Dynamic Properties of Fiber Reinforced Clay

Behzad Amir-Faryar & M. Sherif Aggour
University of Maryland, College Park, MD, USA

15 WCEE
LISBOA 2012

SUMMARY:
Many civil engineering projects are constructed over soft and weak soils leading to the use of various ground improvement techniques, of which soil reinforcement using randomly oriented fibers has become an attractive method of soil stabilization. This is because such fibers have proven to improve the geotechnical properties of clay, such as shear, compression, and tensile strength, etc. However, limited studies of the dynamic properties of fiber reinforced clay have been undertaken.
The objective of this study was the determination of the shear modulus and damping for clay with and without fiber reinforcement. First, the optimum fiber content of the composite was determined. Then, kaolinite reinforced with polypropylene monofilament fibers was tested using the resonant column techniques. Measured responses were used to determine the dynamic properties. It was found that fiber reinforcement at optimum fiber content greatly improved the dynamic properties of clay, by increasing its modulus as well as increasing its damping.

Keywords: shear modulus, damping ratio, monofilament, polypropylene fiber, resonant column test

1. INTRODUCTION

With recent advances in the analytical and testing methods, the behaviour of soils subjected to various types of dynamic loading, such as, earthquakes, ocean waves, machine vibrations, and blasts, are being understood more. The measurement of dynamic soil properties is a vital task in the solution of geotechnical earthquake engineering problems. Any analysis of dynamic engineering problems requires the determination of two important parameters, namely, the shear modulus and damping ratio. These two parameters are usually determined using laboratory or field methods. The selection of testing methods for measurement of dynamic soil properties requires thorough consideration and understanding of the specific problem at hand.

The shear modulus (G) and damping ratio (D) are the two main variable properties in the dynamic response analysis of soils. They are the reason that soils are not considered a linear-elastic material. The shear modulus, and damping of soils are strain dependant.

The vibratory motion of shear waves can cause shear strains on a soil element. The stress-strain curve forms a closed loop called hysteresis loop as shown in Figure 1.

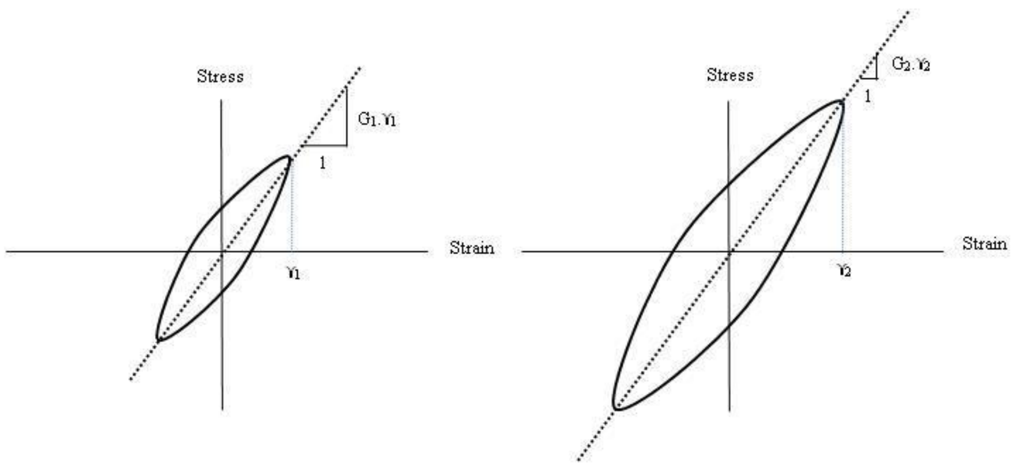

Figure 1. Stress–strain relationship in cyclic loading (Shannon and Wilson, 1972)

From figure 1, the shear modulus and damping can be obtained directly. The damping ratio increases with increasing strains while the shear modulus decreases. The shear modulus and damping can be obtained both in the laboratory and field. Each method of testing has an associated strain range in which the test is conducted. A comprehensive review of laboratory and field testing and procedures to obtain dynamic soil properties are given by Wood, 1978; Hoadley, 1985; Kramer, 1996; Towhata, 2008.

Laboratory tests are typically performed on relatively small soil specimens that are assumed to be representative of a larger body of soil. The ability of laboratory tests to provide accurate rather than precise measurements of soil properties depends on their ability to simulate the initial conditions and loading conditions of the problem of interest in a smaller scale. Laboratory tests provide an opportunity to determine the dynamic properties of soils under dynamic loading for a wide range of strain levels.

