Improvement of apparatus for Sampling and Cone Penetration Test

Rikuto Fujikata[1#], *Kazuo* Tani[1], and *Shun* Nomura[1]

[1] *Tokyo University of Marine Science and Technology, Department of Marine Resources and Energy, 4-5-7 Konan Minato-ku Tokyo 108-0075, Japan*
[#]*Corresponding author: m233047@edu.kaiyodai.ac.jp*

ABSTRACT

In this paper, a new innovative method of geotechnical investigation applicable to seafloor is proposed. This method is the improved version of Sampling and Cone Penetration Test (S&CPT) to evaluate geotechnical properties by Cone Penetration Test (CPT) while collecting continuous samples quickly and inexpensively for offshore geotechnical investigations. In the previous study, demonstration tests on soft cohesive soil were conducted, and some problems were found. The purpose of this study is to modify the sampler to improve penetrability, sampling performance, workability and to examine the applicability for cohesionless soils. Using the improved samplers, demonstration tests were conducted at two sand sites (loose and medium-dense) in Japan. The results of each test were used to examine: (1) sampling performance, and (2) workability. As a result, the following conclusions are drawn: 1) In loose sand, sampling of several meters is possible. In medium-dense sand, the same level of sampling may be possible by providing an appropriate shoe to prevent blockage at the sampler tip. 2) The workability of the proposed apparatus is very high compared to the conventional Cone Penetration Test and Standard Penetration Test.

Keywords: cone penetration test; sampling; geotechnical investigation; seafloor.

1. Introduction

This paper proposes an economical and time-saving sampling technology for collecting continuous samples while conducting Cone Penetration Test (CPT).

1.1. Background

It is necessary to investigate the mechanical properties of the seafloor for installation of wind turbines and cables for an offshore wind farm. CPT is one of the most preferred methods for these investigations. Because this is easy to conduct, and a variety of ground information can be obtained with high depth resolution. However, in arear with high geological activity, it is insufficient to perform geotechnical design based on CPT results alone. This is because CPTs cannot take into account the effects of dynamic loading, resulting in low accuracy in evaluating liquefaction during earthquakes. furthermore, information on strata containing pyroclastic materials as volcanic ashes and/or loams in not reflected in the database for estimating mechanical properties and soil classification.

Sampling at the same time as CPT and comparing the soil samples and the CPT data are useful in improving the accuracy of site characterization especially for soil classification. However, conventional sampling methods require high costs and take long time. There are even more restrictions when investigating the seafloor than when working on the land. Therefore, a new technique is needed to collect ground samples easily during CPT operation.

1.2. Sampling and Cone Penetration Test

To meet this demand, Sampling and Cone Penetration Test (S&CPT) has been proposed, which allows continuous soil samples at the same time as CPT (Tani et al., 2020). Fig. 1 shows an overview of S&CPT. The apparatus consists of samplers, rods, guides, and the CPT probe. The sampler is divided into two parts: treys on which soil samples are placed and shutters which separates the soil samples from the ground and cover them. The treys are connected to the rods by the guides. A shoe is attached to the tip of the shutter. Note that the trays are always above the probe and could not affect the sounding results i.e. CPT data.

The flow of work is as follows.

Step 1: The CPT probe and the trays are penetrated together, and soundings of CPT are conducted.

Step 2: The shutters are penetrated to encapsulate the soil samples after the penetration of CPT probe and the trays is completed.

Step 3: The rods and the samplers are simultaneously lifted. The encapsulated soil samples are lifted by the apparent adhesion acting on the surface of the trays. In some cases, a small core catcher may be attached to the shoer to prevent the soil sample from falling out.

Step 4: The sampler is opened, and the soil sample is cut into 1-meter sections and stored in a core box. In this process, the soil samples are kept undisturbed and retain their shape, preventing evaporation of the pore water.

The quality of the collected samples in S&CPT is “representative disturbed sample” (Class 2 or Class 3 in ISO 22475-1) with preserved water content, although the

