Experimental Study of Dynamic Properties of Soils in Wollo-Kombolcha

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ABSTRACT

The study of dynamic properties of soils is important in order to provide information on the response of soils to dynamic loads and to reduce damages that can be caused by dynamic loads from earthquakes, vibrations from traffic and machines. There is limited study on the dynamic properties of soils in Ethiopia. Soil samples were collected from Kombolcha since it is one of the earthquake-prone areas and is an active industrial development center. 18 soil samples were collected from 6 test pits and cyclic simple shear tests were conducted. Cyclic simple shear tests were conducted at confining pressures of 100kPa, 250kPa, and 400kPa; at wider range of strains of 0.01%, 0.1%, 1%, 2.5%, and 5%; and a sinusoidal shape with 1Hz frequency for 40 cycles. The shear modulus of the soils ranged from 0.52 MPa to 24.9 MPa and the damping ratio ranged from 0.83% to 27.57%. The variation of shear modulus and damping ratio with different factors was also investigated. The shear modulus values increased as confining pressure, number of cycles, and plasticity increased, but it decreased with cyclic strain amplitude and void ratio, whereas damping ratio in contrary for these factors, but not significant for a void ratio. The normalized shear modulus results from this study were compared with the range presented in the literature. The comparative results for the silty sand was strain rate dependent; whereas the normalized shear modulus for the saturated clays showed a similar trend as that of the curves provided by Seed and Idriss (1970). On the other hand, the results from the current study were also compared with results from previous studies in Ethiopia. The findings were mainly similar but some variations of values were observed. These variations could be from differences in soil type, plasticity, void ratio, and over consolidation ratio differences.

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

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1 INTRODUCTION

1.1 Background

It is a critical task in the solution of geotechnical earthquake engineering problems to measure the dynamic soil properties. The important dynamic soil properties are known as shear modulus and damping variations with cyclic strains. The behavior of soils subjected to dynamic loading is influenced by dynamic soil properties (Kramer, 1996). The dynamic soil properties can be used as an input parameter for the design of foundations for machinery and vibrating equipment, analysis of slope stability of embankments under earthquake loading conditions, and also used to model soil behavior under dynamic loading.

The Great Rift Valley region of Ethiopia is an earthquake-prone area. Kombolcha is located on the Western margin of the Main Ethiopian Rift valley (MER) and one of the earthquake-prone areas. The town is categorized under seismicity zone three according to CES-160 (CES, 2015). Fast growth of infrastructure development is observed in the town, especially after the town is selected as an industrial development center. The town has Kombolcha Steel products, a metalworking factory, an industrial park, a beer factory, a Kombolcha textile factory, a dry port, and an airport. Kombolcha is served by a station for the Awash to Weldiya railway project which will boost the growth of the town. The study of the dynamic properties of the soils from Kombolcha town is important, due to the industrialization of the town and its location in an earthquake zone, to reduce damages that infrastructures may sustain from dynamic loads. Therefore, this study is conducted to determine the important dynamic soil properties which are shear modulus and damping ratio of soils in Kombolcha town. These parameters can be determined from the stress-strain behavior of soils under cyclic loading. The stress-strain response of soil to cyclic loading is nonlinear and hysteretic and commonly characterized by a hysteresis loop (Kramer, 1996). The shear modulus (G) that is experimentally determined is the secant modulus obtained by joining the extreme points on the hysteresis loop. The G_{max} of the soil is generally defined at a very low shear strain. The normalized shear modulus is the shear modulus over the maximum shear modulus (G/G_{max}) and it can be used for several purposes. These normalized relationships allow the engineer to use well-established degradation curves and scale them to the measured in-situ value of G_{max} (Luna & Jadi, 2000). The damping Ratio (D) represents the ability of a material to dissipate dynamic load or to dampen the system. As the soil elements lose stiffness with the amplitude of strain, their ability to dampen dynamic forces increases (Luna & Jadi, 2000). Dynamic properties of soils are commonly represented by the variation of equivalent shear modulus (G_{eq}), normalized to the initial shear modulus (G_o), and damping ratio (D) with cyclic shear strain amplitude (γ_c) (Bedr et al., 2019).

Researchers have used different testing methodologies (e.g., resonant column test, piezoelectric bender element test, cyclic triaxial test, and cyclic simple shear test) to determine the dynamic properties of different soils at varying strain levels ((Gabryś et al., 2021),(Zhang et al., 2021),(Bedr et al., 2019),(Sezer et al., 2019), (Fakharianet al., 2019)). Cyclic simple shear tests were used for this study. Representative soil samples were collected from the study area and index property tests were conducted to characterize the soils in the study area. The dynamic properties of the soils were determine using cyclic simple shear tests.

2 MATERIALS AND METHODS

2.1 Description of the Study Area

Kombolcha town is located in North-Central Ethiopia in the South Wollo Zone of the Amhara Region at a latitude and longitude of 11°5′N, 39°44′E, respectively, with an elevation between 1842 and 1915 meters above sea level.

2.2 Experimental Techniques

2.2.1 Sample Collection and Preparation

In this study, soil samples were collected from selected locations in the study area (see Figure 1, and Table 1). Before sampling, visual site investigations were made to consider different

soil types, and to sample evenly in the study area. Six test pits were excavated up to the depth of 3 m as most of the foundation constructions in the area are founded around this depth. Three samples were collected from depths of 1 m, 2m, and 3m from each test pit. A total of 18 samples were collected. Then, field and laboratory tests were conducted on the collected samples. In the field, in-situ density test was conducted using sand cone replacement method, natural moisture content was also determined. For the laboratory testing disturbed soil samples were collected from each layer and used to determine index properties for characterizing the soil to select representative soil materials for the cyclic simple shear tests and the 1D-Consolidation test. Hence, three representative soils samples were selected to conduct these tests. The selected samples were remolded using field density and natural moisture content in the laboratory. The laboratory tests were conducted in the geotechnical laboratory of Addis Ababa Institute of Technology. (AAiT).

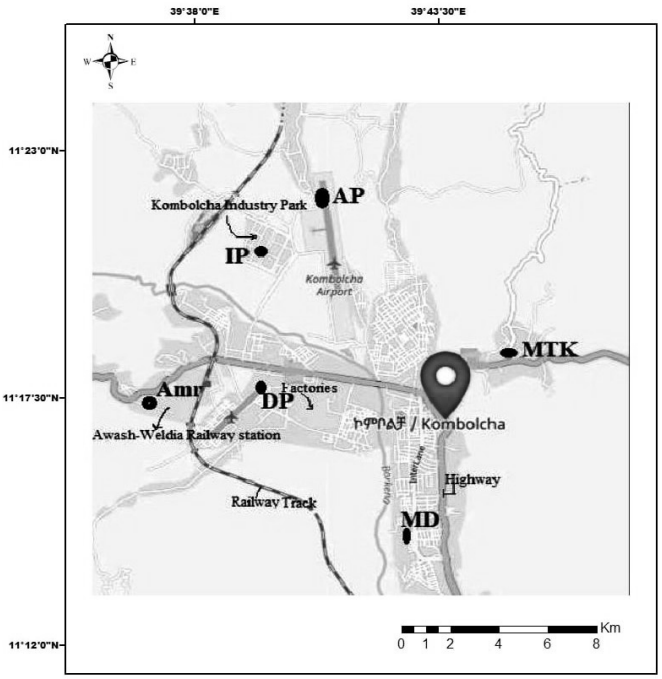


Figure 1 Location of test pits (GPS, 2022)

Table 1 presents the location of the test pits, the code of the test pits, and their coordinates.

