USE OF 'GEL-PUSH' SAMPLING TO OBTAIN UNDISTURBED SANDY SAMPLES FOR LIQUEFACTION ANALYSES

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ABSTRACT: This paper reports on the use of advanced 'Gel-push' (GP) sampling technology for obtaining undisturbed samples of two sandy soils (alluvial and fill deposits). Soil samples were collected by GP sampler and conventional triple-tube (TS) from a site investigation in Mihama, Chiba City (Japan), where severe liquefaction was observed during the 2011 Off the Pacific Coast of Tohoku Earthquake. Preliminary triaxial liquefaction test results clearly evidenced that that the sampling technique highly affected the evaluation of liquefaction resistance of the investigated sands. To confirm these findings, the change in void ratio (density disturbance) and shear velocity (soil fabric disturbance) measurements between field (PS logging method) and laboratory (dynamic measurements by triggers and accelerometers) were analyzed and it was demonstrated that the GP sampler performed better than the TS sampler, since it is able to better minimize the soil structure disturbance during the sampling process.

Key Words: gel-push sampler, liquefaction, Chiba sands, undisturbed samples, shear wave velocity, density

INTRODUCTION

The 2011 Off the Pacific Coast of Tohoku Earthquake (M_W=9) caused severe soil liquefaction over a wide region of Eastern Japan. The Tokyo metropolitan area, that is located more than 300 km away from the epicenter, was no exception. The areas along the Tokyo Bay suffered not only from strong shaking (Figure 1), but also extensive liquefaction damage during the main event and subsequent aftershocks, particularly affecting deposits of fine sands and silty sands of recent fluvial origin (Holocene deposits) or used in land reclamation works.

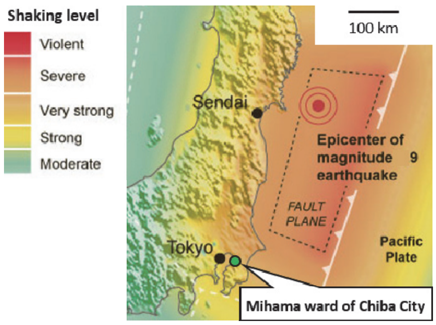

Figure 1 Shaking level map for Eastern Japan during the 2011 Off the Pacific Coast of Tohoku Earthquake (modified from http://www.usgs.gov)

Mihama ward is located in the western part of Chiba City along the coast of Tokyo Bay and consists entirely of reclaimed ground. It was reclaimed by dredge sand and sandy silt taken from the seabed of the nearby Tokyo Bay. Reclamation was carried out by hydraulic filling process from the southern part of the ward towards

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the north from the 1960s until the mid-1980s. Essentially, the soil accumulated on the seabed of Tokyo Bay was dredged, transmitted through sand pipes to the reclamation site and then discharged from outlets. In this process, sand with low fines content accumulated nearby the outlets of the sand transmission pipes, while silty sand with high fines content accumulated far from the outlets. As a result of hydraulic filling, a thick layer of loose and soft soil was created, which is highly vulnerable to liquefaction. Immediately after the 2011 quake, Nakai and Sekiguchi (2011) carried out an exhaustive survey on ground damage in Mihama ward, which revealed that due to liquefaction a huge amount of sand boiling (Figure 2b), ground deformation, tilting and subsidence of buildings were found in almost all zones of Mihama ward. As illustrated in Figure 2b, mal-distribution of liquefaction damage for Mihama ward may be explained by the employed hydraulic land reclamation process, which would also imply that the soil profile may vary significantly in a short distance.

Since May 2014, a field and laboratory investigation program has been undertaken by the Authors to characterize the undrained cyclic strength properties of two sandy soils (Holocene and landfill deposits), retrieved in the Isobe area of Mihama ward (Figure 2a), which experienced liquefaction during the 2011 Off the Pacific coast of Tohoku Earthquake (Figure 2b). In order to properly investigate liquefaction properties of such sandy soils, laboratory tests on undisturbed samples are essential, as soil fabric (particle arrangement) and ageing effects are significant (Ishihara, 1993). However, this is not an easy task, because sandy samples can be disturbed easily during sampling procedures. To overcome this problem, a state-of-the-art technique for obtaining good quality undisturbed samples using a "Gel-push" (GP) sampler was used in this study. GP has been progressively developed over the last decade and successfully employed in New Zealand (Taylor et al., 2012), Taiwan and Japan (Chen et al., 2014). Yet, a comprehensive discussion on the qualitative assessment of GP samples for liquefiable soils has not been made yet and will be addressed here.

