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Characterization of Clay Sedimentation using Piezoelectric Bender Elements

Il-Han Chang[1,a], Gye-Chun Cho[1,b], Joo-Gong Lee[2,c] and Lee-Hyung Kim[3,d]

[1]Dept. of Civil and Environ. Eng., Korea Advanced Institute of Science and Technology 373-1 Guseong-dong, Yuseong-gu, Daejeon 305-701, Korea

[2]Dept. of Tunnel Eng., Dodam E&C Co., Ltd Gyeonggi-Do 431-804, Korea

[3]Dept. of Civil & Environ. Eng., Kongju National University 182 Shinkwan-dong, Kongju, Chungnam-Do 314-701, Korea

[a] harlma@kaist.ac.kr , [b]gyechun@kaist.ac.kr , [c]jowhb@paran.com , [d]leehyung@kongju.ac.kr

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Abstract. Sedimentation is one of the most basic processes in the formation of a soil structure in nature. Many studies have been performed to describe the characteristics of clay sedimentation, based on settlement and water content measurement. In addition, there have been some attempts in numerical modeling to describe soil structure formation as a whole. However, these effects still fall short in explaining the overall process of soil structure formation because some relevant properties are measured after a self-weight consolidation is completed. Furthermore some measurement techniques significantly alter soil structure. Thus, a non-destructive evaluation is necessary for the effective description of soil characteristics during the sedimentation process. In this study, a testing device is designed that continuously monitors the self-weight consolidation process of sedimentation with shear waves. Piezoelectric bender elements are installed into a testing cell to generate and receive shear waves in a small strain regime. Slurries are prepared with kaolinite-type clay and placed in the cell. Shear wave velocities are continuously measured as a function of time during the whole process of the self weight consolidation. The experimental results suggest that as clay sediment is subjected to a certain loading, the shear wave velocity increases as time increases, showing an abrupt change in log time. This abrupt change is relevant to the formation of a stable soil skeleton. It is concluded that the time-dependent variations in shear wave velocity reflect sedimentation and self weight consolidation behavior and the evolution of the effective stress increment.

Introduction

The characterization of a soft clay sediment in nature is important to predict its permanent settlement and strength as an additional load induced by offshore structure construction put into place. The term in-situ sedimentation itself has two main processes. The first is a free fall process, which is influenced by the difference between a gravitational force and buoyancy acting on particles. After this, individual particles attract each other by an electrical force acting between them. This electrical attraction and repulsion is caused by the electrical charges on the clay particle surfaces. Saturated clay has a two-phase soil structure with solid clay particles and voids filled with fluid. Its structure is very weak and collapses easily under additional loading. Thus, the total volume of the clay decreases when it is compressed. For the in-situ sedimentation process, the weight of the overburden soil acts as an applying load to the underlying soil: therefore, the volume of soil decreases and the density increases, aided by its own self weight. This is called a self weight consolidation process, which is the second main process in sedimentation.

In case of kaolinite clay, the free fall process is negligibly short because the electrical attraction immediately flocculates the particles to form a soil structure. Thus, the self weight consolidation process is meaningful in the characterization of the in-situ sedimentation process in most cases of Korean marine clay deposits. The governing equation of the self weight consolidation, which was suggested by Gibson et al. [1] and improved by Pane and Schiffman [2], defines the degree of consolidation as a function of the void ratio by assuming the consolidation coefficient to be constant.

The consolidation coefficient estimation method using the permeability, suggested by Been and Sills [3], is also based on the relationship between the permeability and the void ratio. As the existing theories are based on the void ratio concept, many studies on the in-situ self weight consolidation rely on the settlement monitoring. However, Schiffman et al. [4] found that the degree of settlement precedes the degree of pore water pressure dissipation, which means that the settlement monitoring overestimates the degree of consolidation of the soft soil sediment. Moreover, taking pore pressure measurements using cone penetration testing (CPT) or pore pressure gages has several error factors that can make the results unsatisfactory, such as the tidal effect and soil disturbance factors.

Accordingly, a non-destructive technique is required for the effective monitoring of the effective stress change during the self weight consolidation of a soft clay. A shear wave propagates only through the soil skeleton, and its velocity depends on the effective stress of the soil. In this study, bender element sensors are used to generate and detect small strain shear waves in soils, without disturbance to the soils.

