

Development of Dynamic Simple Shear Apparatus for Small Strain Dynamic Tests on Unsaturated Granular Soils by Bender Element and Ultrasonic Sensors

Ali Akbar Karimzadeh^{1*}, Fardin Jafarzadeh², Adel Ahmadinezhad³

¹ M.Sc. of Geotechnical Engineering, Department of Civil Engineering, Sharif University of Technology, Tehran, Iran.

² Associate Professor, Department of Civil Engineering, Department of Civil Engineering, Sharif University of Technology, Tehran, Iran.

³ Ph.D. of Geotechnical Engineering, Department of Civil Engineering, Sharif University of Technology, Tehran, Iran.

*Corresponding author's Email: a.a.karimzadeh@gmail.com

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ABSTRACT:

Shear modulus and confined modulus are important parameters for static and dynamic analysis in geotechnical applications. Cyclic simple shear apparatus had been developed by mounting bender element and ultrasonic sensors to measure continuous shear wave and pressure wave velocities for determination of G_{max} and M . For this purpose two new pedestals have been fabricated on which HAE ceramic disc and sensors were mounted. A pressure control panel and a hanging column system have been designed to apply high and low matric suction values with high accuracy. Finally, some tests was conducted to verify the result of device performance and to compare with the theoretical results of unsaturated soils.

Key words: Dynamic Simple Shear Apparatus, Bender Element, Ultrasonic, Unsaturated soils, Maximum shear modulus.

1- Introduction

Classic soil mechanics focused on the study of saturated and dry soils but Most of soils involved in many engineering applications such as embankments, earth dams, and mechanically stabilized earth (MSE) walls are unsaturated soil. Soil stiffness, especially shear modulus, is one of the most important parameters in geotechnical engineering especially in dynamic response. Maximum Shear modulus and confined modulus at very small strain (0.001%) are calculated based on elastic theory for propagation of waves at homogenous material. Measurement of soil stiffness using piezoelectric transducers has been implemented in many laboratory equipment such as: Oedometers, Torsional resonant column apparatus and Triaxial cells [1]–[6] but, never implemented in cyclic simple shear before. Kjellman (1951) is pioneering researcher described cyclic simple shear for geotechnical testing which can be attributed to Swedish Geotechnical Institute (SGI). This apparatus was used to determine shear strength [7]. Bjerrum & Landva (1966) developed the Norwegian Geotechnical Institute (NGI), to restrict the specimen form radial strain [8]. Silver & Seed (1971) modified the NGI-type simple shear apparatus by adding a lever arm in the apparatus to carry out small shear strain amplitude. Ishihara & Yamazaki (1980) developed cyclic simple shear, incorporating two pneumatic cyclic loaders in two mutually perpendicular horizontal direction [9]. Boulanger & Seed (1995) developed bi-direction cyclic simple shear for investigating liquefaction on saturated soil under dynamic and monotonic loadings [10]. In this investigation two bender element and ultrasonic sensors was added to cyclic simple shear

apparatus to measure the velocity of P-wave and S-wave for determination of G_{max} and M . For this purpose, the bottom pedestal and top cap were designed for performing small strain and unsaturated tests. In addition, pressure and suction control panel was designed and added to unsaturated system of cyclic simple shear apparatus.

2- The developmental cyclic simple shear apparatus

Fig.1 shows a general schematic layout of the device. The apparatus has been fabricated not only to measure dynamic parameters in all range of strain but also to apply and measure suction upon specimen with high accuracy (± 0.01 kPa). The cyclic simple shear apparatus was manufactured by Wykeham Farrance Co. This apparatus is SGI type that cylinder specimen (22mm height, 70mm diameter) is constrained by a membrane and 22 Staked rings. The shear stress on the specimen is applied by two pneumatic electro-valve which is controlled by PC. The range of shear strain performance of the device is 0.5 to 10 percent (small to large strain) as well as range of shear strain ultrasonic and bender element are 0.0001 percent (very small strain). Therefore, the range of shear strain was improved from very small to large strain by adding two piezoelectric sensors.