In this paper, the effects of sample technique on the liquefaction properties of Chiba sands was evaluate by laboratory undrained cyclic triaxial tests. Then, sampling disturbance was assessed by using comparisons between density and shear wave velocity directly evaluated in-situ and those measured in the laboratory on undisturbed samples extracted by two different sampling techniques, GP sampling and conventional triple-tube (TS) sampling. For this purpose, a borehole P-S logging was performed in the field as well as dynamic small strain measurements were made on the triaxial samples. It was demonstrated that the GP sampling method can produce sand samples with less disturbance and thus more suitable for advanced soil liquefaction analyses compared with those obtained by the TS sampler.

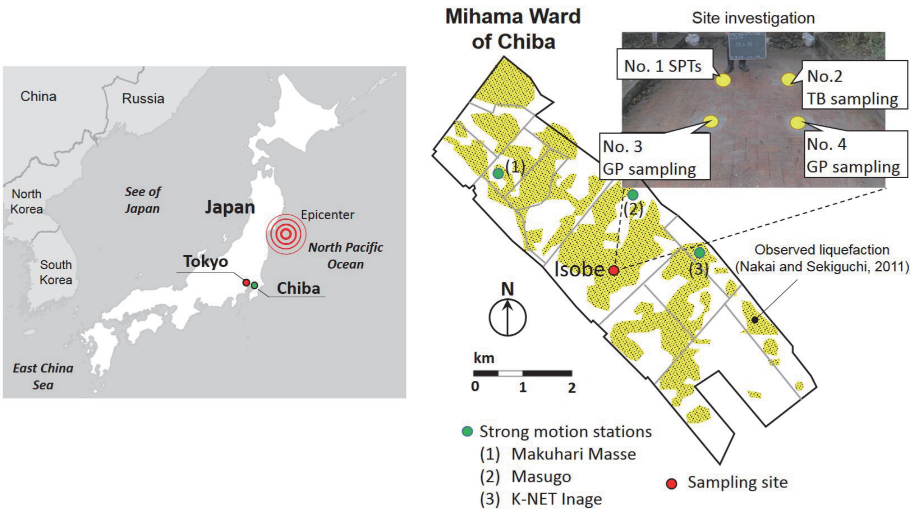


Figure 2 Map of Mihama ward with location of sampling site in Isobe, spatial distribution of liquefaction and location of strong motion stations.

STATE-OF-THE-ART GEP-PUSH SAMPLING TECHNIQUE FOR SANDY SOILS

Sandy samples can be greatly disturbed during sampling procedure. For instance, using conventional tube sampling technique (e.g. rotary-type triple-tube; etc.), the excessive friction generated during penetration tends to cause serious disturbance to the specimens, resulting in partial soil sampling and poor quality. Alternatively, the ground freezing method, used for preserving sampled soil in good quality, frequently causes drifting of fines content and disturbance on sensitive micro-structure during freezing and defrosting processes (Lee et al., 2012).

As a result, over the last decade, a new technique using a GP sampler was introduced by Kiso-Jiban Consultants Co. Ltd. for obtaining undisturbed sandy samples. As described in details by Chen et al. (2014), the GP sampling technique was first developed in Japan to retrieve gravel material as an alternative to the costly ground freezing method. Then, in an attempt to obtain undisturbed high fines content silty sand, the GP sampler was modified to accommodate a thin wall tube inside the sampler to become a triple-tube system. The GP sampler was aimed to allow water-soluble polymeric lubricant (gel) to seep into the tube wall while penetrating the tube into the soil by hydraulic pressure. Moreover, the sampler was equipped with a cutter attached to the guiding tube to permit smooth penetration, and a catcher fixed at bottom of the thin wall tube to prevent soil sample from falling out during uplifting. Due to a very small amount employed, the polymeric gel contaminates only limited superficial portion of the sample. As a result, the GP sampler can effectively reduce the wall friction, so that undisturbed sand samples can be recovered. A schematic illustration of GP sampler operation is shown in Figure 3a. Essentially, the GP sampler is (i) lowered down a cased hole and then (ii) pushed into undisturbed soil. Next, (iii) the catcher is closed and, finally, (iv) the undisturbed sample is brought to the surface.

