A pilot study of in-hole type CPTu using piezoelectric bender elements

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ABSTRACT: In-hole type CPTu equipment which combines the concepts of in-hole test method and piezocone test method was newly developed in order to evaluate the dynamic properties of marine soils. The objective of this paper is to investigate the practical application of in-hole type CPTu. Laboratory tests using kaolinite as soft soil and numerical simulations using finite element method were carried out in this study. The shear wave velocities of kaolinite were measured with time, and the effects of soil disturbance due to the installation of source and receiver were also examined for various distances between source and receiver. It was found that it is necessary to maintain the length of swing arm as well as the distance between source and receiver consistently to obtain the rigorous test results. The laboratory test and numerical results also reveal that the disturbance due to the installation of swing arm apparently affect the shear wave velocity.

1. INTRODUCTION

Seismic piezocone penetration tests (SCPTu) are generally used to obtain dynamic properties of soils as well as cone resistance and penetration pore pressure. However, the SCPTu system can sometimes not be utilized in marine soils because it is difficult to install the source apparatus which generates the shear wave at offshore sites. Mok et al. (2006) and Jang et al. (2008) have developed an in-hole type CPTu equipment by combining the concepts of piezocone test method and in-hole seismic test method (Park et al. 2008). Those tests can be performed without any additional source device because the source and receiver consisting of pizoelectric bender elements are included inside a cone rod (Fig. 1). Bender elements are composite materials consisting of elastic shims and thin piezoceramics, which convert mechanical energy to electrical energy or vice versa. The geotechnical studies utilizing bender elements were also performed by many researchers such as Jung (2005) and Lee and Santamarina

(2005). The objective of this paper is to investigate the practical application of in-hole type CPTu by conducting laboratory tests using kaolinite and performing numerical simulations on the installation aspects. The effects of several parameters including test methods and soil conditions on the test results from in-hole type CPTu were also examined.

2. IN-HOLE TYPE SEISMIC CPTU

As shown in Fig.1, the shear wave velocity of soils at any depth after a stop in penetration of cone can be obtained by measuring the travel time of shear wave, which is transferred from the source to the receiver attached to in-hole type CPTu. Fig. 2 shows a prototype of in-hole type CPTu. Bender elements were attached to the end of cantilever type swing arms located behind the conventional cone. The signal cables connected to the bender elements are extended to the data acquisition system through the cone rod.

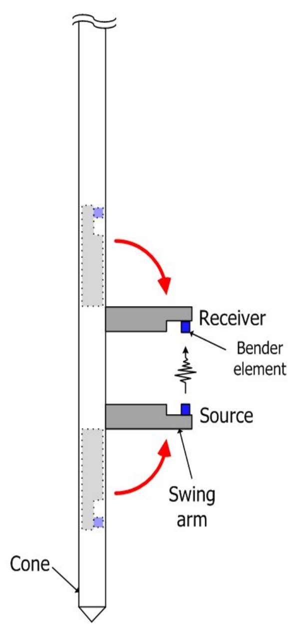

Fig. 1. Definition sketch of in-hole type CPTu

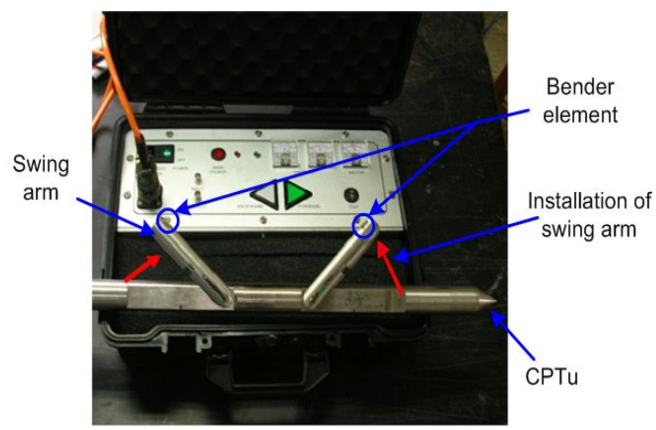

Fig. 2. Prototype of in-hole type CPTu

3. MODEL TEST

In the model tests, a plastic box with 500mm (L) by 300mm (W) by 320mm (H) was utilized as soil box. The testing soil layer was prepared by stirring the kaolinite slurry with an agitator. The initial height of soil layer was about 220 to 250mm. Table 1 presents the index properties of the kaolinitic soil layer.

