Proposal of a new sampling and sounding method using vibration for geotechnical investigation of seabed

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ABSTRACT

In the construction of offshore civil engineering structures or the exploitation of energy and mineral resources in the shallow part of the seabed, it is necessary to investigate mechanical properties of the foundation ground or various characteristics of reservoirs and mineral deposits. Thus, Vibro Sampling and Cone Penetration Test (VS-CPT) was devised for economical and effective submarine geotechnical investigation of the surface layers, about 20 mbsf. To examine an appropriate shape of the probe, model probes were made and driven into the model sand ground. As the results demonstrated that the drivability and sample recovery were not bad when the aperture ratio of the probe, \( R_a \), was 0.5 or higher, a prototype apparatus (Mark 1) was manufactured with \( R_a = 0.67 \). Driving test using a vibratory hammer on a saturated dense sand ground, however, revealed that the tip of the sampler was clogged in the surface layer, and the drivability was low. In addition, the cone resistance is found not suitable for sounding as its measured values were zero.

Keywords: geotechnical investigation, sampling, cone penetration test, sounding, vibratory hammer

1 INTRODUCTION

For site planning and designs of offshore civil engineering structures such as offshore wind power generation facilities, it is necessary to investigate the mechanical characteristics of the surface soil layers and bearing stratum in shallow water areas with a depth of up to several tens of meters. In addition, for exploitation of energy and mineral resources in the shallow parts of the seabed, such as surface methane hydrates and hydrothermal deposits, it is necessary to investigate various characteristics of the reservoirs and deposits in deep water areas with a depth of several hundred meters or more.

Table 1 summarizes the types of ground, depth of water, depth below seafloor, whether samples are collected, and economic efficiency for existing methods of geotechnical investigation (Kayaba et al., 1986: Matsumoto, 1986). For the standard penetration test (SPT, JIS A 1219), which is a dynamic sounding technique commonly used for geotechnical investigation related to port constructions etc., a boring machine should be placed on a self-elevating platform (SEP) because the blows cannot be controlled underwater. Furthermore, since retrieval of the sampler every meter in depth is time consuming, the operational efficiency of offshore work is poor, and thereby the economic efficiency becomes extremely low. On the other hand, the cone penetration test (CPT, JGS 1435) and the field vane shear test (FVT, JGS 1411), which

| Applicable ground | SPT | CPT | FVT | Drilling on SEP | Piston coring | Vibro-coring |
|-------------------|-----|-----|-----|----------------|--------------|--------------|
| Max. water depth (m) | About 50 | About 50 (*) | About 10 (*) | Several tens | Several hundreds | Several hundreds |
| Max. depth below seafloor (m) | Several tens | About 30 | About 10 | Several tens | About 12 | About 10 |
| Sampling | Disturbed | n/a | n/a | Least disturbed | Disturbed | Disturbed |
| Economic efficiency | Low | High | High | Low | High | High |

(*) By using a driving facility seated on the seafloor, this test is applicable for water depths up to several hundred meters.
are static sounding techniques, are efficient because their working times are shorter than SPT. But they can only be used in soft ground due to their low drivability.

As for sampling, although undisturbed or least disturbed soil samples can be obtained by rotary drilling technique, the works at sea is much less economical than the works on the land. Emphasizing economic efficiency, disturbed soil samples can be obtained by the piston coring method or Vibro-coring method (Chiba et al., 1982), but their penetration depths are limited to about 10 meters at most.

The sounding method that is desired is an economical technique that can be applied to wide varieties of seabed from soft clays to soft rocks and in areas with a water depth of several hundred meters, and can measure geotechnical properties up to a depth of several tens of meters below the seafloor. More preferably, the ideal sounding method enables collection of soil samples at the same time. To meet the above demands, the authors devised a new sampling and sounding method and manufactured a prototype device (Mark 1) that can be driven to a depth of 2 meters (Tani and Ikeya, 2018). The concept of the proposed test method and the details of the prototype device are described below.

