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# Development of a sampler designed for laminar box and its application to dynamic centrifuge modeling of footing settlement due to liquefaction

## Mise au point d'un échantillonneur conçu pour boîte laminaire et son application à la modélisation centrifuge dynamique du tassement en pierre dure dû à la liquéfaction

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ABSTRACT
In some soils with fines such as that observed in the Upper Yurakucho Layer of Tokyo, aging effects can also affect the liquefaction strength. In this study, an attempt was made to collect a relatively large undisturbed soil sample containing fines by using a newly designed sampler, and to carry out dynamic centrifuge tests on the obtained soil sample. In designing the sampler, special attention was paid to the application to shaking table tests using a laminar box. To confirm the applicability of the developed sampler, soil sampling from the Upper Yurakucho Layer was conducted at an actual construction site in Tokyo. The applicability of the sampler to shaking table tests with a laminar box was also confirmed, and compared with another dynamic centrifuge test using a reconstituted soil model from the above sample.

RÉSUMÉ
Dans certains sols à teneur en fines supérieure comme il a été observé dans la couche Yurakucho Supérieure de Tokyo, des effets de vieillissement peuvent également affecter la résistance de la liquéfaction. Dans cet article, nous avons tenté de prendre un échantillon relativement large de sol non remué avec des fines en utilisant un échantillonneur de conception nouvelle, et de procéder à des essais centrifuges dynamiques en utilisant l'échantillon de sol obtenu. Lors de la mise au point de l'échantillonneur, une attention particulière a été accordée à l'application à des essais de table à secousses en utilisant une boîte laminaire. Pour confirmer l'applicabilité de l'échantillonneur mis au point, un échantillonnage de sol provenant de la Couche Yurakucho Supérieure a été effectué sur le site même de la construction, à Tokyo. L'applicabilité de l'échantillonneur aux essais de table à secousses avec boîte laminaire a également été confirmée, et les résultats ont été comparables à ceux d'un autre essai centrifuge dynamique avec utilisation d'un modèle de sol reconstitué prélevé sur l'échantillon ci-dessus.

## 1 INTRODUCTION

The Niigata earthquake in 1964 drew attention to the liquefaction phenomenon of the ground, prompting many researchers to conduct various studies on liquefaction. These research results contributed to those of the Hanshin earthquake disaster in 1995, from which arose new findings regarding the liquefaction phenomenon of sand with gravel (as decomposed granite soil) and fines. Furthermore, the liquefaction problem appeared to change from one of stability to one of deformation. In other words, preliminary investigation and examination of deformation and settlement during and after liquefaction has become a necessity. For example, in the case of a structure supported by footing foundation on liquefiable ground, the engineer must predict the degree of settlement and inclination due to liquefaction, and examine the possible need for countermeasures. In recent years, the settlement and inclination of buildings due to ground liquefaction after the occurrence of big earthquakes has been researched in detail. Some results show the relation between the weight of a building and the measured settlement or inclination and so on (for example, Yasuda et al., 2001).

On the other hand, it is known that liquefaction strength of the sandy soil distributed in the lowlands of Tokyo (for example, Upper Yurakucho Layer) depends to a great extent on the fines content (Kamei et al., 2002). Furthermore, dependency of cementation due to so-called aging effects and other geological deposit processes on the liquefaction strength has been reported (for example, Yasuda et al., 2003). Although a number of intensive studies have been conducted on the liquefaction phenomena in element tests through comparisons between disturbed and undisturbed samples, research on the settlement behavior through shaking table tests is very limited.

Based on the above background, this paper describes a sampler developed to collect an undisturbed block soil sample containing fines, and the results of shaking table tests on the sample. This is one of a series of research works that we have carried out to clarify the settlement behavior of footing foundations on liquefiable ground (Kawasaki et al., 1998, Abo et al., 2000, Fujiwara et al., 2001).

