Geomechanics and Engineering, *Vol. 24, No. 2 (2021) 105-113*
DOI: https://doi.org/10.12989/gae.2021.24.2.105

Dynamic behavior of clayey sand over a wide range using dynamic triaxial and resonant column tests

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(Received February 11, 2020, Revised December 13, 2020, Accepted December 31, 2020)

Abstract. Deformations in soils induced by dynamic loads cause damage to the structures above the soil layers. It is important for geotechnical engineering practice that how the soil behaves due to repeated loads and the necessary precautions to be taken accordingly. Turkey is one of the most important seismic regions in Europe and earthquake studies to be conducted in this area are intended to reduce the damage as a result of taking the necessary measures. To determine the properties of soils under dynamic loads, stress-controlled dynamic triaxial and resonant column tests can be performed. In this study, these experiments were implemented in the laboratory on the clayey sand soil samples obtained from Bilecik Söğüt. To evaluate the effects of the confining pressure and rate of loading on the dynamic behavior of soils, samples were dynamically loaded by different rates at varying confining pressures. As a result, the changes in stress-strain properties of soils under dynamic loads were investigated. The alteration in behavior in terms of modulus reduction and damping ratios was obtained to vary a lot with the change of the lateral pressure on soil along with the frequency of the load.

Keywords: dynamic properties; dynamic triaxial; resonant column; stress-strain behavior

1. Introduction

Structural design is mostly dominated by the seismic loads caused by the earthquakes. These cyclic loads change from base through the ground surface in amplitude, frequency content and duration due to the dynamic behavior of soil. Deformations occur in soils during the wave propagation and affect the behavior of the transmission. Therefore, the dynamic behavior of soils due to stresses caused by earthquakes should be investigated to predict the ground surface in a realistic matter. In order to estimate the stress-strain properties of soils under dynamic loads, it is essential to utilize dynamic test equipment such as dynamic triaxial and resonant column. Dynamic soil characteristics include the initial shear modulus G_{max} (or max. shear modulus); normalized dynamic shear modulus G/G_{max} and the damping ratio D at varying shear strains and they should be determined just to understand the soil behavior. These values can be obtained by both in situ and laboratory tests (Vucetic and Dobry 1991, Darendeli 2001, Okur and Ansal 2009).

In the literature, many studies have been done recently on the dynamic behavior of sands (Naeini and Baziar 2004, Sönmezer 2019, Güler and Afacan 2019). As a focus of this study, experiments were carried out to determine the dynamic properties of clayey sands. Resonant column (RC) and dynamic triaxial (TRX) test systems were used to constitute the behavior in the laboratory. These systems, which can be conducted at different levels of deformation, are frequently used in the geotechnical practice.

The RC test system is used for small deformation levels whereas the TRX test system for medium to large deformation levels instead (Kramer 1996).

Using the RC test system, the researchers performed various studies on clay and sand samples and obtained shear modulus change over a range of deformation values of less than 0.1% (Hardin and Richart 1963, Sexena and Reddy 1989, Im *et al.* 2017, Banerjee and Balaji 2018, Li and Senetakis 2018, Morst *et al.* 2019). Similarly, TRX test system was used to evaluate modulus reduction behavior at rather larger deformation levels and various studies were implemented accordingly (Kokusho 1980, Sitharam *et al.* 2004, Okur and Ansal 2007, Kumar *et al.* 2017). These two test systems are considered together and experiments are conducted on different type of soils and modulus reduction and damping curves are examined in a wider range in today's research (Khan *et al.* 2011, El Mohtar *et al.* 2013, Keene 2017, Bayat and Ghalandarzadeh 2017, Bedr *et al.* 2018, Jafarian and Javdanian 2019, Dammala *et al.* 2019). Besides the researches mentioned above, this study will focus on the investigation of the effect of the confining pressures with varying frequencies on the dynamic behavior of soils using both experimental results from the TRX and RC test systems. The transition region of shear strain between two tests will be discussed in detail. In addition, the effect of plasticity index and the damping ratio will be examined and all experiment results will be compared with the models in the literature.

Turkey is located in one of the world major earthquake

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http://www.techno-press.org/?journal=gae&subpage=7
ISSN: 2005-307X (Print), 2092-6219 (Online)

zone, and there have been many earthquakes in the region (i.e., Kocaeli Earthquake and Duzce Earthquake in 1999). These earthquakes had devastating effects in the country, causing great damage on the structures and many fatalities. This study was performed with samples collected from Bilecik province near North Anatolian Fault (NAF) which is one of most seismically active faults in Turkey. This fault is strike-slip and 1150 km long. Examining the Bilecik province in a radius of 100 km, 23 earthquake records of different magnitudes have been reached in the last decade. Regional spectral acceleration at short period S_s: 0.573, S_1: 0.170 and PGA: 0.241 (AFAD 2019). Due to the fact that Bilecik is nearby an active seismic zone and large earthquakes occurred in the past, the dynamic behavior of soils needs to be examined in a realistic way in the laboratory. Site-specific analysis should be performed with the help of in situ sampling to reduce the damage caused by the earthquake (Ansal *et al.* 2011) and it would be only possible if the behavior is modelled accurately.