2 VIBRO SAMPLING AND CONE PENETRATION TEST (VS-CPT)

2.1 Basic features of VS-CPT

Fig. 1 shows the concept of Vibro-Sampling & Cone Penetration Test (VS-CPT). This sampling & sounding method is a kind of dynamic sounding technique in which a probe with a cone at the tip is connected to samplers and is continuously driven by a vibratory hammer. Its basic features are threefold.

1) Since the drivability is expected high due to dynamic action of the vibratory hammer, this method can be used in wide varieties of ground from soft clays to dense sands. Judging from the drivability of vibratory pile driving methods, it can be expected that even the ground equivalent to bearing layers whose SPT N-values as high as 50 can be investigated (TC on VHM, 2015).

2) If a probe with a proper shape and size is used and a sleeve is installed immediately above the shoe, it is expected to obtain long, continuous but disturbed soil samples. Considering the experiences of Vibro-coring method and sheet pile sampling method (commonly known as Geo-slicer method, Nakata and Shimazaki, 1997), the target penetration depth was set to a maximum of about 20 meters due to the ordinary limit of crane lift.

3) The mechanical properties of the ground can be evaluated by sounding technique with various measurements at the probe. Since dynamically driven cone penetration test using impact method is in practical use (Sato and Iwasaki, 1980: Sawada, 2009), the depth profiles of SPT N-value or cone resistance, q_c, can be evaluated, if appropriate instrumentation is implemented for the test using vibratory method.

The penetration depth of the proposed VS-CPT is limited to no more than 20 meters, and its sampled soils are inevitably disturbed. However, this test method is considered much more economical as compared with the conventional sounding techniques for surface layers of seabed, e.g. SPT, CPT and FVT. Because, the working time is shorter, as VS-CPT can be conducted several times a day, whereas the existing test methods may take several days for one test. Moreover, large-scale offshore facilities such as a self-elevating platform (SEP) or subsea driving machine are dispensable. It should be noted that, a penetration depth exceeding 20 meters can be achieved, if the work of connecting additional samplers is possible on a platform. However, the work efficiency is impaired due to long work time, and the sample retrieval from the samplers becomes difficult.

2.2 Test apparatus

The functions of the probe, sampler, and vibratory hammer shown in Fig. 1 are sounding, sampling, and driving, respectively. The power source for the
Fig. 2. Structure around the probe. (Left: longitudinal section, Right: transverse section)

Fig. 3. Procedure of VS-CPT.

vibratory hammer can be installed either immediately above the hammer, i.e. below the water, or on a platform or hull, i.e. above the water. As shown in Fig.1 (Right), a support frame equipped with a leader may be used like Vibro-coring method (Chiba et al., 1982).

Fig. 2 shows the structure around the probe. The probe is supported on the shoe at the tip of the sampler by cross-shaped plates. Cone resistance, $q_c$, etc. are measured immediately above the cone. As the cone is driven into the ground, the soil severely sheared is taken into the sampler through the gap between the probe and the shoe. For the purpose to avoid clogging of the sampler and falling-off of the sampled soils during recovery, a guide cone is provided at the rear end of the probe, and a sleeve is equipped for reducing friction along the inner wall of the sampler.

2.3 Test method

Fig. 3 shows the test procedure. Referring to the Swedish weight sounding test (SWS, JIS A 1221), the procedure of driving the probe was set as penetration by vibration after penetration by self-weight to cope with varieties of soil layers. In order to improve work efficiency, the data measured at the probe is not transmitted, but is continuously recorded on the built-in recording medium from the beginning to the end of the test. After the test equipment is collected, the recorded data are analyzed.

3 MODEL TESTS USING MODEL PROBE

If the clogging occurs near the tip of the sampler, the probe cannot be driven into the ground and soil samples cannot be collected. Thus, to investigate the appropriate shape of the probe that can prevent clogging, some model tests were conducted using the model probe (Hayashi et al., 2018).

