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# LIQUEFACTION OF SILTY SAND-PRELIMINARY STUDIES FROM RECENT TAIWAN, NEW ZEALAND, AND JAPAN EARTHQUAKES

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**ABSTRACT**: In this paper, the authors introduce a well-organized research project aiming to study liquefaction potential of high fines content non-plastic silty sand. Results of this study conclude that soil liquefaction would occur in non-plastic silty sand deposits even with high non-plastic fines contents. Both fines contents and void ratios have deterministic influences to the cyclic resistance of such silty sand material. Most importantly, disturbance effect would have great influence on cyclic resistances and post liquefaction volumetric strains of non-plastic silty sand. Results of this study is hoped to improve engineers' understanding on liquefaction potential of non-plastic silty sand.

**Key Words**: Great East Japan earthquake, Soil Liquefaction, Non-Plastic Silty Sand, Gel-Push Sampler, Fines Content

## INTRODUCTION

Soil liquefaction occurred in non-plastic silty sand deposits has been of great research interests in geotechnical earthquake engineering. During the 1999 Chi-Chi earthquake, serious soil liquefaction damages were observed in central Taiwan including Wu-Feng, Nan-Tou, and Yuen-Lin areas (Figure 1). Post-earthquake study indicated that most soil liquefactions were occurred in silty sand deposits with high fines content. Christchurch city and its vicinity area of New Zealand had also suffered from severe liquefaction damages during series of earthquakes in 2010 to 2011 (Figure 2). Non-plastic silty sand again has been recognized as the major sources of soil liquefaction. Moreover, Tokyo bay area and Chiba perfect was suffered from serious soil liquefaction damages during the 2011 Great East Japan earthquake. Preliminary reconnaissance also concludes that majority liquefaction occurred in the reclaimed silty sand deposits (Figure 3).

Fig. 1 Silty sand liquefaction at Wu-Feng during 1999 Chi Chi earthquake, Taiwan.

Fig. 2 Silty sand liquefaction at central business district of Christchurch during 2010-2011 Christchurch Earthquakes, New Zealand.

Fig. 3 Silty sand liquefaction at Katori City near Tone River during the Great East Japan Earthquake, Chiba, Japan.

Limited research progress was obtained because undisturbed sampling of high fines content silty sand was facing several technical difficulties in the past. The excessive friction generated during penetration of conventional sampler tends to cause serious disturbance to the specimens. In the presented study, the authors had adopted a recently developed “Gel-Push” sampling technique to obtain undisturbed samples of non-plastic silty sand. The newly developed sampler was designed to allow polymer lubricant to seep into the tube wall while the tube was penetrated into the soil. It could effectively reduce the wall friction so as to allow sensitive silty sand specimen to be recovered in good quality. The Gel-Push sampling technique was successfully applied to liquefaction sites located in southern Taiwan, Christchurch in New Zealand, as well as Urayasu area near Tokyo Bay, to retrieve undisturbed non-plastic silty sand specimen.

In this paper, one of the test sites, Hsin Hwa, was selected to present the application of Gel-Push sampler and laboratory tests in an effort to investigate liquefaction potential of non-plastic silty sand with various fines contents. Detailed sampling program and results are first introduced to illustrate advantages of using the newly developed sampler. Laboratory test program on both recovered undisturbed specimens and remolded specimens with different fines contents are then introduced. Purpose of the laboratory tests is to examine engineering features such as influence of fines content on liquefaction potential, influence of void ratio or particle packing state on cyclic stress resistance, effect of disturbance on dynamic engineering properties, and, finally, influences of fines content on post liquefaction volumetric strain.

In summary, the newly developed Gel-Push sampler has been proved to be an excellent tool to acquire good quality soil sample of non-plastic silty sand. Results of the cyclic triaxial tests verify that soil liquefaction would occur in non-plastic silty sand deposits even with high non-plastic fines contents. Both fines contents and void ratios have deterministic influences to the cyclic resistance of such silty sand material. Most importantly, disturbance effect would have great influence on cyclic resistances and post liquefaction volumetric strains of non-plastic silty sand. Results of this study is hoped to improve engineers’ understanding on liquefaction potential of non-plastic silty sand.