In this study, dynamic triaxial (TRX) and resonant column (RC) tests under different stresses were performed on clayey sand samples and in situ behavior of stress-strain properties were investigated. The results of the both experiments were combined to gather modulus reduction and damping behavior unitedly at varying deformation levels.

2. Dynamic behavior of soils

There are two main specifications to understand the behavior of soils under repeated loads: 1) stress-strain behavior over a wide range 2) the soil rigidity. Stress-strain properties of soils are defined as changes in shear modulus and damping ratio values due to cyclic loading for different unit shear deformation levels. As a result of dynamic loading, a conventional loop that shows the stress-strain behavior change of the soil sample is presented in Fig. 1 (taken from Stewart *et al.* 2014) and it is basically called as the ‘hysteresis loop’. These loops combine together and establish the backbone curve.

The maximum dynamic shear modulus, which defines the initial/maximum rigidity of the soil and it can be basically obtain as the slope of the very first loop. Since it is difficult to procure at these deformation levels, the shear

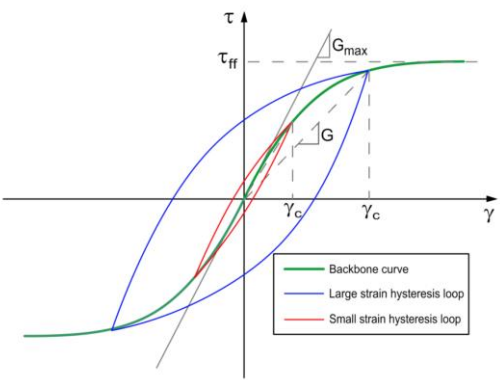

Fig. 1 Stress-strain curve of the soils (Stewart *et al.* 2014)

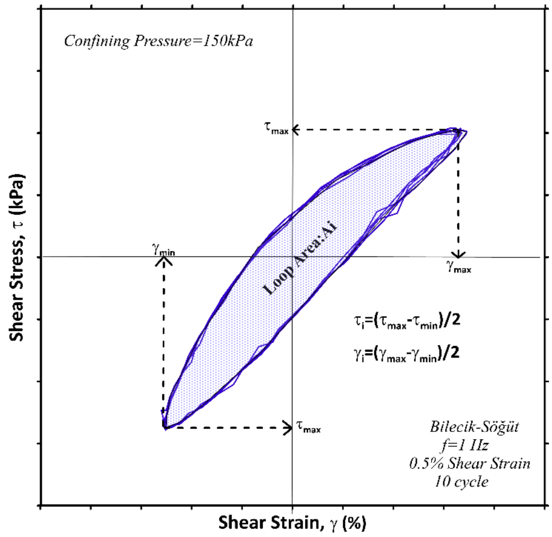

Fig. 2 An example stress-strain loop from a triaxial test corresponding shear strain of 0.5% and the definitions of secant modulus and hysteretic damping (adapted from Kramer 1996)

wave velocity obtained from the field tests can be used to calculate the initial modulus by the following equation alternatively, depending on the shear wave velocity and the density of the soil.

$$G_{max} = \rho V_s^2 \tag{1}$$

The secant shear modulus or shear modulus (G_i) at a certain shear strain can be calculated by taking the slope of the shear stress-strain cycle and can be expressed as in the Eq. (2). Fig. 2 shows a cycle (ith cycle) recorded under one of the triaxial test corresponding 0.5% of shear strain.

$$G_i = \frac{\tau_i}{\gamma_i} \tag{2}$$

Here τ_i is the shear stress and γ_i is the shear strain at the ith cycle. The data gathered from the laboratory may shift right/left or up/down therefore these parameters are adjusted by taking the average of max. and min values of them.