3.1 Model probes and method of model tests

Fig. 4 outlines the model tests. A transparent vinyl chloride pipe (outer diameter $D = 60$ mm, inner diameter $d = 52$ mm and length of 1,000 mm) equipped with a model probe at the tip was driven into a saturated sand ground (silica sand No.7, depth of about 570 mm) prepared in a circular container (inner diameter of about 700 mm).

This model probe was made by a 3D printer (manufactured by Fusion Technology Co., Ltd., L-DEVO M2030TP) using polyactic acid resin. Two model probes with cone diameters, 22 mm (Probe A, $R_s = 0.71$) and 33 mm (Probe B, $R_s = 0.53$), were used to investigate the influence of the aperture ratio $R_s = \frac{4A_w}{\pi d^2}$ defined as the ratio of the cross-sectional area of the opening, $A_w$, relative to the inner-space cross-sectional area of the sampler, $\pi d^2/4$, on the drivability and sampling recovery. In addition, a sampler without a probe model (Probe n/a, $R_s = 1.00$) was also used for comparison.

The model probe was driven into the ground in three steps. As the first step, a portable wall-concreting vibrator (manufactured by Exsen Co., Ltd., EKCA, 4.7 kg, output power 280 W) was placed on the top of the sampler, applying a self-weight of about 50 N. As the second step, vibration with a frequency of 160 to 200 Hz was applied. Finally, as the third step, the same vibration was applied with a quasi-static load of about 200 N.
3.2 Results of model tests

Fig. 5 (Left) shows the non-dimensional penetration depth of the shoe tip, $z/D$, for each driving step. Although the data scattering is large due to poor compaction management of the sand ground and inaccurate control of loading, the drivability was greatly improved by vibration in Step 2 and further quasi-static loading in Step 3.

Fig. 5 (Right) shows the relationship between the recovery ratio of soil sampling $R_s$ (= sample volume / cross-sectional area of probe opening / penetration depth = $\pi d^2 h / 4A_{soil}$, where $h$ is the height of the soil sample) and the non-dimensional penetration depth of the shoe tip, $z/D$. For the aperture ratio, $R_a = 0.50$ to 0.75, and the non-dimensional penetration depth, $z/D = 1 - 7$, the recovery ratio of soil sampling, $R_s$, is found in the range of 0.7 to 1.3. Thus, it can be concluded that samples can be collected continuously for the whole penetration depth.

Moreover, it was found that pulling the sampler with its upper end sealed by hand exerted negative pressure within the sampler, which was effective in preventing the sampled soils from falling-off.

4 DETAILS OF PROTOTYPE APPARATUS (MARK 1)

Using the above results, a prototype apparatus (Mark 1) with the maximum penetration depth of 2 meters was designed and manufactured (Hayashi et al., 2018). The purposes of this device were to examine the drivability of the vibratory hammer, whether the records of cone resistance and acceleration measured at the probe were appropriate for sounding, and whether soil samples could be collected continuously.

4.1 Configuration of Mark 1

As shown in Fig. 6, this prototype apparatus (Mark 1) consists of a chucking plate, samplers, and a probe.

The chucking plate is a structural member that transmits the vibration of the vibratory hammer to the upper end of the sampler.

The samplers are two steel casing tubes with an inner diameter $d = 104$ mm, an outer diameter $D = 114$ mm and a length of 1,000 mm. Between the upper end of the sampler and the chucking plate, a connection pipe equipped with a check valve is inserted to prevent the sampled soils from falling-off during retrieval works. A case for storing the sleeve is inserted between
the lower end of the sampler and the shoe.