## SITE INFORMATION

The high fines content silty sand exists extensively over central to southern parts of western Taiwan. Formation process of such unique geological material was recognized as a result of rapid weathering and abrading process. The studied site locates in Hsin Hwa City, Tainan, Taiwan. This site was selected because widespread soil liquefaction was observed during a magnitude 6.4 earthquake occurred in 2010 (Figure 4). Figure 5 indicates the location of the Hsin Hwa (HH01) site. Total four boreholes were drilled. Gel-Push sampling was conducted in three boreholes, and conventional Shelby tube sampling was also conducted in one for comparison purpose. Figure 6 summarizes the soil profile of the test site. As depicted in Figure 6, silty sand layer locates between 2m to 10m below ground surface contains high fines content ranging from 10% to more than 50%. Figure 7 shows the Scanning Electron Microscope (SEM) image of fines particles obtained from the studied site. As shown in the figure, fines particles of such silty sand material are in angular to sub-angular shapes. This evidence clearly indicates that almost no plasticity could be possibly exerted within such soils.

Fig. 4 Silty sand liquefaction at Hsin Hwa site during 2010 Jia Shan Earthquake, Tainan, Taiwan

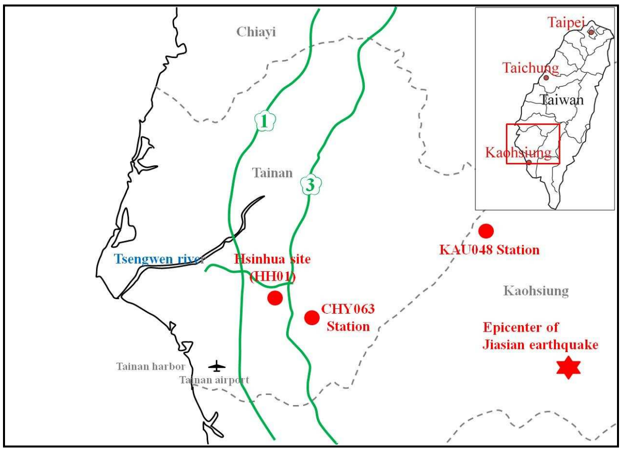


Fig. 5 Location of the Hsin Hwa test site (HH01)

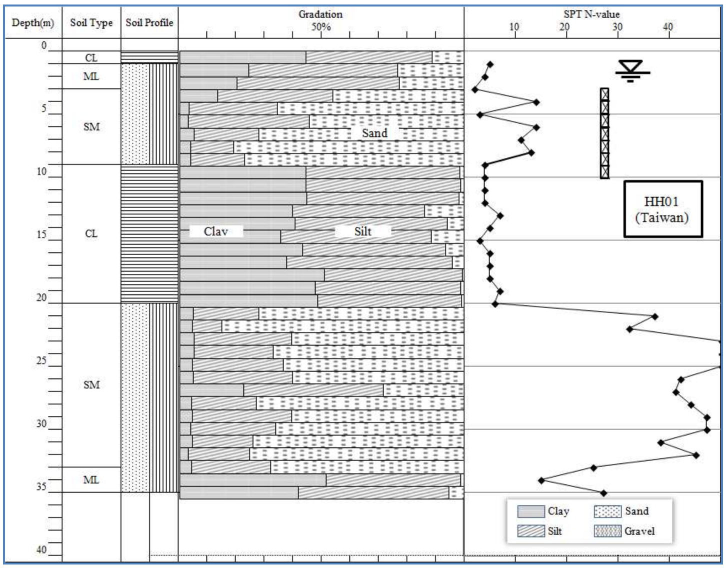


Fig. 6 Soil profile of the Hsin Hwa test site.

## GEL-PUSH SAMPLING TECHNOLOGY

Undisturbed sampling of high fines content silty sand was facing several technical difficulties in the past. Conventional Osterberg’s Shelby tube sampling technique has shortcomings in retrieving good quality high fines content silty sand specimens because the excessive friction generated during penetration tends to cause serious disturbance to the specimens. Therefore, the Shelby tube sampling techniques often results in incomplete soil sample and poor quality. Moreover, the ground freezing technique or tube freezing process those generally were used for preserving sampled soil quality would cause drifting of fines content and disturbance on sensitive micro structure during freezing and de-freezing process. Fines content loss would probably occur when such freezing methodologies are adapted.