Another crucial parameter to define the dynamic soil behavior is the amount of energy dissipated as a result of cycling loads applied to the soil and is defined as the damping ratio. The amount of damping, D, is calculated from the stress-strain hysteresis. The damping properties are used to solve the dynamic problems such as wave propagation through the soil profile and help to find out the amount of the energy transmitted to the upper layers. Using the average of max. and min. shear stresses and strains τ_i and γ_i , the damping ratio is determined by calculating the area of the curve with the hysteresis field ($A_{i,loop}$) , as it is shown in equation 3 (Sobolev and Ter-Martirosyan 2018, Güler and Afacan 2019). The loops with indefinite figures that would not follow the equation are dismissed in determining damping behavior.

$$D_i = \frac{1}{2\pi} \frac{A_{i,loop}}{G_i \cdot \gamma_i^2} \tag{3}$$

Having these properties set correctly helps geotechnical and structural designers to estimate the ground surface behavior correctly and the stresses of structural elements better under seismic loading. This would help to avoid from excessive structural deformation and possible causalities.

3. Material and tests

3.1 Material

The soil sample used in the experiments was obtained from Söğüt district of Bilecik province which is nearby to the NAF zone. The grain size distribution is shown in Fig. 3. Accordingly, it is determined as clayey sand (SC) according to the Unified Soil Classification System. (USCS) (ASTM D2487).

The Atterberg Limits, specific gravity and compaction tests were conducted on the sample to identify the index properties of the clayey sand soil they are presented in in Table 1. The fine content of the soil is determined roughly 43% and the plasticity of clay is about 12%.

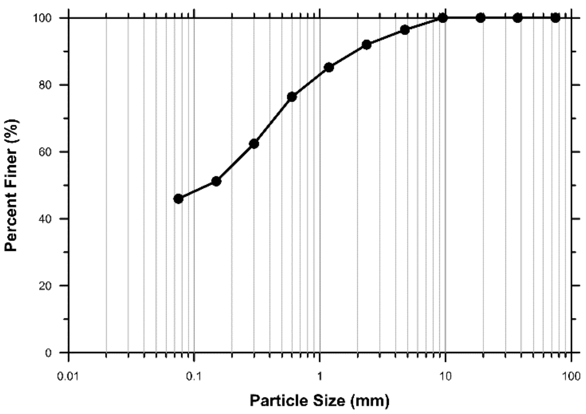

Fig. 3 Grain-size distribution curves of clayey sand

Table 2 Experiments program and specimen details

Confining Pressure kPA	Sample Size mmxmm	Test Program	
Cyclic Triaxial Tests		0.1 Hz	1 Hz
50	70x140	TRX 1	TRX 3
50	70x140	TRX 2	TRX 4
100	70x140	TRX 5	TRX 7
100	70x140	TRX 6	TRX 8
150	70x140	TRX 9	TRX 11
150	70x140	TRX 10	TRX 12
Resonant Column Tests			
50	50x100	RC 1	
50	50x100	RC 2	
100	50x100	RC 3	
100	50x100	RC 4	
150	50x100	RC 5	
150	50x100	RC 6	

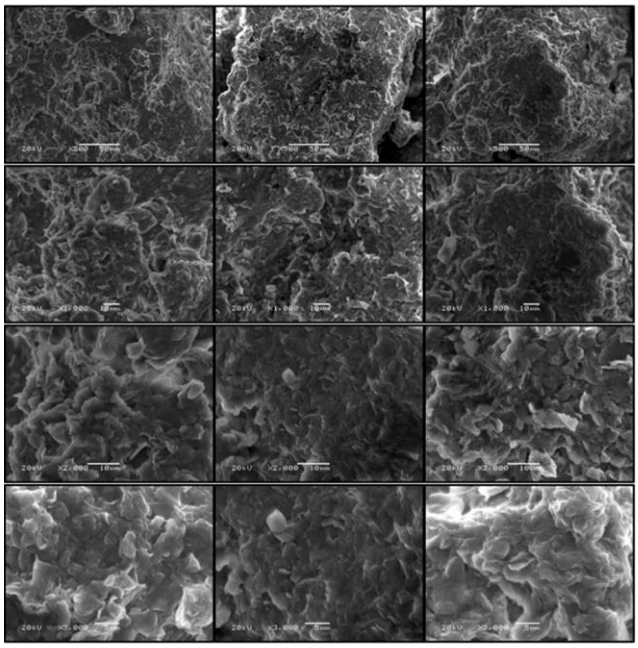
Fig. 4 SEM image of clayey sand

Besides the determination of the basic properties of the soil, SEM (Scanning electron microscope) image of the sample was taken and is shown in Fig. 4. Microstructure photographs of 500, 1000, 2000, 3000 magnifications taken under 20 kV were given by electron microscopy (SEM) of the disturbed sample obtained from the study area. Examining the Fig. 4, it was seen that the micro cavities caused by the placement of the clay sand mixtures are quite small and the microstructure in general provides fullness. In addition, no cracks were found in the micro structure.

3.2 Experimental program

In order to understand the dynamic behavior of soil, 12 cyclic triaxial tests (TRX) and 6 resonant column tests (RC) were performed on the clayey sand samples. Experiments in this study were carried out with the TRX and RC test systems in the Soil Mechanics Laboratory of Eskişehir Osmangazi University and the test program is presented in Table 2.