1.1. Resonant Column Test

The resonant column test is the most frequently used laboratory soil test for measuring low strain properties 10^{-6}-10^{-2} (0.0001%-1%). The method for the resonant column test was first developed by K. Iida in 1939. It has become well accepted worldwide since the 1950s. At first, both a theory and a device for resonant column tests on soils was established, in which the loading frequency at the maximum response was used to come up with elastic properties of soils. At that time, they were not able to apply confining pressure to consolidate the specimen; thus, soil samples with fines and moisture that could maintain shape without pressure application were put into testing.

The Drnevich fixed-free resonant column apparatus is the most common type. The apparatus is used for testing the behavior of a column of soil placed between a pair of platens within a pressurized chamber in which torsional or longitudinal vibrations can be applied. Harmonic loads are usually the most common loading system for which the frequency and amplitude are controlled. However, random loading (Al-Sanad, et. al, 1983), (Al-Sanad & Aggour, 1984), (Amini, et. al, 1988) and impulse loading (Tawfiq, 1986), (Tawfiq, et. al, 1988) have also been used as a loading system in resonant column device. Effect of coupled loading on the dynamic properties of clayey (Tawfiq, 1986) and sandy (Aggour & Zhang, 2006), (Aggour & Zhang, 2008) soils has also been examined. There is other research conducted on natural clayey soils using a fixed-free resonant column apparatus (Hardcastle and Sharma, 1998), (Hoyos, et al, 2008). In addition, Bentonite has been added to make samples with a higher PI for experimental investigation (Inci, et al, 2003). Moreover, the use of lime as a stabilizer in clayey soils has been studied and dynamic properties of lime stabilized clay are determined (Fahoum, et. al, 1996).

The elastic or shear modulus depends on the type of vibration and can be indirectly calculated in terms of the resonant frequency. Shear modulus can be calculated in terms of specimen dimensions and testing apparatus condition using the following equation:

$$G = 4\pi^2 \rho \left(\frac{f_r L}{F}\right)$$

where:
G: shear modulus, ρ: mass density of soil specimen, L: height of specimen, f_r: resonant frequency of the system, F: dimensionless frequency.
Damping using the free-vibration decay method (Logarithmic Decrement Method) is determined by switching off the driving power at resonance and recording the decaying vibration from which the logarithmic decrement is calculated using the following equation:

$$\delta_s = \frac{1}{n} Ln \frac{A_1}{A_{n+1}}$$

where:
δ_s: logarithmic decrement (damping), A_1: initial value of amplitude, A_{n+1}: amplitude after n oscillations.
The damping ratio can also be calculated using following equation:

$$D = \frac{1}{2\pi}[\delta_s(1+S) - \delta_A]$$

where:
δ_A: logarithmic decrement of the apparatus without specimen, S: system energy ratio
δ_s: logarithmic decrement (damping), D: damping ratio.

1.2. Clayey Soils

Clay is known to be a material whose properties puzzled engineers for centuries. There is hardly any kind of soil that is likely to cause more exasperating trouble in connection with engineering projects than clay (Terzaghi, 1928). Engineers are frequently required to build a structure on, through, or with clay materials. Therefore, the nature of clay particles and engineering properties of this type of soil need to be investigated. Clays have been shown to be made up of mainly of a group of crystalline substances known as the clay minerals. Montmorillonite, illite, and kaolinite are the most frequently encountered soils in the field (Eades and Grim, 1960). Kaolinite is a common mineral, the main constituent of kaolin or clay. It is always a secondary mineral formed by weathering or hydrothermal alteration of aluminium silicates, specifically feldspar.

The soil used in this study was Kaolinite. The Atterberg limits were determined to be LL = 49, PL = 29, and PI = 20.

1.3. Fiber Reinforcement

Use of fiber reinforcement in construction materials can be traced back to prehistoric times, when civilizations in Mesopotamia added straw to mud bricks (sun-dried soil bricks). The goal was to provide integrity to a weak matrix by taking the growth of cracks into control and improve soil properties. Early developments in soil fiber composites were in the area of reinforced earth. In the late 1960s, some studies were conducted on the utilization of galvanized steel for reinforcing retaining wall backfill (Vidal, 1978).
The use of randomly reinforced fibers with compacted cohesive soils was examined in 1986. It was shown that the inclusion of fiber could result in greater strength and toughness in compacted fine-grained soil (Freitag, 1986).
The utilization of recycled short monofilament fibers in clayey soil has also resulted in increasing the compressive and shear strengths characteristics of clay. By using an E-meter instrument, it is also

shown that use of waste fibers in clayey soil can improve the damping ratio and shear modulus of the mixture (Akbulut, et al, 2007).