The Gel-Push sampling technique was first developed to retrieve gravel material as an alternative replacing ground freezing method in Japan in 2004. This sampler was then introduced to Taiwan by the authors (Lee and Ishihara) in 2006 in an attempt to obtain undisturbed high fines content silty sand during the forensic investigation of a subway construction failure. It was modified to accommodate the thin wall tube inside the sampler to become a triple tube system. The Gel-Push sampler was designed to allow polymer lubricant to seep into the tube wall while the tube was penetrated into the soil by hydraulic pressure. Figure 8 shows the schematic drawings of the Gel-Push sampler at different stages of sampling process. As shown in the figure, the outer tube is designed to secure the borehole and to keep the penetration rod and piston fixed in alignment during penetration. The middle tube acts as the guiding tube to push sampler into soil. Thin wall tube is secured inside the guiding tube for retrieving soil sample. Figure 9 shows parts of the Gel-Push sampler. While sampling process starts, polymer gel is squeezed out of the chamber and seep into both outside of the guiding tube and inside of the thin wall tube. The sampler is also designed with a cutter attaching to the guiding tube to allow smooth penetration, and a catcher fixed at bottom of the thin wall tube to hold soil specimen from falling out during uplifting. The polymer gel would contaminate limited superficial portion of the specimen because very small amount of polymer gel is applied. However, it could effectively reduce the wall friction so as to allow sensitive silty sand specimen to be recovered in good quality.

Table 1 summarizes sampling results of both conventional Shelby tube sampler and Gel-Push sampler at Hsin Hwa site. The sampling depth is from 4m to 9m below ground surface where most silty sand deposits locate. As depicted in the table, Gel-push sampler had successfully recovered more sample than the tube sampler. For completed sampling length, Gel-Push sampler also preserved more fines contents than tube sampler did. Tube sampler could only preserve clayey portion or coarse sand portion by comparing to soil samples retrieved using Gel-Push sampler. Figure 10 shows the silty sand specimen that was obtained using Gel-Push sampler. Specimens shown in the figure contains more than 25% of fines with water content higher than liquid limit. It was recognized as sensitive non-plastic silty sand material that was difficult to be retrieved in the past by using conventional Shelby tube sampler.

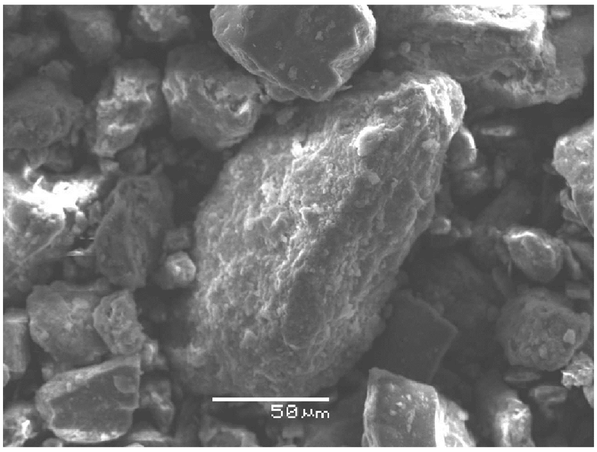


Fig. 7 Scanning Electron Microscope (SEM) image of fines particles obtained from the Hsin Hwa site.

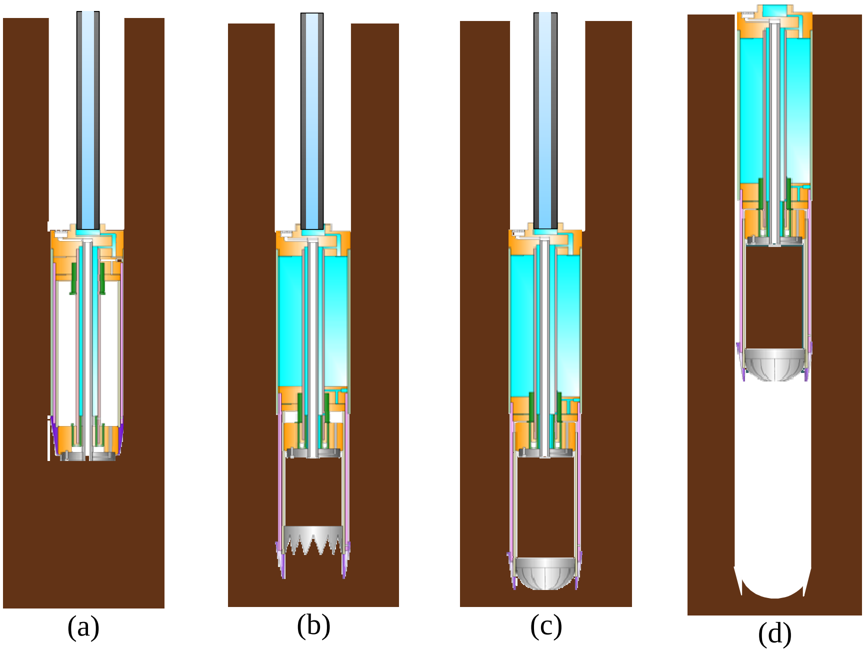

(a) (b) (c) (d)

Fig.8 Schematic drawings of the Gel-Push sampler at different stages of sampling process.

