LABORATORY MEASUREMENTS OF STIFFNESS OF SOFT CLAY USING BENDER ELEMENTS

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ABSTRACT:

Thanks to a new in-situ seismic probe, using bender elements and penetration scheme, a simple linear relationship between undrained shear strength(C_u) and shear wave velocity(V_s) was obtained. This priceless relationship is worthy to be illuminated further in ideal laboratory environment. To avoid sampling disturbance effect, special consolidation cylinders were used to make normally consolidated specimens from kaolinite suspension. The undrained shear strengths of the specimens were measured using unconsolidated undrained triaxial compression tests. Also shear wave velocity measurements were performed prior to shearing the same specimens, using the bender elements installed in the base pedestal and the top cap of the triaxial compression cell. The C_u –V_s relationship is fairly linear and supports the linear trend of clayey silt obtained using field testing. Also the classic density-shear modulus relationship for soft clay proposed by Hardin and Black(1969) was once more verified hereby.

KEYWORDS : Shear Modulus, Undrained Shear Strength, Bender Elements

1. INTRODUCTION

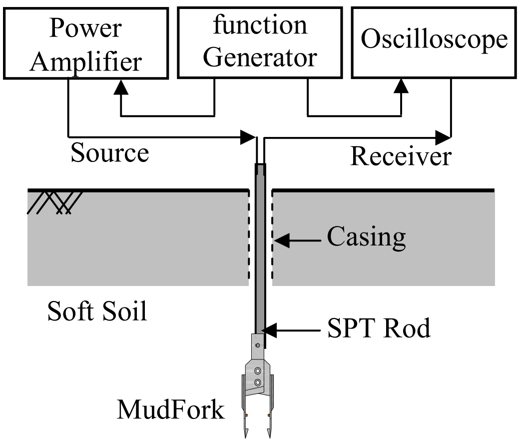
Much effort has been made to evaluate stiffness of soft soil accurately and to correlate with other properties such as strength and density. Recently, a new in-situ seismic probe, using bender elements and penetration scheme, has been developed (Jung et al., 2008a; Jung et al., 2008b) and utilized to correlate the undrained strength and density with shear wave velocity of normally consolidated soil (Oh et al., 2008). A simple linear relationship between shear strength and shear wave velocity was obtained in the research just mentioned. This priceless relationship is worthy to be illuminated further in ideal laboratory environment. To avoid the chronic and harassing nuisance of sampling disturbance effect, special consolidation cylinders were used to make normally consolidated specimens from kaolinite suspension. The undrained shear strengths of the specimens were measured using unconsolidated undrained triaxial compression tests. Also shear wave velocity measurements were carried out prior to shearing the same specimens, using the bender elements installed in the base pedestal and the top cap of the triaxial compression cell. In the following section, the major motivation of the research is further described.

2. BACKGROUND

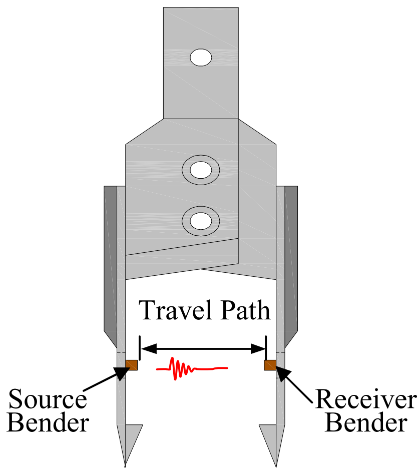
The shear deformation of a normally consolidated soil can be characterized by the hyperbolic model, which shows the larger stiffness, the higher shearing resistance (Kondner, 1963; Hardin & Drenevich, 1972). Because of elastic

relationship of shear modulus and shear wave velocity, shear strength is in turn proportional with shear wave velocity. In this context, cone tip resistance (q_c), which is an indirect measure of shear strength, was correlated with shear modulus by many researchers (Mayne & Rix, 1993; Tanaka & Nishida, 1994, Simonini & Cola, 2000). Thus shear strength and stiffness surely is closely related.
A new in-situ penetration-type technique has been developed utilizing bender elements as shown in Figure 1 (Jung et al., 2008a; Jung et al., 2008b). The piezo-electric probe, called MudFork, is composed of two bender elements mounted on a "fork" having two blades, one element acting as a seismic source perturbing ground and the other one as a receiver monitoring seismic waves. The probe is penetrated using SPT(standard penetration test)rods pushed with a routine boring machine and shear waves signals are recorded at each measurement depth. Shear wave measurements and a set of cone penetration tests were performed, along with triaxial compression tests, at a clayey silt site near Incheon, Korea. A linear relationship between undrained shear strength (C_u, in the unit of kPa) and shear wave velocity (V_s, m/sec.) was obtained as Eqn 2.1 for the normally consolidated clayey silt (Oh et al., 2008).