## 2 SOIL SAMPLING

### 2.1 *Design of sampler for shaking table test*

In this research, we developed a special sampler enabling us to collect an undisturbed block sample for shaking table tests with a laminar box. The main part of the sampler is made of steel pipe with a diameter of 400 mm and a height of 500 mm (Fig. 1). The size was determined by the diameter of the circular laminar box for shaking table tests. The pipe can be divided into two parts when preparing the soil model in a laminar box. The special features of the sampler are as follows:

- The sampler is composed of the main part (height: 500 mm), the cutter part, and the collar part. The cutter and collar parts can be removed from the main part after the sampling. The end tip of the cutter part was sharpened for easier insertion of the sampler into the ground.
- Two covers, i.e. upper and lower, were designed to enable transportation of the sample with minimum disturbance.
- To minimize friction between the soil and the sampler during insertion, a cylinder-shaped rubber membrane (thickness: 0.4 mm) and two sheets of Teflon (thickness: 0.3 mm) were set inside the sampler.

- To restrain disturbance of the sample during insertion to the sampler, the dimensions of the inner parts were carefully adjusted. Especially, the surface of the boundary between the cutter part and the main part was flattened to eliminate any gaps or space.
- For easier preparation of the soil sample in the laminar box after sampling, the main part of the sampler can be divided into two parts. Because the setting activity of the laminar box base plate was considered the most difficult in the shifting activity of the sample, the body part of the sampler and laminar box were made into a conjugated structure.

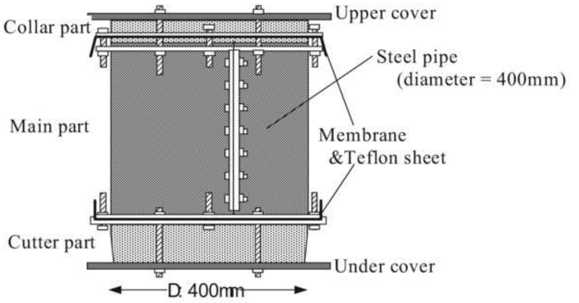


Figure 1. Design of sampler

Table 1. Basic profiles of Upper Yurakucho Layer

| | |
|---|---|
| Soil particle density: $\rho_s$ (g/cm$^2$) | 2.702 |
| Mean grain size: $D_{50}$ (mm) | 0.120 |
| Fine content: $Fc$ (%) | 16.2 |
| Dry density: $\rho_d$ (g/cm$^3$) | 1.498 |
| Maximum void ratio: $e_{max}$ | 1.723 |
| Minimum void ratio: $e_{min}$ | 0.966 |
| Relative density: $Dr$ (%) | 128 |
| Coefficient of permeability: $k$ (cm/sec) | $1.07\times10^{-7}$ |

### 2.2 *Soil Sampling in the field*

The soil was sampled using the developed sampler at a construction site in Tokyo. The sampled soil is Upper Yurakucho Layer obtained at a depth of 4 m from the ground surface. The basic profile of the soil is summarized in Table 1. As shown in the table, the fines content of the soil is medium, like that of Upper Yurakucho Layer soil. Moreover, the relative density of the soil is 128%, which is quite high, and the coefficient of permeability by consolidation test is very low (about $10^{-7}$ cm/sec). This layer is distributed mainly as river sediment in the lowlands of Tokyo, and is covered with reclaimed soil and embankment. The thickness of the soil layer is about 10 m.

The procedures from sampling to shaking table test are shown in Fig. 2. Firstly, the ground was excavated to a depth of 3 m. After smoothing the surface, the sampler was slowly inserted in the ground using a boring machine to provide a reaction. At each insertion of the sampler at the order of several cm, the soil around the sampler was excavated and removed. Although the sampling depth was below the ground water level, drainage of water was not required due to the high content of fines in the ground, and pumping out the excavation point was an adequate countermeasure against ground water. After the sampler reached the target depth, a sufficient amount of surrounding soil was removed, and the ground connection was cut by placing a wedge beneath the sampler. Following these procedures, the sampler was capped at both the upper and lower ends, and packed for transportation after taking waterproofing and anti-vibration measures. A photograph of the sampler at the site is shown in Photo 1.