The soil samples for two different test systems vary and they are both cylindrical and height to diameter value is 2. The dimensions are presented in the table.

Two different frequency levels (0.1 Hz and 1 Hz) were used in this study since the earthquakes consist of different frequency features. 0.1 Hz loading basically is slower than the other and 1 Hz is the common frequency most literature studies depend. The idea is to assess the similarities/differences of the soil behavior under different frequency content.

Overburden pressure is one the most important key parameter to construct the soil behavior along with the plasticity and the stress history of the soil. Hence, 3 confining pressure levels were selected as 50 kPa, 100 kPa and 150 kPa in the test program. One is to model shallower soils and the other two is for deeper soils. The last point about the test program is about the verification of the test

Fig. 5 Dynamic cyclic triaxial test system

Fig. 6 Demonstration of the Resonant column test system and a soil sample

results. Since laboratory testing comprises errors related to human, machine and other factors, 2 identical soil samples were used in the TRX and RC tests for each confining pressure to calibrate the test results. This way, we aim to overcome the possible flaws and evaluate the behavior carefully.

All the soil samples were compacted in a single layer with the help of a compressor instead of using the conventional compaction molds. So that, it was made sure that the uneven layering or application of different energy levels were prevented.

The cyclic triaxial test system by Wykehamm Farance used in this study is demonstrated in Fig. 5. This system is generally used to evaluate the soil behavior at medium and high shear strain levels.

The TRX test equipment is composed of servo valves that provide closed-loop, electro-hydraulic and vertical motion control. The dynamic triaxial test system is capable of measuring vertical load, vertical displacement, pore water pressure and volume changes under stress or strain-controlled loading tests with pre-defined irregular or regular loading types. The applicable maximum cell pressure is 980 kPa and almost 2000 N is the maximum axial load the system can be conducted. The details about the testing can be found in ASTM D5311/D5311M.

Preparing the soil sample in the triaxial test system, filter papers and porous stones were placed on the upper and lower parts of the sample. After the sample is placed in the membrane, the top cap was placed. The membrane and the upper head were connected with the help of a ring. Transferring the load to the sample is important for the accuracy of the experiments. For this reason, a plastic apparatus was placed on the upper head. In addition, multi-silicone grease was applied to the top cap so that the sample and the cap move together. The outer cell of the experimental system is placed and filled with water. First of all, CO_2 gas was passed through the sample and the air was allowed to escape. With the gradual saturation of the sample, the 'B' value was checked and measured as at least 0.95. Then, consolidation was initiated in the sample by increasing the confining pressure in the cell. This process was repeated at different cell pressures (50, 100 and 150 kPa) and the sine wave was applied to the samples at frequencies of 0.1 and 1 Hz. At these stages, experiments were strain controlled and 10 cycles were recorded at each strain. All of the experimental steps were done under undrained conditions.

For the second test group of the study, resonant column test system was used to obtain smaller deformation values. The test system used in the laboratory is shown in Fig. 6 and it was designed by the GCTS testing systems. The machine also allows one to conduct torsional shear tests but it is out of the scope of this paper. Calibration of equipment in RC experimental system has a significant effect on results (Kumar and Clayton, 2007, Clayton *et al.* 2009). Therefore, a calibration process was performed by screwing the calibration bar to the system.

In the RC test system, filter paper was placed on the upper and lower parts of the sample and the test setup was made ready. Here, the proximeter settings were made for deformation measurements, then CO_2 was circulated into the sample, allowing air to escape and the saturation process was started. As the saturation value, again 'B' value was checked and measured as at least 0.96. Following the completion of saturation, the sample was consolidated at desired confined pressure and strain controlled experiments were completed under undrained conditions.

The application of the test detail is standardized by ASTM D 4015-87. It is a fixed- free system where the bottom and top of the system works differently. The bottom of the soil sample is fixed whereas the top is free to rotate at its fundamental frequency. The capacity of the machine is similar to the TRX test system.