$$C_u = 0.38\ V_s - 6.65 \qquad (2.1)$$



a) Testing configuration



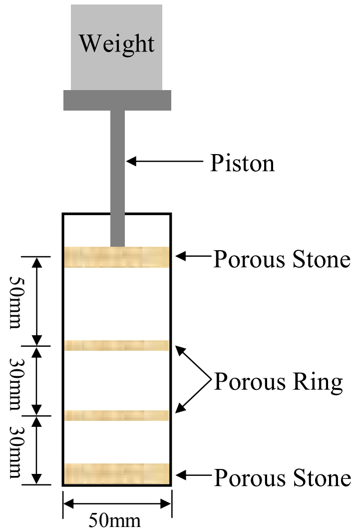
b) MudFork

Figure 1 In-situ seismic test using MudFork

3. SAMPLE PREPARATION

The consolidation cylinder is made of an acrylic tubing of 50mm in inner diameter. For drainage during consolidation, a pair of porous stones was installed as pedestal and top cap, and extra two porous stone rings were added inside of the tubing wall to shorten drainage distance as shown in Figure 2. A batch of kaolinite slurry was made by stirring each 300g of kaolinite and water. The specific gravity and plasticity index of the kaolinite were 2.70 and 30 %, respectively. The suspension was poured into the cylinder and, after sedimented, weight was gradually increased to the final loading over the period of 6 months. Four set of specimens were made with different final weight such as 6.7, 12.3, 18.0, 29.2 kg. Four specimens were consolidated under each final weight, except two specimens made under the weight of 6.7 kg and thus total of 14 specimens were prepared.

a) Picture



b) Schematic diagram

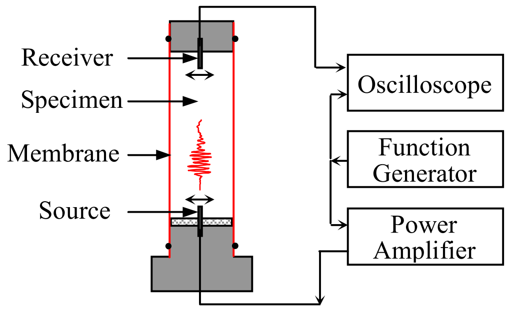
Figure 2 Consolidation cylinder for kaolinite specimen

4. TESTING

4.1. Testing Scheme

The routine procedure of undrained test was adopted except extra measurements of S-wave velocity of each stage of the testing before shearing. The S-wave velocity measurements were performed by installing a bender element on the base pedestal and the top cap of a triaxial cell, respectively as shown in Figure 3a. The bender element on the pedestal was used as seismic source and the other bender element on the top cap measured shear wave propagated through a specimen from the source as shown in the schematic diagram of Figure 3b.

a) Bender elements



b) S-wave measurement

Figure 3 Installation of bender elements and schematic diagram of S-wave measurements

Each specimen was set up in the triaxial cell and was consolidated for 24 hours with the isotropic pressure equivalent to the stresses subjected by the weight in the consolidation cylinder. In this consolidation stage, S-wave velocity was measured with a time interval as shown in Figure 4. As consolidation being progressed, S-wave velocity kept increasing and converged to the final value at around 20 hours. This indicates that the isotropic consolidation pressure surpassed the stresses subjected during specimen formation, and the specimen was surely normally consolidated along the virgin curve. Then, the confining pressure was increased to the target value with the drainage valve closed. The final s-wave measurement was made and finally the specimen was sheared. The stress history of each specimen is shown as Table 1.