Shear Wave Velocity and Effective Stress

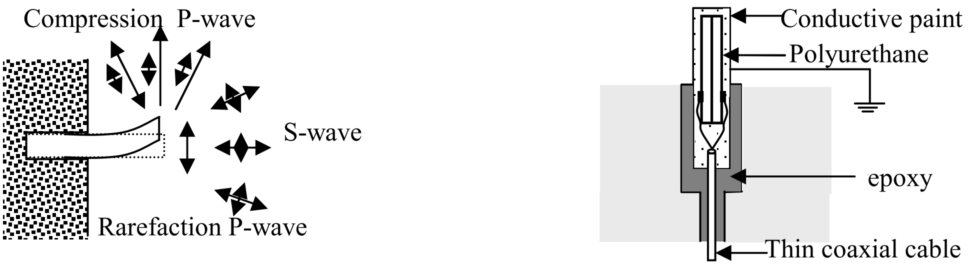
The shear wave velocity of particulate materials under a zero lateral strain loading (one-dimensional consolidation) can be expressed in terms of the vertical effective stress as follows [5]:

$$V_s = \alpha\left(\frac{\sigma'_v}{1\text{kPa}}\right)^{\beta}. \tag{1}$$

V_s is the shear wave velocity and σ'_v is the vertical effective stress, while the parameters α and β are experimentally determined. Generally in clays, the higher the plasticity index, the higher the β exponent and the lower the α factor. Preloading and aging have the opposite effects [5].

Bender Element Sensors

Since Shirley and Hampton [6] initially applied a bender element to soil testing, bender elements have been widely used to characterize various soils using shear wave techniques in the geotechnical engineering field. Piezoelectric-type bender elements are commonly used. The piezoelectric materials used in them, such as quartz or ceramics, expand or shrink depending on their tpye when an electrical current is applied. By combining different piezoelectric materials, the whole element bends because of the different tendency in axial deformation. Because of this, a specially designed bender element can convert the electrical potential to mechanical vibration in a small strain regime, which then generates shear waves in the axial direction and compressive waves in the lateral direction (Fig. 1a).



a. Mechanism b. Installation

Fig. 1 Bender element sensor.

The bimorph bender element used in this study was 12mm in length, 8mm in width, and 0.6mm in thickness. The anode and cathode wires of a coaxial cable were soldered to each side of the bender element. Polyurethane was coated around it for waterproofing. Then, silver paste was layered on for shielding to avoid the effect of coupling and cross-talking induced by unwanted electro-magnetism. Finally, the sensor was placed at the testing device and fixed with epoxy (Fig. 1b). Details in bender element installation and signal interpretation can be found in Lee and Santamarina [7].

Experimental Study

Sedimentation. The in-situ sedimentation process is reproduced with this laboratory testing. A kaolinite slurry of a 300% water content was prepared and poured into a sedimentation tube, which included a separable oedometric cell at the bottom. Bender elements were installed inside the oedometric cell at both lateral and axial directions. The clay particles in the slurry settle down and form weak soil under a normally consolidation state. The weak sediment formed inside the separable oedometric cell represents the initial state of the in-situ sedimentation process. The specimen formed inside the oedometric cell had a diameter of 8 cm and a initial height of 6.5 cm. The oedometric cell was modified to measure shear wave velocity under the one-dimensional loading condition.

Self Weight Consolidation. The in-situ self weight consolidation process was reproduced in a laboratory setting by applying the expected total amount of effective stress to the oedometric cell specimen separated from the sedimentation tube. This simulation arrangement is based on the fact that the total amount of stress that an in-situ soil element receives under sedimentation is decided by its initial location at the beginning of soil structure formation, rendering the constant total stress condition. After a clay is subjected to an additional loading, the excessive pore water pressure dissipates and the effective stress increases with time. The oedometric cell specimen was placed on an oedometer testing device and porous materials were placed both at the top and bottom to allow the water to drain for two directions during the loading. The bottom and side bender elements were installed inside the oedometric cell, while the bender anchored cap was installed on the top of the specimen right just before loading. The experimental devices are shown in Fig. 2. The self weight consolidation of the in-situ sedimentation process was simulated by applying the expected total effective overburden stresses to the top cap sitting on the oedometric cell specimen. During loading, a signal wave was generated and sent to the source bender element. The response of the receiver bender element was recorded. The vertical shear wave travel time was measured between the top and bottom bender elements, while the horizontal shear wave travel time was measured between the side bender