Note that, depending on the type of soil, different GP samplers are available. In this study GP-S sampler (Figures 3b and 3c) was used to obtain loose to medium dense samples of sandy soils, while a rotary sampler (GP-Tr) was employed when it was necessary to penetrate denser/stiffer soil layers.

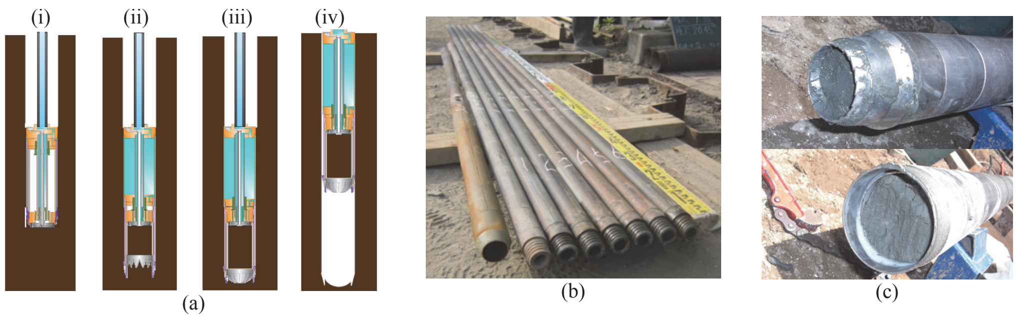


Figure 3 Field instruments used in this study: (a) Illustration of GP sampler operation (from Lee et al., 2012); (b) GP-S sampler used in Isobe; and (c) details of GP-S sampler cutting shoe (top) and a sample surrounded by gel lubricant (bottom)

IN-SITU STRENGTH AND SHEAR WAVE MEASUREMENTS

The use of field tests to compliment drilling, sampling and laboratory testing is a desirable, practical and cost-effective way to directly measure the strength and stiffness property of the soils. In this study, at the investigation site in Isobe area, four boreholes were performed up to a depth of 20 m below the ground surface (Figure 2a) to acquire SPT *N*-values, shear wave velocity (V_s) measurements and define soil profile (borehole No. 1), to collect undisturbed soil samples by using conventional TS sampling (borehole No. 2) as well as by means of advanced GP sampling (boreholes No. 3 and No. 4).

The in-situ V_s data were obtained using the PS suspension logging device shown in Figure 4. This method, introduced by Kitsunezaki (1980), can directly measure accurate and high-resolution V_s profile and therefore has been widely used in Japan. In this study, V_s measurements were taken at 0.5 -meter depth intervals (Figure 3c).

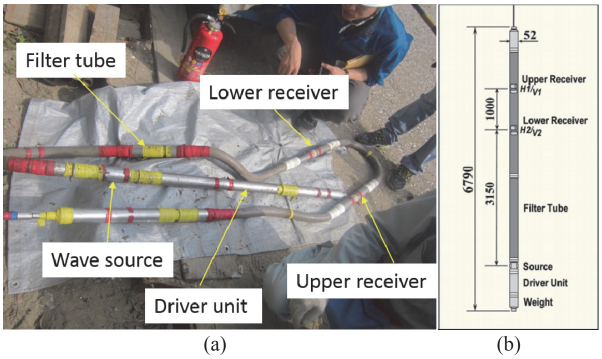


Figure 4 (a) PS suspension logging device used in this study and (b) Typical layout of PS logging probe (Inazaki, 2006)

Subsoil condition at Isobe site is shown in Figure 5, including V_s measurements, *N*-SPT values and fines content (F_c). Essentially, ground consists of a reclaimed deposit (created by hydraulic filling of dredged marine soils, as previously described) undelaying a natural soil deposit of recent fluvial origin (Holocene). The thickness of the reclaimed soil is about 8 m:

- **Fsc**: fill sand with fines (V_s = 80-140 m/s; N <10 and F_c = 12-24%, non-plastic fines);
- **Fc2**: fill clayey soil (V_s = 80-110 m/s; N = 0 and F_c > 70, plastic fines);
- **As1**: alluvial sand (V_s = 120-155 m/s, N = 10-20 and F_c > 60%, non-plastic fines;
- **Ac2**: alluvial clay (V_s = 115-140 m/s and N < 4; and F_c > 80);
- **As2**: alluvial sand (V_s = 175-200 m/s; N = 10-15 and F_c = 15%, non-plastic fines).