Fig. 3 shows a model of the test frame with bender elements. All frames that include swing arms corresponding to source and receiver were made of aluminum. Because the height of soil box (about 250mm) is not enough to simulate the penetration of the swing arms, the test frame were installed by rotating in a 90 degree in the soil box.

Fig. 4 shows the plan view of the test set-up. Four different test frames were installed in the soil box for each test case. ① and ② are the frames for source and receiver in a fixed condition (reference). ③ and ④ shows the frames source and receiver in a swing condition, which are utilized to analyze the effect of disturbance due to installation of swing arm. The distance between fixed condition and swing condition was maintained at about 150mm to minimize the effect of disturbance on the fixed condition.

Table 1. Index properties of kaolinite

Specific gravity	Liquid limit (%)	Plastic limit (%)	Water content (%)
2.61	46.3	22.0	88.5~103.1

Table 2 presents the summary of laboratory model tests. In this study, the effects of the distance (*d*) between source and receiver and the swing arm length (*s*) on the shear wave velocity were investigated. The effect of disturbance due to swing arm installation was also examined by comparing the results of fixed condition with those of swing condition. The test results were normalized by the reference test results.

Fig. 3. A model of test frame with bender element

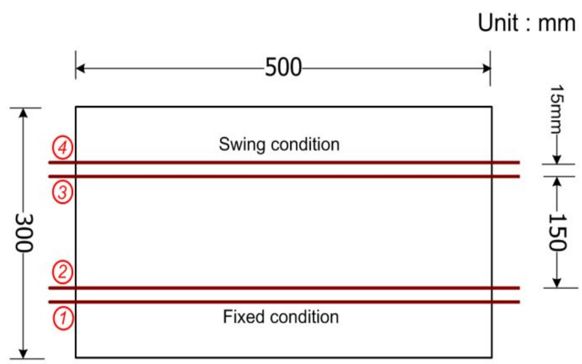

Fig. 4. Plan view of test set-up

Table 2. Summary of laboratory model tests

Distance between source and receiver (*d*)	5cm, **10cm**, 15cm
Swing arm length (*s*)	5cm, **10cm**
Fixed condition vs. Swing condition	d=5cm, 10cm, 15cm

Note: The values in bold correspond to the reference test case in the parametric study

4. NUMERICAL SIMULATIONS

In this study, numerical simulations using a general purposed finite element program ABAQUS (Ver. 6.5) were also conducted, in addition to model tests. Effects of various factors such as distance between source and receiver (d) and the swing arm length (s) on the shear wave velocity were examined and compared with the experimental model test results. The effects of disturbance due to cone penetration and installation of swing arm were neglected in the analysis. Axisymmetric soil elements and infinite elements for the end boundary were utilized. Fig. 5 shows the finite element mesh in this study. For a simplified analysis all elements including bender elements were modeled as elastic elements. For clayey soil, elastic modulus (E) = 300t/m^2, Poisson's ratio ν=0.35, and mass density ρ_s=1.7t/m^3 were assumed. The sampling time interval was set to 50μsec up to 40msec. Table 3 presents the summary of numerical simulations.