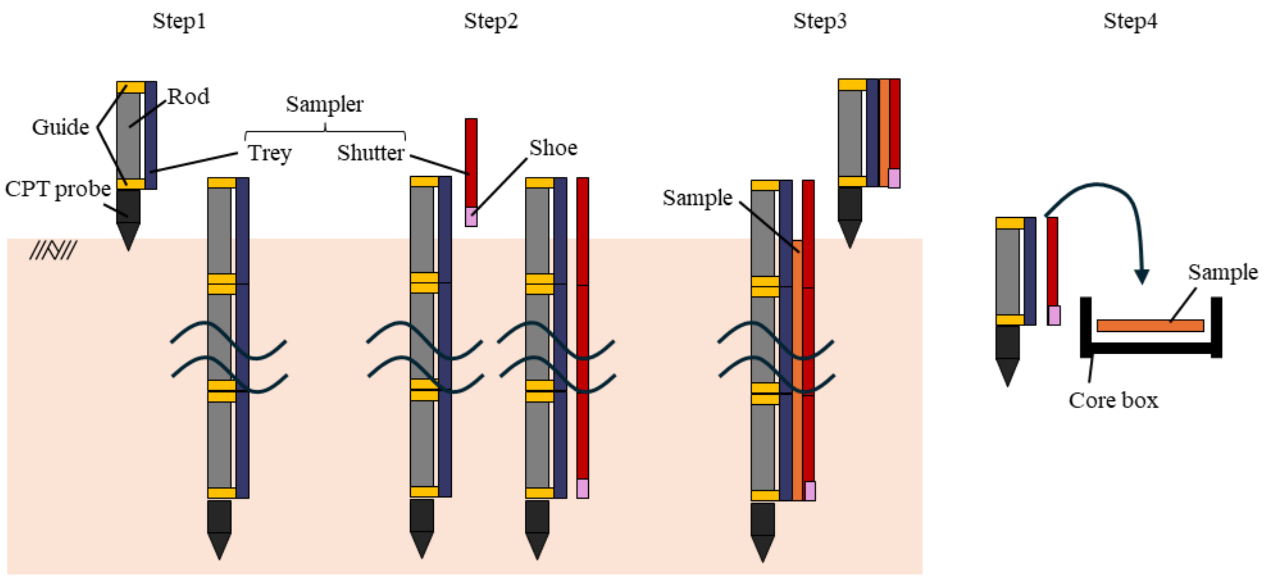

Figure 1. Overview of Sampling and Cone Penetration Test.

soil samples may be disturbed due to shear during sampler penetration (Akimoto et al., 2023). Immediately after Step 4, the natural water content, w_n, is measured, and if the soil samples are taken from below the water table, the relative density, D_r, at the site can be estimated by calculating the void ratio, e, assuming fully the saturated condition, that the degree of saturation, S_r = 100 %. Thus, the mechanical properties can be estimated from the relative density, D_r, of sandy soils, and from the liquid index, $I_L = (w_n - w_p) / I_p$, of clayey soils.

Using S&CPT, previous field test successed to sample 7m of soft clay (N value = 0~2) (Sato et al., 2022). However, the following issues caused by structural problems were identified. Firstly, it took a long time to remove soil samples from the sampler. Secondly, the shutter of the sampler may buckle above the ground during Step 2.

1.3. Purpose and focuses of this study

The purpose of this study is to overcome the issues described in the previous section. Improvement was made on the samplers, and field tests were conducted on loose sand (N value < 20) and medium-dense sand (N value = 20~50) in Japan.

We focused on two perspectives: (1) sampling performance and (2) workability. For the sampling performance, we discuss the length and quality of the soil samples. For the workability, we discuss the time spent for each step shown in Fig. 1.

2. Methodology

Two kinds of samplers were used in this study. They are named “Hexagonal sampler” and “Triangular sampler” from their cross-sectional shapes, respectively. “Hexagonal sampler” was used at "Site A" and “Triangular sampler” was used at "Site B," respectively.

A drilling machine (Geoplobe System, Geoplobe 6610DT) was used with a maximum pushing force of 160 kN. The penetration rate for Step 1 was selected as 20 mm/s. The CPT probes whose diameter is 36 mm measure the cone resistance, q_c, sleeve friction, f_s, and pore water pressure, u, simultaneously with sampling frequency of 10 Hz.

2.1. Hexagonal sampler at Site A

The test was carried out in the loose sand in September 2022. See Akimoto et al. (2023) for a report on CPT measurement.

2.1.1. Specification

Fig. 2 shows an overview of “Hexagonal sampler”. The following are some of its characteristics.

(1) The transversal cross-section of sampler is hexagonal. The trays and the shutters are gutter type with wide opening. The inner and outer walls surface areas of the trays, $A_{t,in}$, $A_{t,out}$, and shutters, $A_{s,in}$, $A_{s,out}$, are large ($A_{t,in}$: 0.083 m^2/m, $A_{t,out}$: 0.096 m^2/m, $A_{s,in}$: 0.072 m^2/m, $A_{t,out}$: 0.125 m^2/m), thereby the penetration resistance become large.

(2) The length of the shutter is 1.0 m, thereby there is a risk of buckling during Step 2 due to its elongated length.

(3) A “rod coupler” must be used between the rods to attach the guides. The trays must be attached on the site in the order of the circled numbers in the figure, thereby it takes a long time in Step 1 compared to conventional CPT.

(4) The trays/shutters separation method is “sliding”, thereby removal of the soil samples from the samplers is difficult which take a significantly long time in Step 4.

(5) In the longitudinal cross-section of the shoe, the edge is slightly curbed inward in order to make the opening narrow by 1 mm. Because it allows for the volume expansion of the soil samples in the samplers by stress relief and/or shearing when the moment the soil passes through the opening.