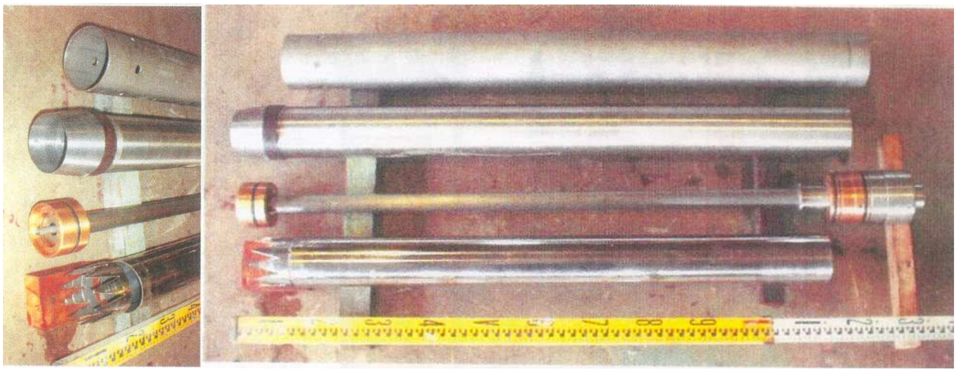


Fig. 9 Parts of Gel-Push sampler.

Table 1 Comparison of sampling results between conventional tube sampler and Gel-Push sampler.

|  | Depth(m) | 4.0-4.9 | 5.0-5.9 | 6.0-6.9 | 7.0-7.9 | 8.0-8.9 | avg. of sample length (cm) |
|---|---|---|---|---|---|---|---|
| Tube sampler | No. | T2 | T3 | T4 | T5 | T6 | 54.6 |
|  | Sample length | 64/80 | 50/80 | 55/80 | 58/80 | 46/80 |  |
|  | Sampling ratio | 80.0% | 62.5% | 68.8% | 72.5% | 57.5% |  |
|  | Fines content | 24.0% | 9.0% | --- | 20.3% | 15.0% |  |
| Gel Push sampler | No. | BT1 | BT2 | BT3 | BT4 | BT5 | 81.8 |
|  | Sample length | 83/90 | 81/90 | 82/90 | 77/90 | 86/90 |  |
|  | Sampling ratio | 92.2% | 90.0% | 91.1% | 85.5% | 95.6% |  |
|  | Fines content | 27.5% | 24.3% | 9.5% | 14.5% | 9.0% |  |

## LABORATORY TEST

Series of cyclic triaxial tests were performed on both recovered undisturbed specimens and remolded specimens with different fines contents to identify dynamic properties of non-plastic silty sand. Purpose of the laboratory tests is to examine following engineering features:

1. Influence of fines content on liquefaction potential of non-plastic silty sand.
2. Influence of void ratio or particle packing state on cyclic stress resistance,
3. Effect of disturbance on dynamic engineering properties, and, finally,
4. Influences of fines content on post liquefaction volumetric strain.

The C. K. Chen type of cyclic traxial testing apparatus is used for this study. Ignition of liquefaction was set as double amplitude of axial strain exceeds 5%. All remolded specimens were formulated to simulating field densities and fines contents obtained from undisturbed specimens. They were prepared using wet damping method to have better control of density. During the preparation, fines were well mixed to account for uniform distribution of fines and to simulate total disturbance.

Figure 11 shows the typical test results of cyclic triaxial tests. As shown in the figure, Gel-Push specimen has better cyclic resistance and possesses larger yielding strain than the remolded specimen under the similar density and deviator stress. Figure 12 summarizes results of cyclic triaxail tests at different sampling depths. As illustrated in the figure, the undisturbed non-plastic silty sand could sustain higher number of cycles when lower cyclic stress ratios were applied, yet number of cycles to cause liquefaction dropped significantly when higher cyclic stress ratios were applied. For specimens at similar void ratio range, silty sand with higher fines contents tends to have smaller cyclic strength. This phenomenon would become much more noticeable on the remolded soil specimens. Moreover, undisturbed soil specimens have higher cyclic strength than remolded specimens with similar fines contents and void ratios. This observation implies that disturbance has great effects on cyclic stress resistance of non-plastic silty sand.