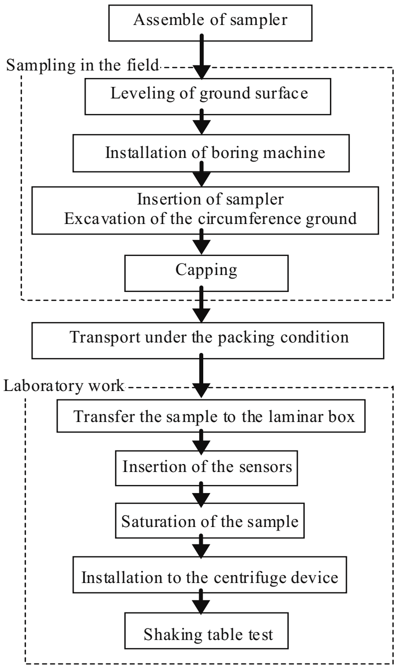


Figure 2. Procedures from sampling to shaking table test

Photo 1. Sampler and soil sampling in the field

## 3 DYNAMIC CENTRIFUGE MODELING OF FOOTING SETTLEMENT ON SAND

### 3.1 *Preparation of centrifuge model*

The soil sample taken at the site was used for dynamic centrifuge modeling. The main procedures for this stage, which are summarized in Fig. 2, include transfer of the soil from the sampler to the laminar box, installation of sensors, and saturation of the soil sample. It was considered very important to minimize disturbance of the sample during the preparation. The following procedures were adopted (see Fig. 3):

a) The cutter part was removed after turning the sampler upside down. After smoothing the soil surface, the base plate of the laminar box was mounted on the soil. Then the sampler was turned right side up.
b) To minimize disturbance of the soil due to the lack of restraints, the main part of the sampler was removed after pulling the rubber membrane upward.
c) After the main part was removed, the rings that are part of the laminar box were mounted one by one. The following procedures were repeated: i) The rubber membrane and Teflon sheet on the sampler were each cut to the height of 1

ring (2 cm). ii) Another rubber membrane for the laminar box was mounted in the sampler. iii) One ring was placed. The gap between the rubber membrane and the soil (about 5 mm) was filled with the same sample at the same density.

d) An accelerometer and pore fluid pressure transducers were mounted in the ground using the following processes. After mounting the shear ring at around the measuring depth, a hole was made horizontally using a hand drill (diameter: 10 mm) from the side of the soil sample. In this procedure, the hand drill was set at an accurate position by using a specially made apparatus. Then, the sensor was inserted into the hole horizontally, and the hole was filled up using the same soil sample. The smallest possible transducers were chosen (at most about 5 mm) to minimize the effects on the soil conditions.

As a reference, the observed shear wave velocity in the field was Vs = 84 (m/sec), and that in the laminar box (under gravity condition) was Vs = 78 (m/sec).