2.1.2. Location

Fig. 3 shows the soil boring log at Site A and the depth profile of N values. The ground below 3.0 m is classified as a loose sand with N values from 0 to 16. The surface layer is a 3.0 m embankment, and the deeper part

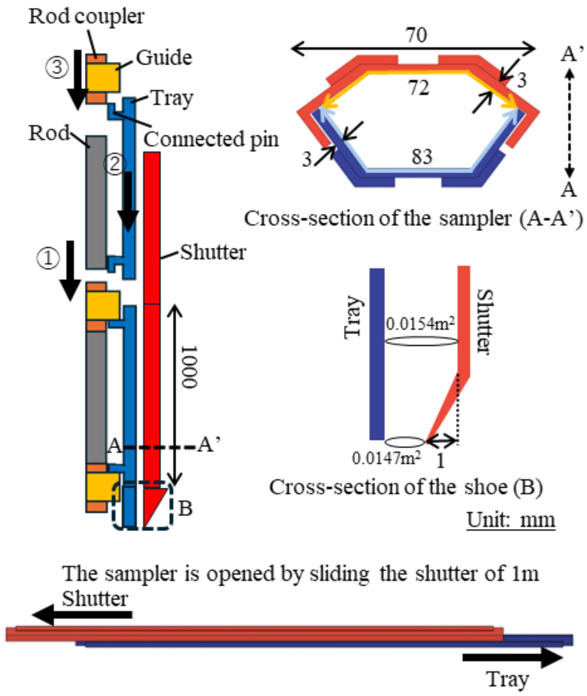

Figure 2. Overview of "Hexagonal sampler" .

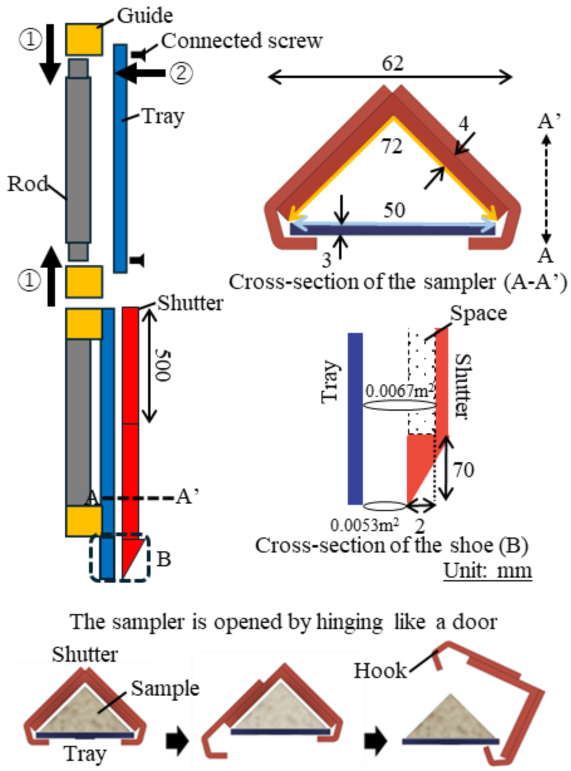

Figure 4. Overview of " Triangular sampler".

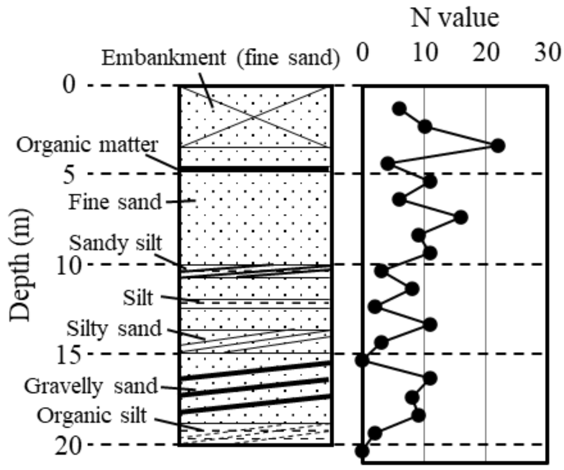

Figure 3. Soil boring log at "Site A".

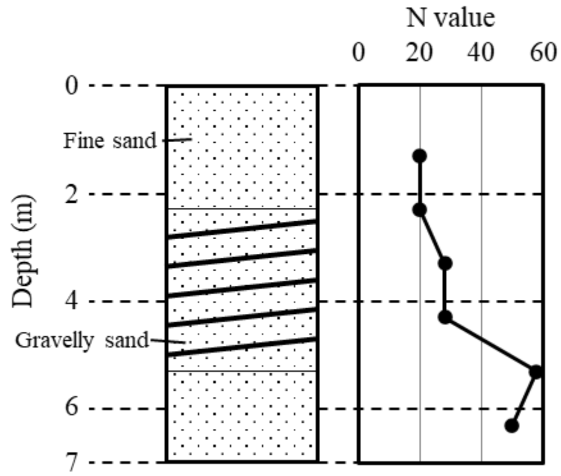

Figure 5. Soil boring log at " Site B".

is Holocene sand layer, consisting mainly of silty fine sands, sandy silt, gravelly sands, and fine sands. Organic matters and shell fragments are interbedded in some parts.

2.2. Triangular sampler at Site B

The test was carried out in November 2023.