Figure 13 summarizes test results of post-liquefaction volumetric strains according to various fines contents. As shown in the figure, remolded specimens clearly possess larger volumetric strains than undisturbed ones. Volumetric strains of remolded specimens would be as high as 8 to 10%, whereas those of undisturbed specimens remain between 2 to 5%.

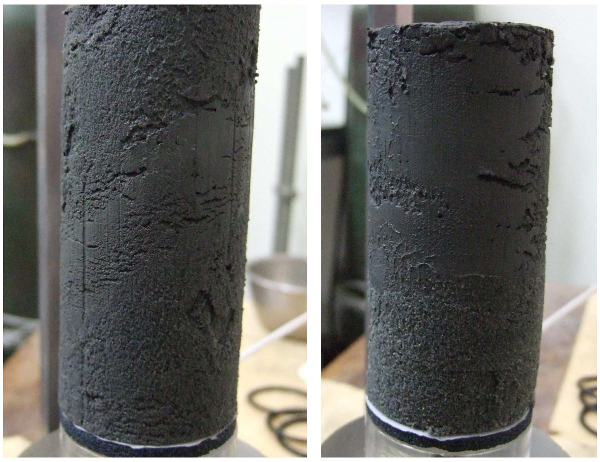
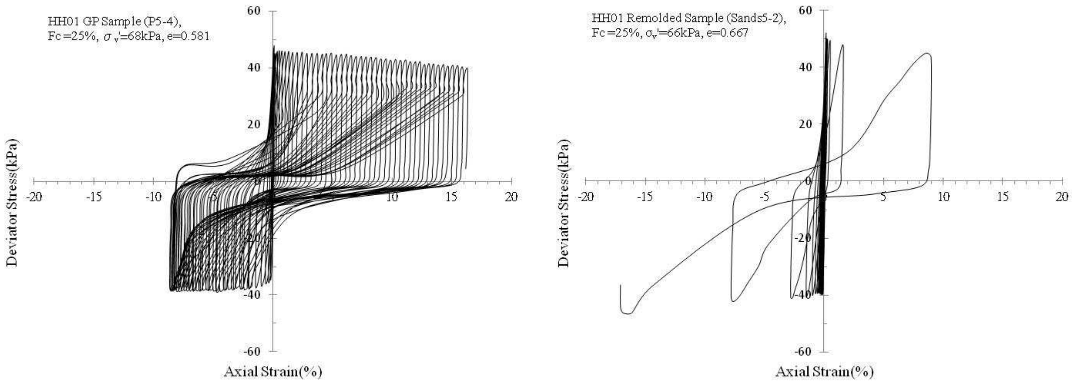


Fig. 10 High fines content silty sand specimen retrieved from Gel-Push sampler.



.(a) .(b)

Fig. 11 Typical results of cyclic triaxial tests (a) undisturbed (b) remolded.

## DICUSSIONS ON ENGINEERING PRACTICES

Generally speaking, specimens with higher fines contents tend to have better particle packing, i.e. lower void ratios in their natural condition. Fines contents and void ratios appear to be the major factors of cyclic stress resistance of the non-plastic silty sand. Figure 14 summarizes cyclic stress ratios according to 5, 15, and 20 cycles of loading for undisturbed specimens. For specimens with similar fines contents, those which have higher void ratios, have lower cyclic stress ratios. For specimens with similar void ratios, those which have higher fines contents, have lower cyclic stress ratios. Attentions were also paid to the difference of test results between undisturbed specimens and remolded ones. As shown in Figure 14, undisturbed non-plastic silty sand specimens have cyclic stress ratio distributed from 0.22 to 0.30 when number of cycles equals to 15. However, cyclic stress ratios of remolded specimens those were prepared at same fines contents and void ratios, distribute from 0.15 to 0.25 under the same cycles of loading. Major reason for such difference would be that microstructures of the undisturbed specimens possess better bonding between coarse grains and better particle packing resulting from natural formation and consolidation process. Another possible reason for such differences could be the existence of clay pockets within the undisturbed specimens. These clay pockets within the specimens would probably result in high cyclic stress ratios during laboratory tests, yet they would have less effect on overall liquefaction potential in the field. The clay material was removed when preparing the remolded specimens.