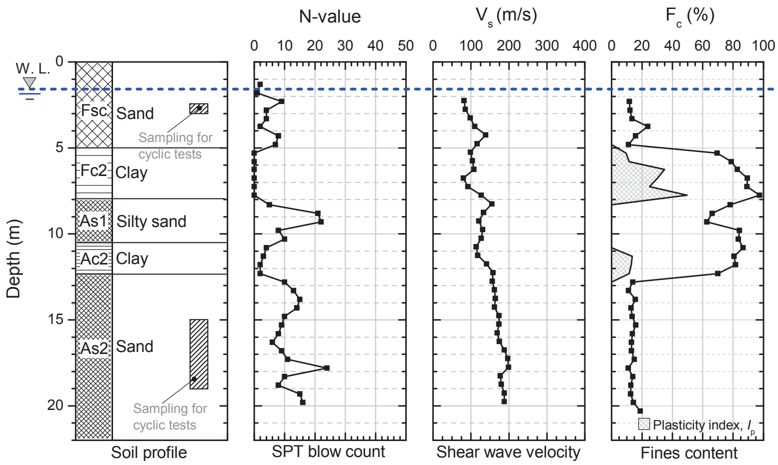


Figure 5 Subsoil condition and field measurements at the sampling site

To have an understanding of the liquefaction occurrence at the sampling site in Isobe, the factor of safety against liquefaction was evaluated according to the Highway Bridge Design Code in Japan (2012). For this analysis, the peak ground acceleration (PGA) recorded at the Makuhari strong motion station (Sikiguchi and Nakai, 2012) located nearby Isobe (Figure 2) was used, since it is believed that compared to Masago and K-net Inage, the soil profile at Makuhari is very similar to that of Isobe being at almost the same distance from the shoreline and thus the site seismic response.

Based on the geotechnical data and the results of the liquefaction site analysis (Figure 7), it is expected that the two layer **Fc2** and **Ac2** containing plastic fines (i.e. clay) as well as the dense sand with high fines content **As1** are less prone to liquefaction. Thus, they likely did not liquefy during the 2011 earthquake. On the contrary, the two loose sands with low content of non-plastic fines **Fsc** and

As2, were highly vulnerable against liquefaction. For this reason, in the laboratory, a series of liquefaction triaxial tests with dynamic measurement were conducted on specimens of **Fsc** and **As2** soils.

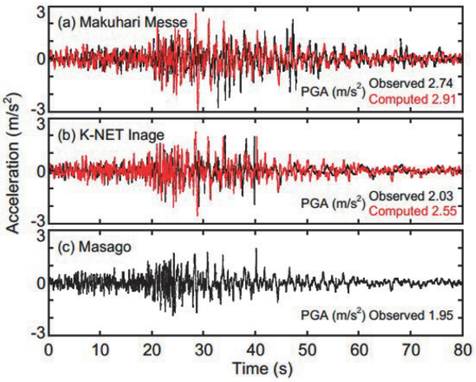


Figure 6 Peak ground acceleration (PGA) measured by several strong motion stations in Mihara ward and computed by Sekiguchi and Nakai (2012)

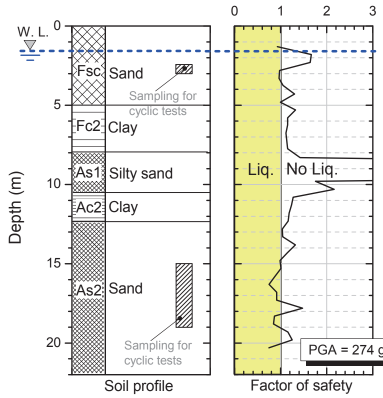


Figure 7 Factor of safey against liquefaction evaluated in this study for the sampling site in Isobe