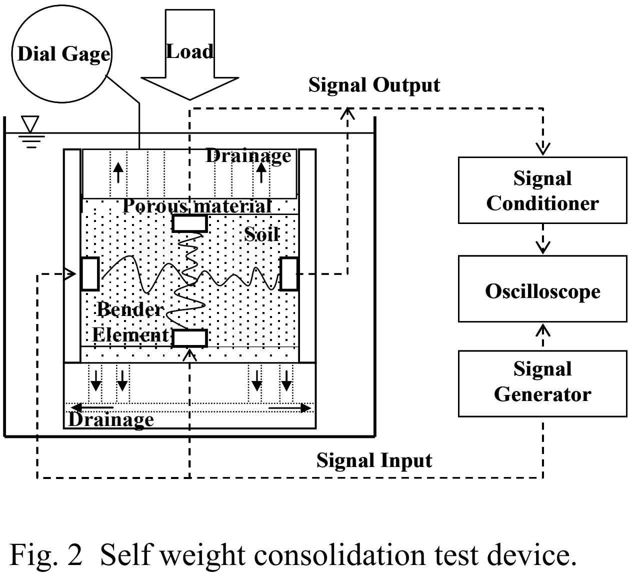


Fig. 2 Self weight consolidation test device.

elements. The vertical deformation of the specimen was measured from a dial gage. The vertical shear wave velocity (m/sec) along time was calculated by dividing the specimen height (m) with the shear wave travel time (sec).

Table 1 Summary of test conditions and experimental results.

Sedimentation		Self Weight Consolidation						
Initial Water Content [%]	Initial Void Ratio	Void Ratio		Applied Load [kPa]	Final Shear Wave Velocity [m/s]		α	β
		Initial	Final		Axial	Lateral		
300	7.80	2.54	1.51	46.2	124.0	102.2	16.17	0.56

Results and analysis

Vertical Effective Stress. The experimental properties are summarized in Table 1. The initial shear wave velocity of the soft clay sediment is low because its particle packing is loose. In the case the of one-dimensional consolidation, when the load that represents the total overburden weight for the self weight consolidation process is applied to the specimen, the total stress is resisted by the excess pore water pressure. The hydraulic pressure head difference causes the pore fluid to flow upward and downward through the drainage path, thus the pore water pressure decreases. Following this the particle packing becomes denser as the pore water pressure decrement transfers to the vertical effective stress increment. The rate of pore pressure dissipation is initially high and continuously decreases according to the permeability diminution while the soil becomes denser. In other words, the effective stress increases with a logarithmic time scale. Accordingly, the increase of the shear wave velocity with time is also expected (Fig. 3a). The vertical effective stress - shear wave velocity relationship of the specimen can be obtained from a regression analysis, as follows (Fig. 3b):

$$V_{s-v} = 16.47\left(\frac{\sigma'_v}{1\text{kPa}}\right)^{0.56} . \tag{2}$$

This equation is used to evaluate the field stress condition, if the field shear wave velocity value is available. The estimated vertical effective stress – shear wave velocity relationship (Eq. 2) can be regarded to be the same as that of the field. Thus, the in-situ stress condition can be estimated by comparing the relationship curve shown in Fig. 3(b) with the field shear wave velocity value.

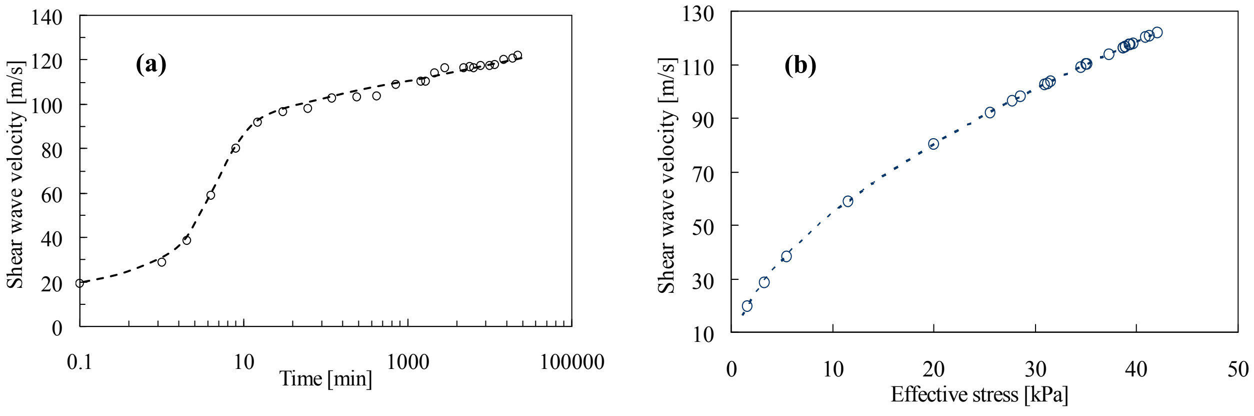
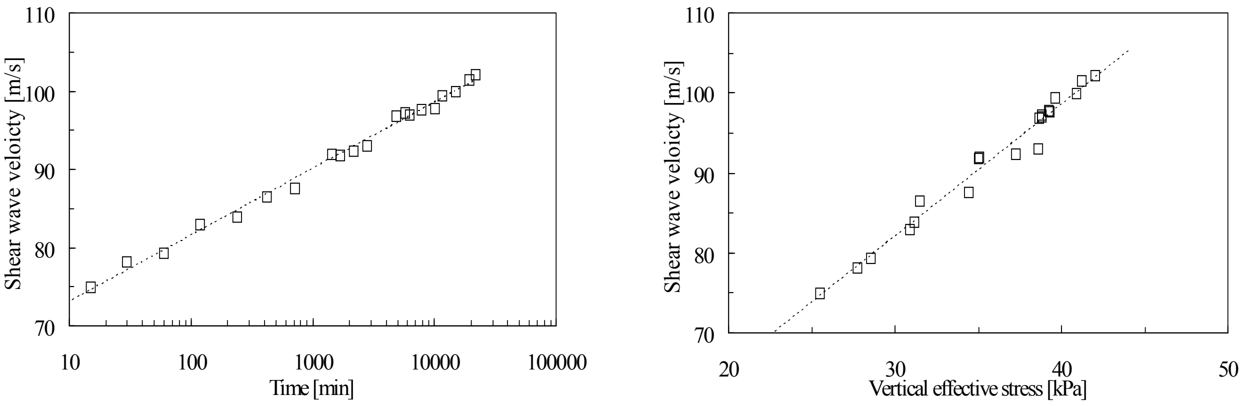