2.2.1. Specification

Fig. 4 shows an overview of "Triangular sampler". The following are some of its characteristics.

(1) The transversal cross-section of sampler is triangular. The trays are plate, and the shutters are angle. The inner and outer walls surface areas of the trays, $A_{t,in}$, $A_{t,out}$, and shutters, $A_{s,in}$, $A_{s,out}$, are small ($A_{t,in}$: 0.050 m^2/m, $A_{t,out}$: 0.050 m^2/m, $A_{s,in}$: 0.072 m^2/m, $A_{t,out}$: 0.080 m^2/m). This geometrical and size modification aims to reduce friction for better penetration performance.

(2) The length of the shutter is 0.5 m. This aims to increase its buckling strength.

(3) The guides are attached directly to the rods to dispose of the rod couplers of "Hexagonal sampler". Therefore, the trays can be attached to the rods in advance, which is expected to improve the workability on site.

(4) The trays/shutters separation method is "hinging", in which the sampler is opened like a door by sliding the hooks on the shutter.

(5) In the longitudinal cross-section of the shoe, the height between inner wall of the shutter and shoe is changed to 2 mm. The shape of shoe is arrowhead-like for ease of production and rigidity. This is expected to reduce resistance during shutter penetration, since sand is less likely to touch the inside of the shutter.

2.2.2. Location

The test site is a sandy beach on the Pacific coast of Japan. Fig. 5 shows the soil boring log at Site B and the depth profile of N values. The ground is a medium-dense sand layer with N values from 20 to 30 at 0.0~5.0 m depth overlying a denser sand layer with N values greater than 50. They consist of fine sands and gravelly sands, sporadically including small fraction of concrete rubbles, organic matters, and shell fragments.

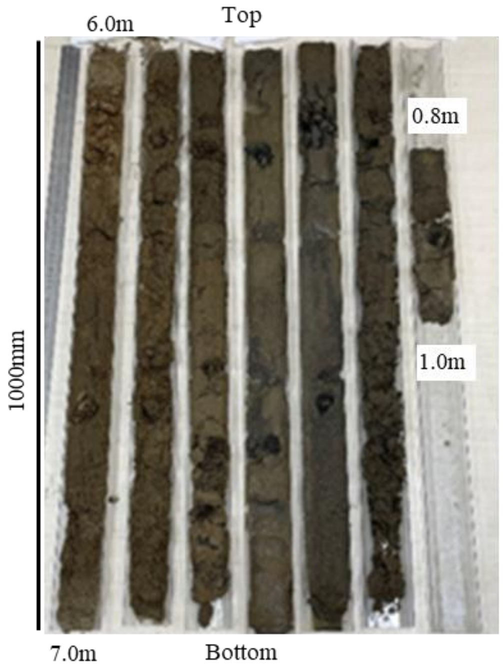

Figure 6. Sample of "Site A".

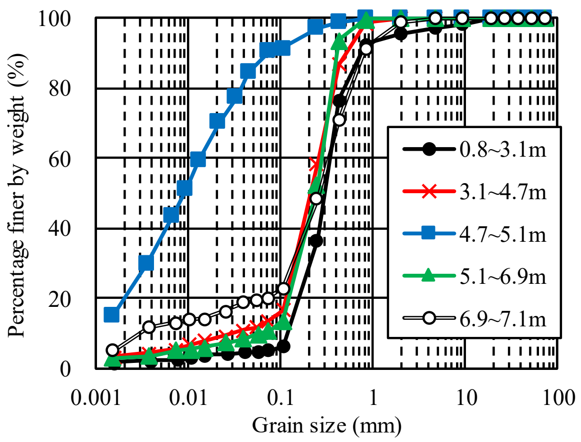

Figure 7. Grain size distribution curves of "Site A".

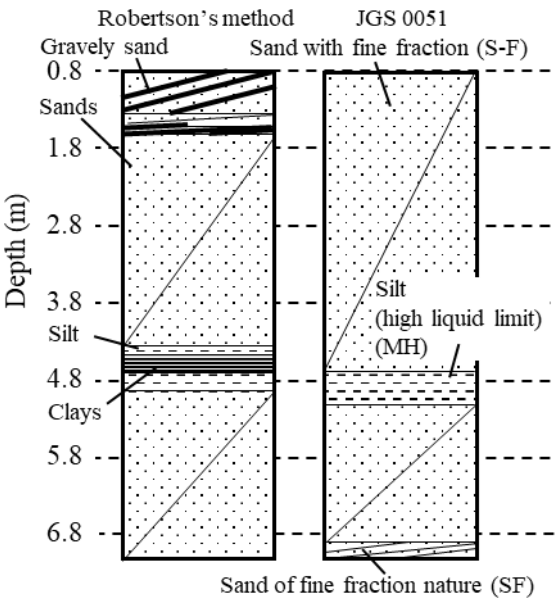

Figure 8. Geological column at "Site A" based on the Robertson's method and method of classification of geomaterials for engineering (JGS 0051).