3.3 Evaluation of initial shear modulus

There are many approaches offered by the scientist to project the maximum dynamic shear modulus in the literature (Jafarian *et al.* 2018a, b). The very first initial shear modulus formula was offered by Hardin and Black in 1968 and the G_{max} value was modeled as connected to void ratio and mean effective stress. The relation for normally consolidated cohesive soils proposed by Hardin and Black is presented in equation 4. In order to calculate G_{max} in kPa, the mean effective stress should also be in kPa.

$$G_{max} = \frac{3270.(2973 - e)^2}{1 + e}.(\sigma'_m)^{0.5} \tag{4}$$

Most of the equations were essentially derived from this equation. Later in 1972, Hardin and Drnevich proposed a new formula used in cohesive soils (Eq. (5)). This equation is a general form and was offered for both normally and over-consolidated clays. In the equation, Pa is introduced as the atmospheric pressure to the older version and the σ_0' is the effective stress instead of mean effective stress. Along with these changes, the constants were also updated. The unit of them can be chosen anything since the come out will be the same.

$$G_{max} = \frac{1222.(2.97 - e)^2}{1 + e}.\sqrt{Pa.\sigma_0{}'} \qquad (5)$$

In 1978 Marcuson and Wahls revised the previous version for cohesive and clayey soils and the new form is presented in Eq. (6).

$$G_{max} = 445\frac{(4.4 - e)^2}{1 + e}(\sigma'_0)^{0.5} \qquad (6)$$

Kokusho *et al.* (1982) recommended a different version for cohesive and clayey soils shown below.

$$G_{max} = 90\frac{(7.32 - e)^2}{1 + e}(\sigma'_0)^{0.6} \qquad (7)$$

Both Marcuson and Wahls (1978) and Kokusho *et al.* (1982) formulas offer a relation between G_{max} and void ratio and the effective stress instead of the mean effective stress that counts for all three stress on the soil. There are other formulas can be found in the literature but these are considered more relevant for estimation the initial shear modulus.

4. Results

In this study, dynamic experiments were performed on soil samples that were obtained from the earthquake zone mentioned above. Dynamic triaxial and resonant column test systems have been carried out on total of 12 experiments at different frequencies and cell pressures. Fig. 7 presents some deformed soil samples from the experiment RC and TRX tests.

Each cycle at different strain levels was recorded and the shear modulus and damping ratio values were obtained with the methodology explained in the previous part. Samples were tested with different confining pressures at frequencies of 1 Hz and 0.1 Hz. The extracted data from each cycle at 50 kPa of confining pressure, the normalized shear modulus-shear strain curves from the 1 Hz and 0.1 Hz

Fig. 7 Deformed samples after TRX experiments

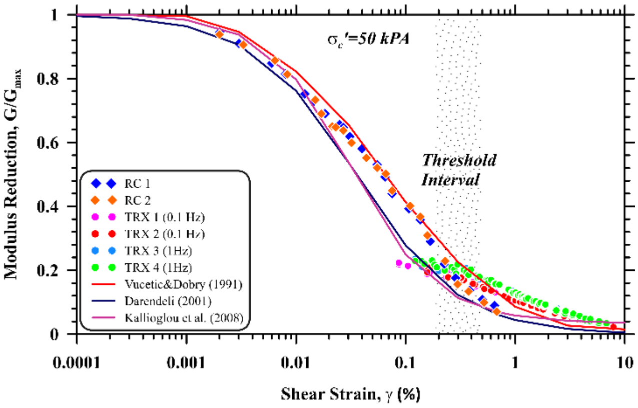

Fig. 8 The normalized shear modulus-shear strain values at 50 kPa of confining pressure

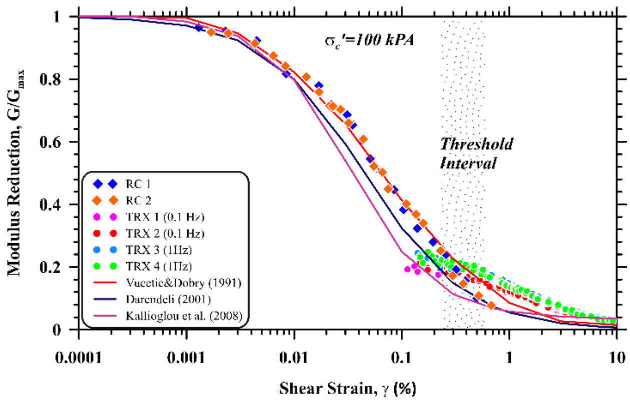

Fig. 9 The normalized shear modulus-shear strain values of the 100 kPa pressure

frequency loadings are shown in Fig. 8. An example loop at %0.5 shear strain from one of the triaxial test was shown in Fig. 2 in order to show how to evaluate the dynamic parameters of soil.

First of all, the test data matched with the Marcuson and Wahls (1978) approach in terms of initial shear modulus compared to other models therefore all the data is normalized with the values calculated from their formulation. Moreover, 3 different models (Vucetic and Dobry (1991), Darendeli (2001) and Kallioglou *et al.* (2008) were introduced to figure for the sake of validation of the test data as seen in the graph.

