Evaluation of cyclic resistance of high quality undisturbed Chiba silty sand samples retrieved by “Gel-Push” sampling technique

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ABSTRACT

This paper focuses on the cyclic resistance assessment of two non-plastic silty sands that likely experienced severe liquefaction during the 2011 Off the Pacific Cost of Tohoku Earthquake (Japan). Several samples were retrieved from fill and alluvial deposits at a site investigation in Chiba. Besides a conventional triple-tube sampler (TB), a cutting-edge sampling technique, namely “Gel-Push sampler” (GP), was adopted to obtain high quality undisturbed samples. In the laboratory, a series of cyclic triaxial tests were conducted on several specimens recovered by both GP and TB samplers. Preliminary results of liquefaction resistance and shear wave velocity compared to field PS logging measurements revealed that that the sampling technique and quality of samples highly affected the evaluation of liquefaction resistance of the investigated sands. Therefore, to address this issue, a classification of sample quality for undisturbed samples was provided, based on change in density and shear velocity/dynamic shear modulus measured in the field and in the laboratory.

Keywords: undisturbed sample, fill, Holocene, non-plastic fines, gel-push sampling, sampling quality

1 INTRODUCTION

A wide region of Eastern Japan (Fig. 1) was severely damaged by soil liquefaction during the 2011 ‘Off the Pacific Coast of Tohoku Earthquake’ (Mw=9) and its major aftershocks. Deposits of fine sands and silty sands of recent fluvial origin (Holocene) or used as landfill materials were particularly affected.

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

Since May 2014 a site investigation program has been undertaken by the Authors in Isobe district of Mihama ward, Chiba City, that is located about 50 km east of Tokyo (Fig. 1), to evaluate the undrained cyclic strength properties of two sandy soils (Holocene and landfill deposits), which is understood to have experienced severe liquefaction during such a severe earthquake (Nakai and Sekiguchi, 2011). Besides conventional triple-tube sampler (TB), the state-of-the-art “Gel-Push sampler” (GP) was adopted to obtain high quality undisturbed samples.

In order to properly investigate liquefaction properties of sandy soils, laboratory tests on undisturbed samples are essential, as soil fabric (particle arrangement) and ageing effects are significant (Ishihara, 1993). However, this may be challenging, because sandy samples can be disturbed easily during sampling procedure (Lunne and Long, 2005; Taylor et al., 2012; Chen et al., 2014). Reflecting such a situation, a new technique for obtaining high quality undisturbed samples using the “Gel-push” (GP) sampler was 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 assessment of the quality of GP samples for liquefaction soil analysis has not yet been made.

In this paper, a classification of sample quality for undisturbed samples is suggested based on comparison between density and shear velocity/dynamic shear modulus directly estimated in-situ and those measured in the laboratory on undisturbed triaxial samples extracted by GP and TB sampling techniques.

2 GEL-PUSH SAMPLING TECHNIQUE

Sandy samples can be greatly disturbed during sampling. For instance, using conventional triple-tube sampling practice, the excessive friction generated during penetration tends to cause severe disturbance to the samples, resulting in partial soil sampling and poor quality. Otherwise, ground freezing methods frequently cause drifting of fines content and disturbance of soil structure during freezing and defrosting processes (Lee et al., 2012).

As a result, over the last decade, a state-of-the-art technique using a GP sampler was introduced by Kiso-Jiban Consultants Co. Ltd. for obtaining high quality undisturbed samples. As described by Chen et al. (2014), the GP sampling technique was first developed in Japan to retrieve gravel material as an alternative to using conventional TB sampling (borehole No. 2), to collect undisturbed soil samples by using conventional TB sampling (borehole No. 1), to collect undisturbed high fines content silty sand, the GP sampler was modified to accommodate a thin wall tube inside the sampler to turn into a triple-tube system. The GP sampler was meant to allow a polymer lubricant to seep into the thin wall tube while penetrating the tube into the soil by hydraulic pressure. Moreover, the sampler was equipped with a cutter attached to the guiding tube to allow smooth penetration, and a catcher fixed at the bottom of the thin wall tube to prevent the soil sample from falling out during uplifting. As a very small amount of polymer gel is employed, it contaminates only a limited superficial portion of the sample. As a result, the GP sampler can effectively reduce the wall friction so that sensitive silty sand specimens can be recovered in good quality. The GP sampler employed in this study is shown in Fig. 2a).

3 ISOBE SITE INVESTIGATION

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 (Fig. 2b) 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 TB 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 a PS suspension logging device. This method, introduced by Kitsunezaki (1980), can directly measure an 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.