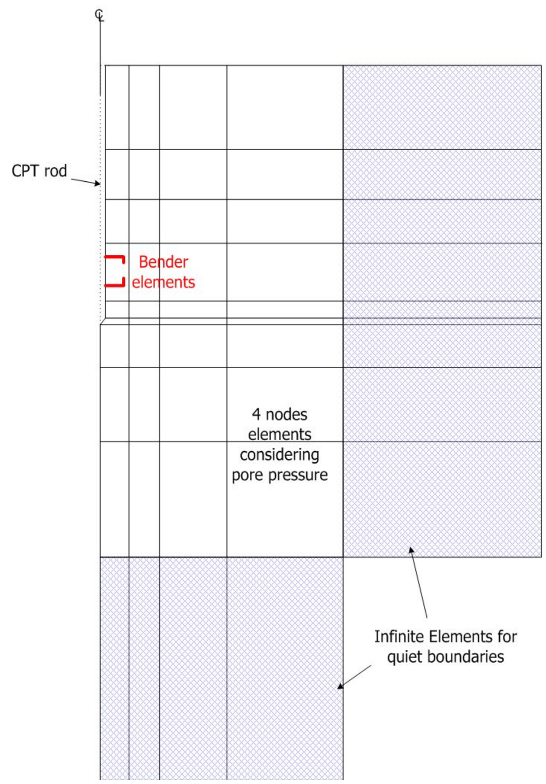

Fig. 5. Finite element mesh

Table 3. Summary of numerical simulations

Distance between source and receiver (d)	5cm, **10cm**, 15cm
Swing arm length (s)	5cm, 7cm, **10cm**, 14cm

Note: The values in bold correspond to the reference case in the parametric study

5. TEST RESULTS

5.1 Derivation of shear wave velocity

To obtain the shear wave velocity (V_s) using bender elements, the travel time (t_d) of shear wave from source (input) to receiver (output) should be measured.

$$V_s = \frac{d}{t_d} = \frac{d}{t - t_0} \quad (1)$$

where, d is distance between source and receiver, t is arrival time of shear wave, t_0 is start time of input wave.

The arrival time of shear wave (t) can be measured by several methods as described in Fig. 6, t_1 is first arrival time of initial output wave, t_2 is the time of maximum of initial output wave, and t_3 is arrival time of 2nd output wave. Cross-correlation methods would be alternatively utilized. Brignoli (1996) and Jung (2005) use t_1, while Lee and Santamarina (2005) utilize t_3 concept to remove the near field effect. Fig. 7 shows the examples of input wave and response wave for model test and numerical simulation. In this study, the direction of polarity of source and receiver was considered, and the first arrival time (t_1) of initial shear wave was selected to calculate the shear wave velocity.

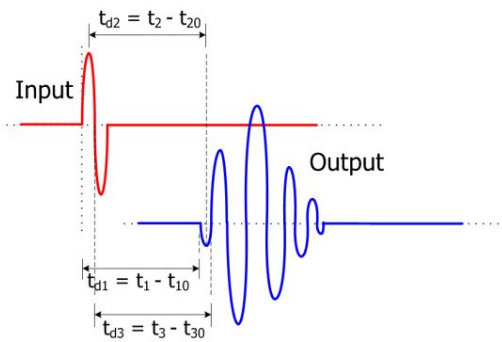

Fig. 6. Derivation methods of travel time of shear wave

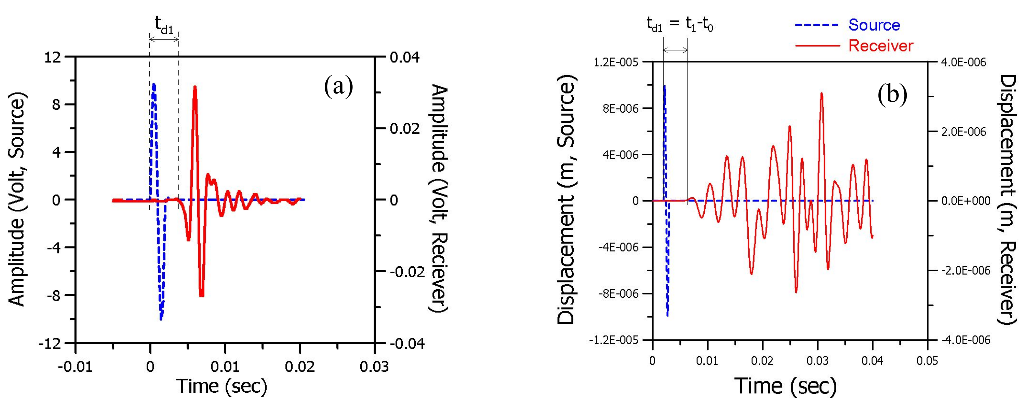

Fig. 7. Examples of input wave and response wave: (a) Model test (Reference case); (b) Numerical simulation (Reference case)

5.2 Change of shear wave velocity during consolidation due to self-weight

Fig. 8 shows the change of shear wave velocity with time after installing the testing frame into the soil box for reference case. It was found that shear wave velocity increases with time due to the self-weight consolidation of kaolinitic soils. This tendency is similar to the studies by Jung (2005) and Mok et al. (2006). As shown in Fig. 8(b), the change in the shear wave velocity is clearly classified into two different lines in the logarithm scale of time. Therefore, the self-weight consolidation characteristics of very soft dredged soils can be effectively verified with in-hole type CPTu in field condition as well as in laboratory.