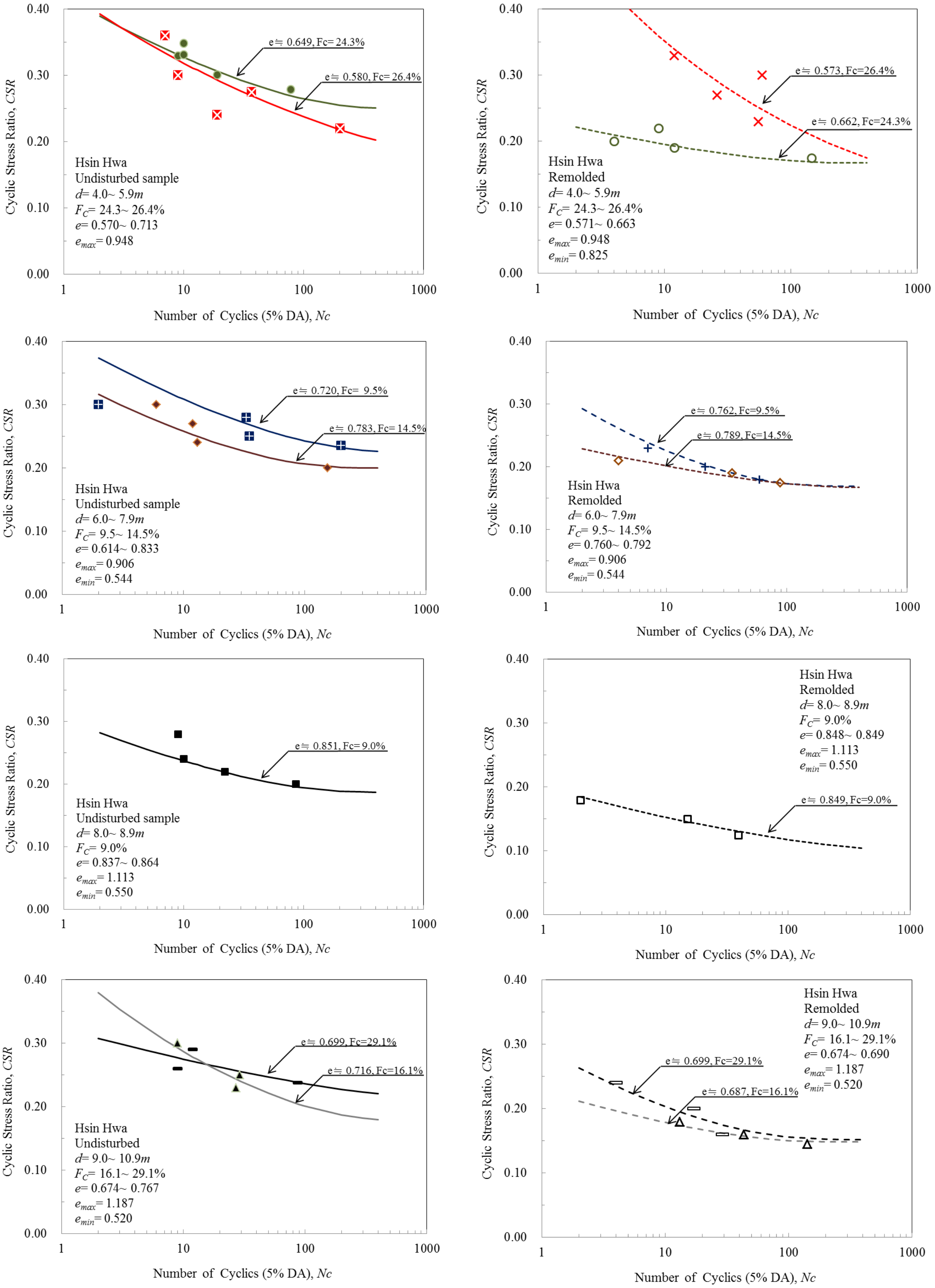


Fig. 12 Results of cyclic triaxial tests at different sampling depths.