In order to obtain the maximum benefit of the use of the fiber in a fiber-reinforced clay, a laboratory compaction testing procedure has been established to obtain the optimum fiber content (Amir-Faryar and Aggour, 2012). For this study, the dynamic testing was performed on a fiber-clay composite at the optimum fiber content (OFC).

The polypropylene fibers used in this study were 1.9 cm (0.75 in) in length virgin homopolymer monofilament. The summary of the properties of the fiber used in this study is presented in Table 1.

Table 1. Properties of Monofilament Fiber

Properties	Monofilament Fiber
Specific Gravity	0.91
Tensile Strength	552-758 MPa (80-110 ksi)
Denier	6
Thickness	0.030 mm (0.0012 in)
Melting Point	Above 160C (320F)
Flash Point	Above 329C (624F)
Autoignition Temperatures	Above 357C (675F)
Electrical & Thermal Conductivity	Low
Acid & Salt Resistance	High
Alkali Resistance	Alkali Proof

2. SAMPLE PREPARATION AND COMPACTION TESTS

The specimens were prepared by mixing kaolinite with various percentages of fiber content (FC) and percentages of mixtures by weight, per Amir-Faryar and Aggour's established compaction procedure (Amir-Faryar and Aggour, 2012).

The soil-water mixture for compaction was prepared by first mixing a measured amount of dry soil (about 2 kg for each test) with a predetermined amount of water by hand and then by a mechanical mixer. In the case of fiber addition, the weight of the specific content of fibers was calculated based on the weight of the air dried soil. The required amount of fiber was first mixed with the dry soil, then water was gradually added. Mixing continued until a uniform mix was produced. Compaction tests were performed on a mixture of kaolinite soil with monofilament fiber immediately after achieving a uniform and homogeneous mixture.

The optimum fiber content was determined to be 0.2% for the composite. The dry density and optimum moisture content for the composite at optimum fiber content was determined to be 12.95 kN/m^3 and 29.9%. An undisturbed sample from the fiber-clay composite at OFC was carefully made using a hollow brass cylinder. A thin membrane was wrapped around the specimen then placed in the resonant column apparatus. Two O-rings were used to block water from seeping into the specimen. Specimens were placed under 34.5 kPa (5 psi) pressure for 1020 minutes in order to complete the primary consolidation period prior to starting the dynamic testing. The dynamic testing was also performed under 34.5 kPa confining pressure.

3. TESTING APPARATUS

The Drnevich resonant column apparatus, a relatively nondestructive testing equipment, was used for this research. The resonant column testing apparatus employs a chamber having a lower and a top platen (active platen) confining a column of soil in between and with means to provide water and compressed air into the chamber for subjecting the column of soil to conditions representative of in-situ soil. A magnet plate supporting torsional and longitudinal accelerometers, in association with fixed coils connected with an electrical circuit, provides for torsional vibration of the soil column. A centrally placed coil on the torsional magnet plate provides for torsional vibration of the soil column and a length measuring transducer (LVDT) cooperating with the upper platen serves to give constant readings of the length changes of the soil column.

The excitation system of the resonant column device is an electromagnetic system comprising of a permanent magnet and coil, which can move in the gap between the North and South Poles of the permanent magnet. For the torsional mode, the assembly comprises four rectangular coils and horseshoe-shaped magnets. The coils are connected to the brackets and the magnets are connected to the top active platen. Equal gaps should be maintained between the magnets and the coils to minimize the development of any bending forces. The torsional coils allow movements (1.3 cm) in the vertical direction to accommodate the change in length during the consolidation process of clay. By generating an AC current of controlled frequency through the coils a magnetic field would be generated that in turn develops torsional forces on the top of the soil column.

During each testing routine, the wave oscillator signals are amplified with the power amplifier and then input to the drive coils after passing through the power resistor in the control box. The pick-up system comprises of a piezoelectric meter (Columbia Model 200-1-H) placed in the active-end platen. The transducer is mounted at a distance of 0.0316 meters from the axes of rotation. The digital multimeter and oscilloscope are used to record the responses. A digital multimeter gives readings of sample acceleration in terms of rms; which in turn can be converted to define the shear strain. The oscilloscope monitors the frequency response of the sample.

4. DYNAMIC TESTING AND DISCUSSION

The dynamic testing was performed on clay with 0% and 0.2% fiber contents with an initial frequency and voltage amplitude of 15 Hz and 50 mV, respectively. The frequency was gradually increased to reach up to the sample resonant frequency while the voltage amplitude remained constant. The test was redone for each sample with 100, 200, and 300 mV voltage amplitudes to obtain data for different shear strains. Summaries of the resonant column test results are shown in Figures 2 and 3.