LABORATORY TESTS WITH DYNAMIC MEASUREMENTS

A number of specimens obtained from the **Fsc** (depth of 2.5-5.0 m; no-plastic fines) and the **As2** (depth of 14.5-19 m; no-plastic fines) were tested in the laboratory. For these soils, particle size distribution curves are plotted in Figure 8. As expected, the alluvial soil is much more homogeneous than the fill material. After sampling, the specimens were careful extruded from the sample tube (Figure 9a) and trimmed (Figure 9b) to be accommodated in the triaxial apparatus (i.e. specimen size of H =10 cm and ϕ = 5 cm). To ensure full saturation (i.e. B-value ≥ 0.97) a back pressure of 200 kPa was applied. Undrained cyclic shearing was then conducted at a frequency of 0.1 Hz on specimens isotropically consolidated. The value of the initial effective confining stress (σ_0') was set as the effective overburden pressure at the sampling depth. Note that, to ensure a better quality of test results, two parallel series of tests were performed in the Institute of Industrial Science (IIS), University of Tokyo, and in the geotechnical laboratory of Kiso-Jiban Consultants Co. Ltd.

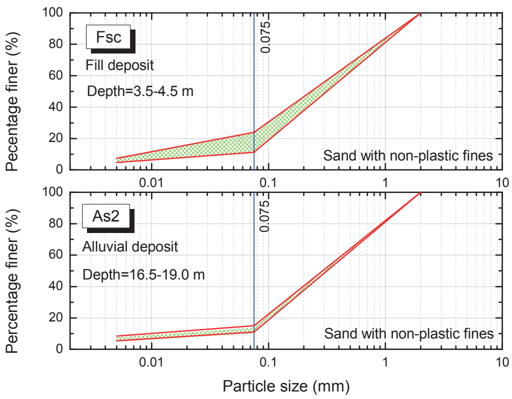


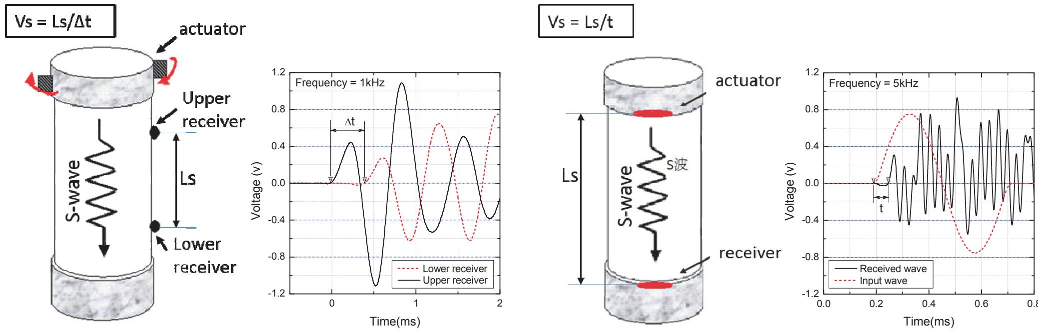
Figure 8 Particle size distribution for Fsc and As2 soils

(a)

(b)

Figure 9 (a) Extruded samples of As2 sandy soil obtained by TS sampler; (b) samples after trimming

Shear wave velocity measurements were made prior to cyclic loading using two equivalent dynamic measurement devices. In the IIS, an S-wave was generated by creating a torsional moment through a pair of actuators mounted on the top cap, while a couple of receivers (accelerometers) glued on the membrane were used to detect the received S-wave (Figure 10a). On the other hand, in the Kiso-Jiban Consultants geotechnical laboratory, a single actuator placed on the top cap was used to produce S-waves and a single receiver placed underneath the pedestal cap was used to capture the received signal (Figure 10b). In both cases, from the analysis of the wave form, the V_s was calculated by the rising-to-rising distance and the measured travelling time (Kiyota et al., 2009, among many). The transmitted wave consisted of a solitary sinusoidal wave having a frequency of 1 or 5 kHz. Typical received S-wave are shown in Figure 10. The travel time was taken as the point of first zero crossing.