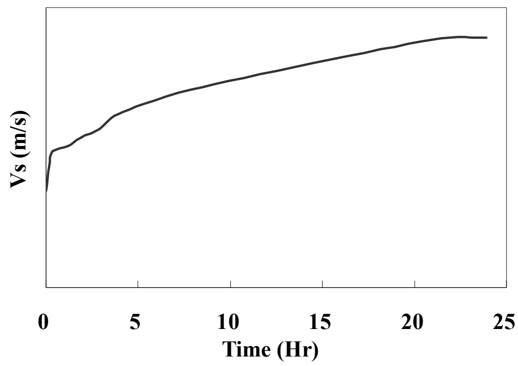


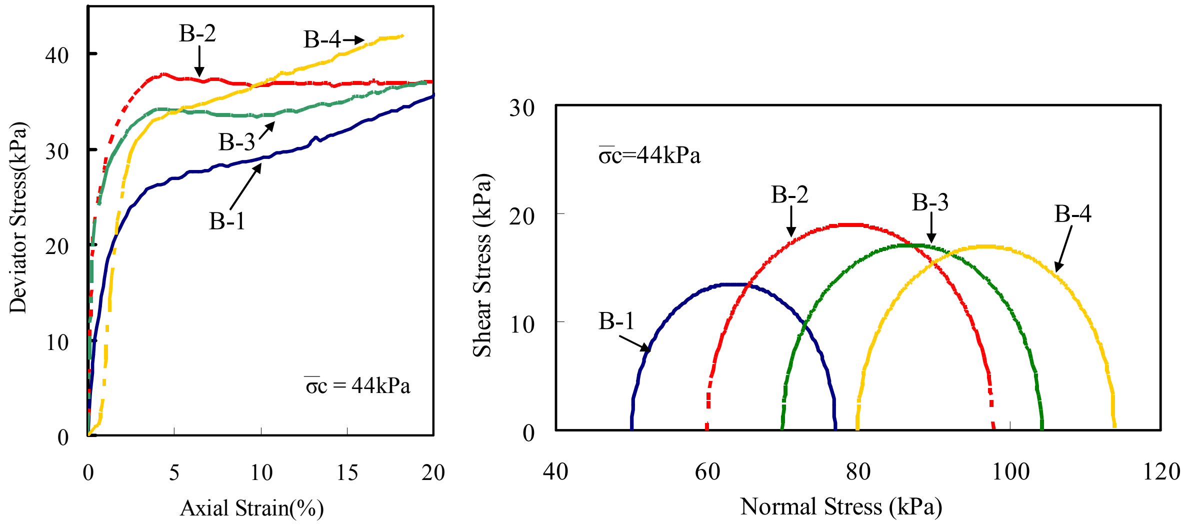
Figure 4 S-wave velocity increment during consolidation

Table 1 Stress history of the specimens

Specimen	Weight (kg)	Consolidation Pressure(kPa)	Confining Pressure (kPa)
A-1	6.7	24	30
A-2			40
B-1	12.3	44	50
B-2			60
B-3			70
B-4			80
C-1	18.0	64	70
C-2			80
C-3			90
C-4			100
D-1	29.2	104	110
D-2			120
D-3			130
D-4			140

4.2. Results

The stress-strain curves and Mohr circles of specimen set B are shown in Figure 5. Even though the specimens were made in the same batch, there were slight variations of strength. The typical shear wave signals are shown in Figure 6. There is no change in S-wave velocity after confining pressure increment under undrained state, which denotes the degree of saturation of 100 % and, in turn, no effective stress change. All other specimens showed similar results except specimen A-2, B-4, C-3 and C-4. Specimen A-2 was leaked and exhibited lower values of strength and s-wave velocity. For specimen B-4, S-wave velocity was increased with confining pressure increased with unidentifiable reason. Specimen C-3 and C-4 also showed abnormal values in S-wave velocity. The abnormal results were eliminated in the following analysis. The results of 14 specimens are presented in the Table 2. The undrained strength and S-wave velocity increase linearly with consolidation pressure.



a) Stress-strain curves b) Mohr circles

Figure 5 Stress-strain curves and Mohr circles of specimen set B

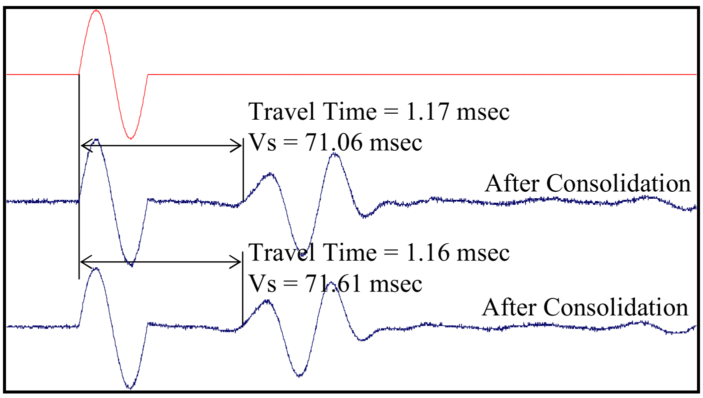


Figure 6 S-wave signals of specimen B-2

Table 2 Strength and S-wave velocity

No.	Undrained Strength Cu(kPa)	S-Wave Velocity, m/sec			Remarks
		Before Consolidation	After Consolidation	After Confining	
A-1	9	17	69	69	
A-2	3*	22	20*	20*	Leaking
B-1	15	26	63	67	
B-2	19	30	71	72	

B-3	17	24	64	66	
B-4	18	30	61*	96	Inexplicable Vs increment
C-1	25	41	135	134	
C-2	31	45	113	113	
C-3	20	46	32*	24*	Unreasonable Vs
C-4	16	52	59*	69*	Unreasonable Vs
D-1	36	47	134	131	
D-2	39	54	137	134	
D-3	38	50	103	102	
D-4	50	40	144	146	

5. CORRELATING S-WAVE VELOCITY

The shear strength of each specimen was plotted with S-wave velocity measured after consolidation as shown in Figure 7. The C_u –V_s relationship is fairly linear and supports the linear trend of clayey silt reported by Park et al. (2008). The plasticity of the clayey silt was in the range of 2-7 % and that of kaolinite is 30%. The two straight line approximations do not seem to be sensitive on plasticity index and this postulation of PI insensitive relationship should be investigated further by testing various clays wide range of plasticity.