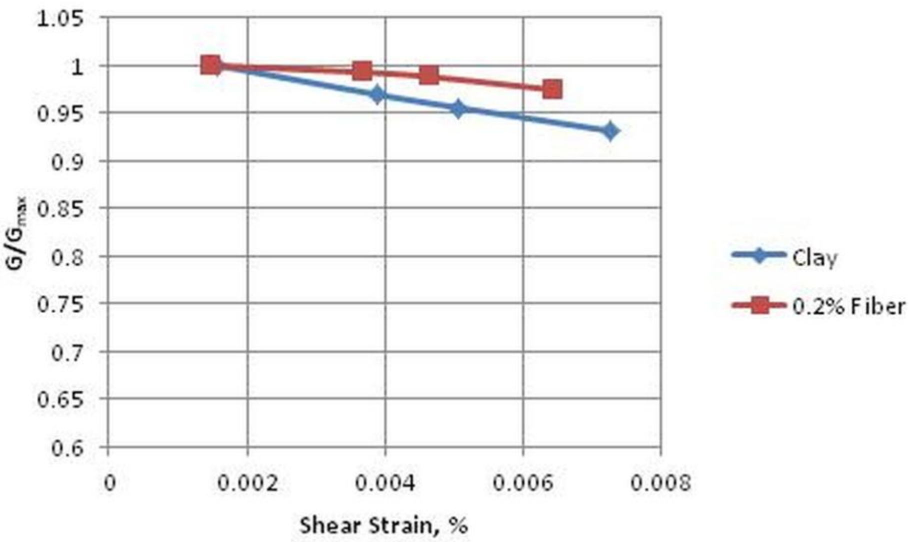

Figure 2. Shear modulus degradation graph of clay and fiber reinforced clay

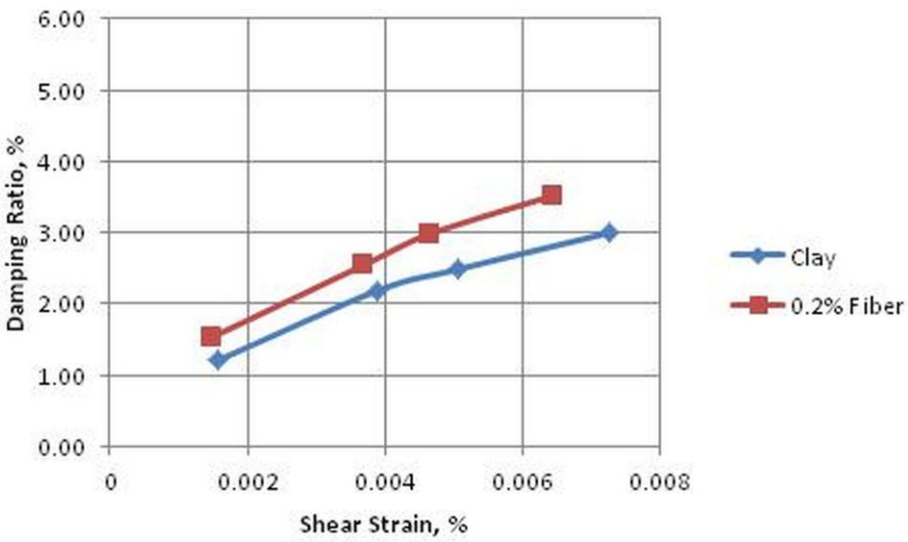

Figure 3. Damping ratio versus shear strain graph of clay and fiber reinforced clay

It should be noted that the shear strain axis plotted is not in a logarithmic scale so as to emphasize the changes in both the shear modulus and damping ratio in the low shear strain range tested for the clay and the fiber reinforced clay. From both figures, it can be seen that the addition of fibers can affect both the shear modulus and the damping ratio of clay. An increase in the values of damping ratio and shear modulus was observed for clay with fiber at low shear strain ranges.

4. CONCLUSIONS

The paper shows that the addition of fiber to clay has improved its dynamic properties. It increases the shear modulus as well as its damping. The main conclusion of this study is that the inclusion of fiber at optimum fiber content as a ground improvement technique will improve the dynamic properties of soft and weak clayey soils at low shear strain. This increase in the value of dynamic properties of clay can be mainly due to the rearrangement of soil particles caused by the addition of fibers. Since the soil at its optimum fiber content becomes fiber-saturated, meaning that all soil voids are mostly filled with fiber, it has produced a stiffer composite while benefiting from the material damping properties of the polypropylene materials. It is important to note that the fact that both the shear modulus and damping have increased provide a double benefit for the dynamic response of a site by increasing the stiffness of the site and reducing its amplitude of vibration.