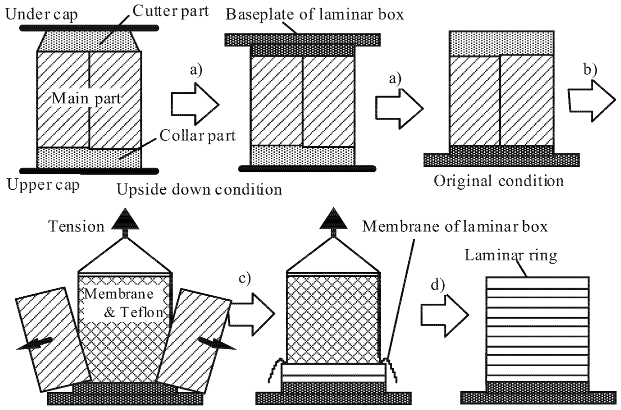


Figure 3. Procedures for transferring sample from sampler to laminar box

### 3.2 *Footing foundation model*

The footing foundation model shown in Fig. 4 was mounted in the above soil model. After the soil was saturated with de-aired water, the shaking table test was conducted using a geotechnical centrifuge with a radius of 2.65 m (see Nagura et al., 1994). Centrifugal acceleration of 50 g was applied to a 1/50 model. The model corresponds to one of the independent 4 foundations of a power transmission tower such as that used for electricity. The density of the footing model was adjusted to 2.4 g/cm$^3$ by mixing ferro powder with mortar. The contact pressure due to the self-weight of the foundation was set at 28.8 kN/m$^2$ under centrifugal acceleration of 50 g. The prototype scale of the foundation is 4.75 m in height and 3.2 m in breadth and length. The model was installed in the soil using extra care so as not to disturb the soil beneath the foundation model. Saturation was conducted by applying de-aired water from the base of the laminar box. The process took two weeks. Note that although dynamic centrifuge modeling dealing with liquefaction generally uses pore fluid with higher viscosity to satisfy similitude, this study uses water, i.e. viscous fluid was not used for the following reasons: i) The structure of the sample is believed to be disturbed when pore water is completely substituted for the viscous fluid; ii) One of the objectives of this study was to compare the behavior of the model using a block sample with that using reconstituted soils.

Sinusoidal wave with the number 20, frequency of 1 Hz, and amplitude of 350 cm/s$^2$ (at prototype scale) was applied to the model. The magnitude was decided taking into consideration liquefaction strength obtained from tri-axial tests of the sample taken from the same site. Note that prototype scale is used in the following results and discussions.

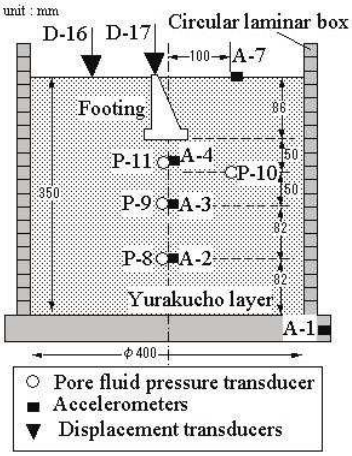


Figure 4. Dynamic centrifuge modeling

### 3.3 *Test results*

The results of testing the undisturbed sample and the reconstituted (disturbed) sample of the same material are shown for comparison. The relative density of the reconstituted sample is 125%.

The time history of the excess pore fluid pressure ratio during shaking and the settlement at the ground surface and the footing are shown in Figs. 5 and 6. As shown in the figure, excess pore fluid pressure rises just after the shaking starts, the maximum pore fluid pressure ratio rises close to 1.0 in the bottom part (P-8, P-9) of the ground. The Boussinesq solution was used to estimate the initial overburden pressure of the soils around the footing. In the upper part (P-10), and the maximum excess pore fluid pressure ratio of the disturbed sample test is larger than that of the undisturbed one. The maximum excess pore fluid pressure ratio of the model ground beneath the footing (P-11) is lower than the circumference ground by the effects of higher confined stress. Distribution of excess pore fluid pressure ratio at the end of shaking is shown in Fig. 7. Although it is not necessarily high precision because of the small number of observation points, it was the high condition of excess pore fluid pressure ratio in the bottom part of the ground. Incidentally, some impurities such as small softened fish bones were observed in the undisturbed soil, which may have be the reason for the slightly lower rate of the pore fluid pressure by forming a flow path. This may suggest that the degree of uniformity in the undisturbed sample is different from that of disturbed sample in this test.

Settlement of the ground surface and the footing began at the start of the shaking; moreover, settlement continued even after the end of shaking. However, it subsided with the disappearance of the excess pore fluid pressure. Settlements obtained from these tests are summarized in Table 2. Final settlement at both soil surface and footing in the disturbed soil model is larger than that of the undisturbed soil model. The proportion of the ground surface settlement to the soil thickness (350 mm) was 0.79 % for the undisturbed soil model, whereas 0.87 % for the disturbed soil model. The difference in the settlement is considered to stem from the difference in the pore fluid pressure generation which is related to the degree of soil disturbance, in other words, difference in liquefaction strength, which is highly dependent on deposit generation and aging effects such as cementation. It is interesting to note that settlement of the footing is smaller than that of the ground surface. This phenomenon differs from previous tests that we conducted using Toyoura sand (Kawasaki et al., 1998). It is considered that the liquefaction level of the model ground beneath the footing is lower than that of the circumference ground by the confined stress effect.