3. Result of field tests

3.1. Hexagonal sampler at Site A

3.1.1. Sampling performance

Fig. 6 shows a photograph of the obtained sample. The tray penetration depth was 8.0 m. However, the shutter could not be penetrated deeper than 7.1 m because the shutter above ground was buckled due to excessive thrust. As a result, a continuous sand sample from 0.8 to 7.1 m was obtained, while the surface layer of 0.0~0.8 m was lost during Step 4.

Fig. 7 shows the size distribution curves for the sample. Fig. 8 compare the geological column estimated by Robertson's method based on CPT data (Robertson, 1990), and by the method of classification of geomaterials for engineering (JGS 0051) using the sampled soils by S&CPT. The geological column determined by JGS 0051 using the sampled soils by this S&CPT agree very well with the soil boring log by SPT shown in Fig. 3. This means that the samples were taken correctly by S&CPT without any severe disturbance nor movement in the depth direction. The soil classification estimated by Robertson's method using CPT data for the shallow depth, from 0.8 to 1.6 m, was gravely sand which is coarser than the correct identification of the sand with fine fraction (S-F). Furthermore, the layer of silt (high liquid limit) (MH) at the depth of 4.7 to 5.1 m was estimated as a clay layer sandwiched between silt layers at depth of 4.5 to 4.9 m. Therefore, in Robertson's method based on CPT data, the depth was underestimated by 0.2 to 0.3 m, and grain size of cohesive soils was prone to be identified as more finely than it actually was, whereas grain size of sandy soil was likely to be judged more coarsely than it actually was.

3.1.2. Workability

For each of the work steps shown in Fig. 1, the average time spent to execute per meter of length is as follows. Step 1: 2.7 min/m, Step 2: 1.6 min/m, Step 3: 2.0 min/m, Step 4: 10 min/m. It should be noted that Step 4 took no less than 30 min/m in some sections. The reason for this time-consuming work is caused by the dense sand taken inside the sampler expanded due to stress relief and/or positive dilatancy effect by shearing, inducing very high resistance against sliding the trays and the shutters.

3.1.3. Points to be improved

Regarding the sampling performance, the shutter penetration was limited due to buckling of the shutter. The sampling depth could be prolonged by increasing the buckling strength of the shutter and reducing the penetration resistance.

Figure 9. Sample of "Site B".

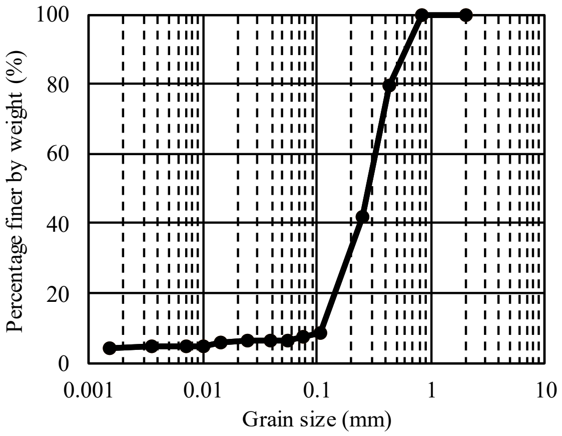

Figure 10. Grain size distribution curve of "Site B".

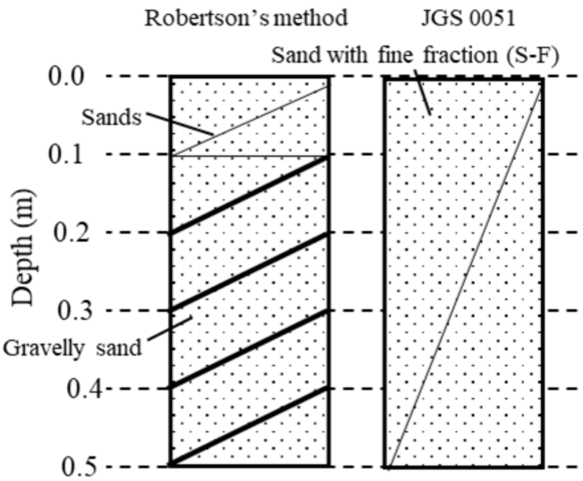

Figure 11. Geological column at "Site A" based on the Robertson's method and method of classification of geomaterials for engineering (JGS 0051).

Regarding the workability, it required approximately 3 min/m for Step 1 to attach the trays on site just before penetration. A mechanism in which the tray is attached to the rod in advance would reduce the working time. It was also suggested that we need to come up with an appropriate method for Step 4 to disassemble the samplers and to take out and convey the soil samples into the core boxes.

3.2. Triangular sampler at Site B

3.2.1. Sampling performance

Fig. 9 shows a photograph of the obtained sample. The tray could be penetrated only 1.5 m because the load applied to the CPT probe reached to the maximum allowable limit of the drilling machine. The shutter could also be penetrated no deeper than 1.0 m because the load applied by the drilling machine also reached its maximum allowable limit. As a result, a continuous sand sample from 0.0 to 0.5 m was obtained, whereas the soil before 0.5 to 1.0 m did not intrude the sampler due to soil blockage at the shoe.