ACKNOWLEDGEMENT

The authors would like to thank Mr. Robert Woodke of Northern Virginia Community College (NVCC) for machining the sampling cylinders for this research.

REFERENCES

Aggour, M.S. and Zhang, J.X. (2006). Degradation of Sands Due to Combined Sinusoidal Loading. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE,* **132:12**, 1628-1632.

Aggour, M.S. and Zhang, J.X. (2008). Modulus and Damping Evaluations of Sands Subjected to Combined Dynamic Loadings. *International Journal of Geotechnical Engineering*, **2:4**, 369-380.

Akbulut, S., Arasan, S., and Kalkan, E. (2007). Modification of Clayey Soils Using Scrap Tire Rubber and Synthetic fibers. *Applied Clay Science* **38**, 23-32.

Al-Sanad, H., Aggour, M.S., and Yang, J.C.S. (1983). Dynamic Shear Modulus and Damping Ratio From Random Loading Tests. *Geotechnical Testing Journal, GTJODJ* **6:3**, 120-127.

Al-Sanad, H. and Aggour, M. (1984). Dynamic Soil Properties from Sinusoidal and Random Vibrations. *Proceedings, 8th World Conference on Earthquake Engineering* **Vol 3**, 15-22.

Amini, F., Tawfiq, K. and Aggour, M.S. (1988). Cohesionless Soil Behavior Under Random Excitation Conditions. *Journal of Geotechnical Engineering*, ASCE, **114:8**, 896-914.

Amir-Faryar, B., and Aggour, M.S. (2012). Determination of Optimum Fiber Content in a Fiber-Reinforced Clay. *ASTM Journal of Testing and Evaluation* **40:2**, 334-337.

Eades, J. and Grim, R. (1966). A Quick Test to Determine Lime Requirements for Lime Stabilization. *Highway Research Record* **139**.

Fahoum, K., Aggour, M.S. and Amini, F. (1996). Dynamic Properties of Cohesive Soils Treated with Lime. *Journal of Geotechnical Engineering*, ASCE, **122:5**, 382-389.

Freitag, D. (1986). Soil Randomly Reinforced with Fibers. *ASCE Journal of Geotechnical Engineering* **112:8**, 823-836.

Hoadley, P. (1985), Analysis and Design of Foundations for Vibrations, "Measurements of Dynamic Soil Properties, P. Moore, Ed".

Hardcastle, J. & Sharma, S. (1998). Shear Modulus and Damping of Unsaturated Loess. *Geotechnical Special Publication, ASCE, NY*, 178-188.

Hoyos, L., Takkabutr, P., Puppala, A., & Hossain, M. (2008). Dynamic Response of Unsaturated Soils Using Resonant Column and Bender Element Testing Techniques. *Geotechnical Earthquake Engineering and Soil Dynamics Geo-Institute of ASCE* **Vol IV**.

Inci, G., Yesiller, N., & Kagawa, T. (2003). Experimental Investigation of Dynamic Response of Compacted Clayey Soils. *Geotechnical Testing Journal* ***26*****:2**,125-141.

Kramer, S. (1996), Geotechnical Earthquake Engineering. Prentice Hall.

Shannon and Wilson (1972). Soil Behavior Under Earthquake Loadings Conditions: State of the Art Evaluationof Soil Characteristics for Seismic Response Analyses. Shannon and Wilson, Inc.

Tawfiq, K. (1986). Effect of Time and Anisotropy on Dynamic Properties of Cohesive Soils, *Dissertation presented to the University of Maryland in Partial Fulfillment of the Requirements for the Degree ofDoctor of Philosophy*. College Park, MD: UMCP.

Terzaghi, K. (1928). The Physical Properties of Clay. *The Tech. Engineering News* **9:1**, 10-11.

Towhata, I. (2008), Geotechnical Earthquake Engineering. Springer.

Vidal, H. (1978). The Development and Future of Reinforced Earth. *Proceedings ASCE Symp. on Earth Reinforcement*, 1-62.

Woods, R. (1978). Measurements of Dynamic Soil Properties. *Proceedings Earthquake Engineering and Soil Dynamics*. Pasadena: ASCE Specialty Conference. **Vol 1**, 91-178.