Figure 15 summarizes both disturbance effect and influence of fines contents to liquefaction resistance of various non-plastic silty sand deposits tested in this study. Vertical axial of Figure 15 is the cyclic stress ratio deduction defined as the cyclic stress ratio of remolded specimens divided by those of undisturbed specimens at the same fines contents and void ratio. Horizontal axial of the figure is the fines contents. It was found that higher non-plastic fines content of silty sand would result in lower cyclic liquefaction resistance. The indicated trends would become more obvious when such non-plastic silty sand was subjected to disturbance. The disturbance deduction could be as high as 40% for Hsin Hwa silty sand with 26% of fines.

Furthermore, results of the cyclic triaxial tests on undisturbed specimens were converted into field cyclic resistance ratio by taking the cyclic stress ratios at number of cycle of 20. Field standard penetration test N values at sampling locations were also converted to corrected blow count, $N_{1\text{-}60}$, accordingly. Figure 16 summarize results of such data interpretation in comparison to the semi-empirical chart that proposed by Youd and Idirss (1997). As shown in the figure, test results of non-plastic silty sand exhibit different tendency from the proposed curves. It was found that higher non-plastic fines content of silty sand would result in lower cyclic liquefaction resistance.

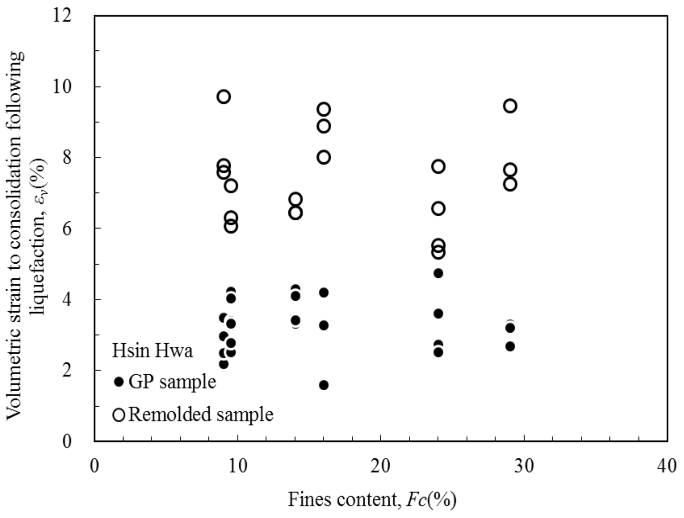


Fig. 13 Test results of post-liquefaction volumetric strains according to various fines contents.

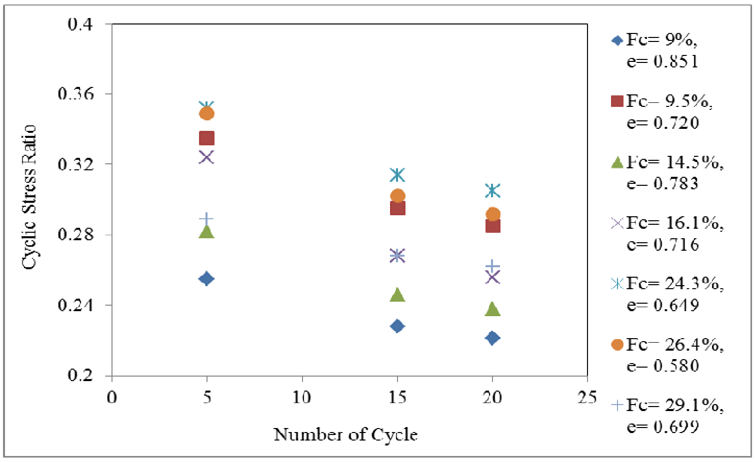


Fig. 14 Cyclic stress ratios according to 5, 15, and 20 cycles of loading for undisturbed specimens.