Fig. 10 shows the grain size distribution curve for the sample. Fig. 11 compare the geological column estimated by Robertson's method based on CPT data (Robertson, 1990), and by the method of classification of geomaterials for engineering (JGS 0051) using the sampled soils by this S&CPT. The soil classification estimated by Robertson's method was classified gravelly sand from 0.1 to 0.5 m depth. The results from JGS 0051 using the sampled soils by S&CPT are sand with fine fraction (S-F). Therefore, the grain size of sandy soil was judged more coarsely than it actually was.

3.2.2. Workability

For each of the work steps shown in Fig. 1, the average time spent to execute for every 1.0 m length is as follows. Step 1: 1.4 min/m, Step 2: 2.3 min/m, Step 3: 1.1 min/m, Step 4: 1.0 min/m. The working time for Steps 1, 3, and 4 was significantly reduced, and the total work efficiency was improved by more than three times than that of "Hexagonal sampler". Only Step 2 was 0.7 min/m slower than "Hexagonal sampler." This was due to the modification of the shutter length from 1.0 m to 0.5 m, which doubled the number of pushing cycles required for 1.0 m penetration of the shutter.

3.2.3. Points to be improved

Regarding the sampling performance, soil clogging must be prevented for continuous soil sampling. As shown in Figure 4, there is a 70 mm region in the shoe that does not allow for volumetric expansion. This may be the cause of the blockage.

Regarding the workability, the test conducted at Site B showed extremely high performance, as the work time is only about twice that of conventional CPTs. It is important that the countermeasure for the above-mentioned clogging problem must not impair this efficiency.

4. Discussion

4.1. Sampling performance

Sampling is supposed to be conducted by satisfying the following requirements in the longitudinal cross-section of the sampler in Step 1, 2 and 3 as shown in Fig. 12.

a) Minimize the friction between the trays and the ground during Step 1.

b) Keep a gap between the soil sample and the shutters during Step 2.

c) Avoid blockage at the sampler tip during Step 2.

d) Carefully lift the apparatus with the soil samples so that the trays can retain the soil samples with apparent adhesion during Step 3.

The requirement of a) for Step 1 depends on the inner surface area of the trays. If it becomes smaller, the frictional resistance is reduced, which thereby the penetration depth of the trays and the CPT probe is

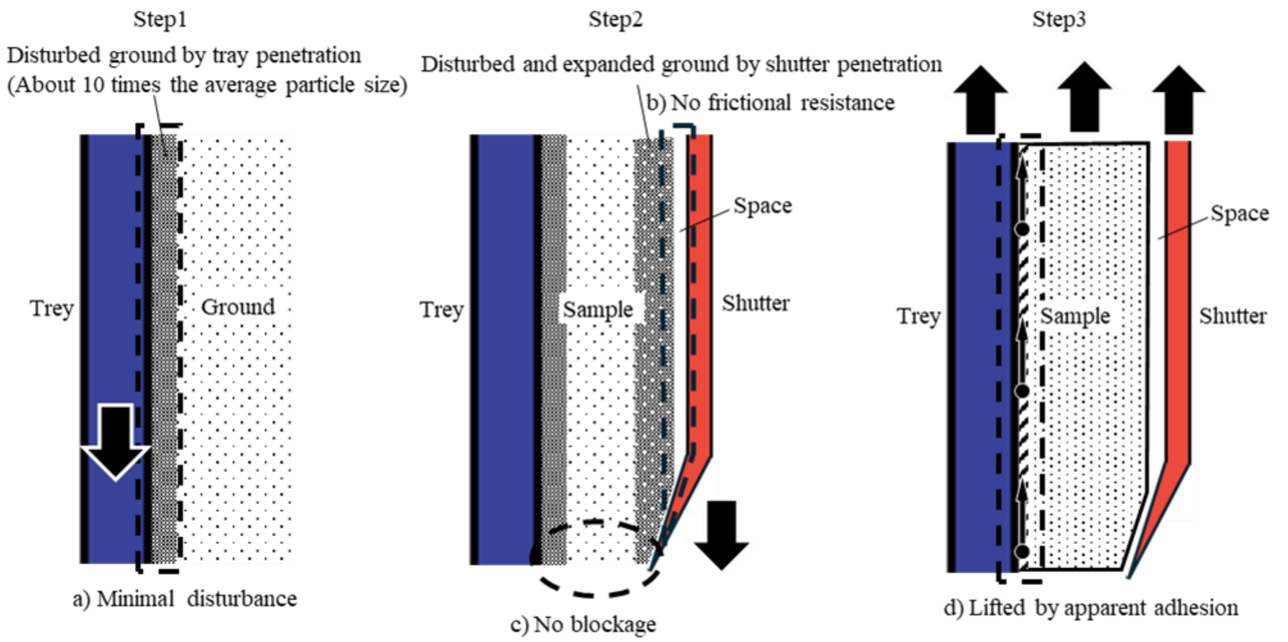

Figure 12. Requirements for sampling.

increased, and the quality of the retrieved sample is better due to the smal ler disturbed area.