One clear thing about the data gathered from the RC tests is that shear modulus at small strains until %0.01 lie between Vucetic and Dobry's model (VDM) with other two and there is almost a perfect match of the data between %0.02 to %0.2 of shear strain with VDM. Over this range, the data drops sharply and move away from VDM and converge to the other two models.

Regarding the data extracted from TRX tests, some data scattered over the range of %0.2 to %0.5 and appear between VDM and others for both slow and faster loadings. Although the data over 0.5% of shear strain is underestimated by all the models, the shear modulus followed the pattern of VDM for different frequencies. There is an obvious distinction between the modulus values for two type of loading that the soil samples behaved more

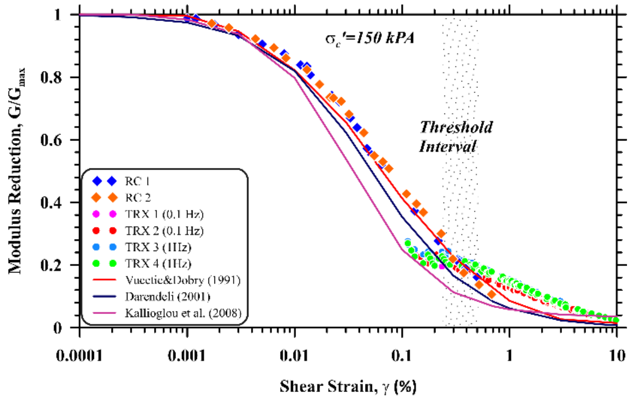

Fig. 10 The normalized shear modulus-shear strain values of the 150 kPa pressure

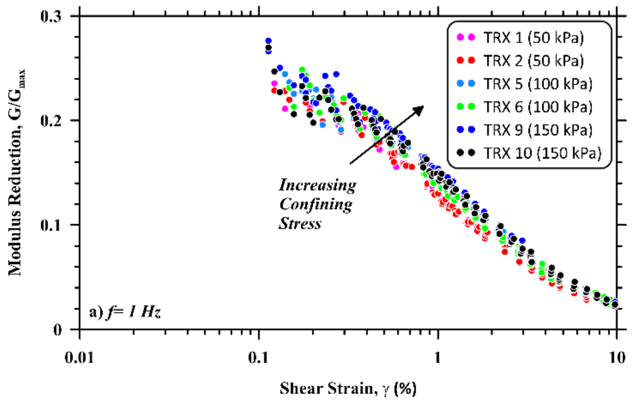

Fig. 11 The normalized shear modulus-shear strain values for the 1 Hz loading

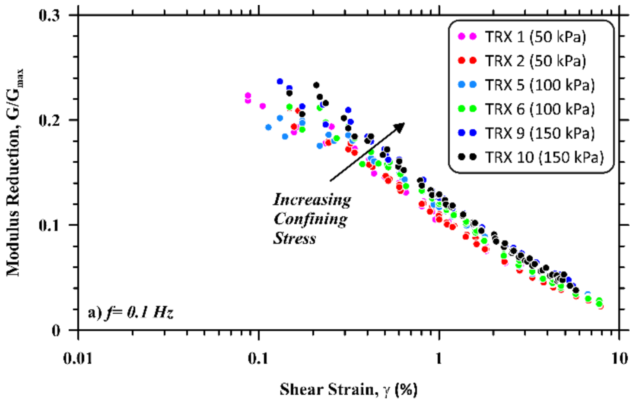

Fig. 12 The normalized shear modulus-shear strain values for the 0.1 Hz loading

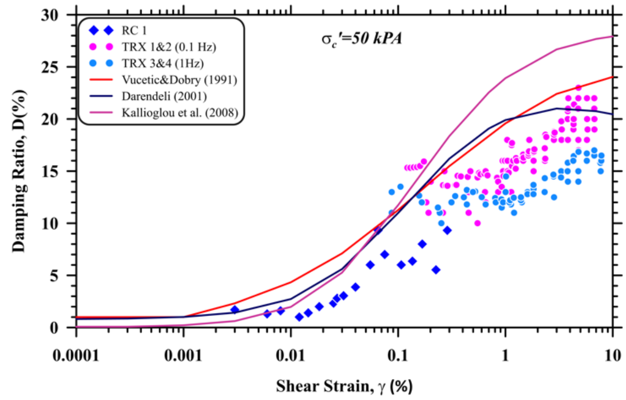

Fig. 13 The damping ratios calculated from the tests at 50 kPa of cell pressure

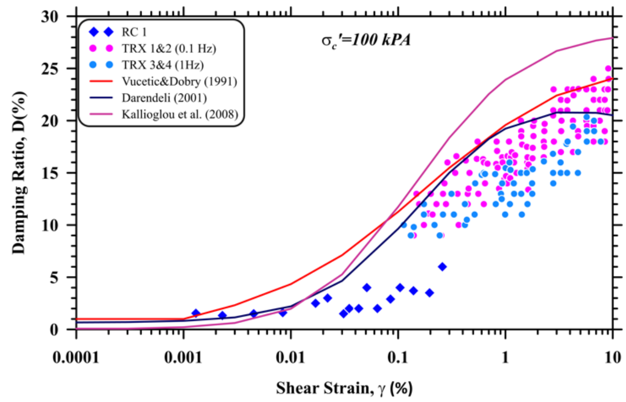

Fig. 14 The damping ratios calculated from the tests at 100 kPa of cell pressure

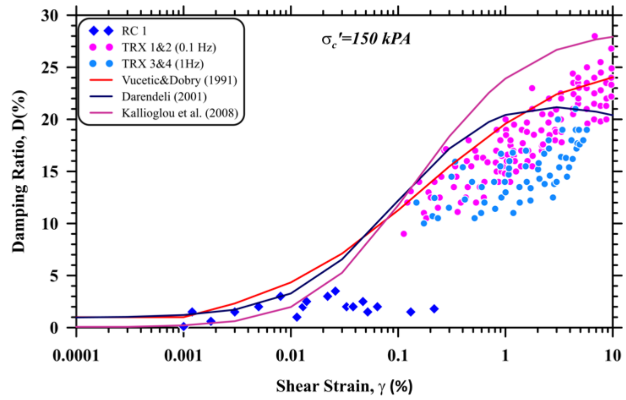

Fig. 15 The damping ratios calculated from the tests at 150 kPa of cell pressure

rigid at 1 Hz loading than 0.1 Hz loading. This underlines the importance of the frequency content on the rigidity of clayey sandy soils.

Moving on to the evaluation of the data obtained from the tests conducted at 100 kPa of cell pressure, there is a noticeable shift to the up for both RC and TRX data (Fig. 9). Almost all the data of RC tests falls into the VDM curve up until %0.2 of shear strain and the TRX data happened to be over all the curves similarly to the data at 50 kPa of cell pressure. VDM is the best model to represent the data but over %1 of shear strain all the models missed the test data. The last comment is that the frequency difference got smaller at this confining pressure.

Finally, the data collected from the samples confined at 150 kPa for different frequencies is shown in Fig. 10. This time, the data was underestimated by all 3 models although the path of the data is very similar to the VDM curve.