Subsoil condition at Isobe site is shown in Fig. 2c, including $V_s$ measurements and N-SPT values, density of saturated soil ($\rho_{sat}$) and fines content ($F_c$). Essentially, the ground consists of an 8-meter thick reclaimed deposit (created by hydraulic filling of dredged marine soils; Nakai and Sekiguchi, 2011) underlying a natural soil deposit of recent fluvial origin (Holocene):

- $F_{sc}$: fill sand with fines ($V_s = 80-140$ m/s; $N \leq 10$ and $F_c = 12-24\%$, non-plastic fines);
- $F_{c2}$: fill clayey soil ($V_s = 80-110$ m/s; $N = 0$ and $F_c > 70$, plastic fines);
- $F_{a1}$: alluvial sand ($V_s = 120-155$ m/s, $N = 10-20$ and $F_c > 60\%$, non-plastic fines);
- $F_{a2}$: alluvial clay ($V_s = 115-140$ m/s and $N < 4$; and $F_c > 80$);
- $F_{sc}$: alluvial sand ($V_s = 175-200$ m/s; $N = 10-15$ and $F_c = 15\%$, non-plastic fines).

Based on these geotechnical data, it is expected that the two layer $F_{c2}$ and $F_{a2}$ containing plastic fines (i.e. clay) as well as the dense sand with high fines content $F_{a1}$ are less prone to liquefaction; thus, likely did not liquefy during the 2011 earthquake. On the contrary, the two loose sands with low content of non-plastic fines $F_{sc}$ and $F_{a2}$, are highly vulnerable to liquefaction. For this reason, in the laboratory, a series of liquefaction triaxial tests with dynamic measurement were conducted on specimens of $F_{sc}$ and $F_{a2}$ soils.
N-value provided by field SPTs and in-situ \( V_s \) measurement are the two mostly used parameters for evaluating liquefaction potential of the soils. For the Fsc and As2 soil deposits here examined, the relationship between \( V_s \) and adjusted SPT N-value (\( N_a \); Tokimatsu and Yoshimi, 1983) is presented in Fig. 3. Note that \( N_a \) accounts for the effects of the effective overburden stress (\( \sigma_{\text{vo}} \)) and fines content (\( F_c \)). Here, it was calculated by using Eqn. (1), which is valid for \( F_c \geq 10\% \) (Tokimatsu and Yoshimi, 1983):

\[
N_a = \frac{1.7}{\sigma_{\text{vo}}/98 + 0.7} N + (0.1F_c + 4)
\]  

(1)

Interestingly, as shown in Fig. 3, while \( N_a \) values are mostly grouped in the range of 10 to 20, the \( V_s \) values are very different between the two soil deposits, being much higher for the natural soil. This can be attributed to different fabric and stiffness of soils, reflecting different deposition processes and ageing effects. Consequently, it is expected that also the liquefaction resistance of such soil deposits will be very different. These findings also suggest that, in order to capture fabric and ageing effects, soil liquefaction strength would be better evaluated based on \( V_s \) measurements rather than using \( N_a \).

### 4 LABORATORY TESTS WITH DYNAMIC MEASUREMENTS

So far, a total of 35 specimens, obtained from the Fsc (depth of 2.5-5.0 m) and the As2 (depth of 14.5-19.0 m) deposits, were tested in the laboratory. For these two sands, particle size distribution curves are plotted in Fig. 4. As expected, the alluvial soil is much more homogeneous than the fill material.

After sampling, the specimens were carefully extruded from the sample tube (Fig. 5a) and trimmed (Fig. 5b) to be accommodated in the triaxial apparatus (i.e. specimen size of \( H = 10 \) cm and \( \phi = 5 \) cm). To ensure full saturation (i.e. B-value \( \geq 0.97 \)), 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 at different confining pressures representative of field stress conditions. Note that, to ensure a better quality of test results, two parallel series of tests were performed at the Institute of Industrial Science (IIS), University of Tokyo, and in the geotechnical laboratory of Kiso-Jiban Consultants Co. Ltd.

Shear wave velocity measurements were made prior to cyclic loading using two equivalent dynamic measurement devices. At the IIS, an S-wave was generated by creating a torsional moment through two actuators mounted on the top cap, while two receivers (accelerometers) glued on the membrane were used to detect the received S-wave (Fig. 6). 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. In both cases, from the analysis of the wave form, \( V_s \) was calculated by the rising-to-rising distance and the measured travelling time (Kiyota et al., 2013, among many). The transmitted wave consisted of a solitary sinusoidal wave having a frequency of 1 kHz. Typical received S-waves are shown in Fig. 6. The travel time was taken as the point of first zero crossing.
Fig. 6. Sketch of dynamic measurement devices employed in the IIS (University of Tokyo) and a typical S-wave signal

Comparison of liquefaction resistance curves of sand specimens retrieved by both GP and TB sampling methods for Fsc and As2 are shown in Fig. 7. Note that the liquefaction resistance here was defined as the number of cycles to cause shear strain double amplitude ($\varepsilon_{q,DA}$) of 5%.