Table 1 Location of test pits and their coordinates

Location of Test pits	Code of test pits	Coordinates		Elevation (m)
		Lat. (^{0})	Long. (^{0})	
AirPort	AP	11.112	39.725	18
Dry Port	DP	11.084	39.713	1875
Industry Park	IP	11.112	39.714	1894
Around Amar Factory	Amar	11.082	39.698	1902
Around Medhaniale m Church	MD	11.064	39.736	1812
Around Mitikolo	MTK	11.090	39.747	1914
Remark: AP1 means, Location = Air Port and Depth = 1m; same for others test pits				

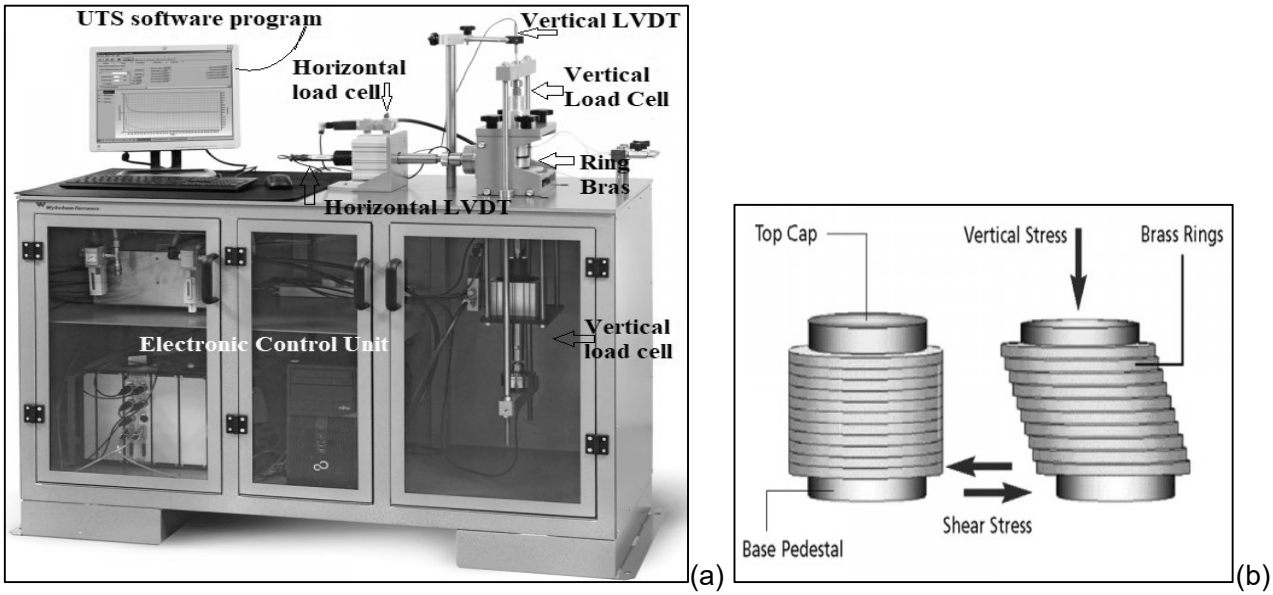
2.2.2.Cyclic Simple Shear Test Apparatus The cyclic simple shear test is used to investigate the dynamic behavior of soils. The test is used to study the cyclic response of both the fine-grained and coarse-grained soils. The cyclic behavior can be investigated either by keeping the vertical stress constant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

Nowadays, there are different types of cyclic simple shear apparatuses in use. In this research, the type of apparatus that was used is the 31-WF7500 developed by Industrial Process Controls (IPC Global) Limited using the Universal Testing System (UTS).

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

2.2.1. Cyclic simple shear testing procedures used in this study

The cyclic simple shear stress tests are conducted according to ASTM D 6528-17. Soil samples of 70 mm diameter and 20 mm height were used to maintain a height to diameter ratio of less than 0.4. The specimen was remolded when the soil passes through a 4.75 mm standard sieve size and the sample was prepared by tamping techniques. 1 Hz loading frequency was chosen as recommended by Ishihara (1996), Kramer (1996) and commonly adopted by several other researchers (Vucetic & Dobry, 1991;, Ayele (2022), Kumar et al. (2017)). A specimen was subjected to 40 cycles of sinusoidal strain-controlled loading (ASTM D6528-17, 2017). Sine wave was used since it gives approximately 30% higher cyclic strength than rectangular or triangular waveforms (Kumar et al., 2014). In most seismic events, the number of significant cycles is likely to be less than 20. For practical purpose, the 5th cycles are likely to provide reasonable values (Das, 2011). Axial stresses of 100 kPa, 250 kPa, and 400 kPa were used to see the effect of confining pressure on the value of shear modulus and damping ratio. Shear strain values of 0.01 %, 0.1 %, 1 %, 2.5 %, and 5 % were selected to study the effect at a wider strain range. The number of cycles used is 40 with 50 data points for each cycle. A picture of the machine used for this study and a description of its basic elements is presented in Figure 2.



(a) (b)

Figure 2 (a) Cyclic simple shear machine found in AAiT and (b) Schematic of shear deformation of O-rings in the simple shear device (photo credit Controls group)

3 Result and discussion

3.1 Index Property Test Results

The index property tests conducted in this study are field density test, natural moisture content test, grain size analysis, specific gravity test, Atterberg limit tests and free swell index test. One-dimensional consolidation tests were conducted to determine pre-consolidation pressure values required for the computation of shear modulus. All the tests were conducted using corresponding ASTM standards. A summary of the results from these tests is presented in Table 2. The void ratio was also calculated for the primary purpose of determining the maximum shear modulus from the empirical equation.

3.2 Cyclic Simple Shear Test Results

The remolded soil samples were used under a confining pressure and shear strain for all typical test pits and the output was found from the test through MS-Excel in tabular form. A hysteresis loop of Amar3 at 250kPa axial stress and 2.5% axial strain for all 40 cycles were determined from the output (see Figure 3).

Table 2 Summary of index properties test and consolidation test results

Test Pits	Dry Port (DP)			Medhanialem Church (MD)			Around Amar Factory (Amar)		
Depth	1m	2m	3m	1m	2m	3m	1m	2m	3m
Bulk density (g/cc)	1.59	1.66	1.61	1.66	1.64	1.79	1.46	1.53	1.52
Moisture Content (%)	33.8	33.4	32.4	17.7	17.3	16.4	28	28.9	24.9
Dry density (g/cc)	1.19	1.24	1.21	1.41	1.4	1.54	1.14	1.19	1.22
Liquid Limit (%)	74	75	77	54	53	51	75	77	63
Plastic Limit (%)	34	33	30	42	35	39	34	33	31
Plastic index (%)	40	42	47	12	18	12	41	44	32
Gravel fraction (%)	0.4	0.1	0.1	19.3	10.1	10.1	3.4	3.4	0.4
Sand fraction (%)	8	9.9	5.1	54.6	68.2	69.6	12.7	12.7	14.7
Silt fraction (%)	25.6	29	40.8	20	15.58	15.43	26.1	33.7	38.9
Clay fraction (%)	66	61	54	6.11	6.12	4.87	57.8	50.2	46
Free Swell Index (%)	80	85	95	15	10	15	80	75	55
Specific Gravity (Gs)	2.71	2.73	2.71	2.66	2.68	2.67	2.7	2.72	2.69
AASHTO	A-7-5			A-2-7			A-7-5		
USCS	CH			SM			CH		
Pre-consolidation Pressure (kPa)	98			42			72		