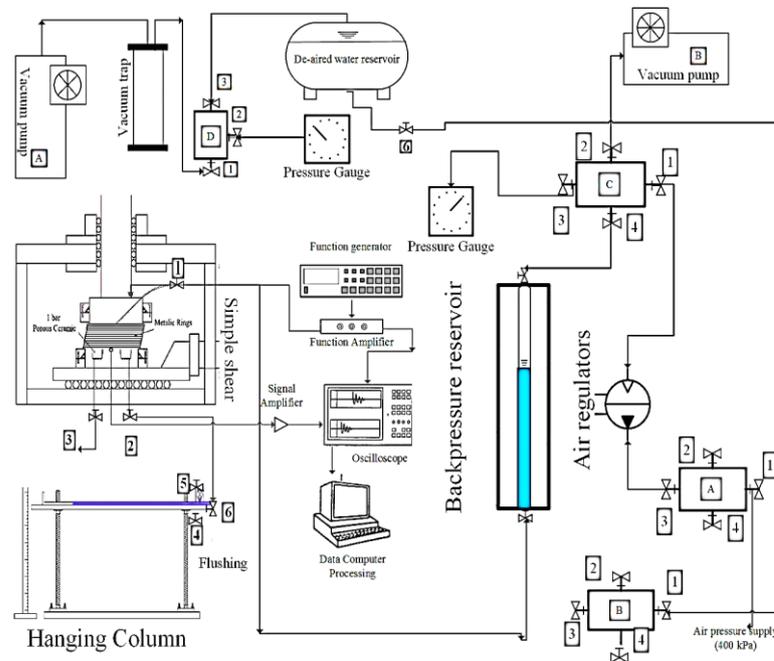


Fig.1. The general schematic of the unsaturated simple shear set up.

3- Modification of top and bottom pedestals for installing bender element and ultrasonic sensors

To modify this apparatus, a new bottom pedestal have been fabricated on which HAE ceramic disc and sensors were mounted as well as top pedestal have been designed to install piezoelectric sensor. To remove any dissolved air bubbles which can appear beneath the ceramic disk, a flushing system was incorporated by carving spiral grooves beneath the ceramic disk. More detail is depicted in Fig. 2 and Fig.3.

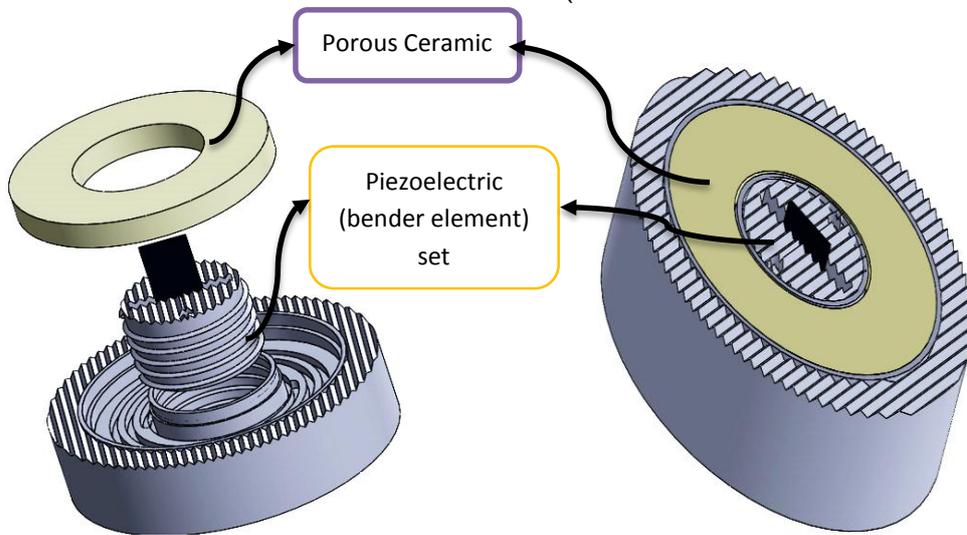


Fig. 2. The bottom pedestal schematic along with piezoelectric sensor and HAE ceramic.