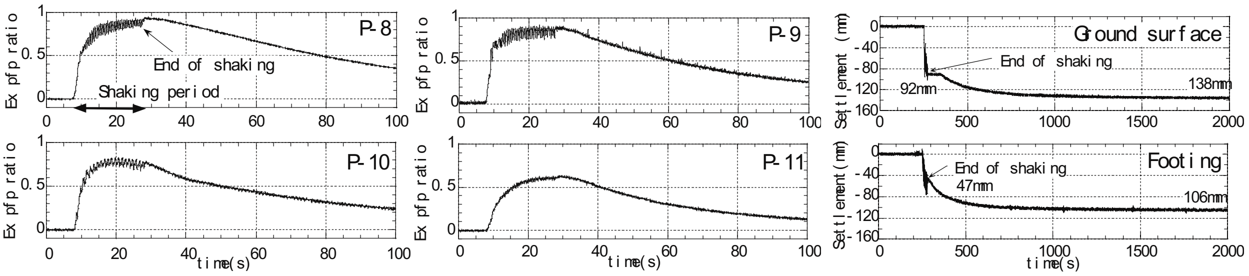


Figure 5. Time histories of excess pore fluid pressure ratio and settlement (undisturbed soil sample)

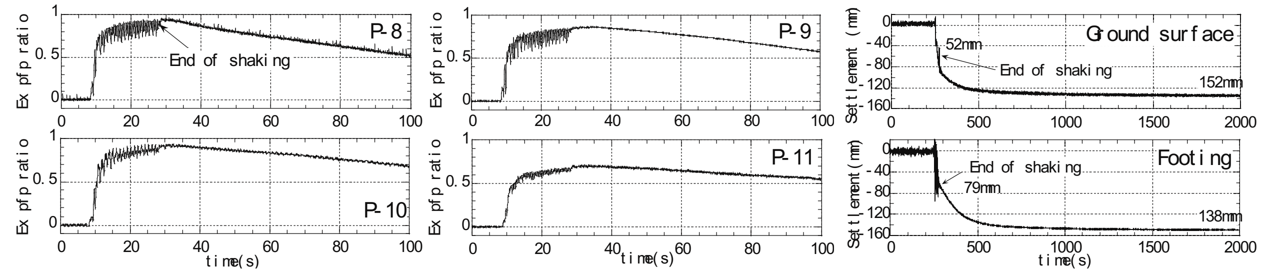
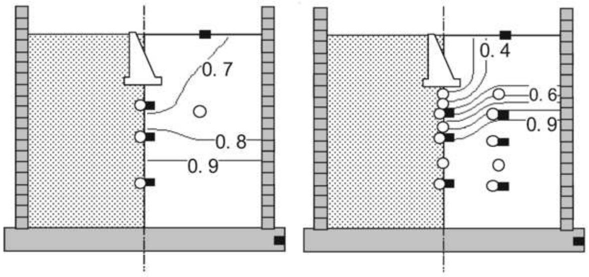


Figure 6. Time histories of excess pore fluid pressure ratio and settlement (disturbed soil sample)



(a) Undisturbed sample (b) Disturbed sample

Figure 7. Distribution of excess pore fluid pressure ratio (Just at end of shaking)

Table 2. Settlement of the ground surface and footing

| Sample | Just at end of shaking | | Final settlement | |
|---|---|---|---|---|
| | Footing | Ground surface | Footing | Ground surface |
| Undisturbed | 47 | 92 | 106 | 138 |
| Disturbed | 79 | 52 | 138 | 152 |

(mm)

## 4 CONCLUSIONS

This paper describes the sampler developed to collect an undisturbed block soil sample containing fines, and presents the results of shaking table tests using the sample. The following conclusions were drawn:

1) A large soil sampler was developed specially designed for collecting an undisturbed sample for dynamic centrifuge modeling with the use of a laminar box. Through dynamic centrifuge testing on undisturbed and disturbed soil samples, the applicability of the sampler was confirmed at the actual construction site in Tokyo, where a soil sample with relatively higher fines content was collected.
2) The difference in settlement was seen as a result of the dynamic centrifuge test in the undisturbed sample and the disturbed sample. In other words, it is considered to be a difference in the pore fluid pressure ratio distribution caused by the difference in liquefaction strength. The difference in liquefaction strength is caused by the difference in deposit generation and aging effects such as cementation. The influence of factors leading to this difference in settlement is a subject for future research.

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