(a) (b)

Figure 10 Sketch of dynamic measurement devices employed in this study with typical S-wave signal: (a) in the IIS, University of Tokyo and (b) in the Kiso-Jiban geotechnical laboratory

As mentioned earlier the liquefaction strength of GP and TS samples was determined in the laboratory by using a cyclic triaxial tests apparatus. Figures 11 and 12 show typical liquefaction behavior of two alluvial soil samples retrieved at the same depth below ground surface by TS and GP sampling methods, respectively. Although they were tested under the same cyclic stress conditions (i.e. CSR = 0.232-0.235), and the samples had similar V_s value of about 185 m/s, their cyclic response was quite different. The TS sample appears to be much stronger than the GP sample against liquefaction and cyclic strain development. This feature clearly show the great influence that the sampling technique may have on the evaluation of liquefaction resistance of undisturbed samples.

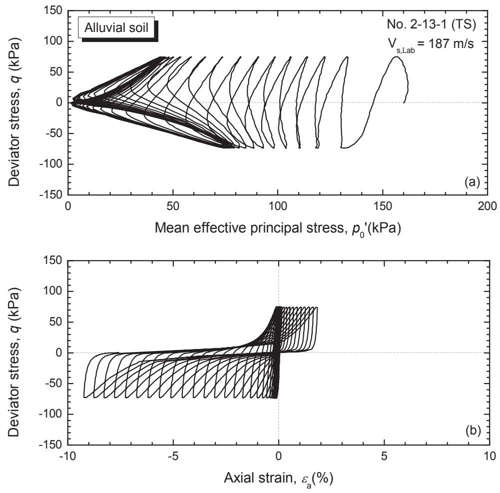


Figure 11 Cyclic undrained behavior of alluvial sand sample retrieved by TS method (CSR = 0.232; σ0’ = 115 kPa)

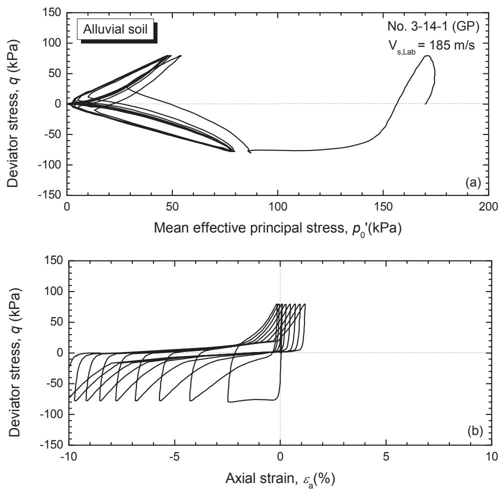
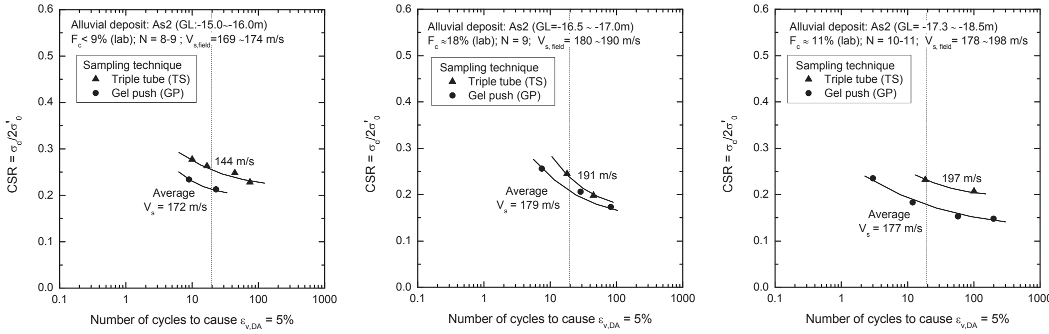


Figure 12 Cyclic undrained behavior of alluvial sand sample retrieved by GP method (CSR = 0.235; σ0’ = 120 kPa)

Comparison of various liquefaction resistance curves for **As2** and **Fsc** samples, respectively, retrieved by both GP and TS sampling methods are shown in Figures 13 and 14. Note that the liquefaction resistance was defined as the number of cycles to cause double amplitude axial strain ($\varepsilon_{v,DA}$) of 5%. Note also that comparison was made for samples retrieved at the same depth below ground surface (i.e. same effective confining stress was applied during the cyclic triaxial tests), N-SPT values and fines content (as evaluated by sieve analysis in the laboratory). In the figures, average laboratory-measured V_s values were also reported for completeness.