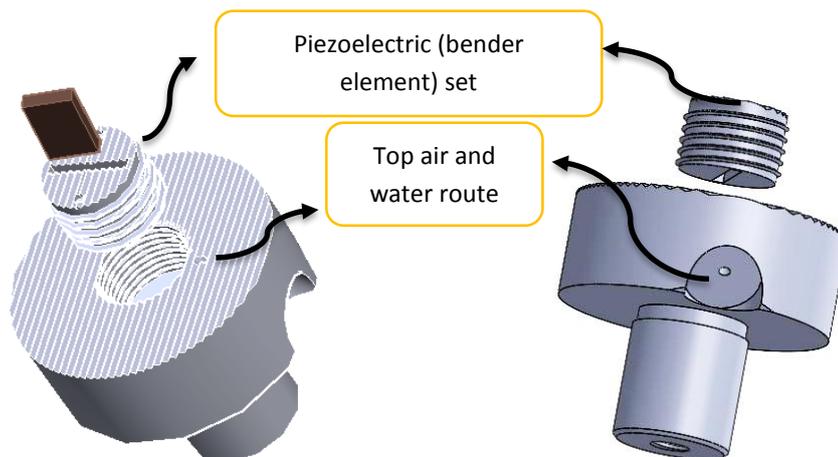


Fig.3. The top cap schematic along with piezoelectric sensor.

4- Suction control system

Hanging column and axis translation technique were used together to measure and control matric suction to the specimen. Therefore, low suction (0 to 7.5 kPa) with high accuracy (± 0.01 kPa) was applied by hanging column and high suction (7.5 to 100 kPa) was applied by pressure plate system. For combining the two systems, a pressure board was manufactured, which supply air pressure and water to bottom and top of the sample as well as measure air and water pressure during the test.



Fig.4. The pressure panel system for applying and measuring matric suction.

5- Material

The soil was used in this research, was collected from Babolsar shore in Mazanderan province in north of Iran, which classified as medium poorly graded sand in unified soil classification system by ASTM D2487[12]. Particle size distribution curve of Babolsar sand is shown in Fig.5 (a). Physical properties were determined by using ASTM standard is shown in Table 1[13]–[16]. Fig.5 (b) shows the soil water characteristic curve of Babolsar sand in 60% relative density under 50 kPa net vertical stress was determined using hanging column which was defined for Measuring SWCC for Gravel Soils at Very Low Suctions by Li et al. (2009) [17]. Accordingly, air entry and residual values, and residual degree of saturation were obtained equal to 2.4 kPa, 5.1 kPa and 7.7%; respectively.

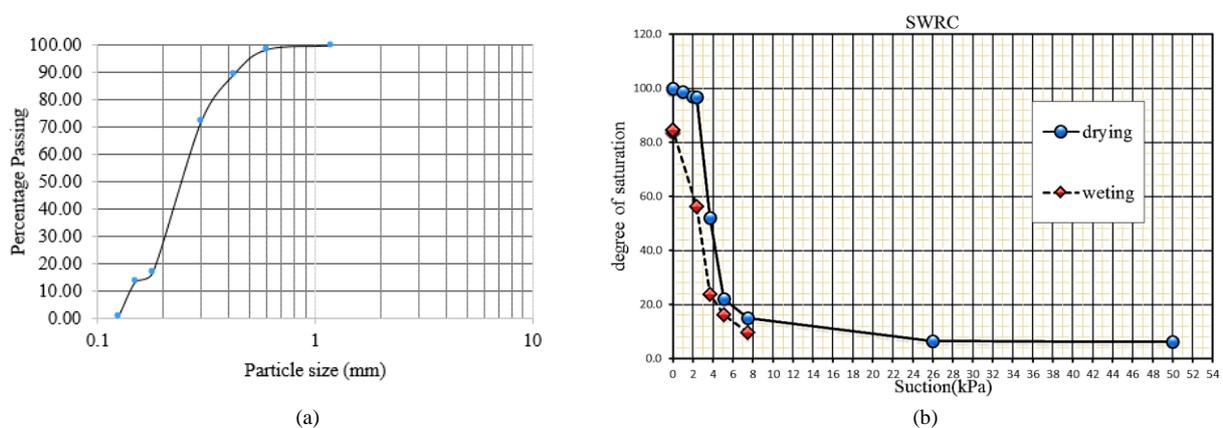


Fig.5. (a) Particle size distribution curve; (b) SWCC of tested soil drying and wetting path