There is a transition area between RC and TRX tests and it is called threshold interval (Vucetic and Dobry, 1991). The later part of RC test data and initial part of TRX test data fall into in this interval showing that the data together departs from a certain path. It seems that the data matches very well with the VDM especially at lower confining pressures therefore the data from the RC and TRX tests in the threshold part may not be best to use. Another point is that the interval moves to the right as the confining pressure increases.

In order to assess the importance of confining pressure, all the data from the TRX tests were put together at different frequencies and is shown in Figure 11 (f=1 Hz) and 12 (f=0.1 Hz).

Interpreting the figures together, the confining pressure is a crucial parameter estimating the shear modulus at varying strains regardless of the loading rate. However, the data condensed in a small interval for 1 Hz loading compared to the 0.1 Hz and this is an evident that the loading rate should also be considered in the prediction of the shear modulus.

Darendeli (2001) model is the only model that considers the confining pressure yet it underestimated the data at any confining pressure and frequency. The reason for that is the structure of the soil having both sand and clay almost in the same dominance. Therefore, the effect of sand deviates the behavior in a positive manner in terms of soil rigidity.

Although soil is classified as clayey sand according to the USCS, the harmony of the data and VDM showed that plasticity is still one of the most leading criteria and controls the nature of modulus reduction at varying shear strain even in a sand mix.

Last part of the study focuses on the damping behavior of the soil using the RC and TRX test data. The loops from the different rate of loadings at varying confining pressures were extracted and the damping ratios were calculated as explained above. The first set of the obtained values along with the 3 different models are shown in Fig. 13 for the cell pressure of 50 kPa.

The figure shows that the data is much scattered compared to the shear modulus data. Aside a few points, the observed damping ratios are well above the literature models. Regarding the data extracted from the RC tests, they follow the path of Kallioglou *et al.* (2008) but there is almost %2 difference between the data until %0.1 of shear strain. Over this value, the damping ratios missed the track and stayed a little bit lower. Similar behavior was observed for the data obtained from the TRX tests. Over %0.3 of shear strain, the data is almost %3-5 lower than the two literature models (Darendeli, 2001 and Vucetic and Dobry, 1991) for the data from the 0.1Hz frequency loading and even higher for the loading with 1 Hz.