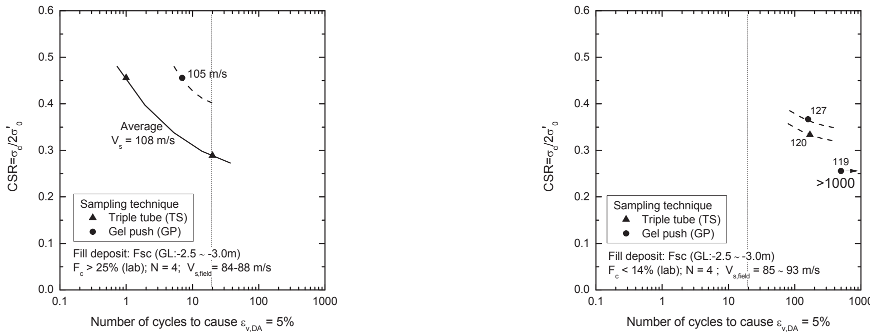
As shown in Figure 13, in the case of the alluvial soil **As2**, it seems that the liquefaction resistance of GP samples is a bit lower than that of the TS samples. However, in general, there is not a significant difference. Note that, in Figure 13a the values of V_s measured for the TS samples was slightly lower than that in-situ evaluated by PS logging, thus some differences in liquefaction resistance can be anticipated. From this analysis, it was found that the difference of sample technique methods did not affect the evaluation of liquefaction resistance for examined alluvial sands with SPT-N value of 8-11.

On the other hand, in the case of the reclaimed layer **Fsc** shown in Figure 14, all samples collected by both sampling techniques had significant strength against liquefaction although a low SPT-N values of 4. Since there are insufficient data to assess the sample quality, further experiments on the **Fsc** samples are required.



(a) (b) (c)

Figure 13 Comparison of liquefaction curves for the As2 alluvial soil samples retrieved by GP and TS samplers



(a) (b)

Figure 14 Liquefaction curves for fill soil samples retrieved by GP and TS sampling methods

SAMPLE DISTURBANCE ASSESSMENT

There are many factors that can affect the quality of an undisturbed sample (See et al, 1982; Lunne and Long, 2005; Taylor et al., 2012; among many), such as drilling (stress-relief), sampling (mechanical disturbance due to ration and penetration), dewatering after sampling, transportation and storage, sample extrusion and trimming as well as specimen preparation for laboratory testing.

Consequently, it is very difficult to obtain and maintain high quality samples (i.e. minimal disturbance to soil fabric and density) in every step of sampling work, especially in the case of sandy soils.

Although significant, it is difficult if not impossible to consider all these effects in the laboratory testing. However, for a rational design in the practical work, it is crucial to establish acceptable sample disturbance levels. This is attempted in this study by comparing the change in soil properties between in-situ and laboratory measurements at the same effective stress state. With this objective, sample disturbance is discussed hereafter considering two important factors:

- Change in void ratio (e), which reflects the change in density; and
- Change in shear wave velocity, which captures the change in soil fabric.

Density disturbance

In this paper, the change in density (disturbance) was evaluated by means of the ratio between the void ratios evaluated in the laboratory and in the field i.e. $e_{,\mathrm{Lab}}/e_{,\mathrm{Field}}$. So that, for $e_{,\mathrm{Lab}}/e_{,\mathrm{Field}} > 1$ the sample become loosened during sampling process. Alternatively, for $e_{,\mathrm{Lab}}/e_{,\mathrm{Field}} < 1$ the sample densified during sampling process. The sample is intact (no disturbance) for $e_{,\mathrm{Lab}}/e_{,\mathrm{Field}} = 1$.

Soil fabric disturbance

As mentioned earlier, the change in V_s would capture the change in soil fabric (soil structure disturbance), but actually it could include also the change in density. To have a clear separation between the change in soil fabric and that in density, hereafter V_s was normalized by the square root of the void ratio function ($f(e)$):

$$V_s^* = V_s / \sqrt{f(e)} \qquad (2)$$

where $f(e)$ was conveniently chosen as $f(e) = e^{-1.3}$, as proposed by (Jamiolkowski, 1991).