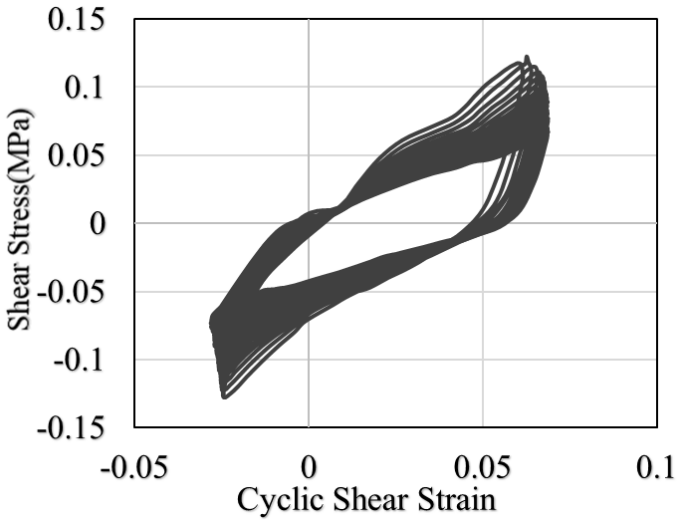


Figure 3 the hysteresis loops of Amar3 soil under 250kPa axial pressure and 2.5% cyclic shear strain for 40 cycles.

3.2.1 Determination of Shear Modulus and Damping Ratio

The values of shear modulus and damping ratio were determined from the hysteresis loop, based on the raw data obtained from the cyclic simple shear test. The calculation of the determination of shear modulus and damping ratio values are shown in the following Figure 4 and Table 3.

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

Shear stress, $\tau = \frac{\text{Shear Force}}{\text{Area of sample}} = \frac{F}{A}$ (1)

Shear strain, $\gamma = \frac{\text{Lateral LVDT}}{\text{Height of sample}}$ (2)

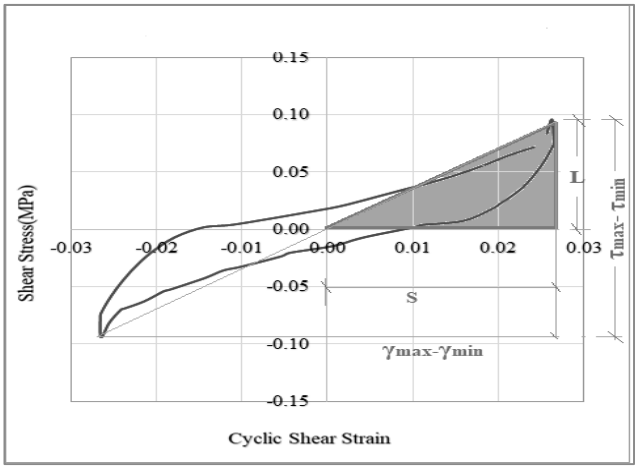


Figure 4 Hysteresis loop and triangle using stress-strain values of DP3 of 250kPa axial stress and 2.5% axial strain at 5th cycle

Using equation (1) and (2), and figure 4 shear modulus (G) and damping ratio (D) are determined as shown in Table 3.

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

Table 3 Calculation of shear modulus and damping ratio

Calculation of Shear Modulus (G)		Calculation of Damping Ratio (D)	
Calculation	Value	Calculation	Value
$\tau_{max} = L$	0.0956	$A_{loop}=\frac{1}{2}*\sum_{i=1}^{n}(\tau_i - \tau_{i+1}) \times (\gamma_i+\gamma_i)$	0.0016
τ_{min}	-0.0939		
$\tau_{max} - \tau_{min}$	.1896	$A_\Delta = 0.5 \times (L \times S)$	0.00095
$\gamma_{max} = S$	0.0266		
γ_{min}	-0.0266	$D = \frac{A_{loop}}{(4\pi A_\Delta)}$	0.1356
$\gamma_{max} - \gamma_{min}$	0.0531		
$G[MPa] = \frac{(\tau_{max} - \tau_{min})}{(\gamma_{max} - \gamma_{min})}$	**3.57**	D [%]	**13.57**

Where: τ_{max} is maximum shear stress, τ_{min} is minimum shear stress, γ_{max} is maximum shear strain, γ_{min} is minimum shear strain, A_{loop} is the area of the hysteresis loop, and A_Δ is the area of the triangle.

Using a similar procedure for all number of cycles at each strain and stresses of each test pit were determined. The following table shows the value of shear modulus and damping ratio for one selected pit (DP3) and confining stress (250kPa) with selected cycles and all strains.

Table 4 Shear modulus and damping ratio of DP3 at 250kPa of 1st, 5th, 10th, 20th, 30th, and 40th cycles, and all strains

Table 4 Shear modulus and damping ratio of DP3 at 250kPa of 1st, 5th, 10th, 20th, 30th, and 40th cycles, and all strains

No. of cycles	0.01	0.10	1.00	2.50	5.00	0.01	0.10	1.00	2.50	5.00
	G (MPa)					D (%)				
1	7.63	5.58	4.71	3.50	1.07	2.30	3.25	6.65	15.19	16.80
5	7.66	5.66	4.77	**3.57**	1.14	2.28	3.19	6.07	**13.57**	14.94
10	7.69	5.73	4.82	3.60	1.20	2.26	3.13	5.94	12.27	14.36
20	8.20	6.28	5.26	3.70	1.25	2.03	2.77	4.96	10.90	13.35
30	8.40	6.68	5.69	3.76	1.31	1.94	2.55	4.22	9.30	12.36
40	8.74	6.89	5.85	4.30	1.43	1.82	2.46	3.74	8.00	10.56

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

The initial shear modulus/maximum shear modulus was determined from empirical correlations of soil type and index properties that were developed by (Hardin & Drench, 1972). The pre-consolidation pressure determined from the one-dimensional consolidation test was used to determine the over consolidation ratio (OCR). The calculation used to determine the maximum shear modulus for the above shear modulus value (from Table 3, G=**3.57MPa**) is shown below and tabulated for all typical pits, axial stresses, and cyclic strains at the 5th cycle (see Table 6). The equation used to calculate the maximum shear modulus (G_{max}) is given below;

$$G_{\max} = 3230 * (\frac{(2.97-e)^2}{(1+e)})(OCR)^a(\sigma'_o)^{1/2} \quad (3)$$

Where $G_{\max}$= maximum shear modulus in kPa, OCR = over consolidation ratio, e is the void ratio of the soil e=$\frac{G_s}{\gamma_d}$ -1 (4)

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

Table 5 Empirical values of 'a' with respect to plasticity index (Hardin & Drnevitch, 1972)

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

σ'_o is mean effective confining pressure in kPa

For field conditions σ'_o can be determined as $\sigma'_o(kPa) = \frac{(\sigma'_v+2k_o\sigma'_v)}{3}$ (5)

σ'_v= Vertical effective stress, K_o = Coefficient of lateral earth pressure at rest and it is often taken as 0.5 (Seed et al., 1986), the Void ratio (e) of a typical soil of DP3 is 1.24 and a plasticity index (PI) is 47 using this by interpolation the value of 'a' is equal to 0.34, and the value of OCR was determined by the ratio of pre-consolidation pressure (P_c) to present/normal pressure (P_o).