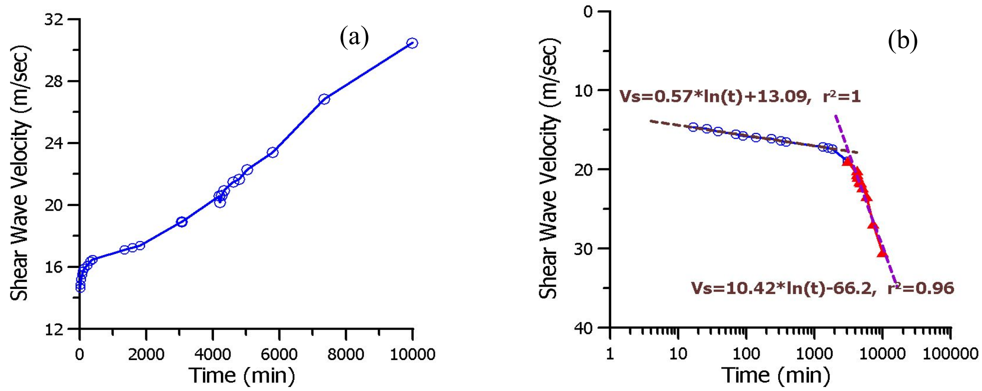

Fig. 8. Change of shear wave velocity with time (Reference case): Time-shear wave velocity curve; (b) Logarithm scale of time vs. V_s

5.3 Effect of distance (d) between source and receiver

Fig. 9 shows the effect of distance (d) between source and receiver on the shear wave velocity from the model test and numerical simulation, respectively. It was found from Fig. 9(a) for model test results that shear wave velocity decreases as d increases. From the numerical simulations results, the V_s values calculated from the arrival time, t_1 were compared with V_{inp} values derived from input variable used in the numerical simulation. As shown in Fig. 8(b), the V_{cal}/V_{inp} ratio is almost same as 1.0 at d=10cm and the ratio decreases with increasing d, which is almost same trend as model test results. From both results, it was concluded that it is necessary to maintain the distance (d) between source and receiver constant (about 10cm) during the test to obtain consistent test results with in-hole type CPTu.

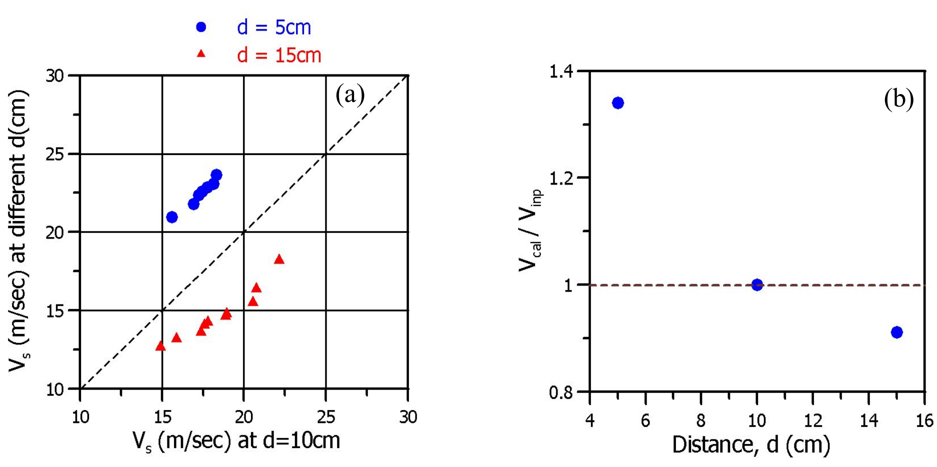

Fig. 9. Effect of distance (d) between source and receiver: V_s for different d (model tests); (b) V_{cal}/V_{inp} with d (numerical results)