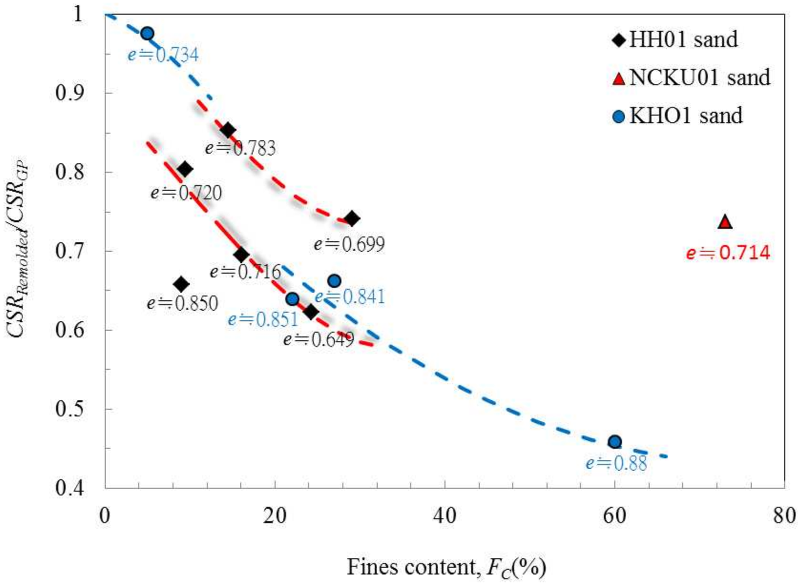


Fig. 15 Summary of fines content influence and disturbance effects on cyclic stress ratio of non-plastic silty sand.

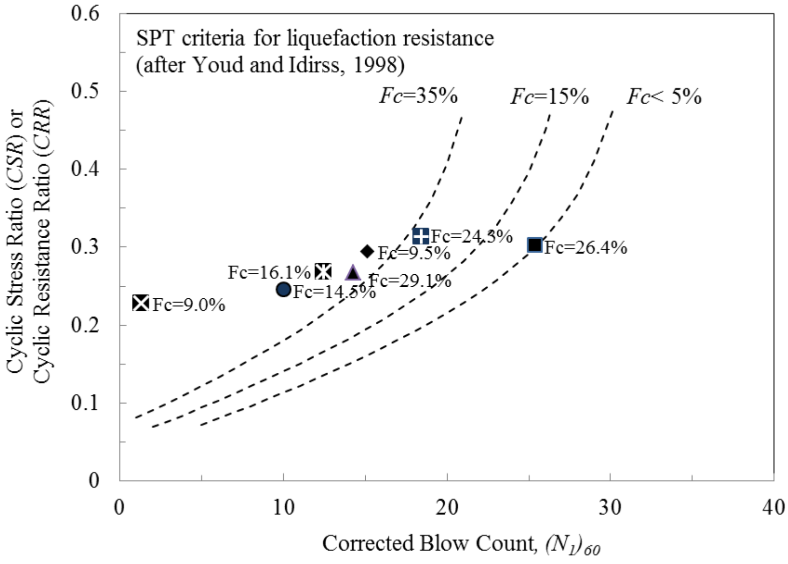


Fig. 16 Summary of test results in correlation to field blow counts.

## CONCLUSIONS AND FUTURE RESEARCHES

In summary, the newly developed Gel-Push sampler has been proved to be an excellent tool to acquire good quality undisturbed sample of non-plastic silty sand. Its triple tube system and use of polymer gel appear to be able to effectively reduce sampling disturbance such as wall friction. It would allow engineering properties of non-plastic silty sand material to be investigated at their original states.

Results of the cyclic triaxial tests verify that soil liquefaction would occur in non-plastic silty sand deposits even with high non-plastic fines contents. Both fines contents and void ratios have deterministic influences to the cyclic resistance of such silty sand material. For specimens at similar void ratio range, silty sand with higher fines contents tends to have smaller cyclic strength. This phenomenon would become much more noticeable on the remolded soil specimens. Moreover, by comparing the test results between undisturbed and remolded specimens, it could be concluded that undisturbed specimens would have better liquefaction resistance than the remolded ones with similar void ratio and fines contents. Aging effects such as particle bonding between coarse grains and particle packing during natural formation and consolidation process of the studied non-plastic silty sand would have deterministic influences on its liquefaction potential.

In conclusion, void ratio, fines content, and aging effect are recognized as the three major influence factors to liquefaction potential of non-plastic silty sand. In this preliminary study, only general trends of effects of these factors were identified. In order to improve the liquefaction evaluation on non-plastic silty sand, more research efforts should be paid to further investigate combined effects of these factors. For future researches, the authors would like to propose the idea of international test sites. Detailed soil investigation including Gel-Push sampling, field testing such as wave velocity measurement, laboratory tests, and etc. could be arranged at both liquefaction and non-liquefaction sites at affected areas of recent 1999 Chi-Chi earthquake in Taiwan, 2010~2011 Christchurch earthquakes in New Zealand, and 2011 Great East Japan earthquake in Japan. Results of such a joint study would provide necessary data to establish empirical evaluation method, criteria, and settlement prediction of liquefaction caused by non-plastic siltysand.

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