OCR = $\frac{P_c}{P_o}$=$\frac{98}{250}$= 0.392, $\sigma'_o = \frac{(\sigma'_v+2K_o\sigma'_v)}{3}$ = $\sigma'_o = \frac{(250+2\times0.5\times250)}{3}$= 166.67kPa, K_o= 0.5

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

Using this value, the normalized shear modulus was determined as $\frac{G}{G_{max}} = \frac{3.57}{40.58} =$ **0.09**

Table 6 Maximum shear modulus G_{max} and normalized shear modulus $\frac{G}{G_{max}}$values

Parameter required for G_{max}	Amar3		DP3	MD3
PI (%)	32		47	12
a	0.25		0.34	0.11
e	1.21		1.24	0.73
P_c (kPa)	72		98	42
K_o	0.50		0.50	0.50
Test pits	Other Parameters to compute G_{max}			
	P_o (kPa)	OCR	σ'_o(kPa)	G_{max} (MPa)
Amar3	100	0.72	66.67	34.30
	250	0.29	166.67	43.05
	400	0.18	266.67	48.37
DP3	100	0.98	66.67	35.00
	250	**0.39**	**166.67**	**40.58**
	400	0.25	266.67	43.78
MD3	100	0.42	66.67	69.24
	250	0.17	166.67	99.16
	400	0.11	266.67	119.23
$\frac{G}{G_{max}}$ and D values				

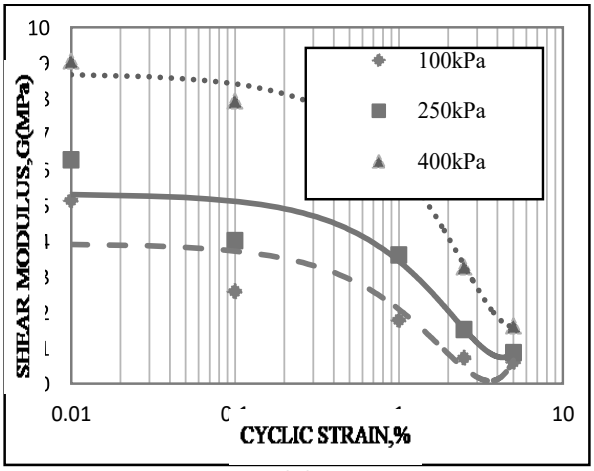
P_o(kPa)	Shear Strain	Amar3(CLAY(PI=32))		DP3(CLAY(PI=47))		MD3(SILTY SAND)	
		$\frac{G}{G_{max}}$	D	$\frac{G}{G_{max}}$	D	$\frac{G}{G_{max}}$	D
100	0.01	0.15	4.55	0.2	3.61	0.13	3.08
	0.1	0.08	5.87	0.1	4.29	0.1	4.7
	1	0.05	8.31	0.05	7.53	0.06	7.03
	2.5	0.02	17.73	0.02	16.79	0.04	16.5
	5	0.02	21.56	0.02	22.4	0.02	19.68
250	0.01	0.15	3.03	0.19	2.28	0.14	1.43
	0.1	0.09	5.14	0.14	3.19	0.08	4.17
	1	0.08	7.42	0.12	6.07	0.06	5.33
	2.5	0.03	10.13	**0.09**	13.57	0.05	13.31
	5	0.02	17.54	0.03	16.48	0.04	14.17
400	0.01	0.19	2.35	0.23	1.54	0.16	1.06
	0.1	0.16	4.22	0.2	2.84	0.12	2.4
	1	0.13	6.93	0.18	3.74	0.08	3.06
	2.5	0.07	8.71	0.08	11.82	0.06	7.26
	5	0.03	15.8	0.04	12.04	0.04	11.67

3.2.3 Factors Influencing Shear Modulus and Damping Ratio

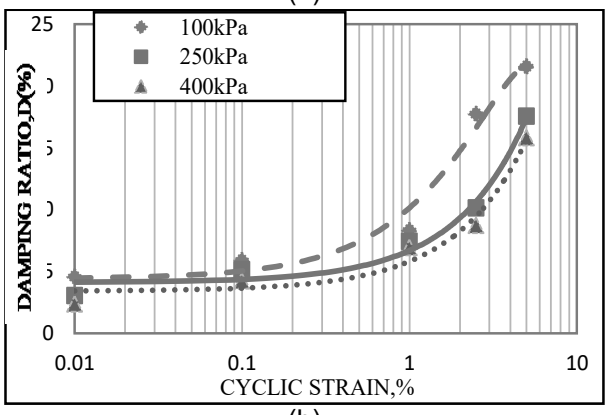
The dynamic shear modulus and damping ratio are affected by many factors. In this study, the effect of some of these factors, such as confining pressure, shear strain amplitude, number of loading cycles, soil type, void ratio, and soil plasticity, is investigated.

3.2.3.1 Variation of Shear Modulus and Damping Ratio with Confining pressure

It is observed from Figure 5 (a) that the shear modulus increases with increasing confining pressure. The reason is that the compactness of the soil due to confining stresses causes an increase in density leading to relatively higher stiffness. From Figure 5 (b), it is observed that specimens subjected to lower confining pressure (100 kPa) have a higher damping ratio in comparison to those at higher confining pressure (250 kPa and 400 kPa). This is because compactness reduces the deformation of soils, which leads to the reduction of energy loss or damping ratio. These behaviors are similar with the results of El Mohtar et al.(2013),(Arficho, 2021) and Birhanu (2019).



(a)

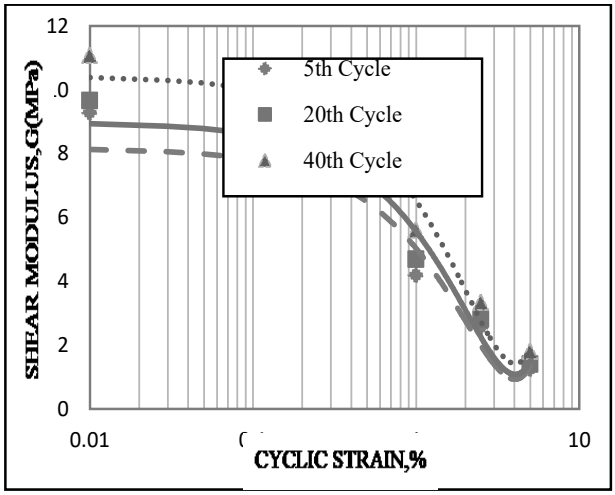


(b)

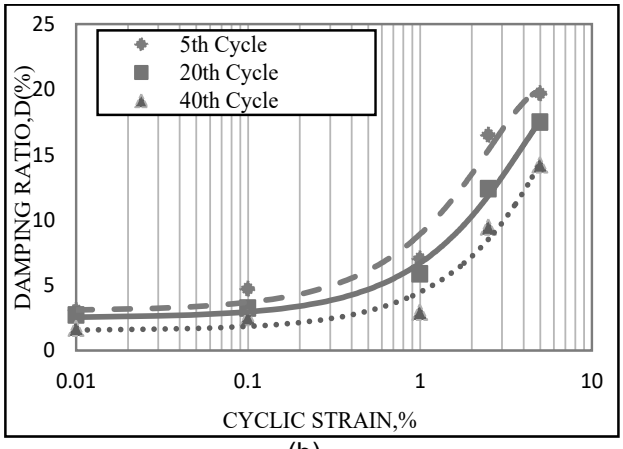
Figure 5 Variation of shear modulus (a) and damping ratio (b) of Amar3 clay soil with confining pressure

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

Shear modulus and damping ratio of cyclically loaded soils vary significantly with the amplitude of shear strain due to nonlinear deformation characteristics (Hardin & Drnevitch, 1972). Figure 6 (a and b) shows that shear modulus decreases while the damping ratio increases as the cyclic shear strain increases. This is because at higher values of shear strain, the soil strength becomes smaller to resist deformation and more energy is released to yield high deformation and damping ratio increases with increasing cyclic shear strain due to energy dissipation during deformation of soil. Similar observations were reported by many other researchers such as ((Hardin & Drnevitch, 1972), (Sezer et al., 2019), and (Asfaw, 2015).