The measurement part of the probe, 46 mm in outer diameter and about 300 mm in length, houses an electronic board (manufactured by IO Technic Corp., HUNTER JUNIOR 14, HJ-500), about 38 mm wide and about 220 mm long, for instrumentation. The cone with an apex angle of 90 degree has the same diameter as the measurement part, 46 mm, and the aperture ratio of the probe is \( R_a = 0.67 \).

4.2 Instrumentation

The instrumentation of the probe is for measurement of cone resistance and accelerations. The cone resistance is measured by a pressure gauge (TE Connectivity, FP110) with a capacity of 50 MPa on a diaphragm of 26 mm in diameter. As the maximum load, \( Q_{\text{max}} \), is about 26 kN, the capacity of the cone resistance, \( q_c \), is about 16 MPa. The accelerations in three directions orthogonal to each other are measured with an accelerometer with a capacity of ± 2 g (manufactured by Aichi Steel Corp., 6-axis motion sensor AMI603) to monitor vibration and tilting of the probe.

5 MODEL TESTS USING PROTOTYPE APPARATUS (MARK 1)

A series of model tests were conducted using the prototype apparatus (Mark 1), to investigate its drivability, sample recovery and sounding ability.

5.1 Method of model tests

Fig. 7 outlines the model tests. A dense saturated sand ground (silica sand No.7, depth of about 700 mm) was prepared in a circular container (inner diameter of about 460 mm) by compaction using an electric concrete vibrator. The prototype apparatus (Mark 1) was driven into the model ground by the vibratory hammer (Handy Vibro HDV-25E manufactured by Chowa Kogyo Co., Ltd., the excitation force about 3.6 kN at the frequency of 46.7 Hz). Three accelerometers, in the vertical & two horizontal directions, and a displacement transducer were placed on the hammer, and a load cell was installed on the steel chain that carried the whole equipment.

5.2 Results of model tests

Fig. 8 shows a typical example of the relationship between the measured loads, \( T \) & \( Q_c \), and the penetration depth, where \( T \) is the tensile load measured on the steel chain, \( Q_c \) is the cone load measured at the probe, and \( z_c \) is the depth of the cone base.

At the start of the test, \( z_c = -0.15 \) m, the tensile load, \( T \), was about 0.8 kN, the self-weight of the whole equipment. As the probe penetrated into the model
ground, \(0 < z_c < 0.3\) m, the values of \(T\) decreased and became zero at \(z_c = 0.3\) m, which implies the entire equipment was held by the model ground. The maximum penetration depth was rather small, \(z_{c,\text{max}} = 0.46\) m, indicating insufficient drivability of the Handy Vibro. Whereas the values of cone resistance, \(Q_c\), were almost zero throughout the driving process. It is probably because the sand immediately vicinity of the cone was liquefied by the action of vibration.

After the test, there found only a small amount of sand sample stored in the sampler, less than 1 kg. This is attributed to clogging at the shoe as shown in Fig. 9.

For future development, it is necessary to propose measurements for suitable sounding technique other than the cone resistance during vibratory driving, and countermeasures to prevent clogging to improve sample recovery and drivability.

6 CONCLUSIONS

A new sampling and sounding method, named Vibro Sampling and Cone Penetration Test (VS-CPT), was proposed as an economical and effective geotechnical investigation method for shallow ground about 20 meters below seafloor.

To examine the feasibility of the proposed method, a prototype apparatus (Mark 1) was manufactured and driven into the model sand ground. The test results indicated that neither the sample recovery nor the drivability were satisfactory because clogging occurred at the shoe. Moreover, the cone resistance was found not suitable for evaluating the characteristics of the ground as it was strongly influenced by vibration.

ACKNOWLEDGEMENTS

The authors are grateful to Mr. T. Kitamura and Mr. H. Takahashi of Chowa Kogyo Co., Ltd. for lending the vibratory hammer, and to Mr. T. Kaneko of IO Technic Corp. and Mr. T. Tachikawa of Tachikawa Machinery Works Corp. for manufacturing the prototype apparatus.

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