Table 1: Selected physical and mechanical properties of Babolsar sand.

| Maximum void ratio e_{max} | Minimum void ratio e_{min} | D_{10} | D_{60} | D_{30} | C_u | C_u | Specific gravity of solid particles G_s |
|---------------------------------|---------------------------------|----------|----------|----------|-------|-------|--|
| 0.806 | 0.575 | 0.15 | 0.28 | 0.2 | 1.867 | 0.952 | 2.793 |

6-Testing approach

Experimental tests was conducted in various stages:

- 1-High pressure water (greater than air entry of HAE ceramic) was applied on HAE ceramic for saturating ceramic disc, until no air bubbles was observed in outlet water pipe for a period of 4 to 6 hours.
- 2-Specimens were prepared (70 mm diameter, 22 mm height), using moist-tamping method with initial water content equal to 5% and relative density of 45%.
- 3-Prepared sample was consolidated with a vertical load equal to 5 kPa; vacuum pressure about 45 kPa was applied and maintained constant for saturating the sample for about 3 days.
- 4-Vacuum was then removed and saturated soil was consolidated up to 50 kPa vertical stress which led to increase the relative density up to approximate 60% (57% to 63%) consequently.
- 5-Suction was applied on specimen and outlet volume of water measured. When discharge of outlet water rate became less than 0.008 cc per hours, the valve at bottom of the sample was closed.
- 6- Shear wave or pressure wave was sent by function generator and received by oscilloscope and duration of travel wave was measured. Afterward wave velocity and maximum shear modulus and confined modulus were calculated by equation 1, 2 and 3 respectively.

$$V = \frac{L}{t} \quad (1)$$

Where L is the minimum distance of two sensors and t is the travel time.

$$G_{max} = \rho V_s^2 \quad (2)$$

Where G_{max} is the maximum shear modulus, ρ is the soil density and V_s is the shear wave velocity.

$$M = \rho V_p^2 \quad (3)$$

Where M is confined modulus and V_p is the pressure wave velocity. To study the effect of degree of saturation and matric suction on small strain shear modulus and confined modulus of sand, tests were performed in various matric suction values. Test details were shown in Table 2.

Table 2: general testing program

| | | | | | | | | | | |
|-------------------|-------------------------|----------------------|----------------------------|-------|-------------------------------|-----------|----------------------------------|---------|---------|--------|
| ultrasonic | Drying path suctions | 0 kPa (saturated) | 1 kPa | 2 kPa | 2.4 kPa Air entry point | 3.7(kPa) | 5.1 (kPa) (Residual point) | 7.5 kPa | 26 kPa | 50 kPa |
| Bender element | | 0 kPa | 2.2 kPa air entry point | | 3.7 kPa | | 5.1 kPa Residual point | | 7.5 kPa | |

7- Experimental results

The shape of waves, were used in this investigation, were sinusoidal shape as shown in Fig. 6. Two test were conducted by bender element and ultrasonic on two different specimens.

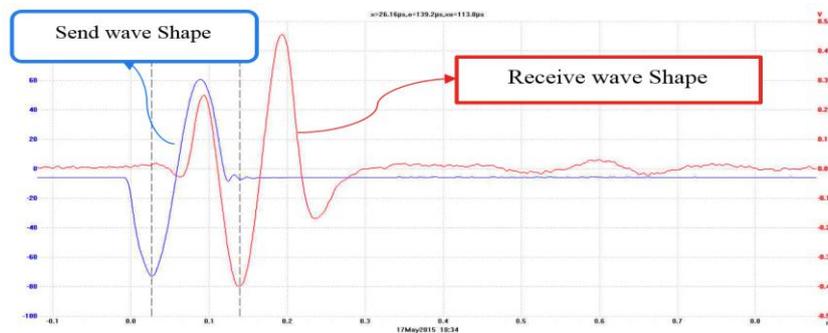


Fig. 6. Sending and receiving wave of bender element for frequency 8 kHz and suction stress 2 kPa