(a)

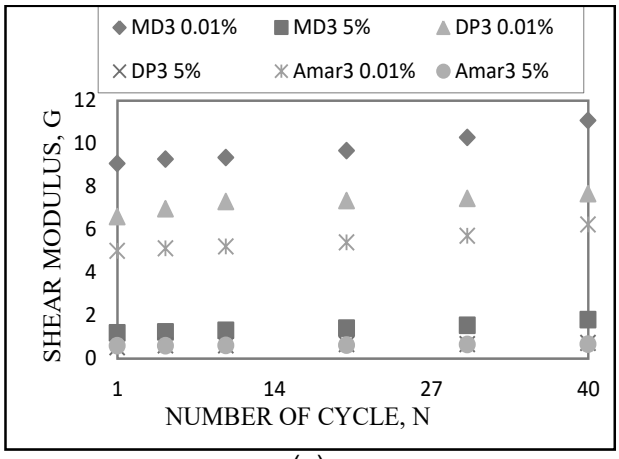


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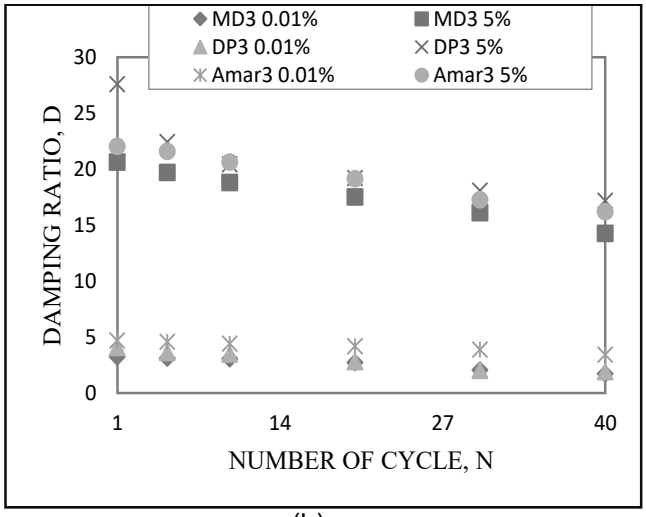
Figure 6 Variation of shear modulus (a) and damping ratio (b) of MD3 silty sand soil with cyclic shear strain amplitude

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

The results presented in Figure 7 (a and b) indicate that the shear modulus increases as number of cycles increases and the damping ratio decreases with an increasing number of cycles. The trend observed is reported by Seed et al. (1986) and Bekele (2020)). Das (2011) indicates that the values determined at the 5th cycle are likely to provide reasonable values for all practical purposes. Due to this reason, in this study, the values determined at the 5th cycle are considered for most analysis purposes.



(a)



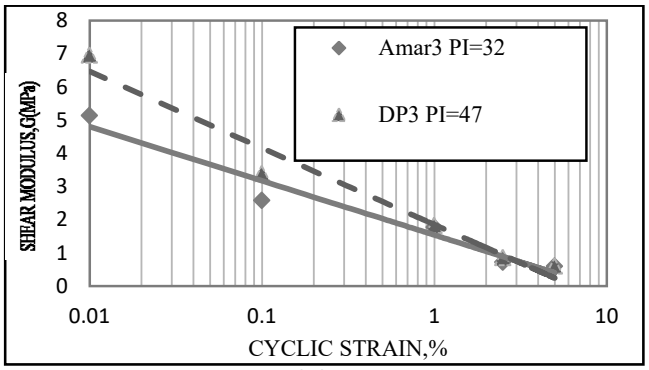
(b)

Figure 7 Variation of shear modulus (a) and damping ratio (b) with number of loading cycles for 100kPa axial stress and two different strains (0.01% and 5%)

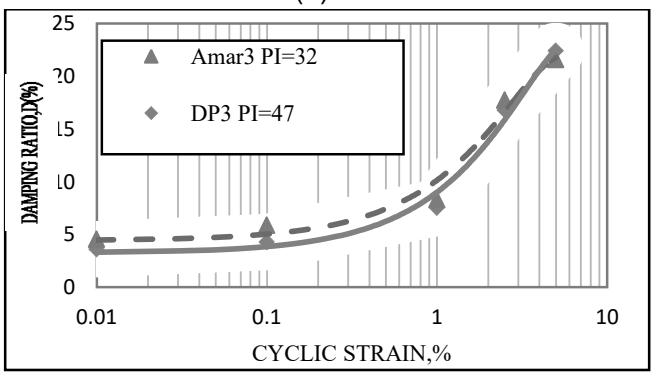
3.2.3.4 Variation of Shear Modulus and Damping Ratio with Soil Plasticity

As shown in the figure 8 (a and b), the shear modulus increases, and the damping ratio

decreases as the soil plasticity increases with the same axial stress and soil type (Clay is chosen for this study). This trend is in good agreement with well-established curve by Vucetic and Dobry (1991). However, the effect was not significant for larger strains ($\gamma_c \geq 1\%$). This is because highly plastic soils tend to have a more linear cyclic stress-strain response at smaller strains and degrade less at larger shear strain (Vucetic & Dobry, 1991),



(a)

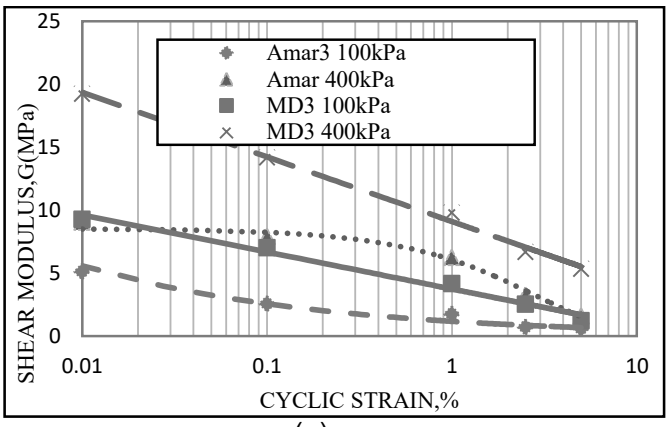


(b)

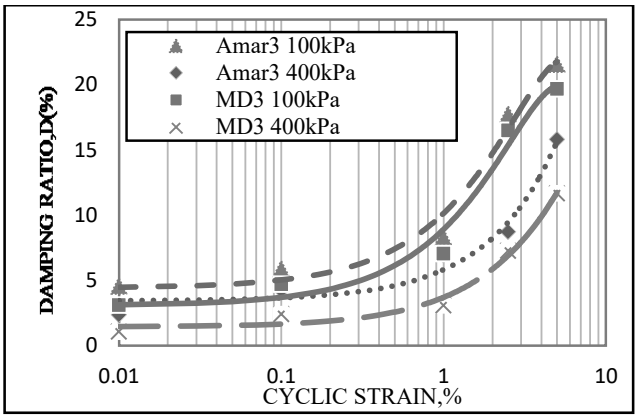
Figure 8 Variation of shear modulus(a) of Kombolcha clay soil and damping ratio (b) with soil plasticity at a confining pressure of 100kPa

3.2.3.5 Variation of Shear Modulus and Damping Ratio with Soil Type

From figures 9 (a and b), it is observed that the silty sand (MD3) has higher shear modulus values than the clay soil (Amar3), especially at maximum confining stress (i.e., 400kPa). This is because coarser materials show good resistance to cyclic shear under high confining stress (Luna & Jadi, 2000).The effect of soil type decreases at larger shear strain, especially for lower confining stress. However, the effect is not significant for the damping ratio value. Welay (2017) observed similar behavior for sand and silt soil.