Fig. 3 The variation of shear wave velocity during consolidation.



(a) Horizontal shear wave increment. (b) Relationship with vertical effective stress.

Fig. 4 Horizontal shear wave velocity variation during the self weight consolidation process.

Horizontal Shear Wave Velocity. Fig. 4(a) shows the variation of horizontal shear wave velocity with time. The results also show the high accuracy of the bender element sensors for horizontal shear wave monitoring. The horizontal shear wave velocity has a linear relationship with time on the semi-logarithmic plane.

$$V_{s-h}(\mathrm{m/s}) = 64.58 + 3.69 \ln t(\mathrm{min}) . \tag{3}$$

where V_{s-h} is the shear wave velocity in which the propagation direction and particle movement are both horizontal. The relationship between the vertical effective stress and horizontal shear wave velocity shown in Fig. 4(b) is as follows:

$$V_{s-h} = 9.71\left(\frac{\sigma'_v}{1\mathrm{kPa}}\right)^{0.63} . \tag{4}$$

As the horizontal strain is not allowed in the oedometric cell, the soil specimen is in a state of elastic equilibrium. The ratio of the horizontal stress to the vertical stress, which is called the coefficient of earth pressure at rest, K_o, is constant [8]. Thus, the horizontal shear wave behavior represents the K_o condition of the in-situ process. The horizontal shear wave velocity and vertical effective stress have the relationship as follows [5]:

$$V_{s-h} = \alpha_1\left(\frac{K_o\sigma'_v}{1\mathrm{kPa}}\right)^{\beta_1} = \alpha_1 K_o^{\beta_1}\left(\frac{\sigma'_v}{1\mathrm{kPa}}\right)^{\beta_1} . \tag{5}$$

β_1 is assumed to be 0.63 from Eq. 4, thus Eq. 5 can be written:

$$V_{s-h} = \alpha_1 K_o^{0.63}\left(\frac{\sigma'_v}{1\mathrm{kPa}}\right)^{0.63} = 9.71\left(\frac{\sigma'_v}{1\mathrm{kPa}}\right)^{0.63} . \tag{6}$$

Finally, the coefficient of earth pressure at rest, K_o, can be defined:

$$K_o = \left(\frac{9.71}{\alpha_1}\right)^{1.59} . \tag{7}$$

As α_1 is constant, Eq. 7 shows that K_o remains constant during the self weight consolidation.

Conclusions

The piezoelectric bender element sensors are useful for measuring not only the vertical shear wave velocity, but also the horizontal shear wave velocity behavior for the self weight consolidation process of clay sedimentation. When α and β factors are experimentally determined, the bender element is able to evaluate the vertical effective stress – shear wave velocity relationship. The vertical effective stress is calculable when the shear wave velocity value of a dredged reclamation site is available. The horizontal shear wave velocity results show that in the case of an elastic equilibrium condition, horizontal shear wave velocity is a function of the vertical effective stress, and increases continuously during the self weight consolidation process. The coefficient of lateral earth pressure at rest (K_o) remains constant during self weight consolidation. According to its viable application for effective stress evaluation, the shear wave technique using piezoelectric bender elements may eventually be utilized to take advantage of characterizing the design properties such as vertical and horizontal effective stresses, degree of consolidation, consolidation coefficient, density, and shear strength for reclaimed soft clay sediments.

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