Figure 7 (a) shows the variation of shear velocity versus total effective stress (Bishop Method) which is acquired by the equation (4) and Figure 7(b) shows the variation of pressure velocity versus total effective stress. Variation of shear and pressure wave velocity versus total effective stress is identical, therefore shear and pressure wave velocity have a direct relation with total effective stress.

$$\sigma'_{total} = \sigma'_n + \psi S_r \tag{4}$$

In drying path, shear modulus increased significantly until air entry point, decreased in transition zone and then increased again in residual zone. The variation of maximum shear modulus is completely identical with total effective stress.

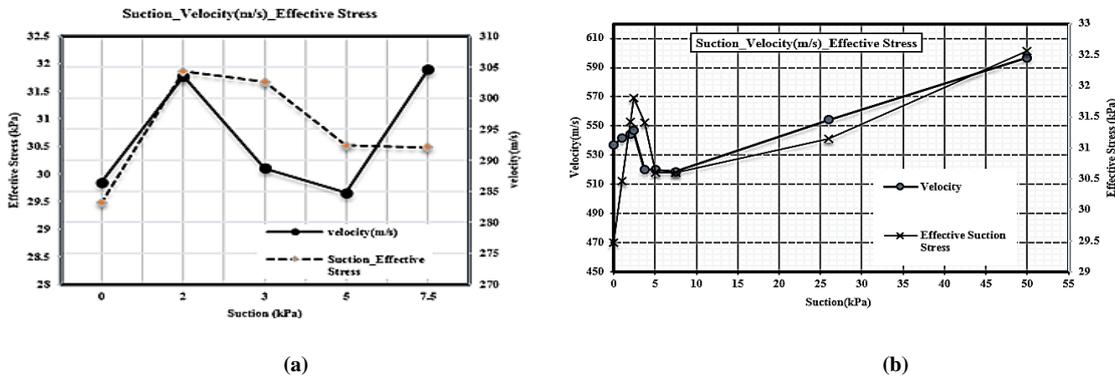


Fig.7. (a) Shear velocity versus total effective stress (b) pressure velocity versus total effective stress.

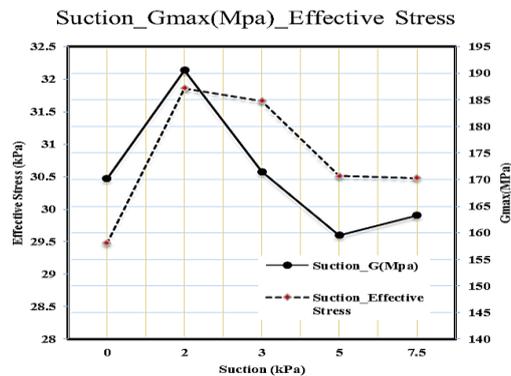


Fig. 8. The variation of maximum shear modulus versus total effective stress.

8- Conclusions

The main purpose of this investigation is the development of the cyclic simple shear apparatus for determination the stiffness modulus of unsaturated sandy soil in very small strain amplitude (0.001%). To achieve this purpose, piezoelectric sensors were installed on unsaturated cyclic simple shear device to accurately measure the velocity of stress waves. The major problem for development of this apparatus to overcome with, was the height limitation and rigid lateral boundary of the sample which distorted the received waves. In order to control suction and degree of saturation, bottom pedestal of the device were modified to separate pore air and pore water pressure. A Hanging column system were utilized to apply low suction values and also to measure the changes in volume of sample water as well as a pressure panel to apply high suction values. Then, the stiffness modulus of the unsaturated soil were calculated using the elasticity equations. To verify the performance of apparatus the soil water characteristic curve of Babolsar sand with relative density of 60% and the wave velocity were determined simultaneously. Results show that the trend variation of stress wave velocity is consistent with the variation of Bishop's effective stress. Also In drying path, shear modulus increased significantly until air entry point, decreased in transition zone and then increased again in residual zone. The variation of maximum shear modulus is completely identical with total effective stress.

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