(a)

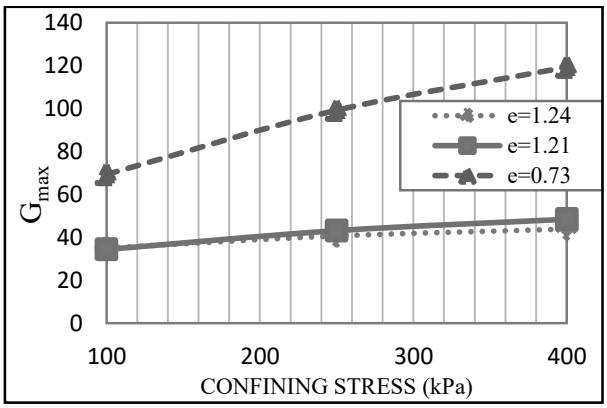


(b)

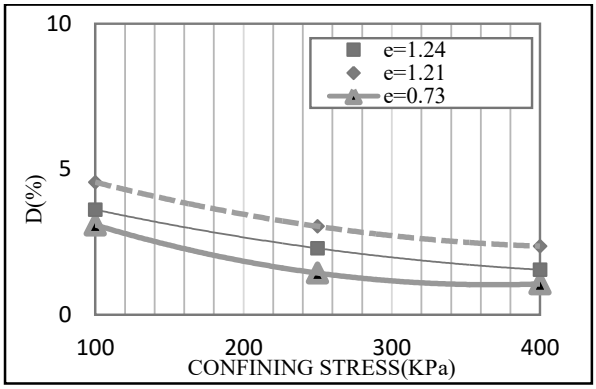
Figure 9 Variation of shear modulus (a) and damping ratio (b) with Clay (Amar3) and Silty Sand (MD3) soil type

3.2.3.6 Variation of Shear Modulus and Damping Ratio with Void Ratio

Figure 10 illustrated that, as the void ratio increases, the maximum shear modulus decreases and the damping ratio increases. The reason for this behavior is that when void ratio decreases, the area of contact between soil particles becomes closer and results in increase of shear modulus.



(a)

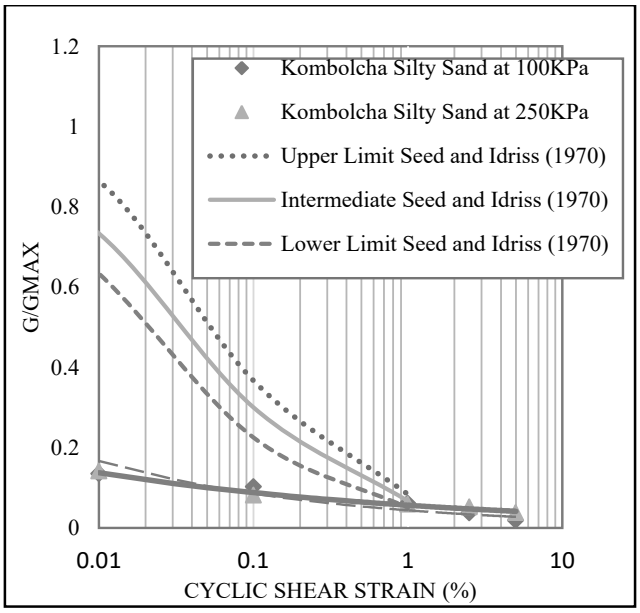


(b)

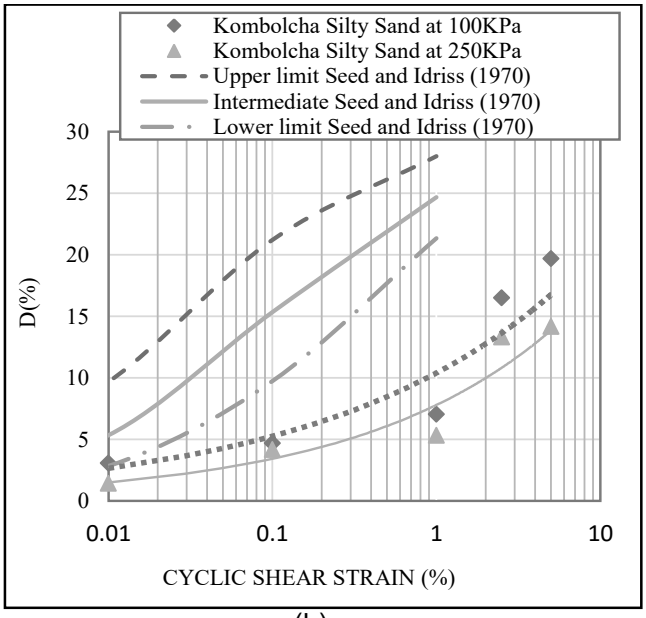
Figure 10 Variation of the maximum shear modulus (a) and damping ratio (b) of Kombolcha soil with void ratio

3.2.4 Comparison of Cyclic Test Results with Previous Studies

The value of normalized shear modulus and damping ratio determined are compared with a curve given by Seed and Idriss (1970) for both sand soil and saturated clay soil and with different previous local reports by considering similar soil type (clay and sand), confining pressure (100kPa and 400kPa), and shear strain and a discussion of the comparative results is presented in the following sections.



(a)

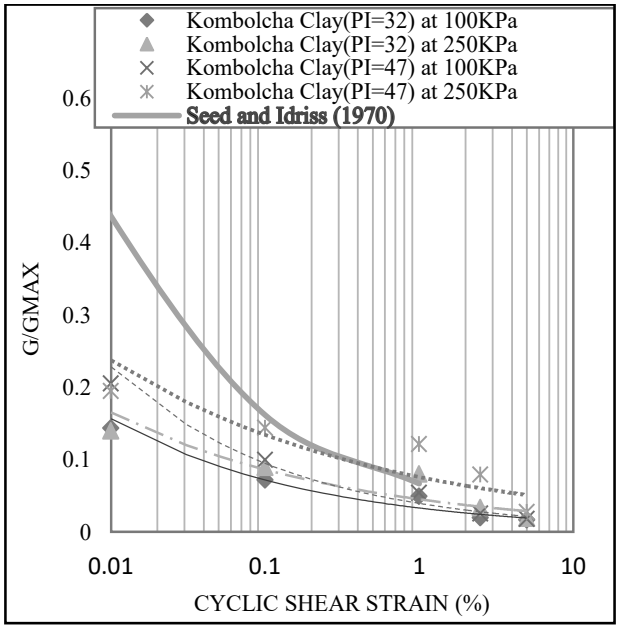


(b)

