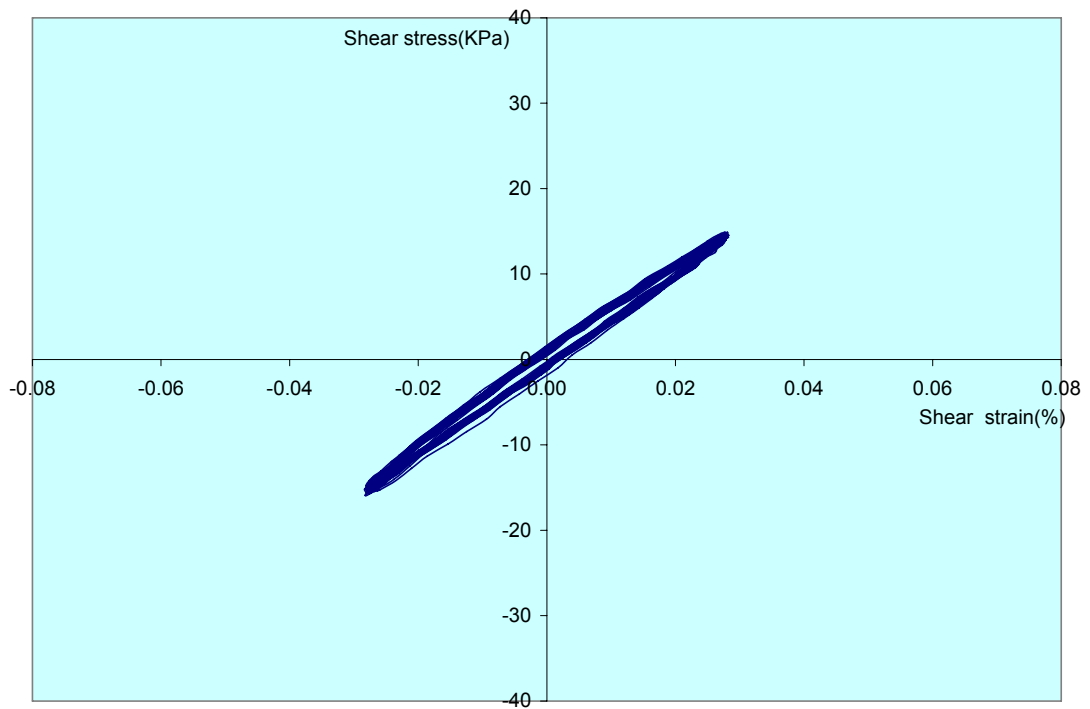


Figure B-2: Graphs of hysteresis loops for a maximum single amplitude strain of 0.03 % ( $\sigma'_v = 400\text{KPa}$ ,  $D_r = 46\%$ )

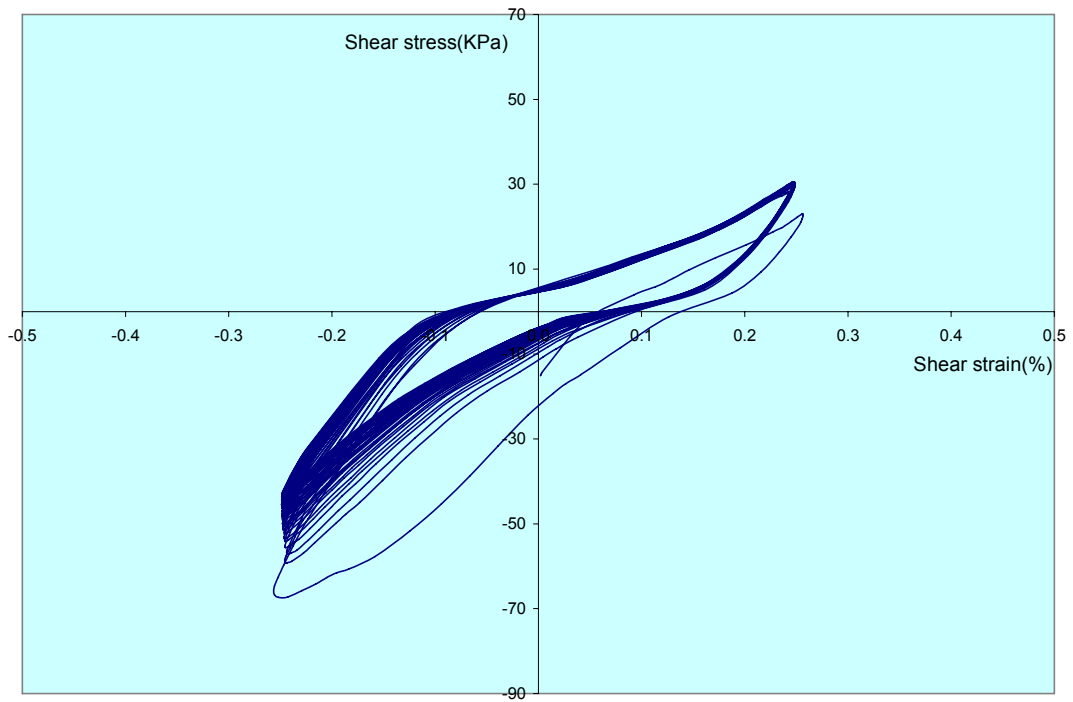


Figure B-3: Graphs of hysteresis loops for a maximum single amplitude strain of 0.25 % ( $\sigma'_v = 300\text{KPa}$ ,  $D_r = 51\%$ )

Declaration:

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

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Place: Faculty of Technology, Addis Ababa University

Date of Submission: June 2010