There is also a vital point here is that the frequency effect plays on important role on the damping behavior of soils, as well. Slower loadings caused higher energy that soil observes whereas the soil loaded with the faster rate demonstrated %5 lower damping ratios. Both data sets cluster around a line and not many data points mix each other at the confining pressure of 50 kPa.

Final comment of the figure is about the small strain damping. Most literature models offer almost %0 damping ratio for very small strain level; however, there is %2-3 of small strain damping calculated from the RC tests.

The data gathered from the tests at the confining pressure of 100 kPa is presented in Fig. 14. It can be stated that there is rather a shallower trend for the damping ratios from the RC tests compared to the Figure 13. Again, %2-3 of damping ratios are noted for the small strains however the data is a bit off after %0.02-0.03 of shear strain in regards to the literature models.

The Vucetic and Dobry (1991) line is almost upper limit for the data calculated from the TRX tests. Since the model was constituted at a confining pressure of 1 Atmospheric pressure (101.325 kPa), the data has a great similarity with the offered model. There is a bit scatter but the tendency of the data is most likely to follow the general behavior. Other two literature models are not too off to match the data but the decrease in damping ratios over %2 of shear strain for the Darendeli (2001) behavior was not recognized in the test data.

In terms of the rate of loading, there is still a bit difference between two different loading types, 0.1Hz data being higher again. The distinction between two data tests are not that clear for at this confining pressure. Similarly, the damping ratios at the 150 of cell pressure is shown in Fig. 15.

As seen in the figure, there is almost a flat behavior for the damping ratios for the RC tests at the highest confining pressure. It brings a conclusion about the RC tests that the observed damping ratios get shallower trend as increasing the effective stress. At high level of stresses, the data seems off track compared to the literature models especially over %0.02-0.3 of shear strains.

With regard to the data of TRX tests, there is a bit shift upward but the scatter is still a lot. It is obvious that damping ratios can differ largely at varying shear strains for diverse rate of loadings. At this point, the behavior contradicts with the shear modulus behavior staying on a straight trend line rather being spread over in a %5-6 range.

5. Conclusions

In this study, dynamic triaxial test system (TRX) and resonant column test system (RC) were used to investigate the dynamic properties of the soil under different frequencies and confining pressures. There are concrete points that should be underlined boldly as a result of the analysis and they can be summarized as follows:

Effect of confining pressure:

The most important come out of the study is that the confining pressure is definitely an essential parameter that directly affects the dynamic behavior of soils. Equivalent samples were confined at different pressures and dynamically loaded and there is almost %20 difference recognized at small to medium shear strains. As it increases, the difference tends to lower and disappear at very high strain levels.

Effect of rate of loading:

The dynamic loads can be very particular in terms of type of wave, duration, frequency, etc. Lower rate of loading results soils to show more rigidity compared to faster loadings at any confining pressure. The variation is very distinct for lower cell pressures and it gets narrower as the shear strain increases but it is always there in terms of modulus behavior. As regards to the damping presence, the discrepancy becomes more obvious. Although there is a big spread over of the data, starting from %3 to %7 of damping difference is inevitable for larger confining pressure.

Threshold region:

The threshold region was defined by Vucetic and Dobry in 1991 and the region was investigated in a different sense. Considering the modulus reduction behavior, varying threshold intervals were detected for increasing cell pressures. What we observe here is that the RC test and TRX test data may not be dependable compared to the literature models for defined interval. This region is at the end of the RC test and at the beginning of the TRX test meaning that both test data at the medium strain levels should be carefully used. When combine them together, the general behavior is easily constructed solely RC test or TRX test data may not be used to understand the behavior of soil at this strain level but as seen in the figure.

Plasticity of Soils:

Most literature models were designed on soil being either clay or sand. However, the case in reality is so different that soil composes of mix types. In this study, plasticity index was kept constant not to mislead the study on the effect of plasticity; however, the plasticity of soil (even for a sandy soil) is a key parameter to estimate the dynamic behavior as seen the harmony of data with the Vucetic and Dobry (1991) model.

Damping Behavior:

Two main points should be mentioned here that 1) %2-3 of damping ratios were calculated at small strains and 2) there is always an increasing tendency in damping in contrast to the Darendeli (2001) model at over %2 of shear strain. Moreover, the damping ratios gathered from the RC tests at higher confining pressures were found to be flatter opposing to the literature models therefore one should be rigorous to evaluate the damping behavior at this shear strain level.

The laboratory studies on the assessment of the dynamic behavior of soils are very crucial in practice. As concluded above there is so much variation on the behavior with the effect of different parameters. Therefore, the need of more study on the behavior of soils (especially mixed soils) is always be there and the effect of the rate of loading divert the dynamic behavior so it should be considered in the seismic design.

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