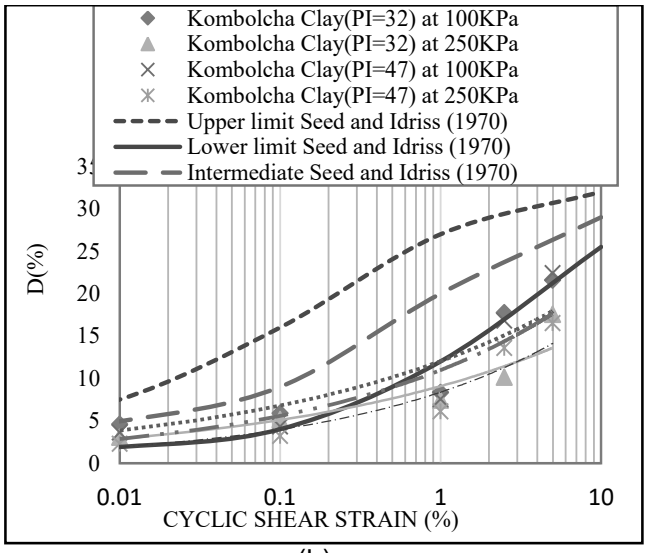
Figure 11 Comparison of (a) Normalized shear modulus and (b) damping ratio of Kombolcha silty sand soil with the curves developed for sands by Seed and Idriss (1970)

In Figure 11 (a), it can be observed that the normalized shear modulus values of the Kombolcha silty sand soil were lower than the limit of Seed and Idriss (1970) at a smaller strain ($\gamma_c \leq$ 0.6% However, for higher strains (>0.6%) the normalized shear modulus values agree with the curve by Seed and Idriss (1970). The damping ratio values, presented in Figure 11 (b), are below the limit given by Seed and Idriss (1970) for sand with a similar trend.

The normalized shear modulus values of Kombolcha Clay soil exhibited similar behavior when compared with the curve given for saturated clay (see Figure 12 (a)). and from Figure 12 (b) it can be seen that; half of the values are within the limit and half of them are below the limit.



(a)

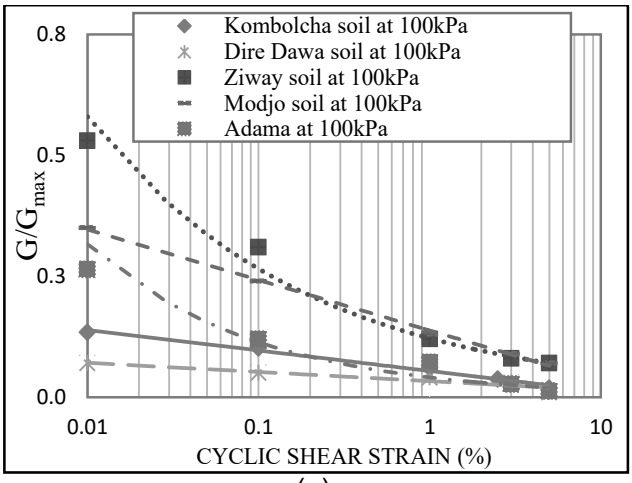


(b)

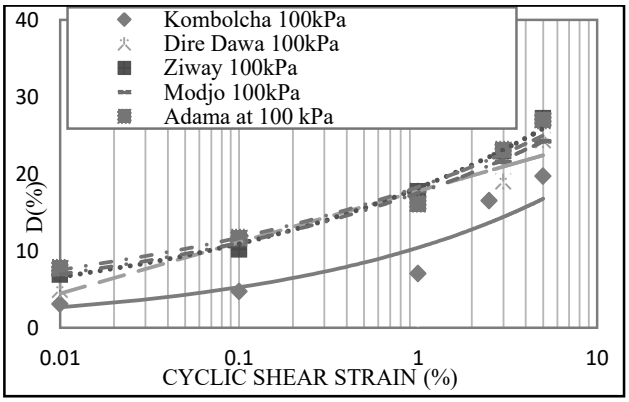
Figure 12 Comparison of (a) Normalized shear modulus and (b) damping ratio values of Kombolcha clay soil with the curves developed for saturated clay by Seed and Idriss (1970)

In general, the reason for the values determined for Kombolcha soil is somehow lying out of ranges from the limits given by Seed and Idriss (1970) could be the type of testing machine, since earlier studies were determined by the resonant column and the cyclic triaxial test. Method of sample preparation could also be the other reason for this difference. The results in this study were obtained using remolded sample; whereas, the limits by Seed and Idriss (1970) were provided from tests on undisturbed samples. Previous studied also indicate that the cyclic strength of undisturbed specimens was about 15% greater than that of remolded specimens (Kumar, 2014).

Comparison of Kombolcha silty sand soil with Adama silty sand (Feyissa, 2011), Dire Dawa sand (Welay, 2017), Modjo silty sand (Asfaw, 2015), and Ziway silty sand (Mengistu, 2015) soils was also carried out and the comparative results are presented in Figure 13 and Figure 14.

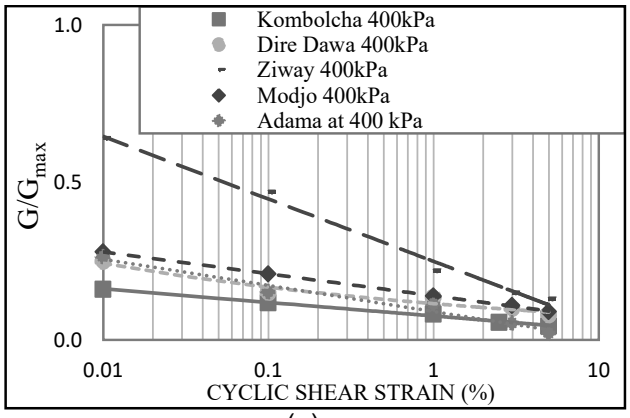


(a)

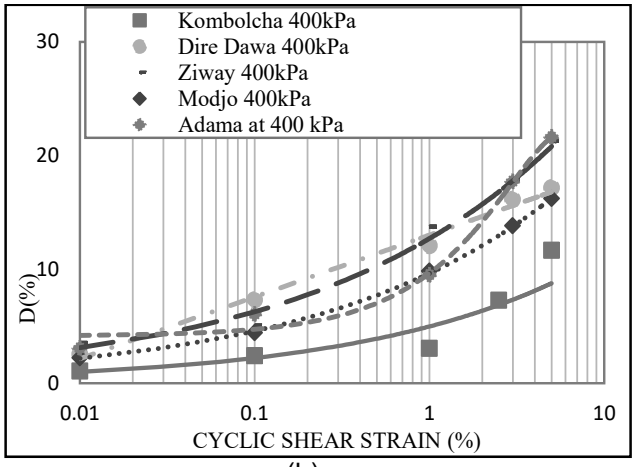


(b)

Figure 13 Comparison of Normalized shear modulus(a) and damping ratio(b) of Kombolcha silty sand soil with Dire Dawa sand, Ziway, Modjo, and Adama silty sand soils at 100kPa



(a)

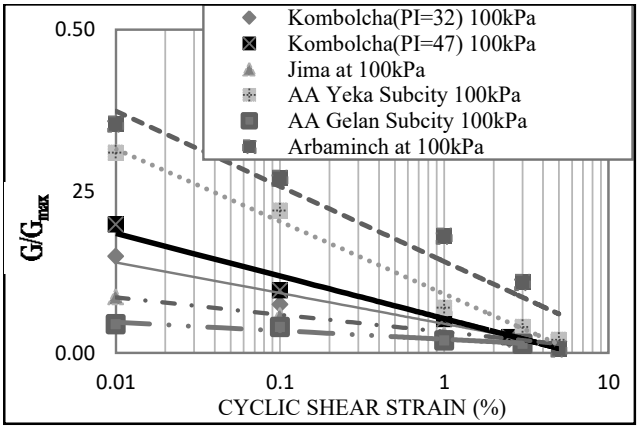


(b)