The requirement of b) for Step 2 depends on securing space to store the soil sample taken into the sampler through the opening of the shoe, i.e. the tip of the shutter. If sufficient clearance is ensured between the soil sample and the inner wall of the shutters, disturbance of the soil due to penetration of the shutter can be minimized. For this, the area of the tip opening must be slightly smaller than the cross-sectional area of the sampler. This increases the penetration depth of shutter and improves the quality of the soil samples.

The requirement of c) for Step 2 depends on the shape of the shoe. The encapsulated soil sample tends to expand inside the sampler due to shearing and/or stress relief. If the shape of the shoe cannot accommodate this volumetric expansion, the shutter tip becomes blocked, preventing further sample collection.

Finally, the requirement of d) for Step 3 depends on the apparent adhesion of soil on the surface of the tray. If the apparent adhesion is large enough to prevent the soil sample from falling due to gravity, the soil samples can be safely stored in the sampler and lifted to the ground surface.

For each requirement, "Hexagonal sampler" and "Triangular sampler" are compared and discussed. Table 1 shows a comparison of performance.

The disturbed areas due to shearing and the rate of expansion due to dilatancy were assumed to be as follows. The grain size accumulation curve shown in Fig. 7 and Fig. 10 indicate that the average particle size D_{50} is 0.3 mm at Site A and 0.27 mm at Site B respectively. The thickness of the disturbed layer where volumetric deformation occurs due to shearing is assumed to be about ten times the average grain size. Therefore, they are assumed to be 3.0 mm for "Hexagonal sampler" and 2.7 mm for "Triangular sampler", respectively. The maximum volumetric strains were assumed to be 5 % at Site A of the loose sand using "Hexagonal sampler" and 10 % at Site B of the medium-dense sand using "Triangular sampler".

In a), the predicted disturbed area of the soil is 0.023 m^2 for "Hexagonal sampler" and 0.011 m^2 for "Triangular sampler" in each transversal cross-section of samplers as shown in Fig. 13. The trays penetration depth and quality

Table 1. Comparison of sampling performance.

	Hexagonal sampler	**Triangular sampler**
Disturbed area	0.023 m^2 (Large)	0.011 m^2 (Small)
Space size	0.007 m^2 (Small)	0.014 m^2 (Large)
Blockage	Not occur	Occur
Sample retention capacity	$5.6\tau/\rho g$ (Small)	$9.4\tau/\rho g$ (Large)

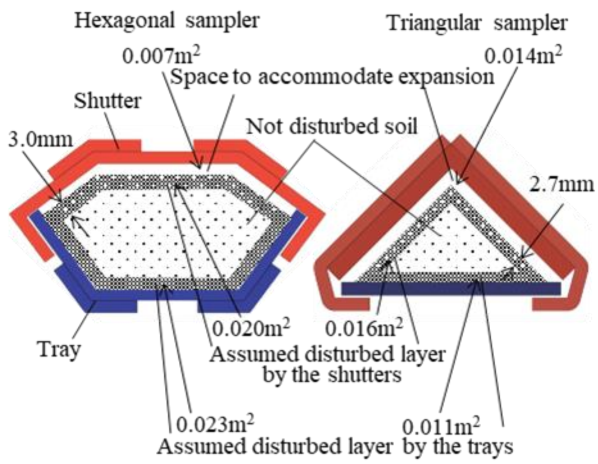

Figure 13. Assumed disturbed area and provided clearance.

of the retrieved soil sample is expected to be better in "Triangular sampler".

In b), the predicted dilatancy area of the soil is 0.020 m^2 for "Hexagonal sampler" and 0.016 m^2 for "Triangular sampler" in each transversal cross-section of samplers as shown in Fig. 13. Assuming the maximum volumetric strains, the increment of soil after expansion is predicted to be $0.020 \times 0.05 \approx 0.001$ m^2 for "Hexagonal sampler" and $0.016 \times 0.1 \approx 0.002$ m^2 for "Triangular sampler". In contrast, the provided gaps to accommodate expansion are 0.007 m^2 (> 0.001 m^2) for "Hexagonal sampler" and 0.014 m^2 (> 0.002 m^2) for "Triangular sampler" as shown in Fig. 13. It can be said that both space in the sample are sufficient.

In c), as shown in Fig. 14, the shoe of "Hexagonal sampler" is slightly curved inward, while the shoe "Triangular sampler" has a 70 mm straight length that does not allow volumetric deformation. Thus, the blockage did not occur in the "Hexagonal sampler", while it occurred in the "Triangular sampler", suggesting that the length of this section that does not allow volume expansion.