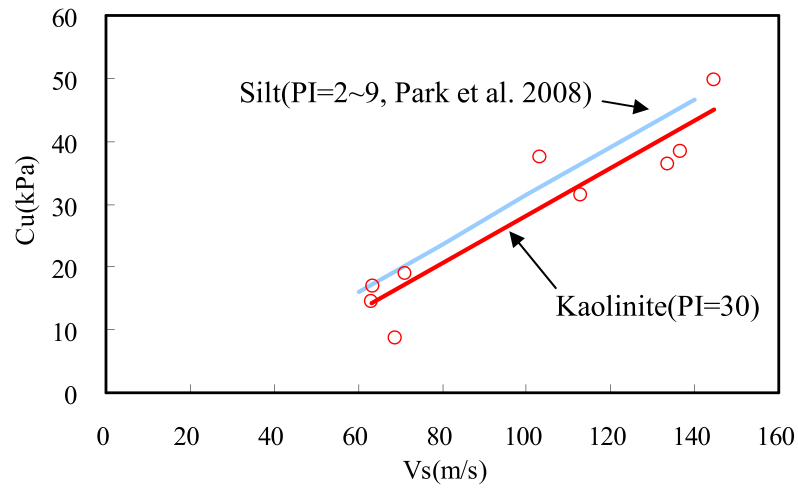


Figure 7 Shear strength and S-wave velocity relationship

The shear moduli were calculated from the measured S-wave velocities and in turn void ratios were evaluated using the empirical relationship between shear modulus and void ratio proposed by Hardin and Black (1969) as Eqn 4.1.

$$G_{max} = 1230 OCR^k \frac{(2.973 - e)^2}{1+e} \sqrt{\sigma_0} \qquad (4.1)$$

where G_{max} is shear modulus in psi, σ is effective stress in psi, OCR is overconsolidation ratio, e is void ratio and k is the coefficient related with plasticity index. The estimated void ratios were plotted with the measured values from the specimens in Figure 8. The empirical relationship was once more validated with the good agreement.

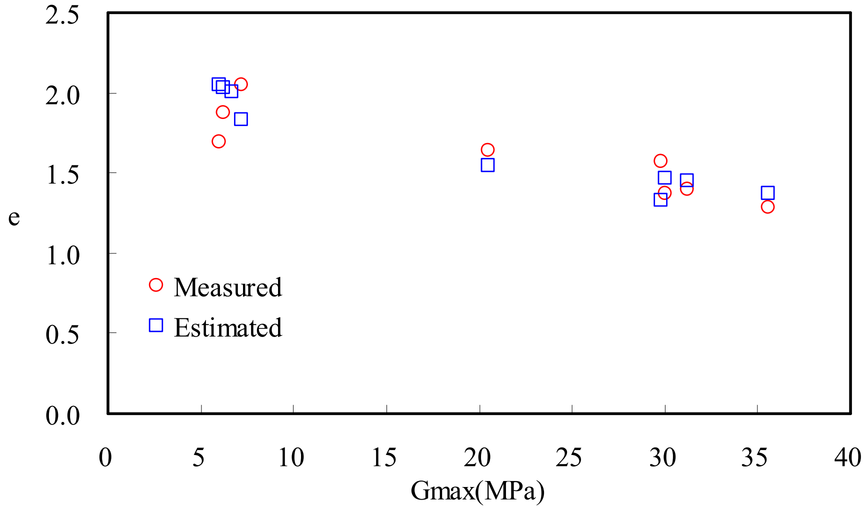


Figure 8 Void ratio and shear modulus relationship

5. CONCLUSIONS

Thanks to a new in-situ seismic probe, using bender elements and penetration scheme, a simple linear relationship between undrained shear strength(C_u) and shear wave velocity(V_s) was obtained. This priceless relationship is worthy to be illuminated further in ideal laboratory environment. To avoid sampling disturbance effect, special consolidation cylinders were used to make normally consolidated specimens from kaolinite suspension. Shear wave velocities were measured prior to shearing the same specimens, using the bender elements installed in the base pedestal and the top cap of the triaxial compression cell. The C_u –V_s relationship is fairly linear and supports the linear trend of clayey silt obtained using field testing. Also the classic density-shear modulus relationship for soft clay proposed by Hardin and Black (1969) was once more verified hereby.

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