Combined sample disturbance

Figure 15 reports the case of alluvial sand **As2** specimens retrieved at three different depths with SPT-N values of 8-11. It appears that the GP sampler performed slightly better than the TS. In particular, the GP sampler was able to minimize the soil structure disturbance during the sampling process compared to the TS sampler. On the other hand, in both cases the density disturbance was reduced.

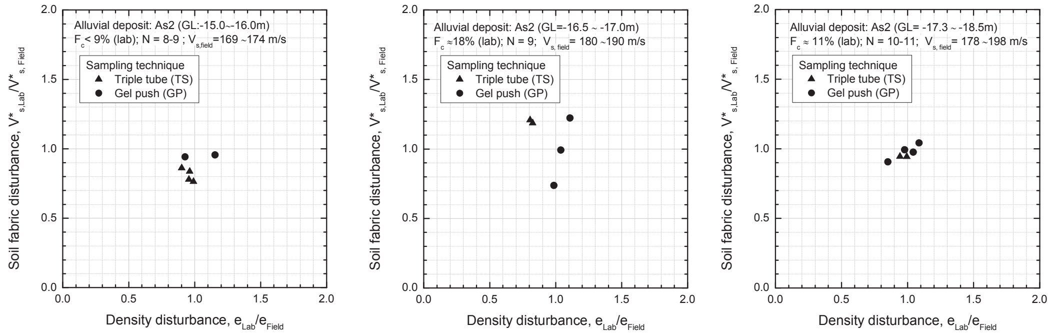


Figure 15 Disturbance of samples of alluvial sandy soil As2 retrieved by GP and TS samplers

Figure 16 presents the case of filled sand **Fsc** specimens retrieved at the same depth with SPT-N value of 4, but having different fines content. In general, it can be said that the TS sampler produced both a higher soil structure disturbance and a larger density disturbance during the sampling process compared to the GP sampler. However, the GP sampler performed slightly better than the TS sampler. Note that, due to limited number of data as well as the highly heterogeneous properties of fill sand compared to the natural sand, additional tests are being currently performed on fill sand specimens to confirm such findings.

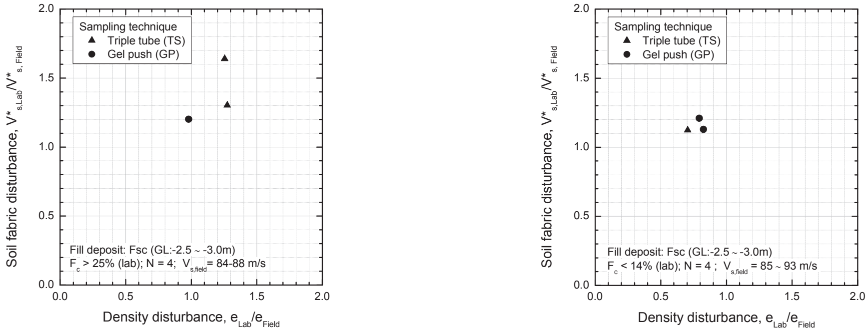


Figure 16 Disturbance of samples of fill sandy soil Fsc retrieved by GP and TS samplers

CONCLUSIONS

In this this paper the use of the innovative 'Gel-push' (GP) sampling technology for obtaining undisturbed samples of two sandy soils (alluvial and fill deposits) was investigated. Its applicability was compared with that of conventional triple-tube (TS), which is widely used in the geotechnical practice in Japan. It was judged based on the liquefaction resistance of sands obtained by cyclic trial tests, as well as the change in void ratio (density disturbance) and shear velocity (soil fabric disturbance) measurements between field (PS logging method) and laboratory (dynamic measurements by triggers and accelerometers).

The effect of sampling technique on the liquefaction resistance was found to be somehow significant in the case of the landfill soil compared with the alluvial sand. However, it was demonstrated that the GP sampling method can produce undisturbed samples with less disturbance and thus more suitable for advanced soil liquefaction analyses compared with those obtained by the TS sampler.

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