In d), the soil samples can be lifted if the ratio of the apparent adhesion acting on the inner wall of the trays to the gravitational force effected on the soil samples is large. Where gravitational acceleration is g, the density of the soil samples is ρ, the shear stress on the inner wall of the trays is τ, the volume of the soil samples is V, and the surface area of the inner wall of the trays is A. "Triangular sampler" has V= 0.0053 m^3 and A = 0.05 m^2, resulting in $9.4\tau/\rho g$, while "Hexagonal sampler" has V= 0.0147 m^3 and A = 0.083 m^2 resulting in $5.6\tau/\rho g$. Therefore, "Triangular sampler" has a higher sample holding capacity. "Hexagonal sampler" did not cause any sample dropout in Step 3, indicating that "Triangular sampler" also has sufficient sample retention capacity.

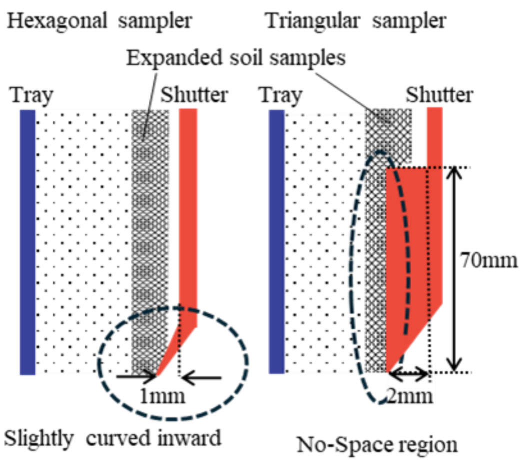

Figure 14. Tip shapes of each sampler's shoe.

Table 2. Comparison of required time (min/m).

		Step 1	Step 2	Step 3	Step 4	Total
S&CPT	**Hexagonal sampler**	2.7	1.6	2.0	10	16.3
	Triangular sampler	1.4	2.3	1.1	1.0	5.8
CPT		1.4	-	0.5	-	1.9

4.2. Workability

Table 2 compare the time required for each step shown in Fig.1 for "Hexagonal sampler", "Triangular sampler" of S&CPT and CPT.

In total, the workability of "Triangular sampler" is three times higher than that of "Hexagonal sampler". It is because, in Step 4, "Triangular sampler" can significantly reduce the times for sample removed as compared to "Hexagonal sampler". This shows that the proposed sample removal method with "hinging" is remarkably workable. Moreover, Step 1 (tray & CPT probe penetration) and Step 3 (lifting) took half the time. However, Step 2 (shutter penetration) took longer time 0.7 min/m because two shutters were required per meter.

Comparing "Triangular sampler" of S&CPT and CPT, "Triangular sampler" takes about twice as long as CPT in Steps 1-3. Even if Step 4 is considered, the work time is about three times longer. Considering that a continuous sample can be obtained to complement CPT results, it can be said that the improved S&CPT using "Triangular sampler," has a high workability in terms of practicality.

In "Triangular sampler", SPT, which is more commonly used than CPT in Japan, took an average of 12 minutes per meter for sounding and sampling of 6 meters at Site B. Comparing SPT and S&CPT, it seems that S&CPT can collect continuous samples and has much better workability in sand with N values less than 30.

5. Conclusions

Economical and time-saving sampling technology needs to be developed to complement the results of the Cone Penetration Test (CPT), which is one of the most common site characterization methods for marine soils. To meet this demand, a Sampling and Cone Penetration Test (S&CPT) has been proposed that can collect continuous samples while conducting CPT. In this study, S&CPT was improved to enhance its sampling performance and workability. Field tests were conducted at two sites on the loose and medium-dense sandy ground in Japan.

The following are main conclusions.

- In loose sand, sampling of several meters is possible. In medium-dense sand, the same level of sampling may be possible by providing an appropriate shoe to prevent blockage at the sampler tip.
- The time required for S&CPT is about two to three times that of conventional CPT. S&CPT have extremely high workability.

Acknowledgements

This work was supported by JSPS KAKENHI Grant Number JP22H01585. The authors are grateful to Jibanshikenjo Co. Ltd. for conducting the field test.

References

Akimoto, Y, Tani, K, Nomura, S, and Ikeya, T. 2023. "Study on application of Sampling and Cone Penetration Test to sandy ground." Journal of JSCE (Marine Development), vol.79, issue18. https://doi.org/10.2208/jscejj.23-18049

International Organization for Standardization. "ISO 22475-1:2021 Geotechnical investigation and testing — Sampling methods and groundwater measurements — Part 1: Technical principles for the sampling of soil, rock and groundwater", 2021.

Robertson. P. K. 1990. "Soil classification using the cone penetration test." Canadian Geotechnical Journal, 27(1), pp151–158. https://doi.org/10.1139/t90-014

Sato, A., Tani, K., Ikeya, T, and Nomura, S. 2022. "Development of a method to perform continuous sampling and CPT in soft ground." Journal of JSCE (Marine Development), vol.78, issue2, pp.I_763-I_768. https://doi.org/10.2208/jscejoe.78.2_I_763

Tani, K., Ikeya, T. and Inazu, D. 2020. "A study on feasibility of the method of sampling and cone penetration test." Proc. 14th ISOPE PACOMS-2020 Sym., Dalian, P20-156, pp.279-284.