5.4 Effect of swing arm length (s)

The effect of swing arm length (s), i.e., the distance between cone rod and bender elements, on the shear wave velocity was also investigated. Fig. 10 shows the changes in V_s for different swing arm lengths. The model test results reveal that the

V_s values at s=5cm are higher than those at s=10cm irrespective of distance (d) between source and receiver. This tendency coincides with the numerical results as shown in Fig. 10(b), which expresses the V_{cal}/V_{inp} ratio decreases as swing arm length increases. It is important to keep the swing arm length constant during the test as well as the distance between source and receiver, as discussed in section 5.3.

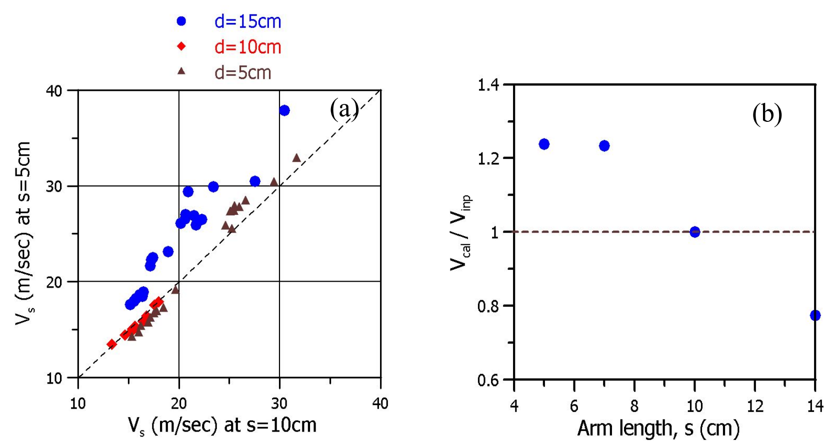

Fig. 10. Effect of with swing arm length (s): V_s for various s (model test results); (b) V_{cal}/V_{inp} for various s (numerical results)

5.5 Effect of disturbance due to installation of swing arm

For the in-hole type CPTu the swing arm should be unfolded at any testing depth. The effect of disturbance due to installation of swing arm is shown in Fig. 11. The ratio of $V_{s,s}/V_{s,f}$ was obtained from model test results; $V_{s,s}$ and $V_{s,f}$ are the shear wave velocities for swing condition and fixed condition, respectively. It was found that the effect of disturbance decreased as the distance between source and receiver increased, and the shear wave velocity (i.e., the strength) of soils increased. Jang et al. (2008) presents the change of V_s after installation of swing arm can be estimated from the regression curve.

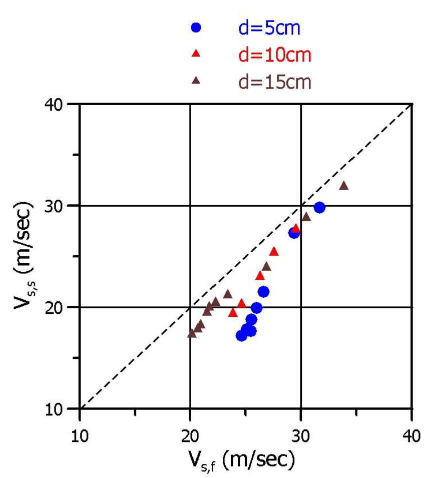

Fig. 11. Effect of disturbance due to installation of swing arm (model test results)

6. CONCLUSIONS

From the experimental model tests and numerical simulations with in-hole type CPTu, which was introduced to obtain the dynamic properties (V_s) of marine soils without additional source device, the practical application of in-hole type CPTu was investigated.

The shear wave velocities of kaolinite measured with time revealed that the self-weight consolidation characteristics of very soft dredged soils can be effectively investigated with in-hole type CPTu in field condition as well as in laboratory. Both model tests and numerical simulation results showed that it is necessary to maintain the swing arm length constant during the test as well as the distance between source and receiver to obtain the consistent test results with in-hole type CPTu. Also it is found that the disturbance due to the installation of swing arm apparently affect the shear wave velocity.

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