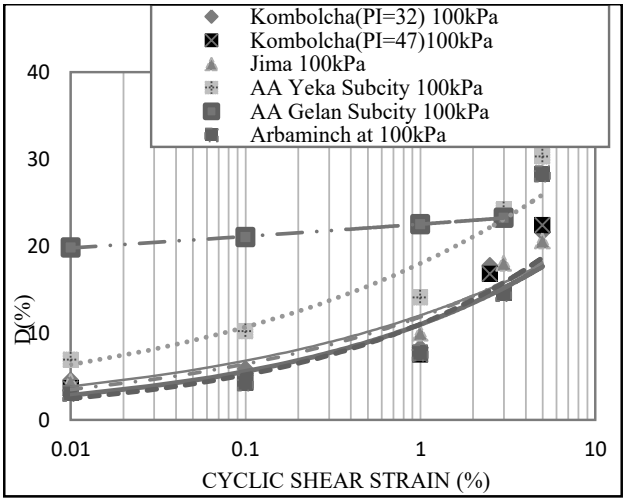
Figure 14 Comparison of Normalized shear modulus(a) and damping ratio(b) of Kombolcha silty sand with for Dire Dawa sand, Ziway, Modjo, and Adama silty sand soils at 400kPa

From Figure 13 (a) it is observed that the normalized shear modulus of silty sand at 100kPa is in good agreement with Adama silty sand when strain $\geq 0.1\%$ and Dire Dawa sand soil for all strain values. However, it is lower than the curves given for Modjo and Ziway Silty sand soils. At confining stress of 400kPa Kombolcha silty sand soil is in good agreement with Adama silty sand soil for larger strain ($\geq 2.5\%$), but slightly lower for strain $< 2.5\%$ strain and has a lower value of normalized shear modulus compared with Dire Dawa sand, Ziway, and Modjo silty sand soils (see Figure 14(a)). The value of the damping ratio for silty sand is the least for both 100kPa and 400kPa (see Figures 13(b) and 14(b)). From this result, it can be said that Kombolcha Silty sand has slightly less value of both G/Gmax and damping ratio as compared with Dire Dawa, Ziway, and Modjo results but is compatible with Adama silty sand soil of normalized shear modulus.

Comparison of Kombolcha clay soil with Jimma silty clay (Birhanu, 2019), Arbaminch clay (Dimer, 2013), Yeka clay (Bekele, 2020), and Gelan clay (Ayele, 2022) soils were done and the results from the comparison are presented in Figure 15 and Figure 16.

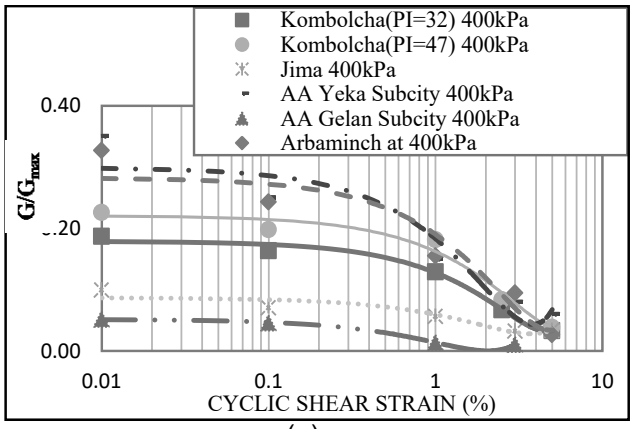


(a)

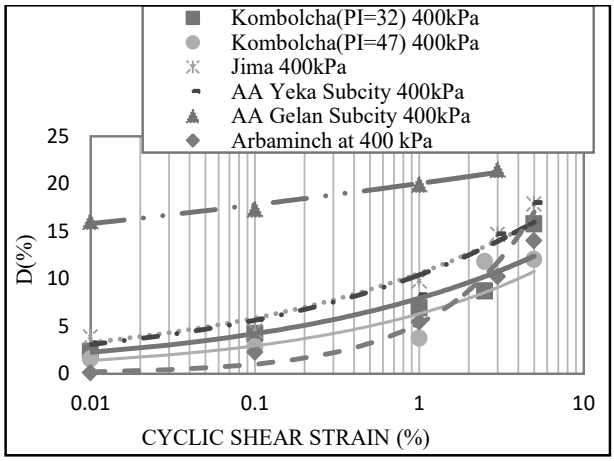


(b)

Figure 15 Comparison of Normalized shear modulus(a) and damping ratio(b) of Kombolcha clay soil with Jima, Arbaminch, Yeka, and Gelan clay soils at 100kPa



(a)



(b)

Figure 16 Comparison of Normalized shear modulus(a) and damping ratio(b) of Kombolcha clay soil with Jima, Arbaminch, Yeka, and Gelan clay soils at 400kPa.

From figures 15 (a) and 16 (a) it is illustrated that the G/Gmax of Kombolcha clay soil is in a good agreement with Jima and Gelan, but lower than Yeka and Arbaminch clay soils for both plasticity index (PI=32 and PI=47) and confining pressure (100kPa and 400kPa) variations for all strain. For strain values ≥ 1% Kombolcha clay soil is compatible with all local soils. In the case of damping ratio, Kombolcha clay soil (PI=32 and PI=47) has a good agreement with Jima and Arbaminch clay soil at 100kPa confining stress and lower than Yeka and Gelan clay soils. For 400 kPa confining pressure, Kombolcha clay soil has a good agreement with Arbaminch clay soil, but a lower damping ratio as compared with Yeka, Gelan, and Jima clay soils (see Figures 15(b) and 16(b)).

Generally, the values for the soils from Kombolcha were a bit lower than the soils from the other towns. This could be due to the difference in soil type, sample preparation, stress history, and density.

4. CONCLUSION

This study has investigated the dynamic properties (shear modulus (G) and Damping ratio (D) values) of soils from Kombolcha using cyclic simple shear test apparatus. The following conclusions are drawn based on analysis and interpretation of the laboratory test results:

- The shear modules for the clay-type samples ranges from 0.52 MPa to 10.79 MPa, the damping ratios are between 1.36% and 27.57%, and maximum shear modulus ranges from 34.3MPa to 48.57MPa. These range of values for Kombolcha clay soils are somewhat similar to values from previous studies on similar type of soils.
- The shear modules for the silty-sand- type samples ranges from 1.19 MPa to 24.9 MPa, the damping ratios are between 0.83% and 20.60%, and maximum shear modulus ranges from 69.24 MPa to 119.23 MPa. These range of values for Kombolcha silty sand soils are somewhat similar to the values from previous studies on similar type of soils.

- The normalized shear modulus values of the Kombolcha silty sand soil were lower than the limit of Seed and Idriss (1970) at a smaller strain ($\gamma_c \leq 0.6\%$). However, for higher strains ($\gamma_c > 0.6\%$) the normalized shear modulus values compare well with the limits provided by Seed and Idriss (1970). The damping ratio values are below the limit given by Seed and Idriss (1970) for sand but with a similar trend.
- The normalized shear modulus values of Kombolcha Clay soil exhibited similar behavior when compared with the curve given for saturated clay by Seed and Idriss (1970),

- The influence of different parameters on dynamic properties of Kombolcha soils was investigated and it was observed that the value of shear modulus increased as confining pressure, number of cycles, and plasticity increased, but it decreased with cyclic strain amplitude and void ratio (for G_{max}). Similar trends were observed by other researchers.
- The damping ratio values increased as cyclic shear strain amplitude increased, but it decreased as confining pressure, number of cycles, and plasticity increased. Similar trends were observed by other researchers.
- The shear modulus and damping value of Kombolcha soil determined from this study could be used as an input parameter for the design of structures subjected to dynamic loads. The results are applicable for strain range from 0.01% to 5%.

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