From this analysis, it is evident that the sampling technique and sample quality highly affected the evaluation of liquefaction resistance for examined sands. In the section, an attempt was made to address this issue.

5 SAMPLE QUALITY ASSESSMENT AND CLASSIFICATION

There are many factors that can affect the quality of an undisturbed sample (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 irrational 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 quality 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.

Nevertheless, the change in $V_s$ 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 ($f(e)$):

$$V'_s = V_s / \sqrt{f(e)}$$

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

In Fig. 8 the available field and experimental data are plotted in terms of $e_{\text{Field}}/e_{\text{Lab}}$ vs. $V'_{s,\text{Field}}/V'_{s,\text{Lab}}$ relationship. Interestingly, regardless of sampling procedure, the alluvial soil seems to become weaker, while fill material appears to become stiffer during the sampling process. So that, in both cases a major change in soil fabric is revealed. This trend was also observed in previous studies by Hatanaka (1995).

Significantly, the shear wave velocity measurements from laboratory tests tend to diverge from those evaluated in-situ by about 20-30%. According to Hatanaka (1995), such variance is acceptable. On the other hand, the void ratio from the laboratory tests have a tendency to deviate from that measured in-situ by about 10-20%.

Fig. 7. Liquefaction curves obtained for (a) Fsc and (b) As2 sand specimens tested in this study.

As shown in Fig. 7a, in the case of the fill material Fsc, data points are rather dispersed but enclosed within a specific area, irrespective of the used sampling technique. On the other hand, in the case of the natural soil As2, two distinct zones can be observed (Fig. 7b). One for the samples retrieved by GP and the other one for those obtained by TB. In particular, it seems that the liquefaction resistance of GP samples is much lower than the TB samples.
Considering both the change in density and the change in soil fabric, hereafter a method was proposed for assessing the quality of undisturbed samples (Figs. 9 and 10). To this scope, two types of disturbance were defined (i.e. density and soil structure disturbances) and several levels of quality samples were proposed, as summarized in Table 1. Note that, this is an extension of the work presented by Chiaro et al. (2015), where only the change in dynamic shear modulus, which captures the change in density and soil fabric all together, was considered in the evaluation of sample quality.

Table 1. Proposed disturbance levels and sampling quality classes for undisturbed samples retrieved by GP and TB

| Sampling quality | Disturbance level | Density | Soil fabric |
|------------------|-------------------|---------|-------------|
|                  | D_d = \left| \frac{e_{lab} - e_{field}}{e_{field}} \right| | D_f = \left| \frac{V^*_{lab} - V^*_{field}}{V^*_{field}} \right| |
| A                | D_d < 0.10        | D_f < 0.20 |
| B                | 0.10 ≤ D_d < 0.20 | 0.20 ≤ D_f < 0.40 |
| C                | 0.20 ≤ D_d < 0.30 | 0.40 ≤ D_f < 0.60 |
| D                | D_d ≥ 0.30        | D_f ≥ 0.60 |

The sampling quality can be affected by many factors. To overcome this issue and better judge the quality of GP samples with respect to TB samples, in Figs. 9 and 10, comparisons are only presented for those specimens having similar properties (Fsc and N) and retrieved at the same depth (i.e. same stress state). Separate plots are shown for the alluvial and fill sands.

5.1 Sampling quality of alluvial sandy soil

Fig 9 reports the case of alluvial sand As2 specimens retrieved at three different depths. It appears that the GP sampler performed slightly better than the TB. In particular, the GP sampler was able to minimize the soil structure disturbance during the sampling process compared to TB sampler. On the other hand, in both cases the density disturbance was reduced well.

5.2 Sampling quality of fill sandy soil

Fig 10 presents the case of fill sand Fsc specimens retrieved at the same depth, but having different fines content. In general, it can be said that the TB sampler was produced both a higher soil structure disturbance and a larger density disturbance during the sampling process compared to GP sampler. Thus, GP sampler performed better than TB 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.

![Fig. 10. Quality assessment of undisturbed samples retrieved for fill sandy soil Fsc by GP and TB](image)

6 CONCLUSIONS

In this paper the cyclic resistance of two non-plastic silty sand samples, retrieved from fill and alluvial deposits, was evaluated. Besides the conventional triple-tube sampler (TB), a cutting-edge sampling technique, namely the “Gel-Push sampler” (GP), was adopted to obtain high quality undisturbed samples. Laboratory triaxial tests revealed that the sampling technique and sample quality highly affected the evaluation of liquefaction resistance for examined sands. To clarify this issue and assess separately the disturbance due to the change in density and soil fabric during the sampling process, a chart with different levels of sampling quality was proposed. Significantly, it was confirmed that the GP sampler performed better than the TB sampler, since it is able to better minimize the soil structure disturbance during the sampling process.

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