Post-liquefaction Volumetric Strain Behavior of Non-plastic Silty Sand – a Case Study of Hsin-Hwa Liquefaction

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Abstract

Since the destruction phenomenon of soil liquefaction was proposed in 1920, soil liquefaction was turned into popular topic in geotechnical Engineering. Soil liquefaction potential became the main research target, but post-liquefaction secondary disasters were paid slight attention. In fact, post-liquefaction subsidence occurred significant safety issues to people lives, such as land settlement, house collapse and seawall damage. Severe earthquakes occurred in Japan, Taiwan and New Zealand in recent years, the wide distribution of non-plastic silty sand was observed in the damage area. Related researchers devoted more effort to the special soil liquefaction engineering properties of non-plastic silty sand and proposed plenty research results.

In this study, Hsinhwa area in Taiwan was selected as research site to investigate the post-liquefaction volumetric strain behavior of non-plastic silty sand. High quality undisturbed soil specimens were obtained by undisturbed sampling technique for laboratory tests, the influence of void ratio, fines content and disturbance effect to post-liquefaction volumetric strain of non-plastic silty sand were investigated. According to the test results, post-liquefaction volumetric strain of non-plastic silty sand increased with void ratio, fines content and disturbance effect increased, it indicated that non-plastic silty sand was a sensitive and susceptible to soil disturbance. In addition, a more direct preliminary assessment method was proposed in this study. Research progress presented here is hoped to be helpful in understanding post-liquefaction volumetric strain behavior of non-plastic silty sand in future engineering applications.

Key Words: Non-plastic Silty Sand, Post-liquefaction Volumetric Strain, Void Ratio, Fines Content, Disturbance Effect

1. Introduction

The geology of Taiwan west coast is composed by quaternary alluvium of sand and silty sand, which is sensitive and weak to subsidence. The mainly causes of subsidence on west coast area are over-pumping of groundwater, ground load increasing, and soil liquefaction. The development process of first two causes is slower than other, large amount of subsidence was accumulated with long term, moreover, whose preventive manners are clear and easy to control. On the contrary, the development process of settlement results from soil liquefaction is fast, serious disaster and damage were occurred by instant and large scale differences subsidence, such as building collapse, underground lifelines fracture, highway collapse, dike dams, reservoirs cracking, embankment burst, even the flood. This kind compound disaster after earthquake is more serious than the

Soil particles deposition of saturated loose sand layer was a loose arrangement state before the earthquake, strong cyclic loading made the soil pore water pressure rising at earthquake state, and decreased the soil effective stress gradually to liquefy. After earthquake occurred, because the excess pore water pressure of liquefied soil layer dissipated, soil structure became denser, and it decreased soil volume to cause post-liquefaction volumetric strain. Ground surface subsidence phenomenon was occurred, and the ground surface settlement was related to the volume of drain water [1,2]. This phenomenon which is similar to the consolidation settlement of clay layer called post-liquefaction consolidation settlement.

[3] investigated the post-liquefaction volumetric strain of Monterey sand by performing cyclic triaxial tests. They concluded that the maximum volumetric strain of Monterey sand was about 1%, and soil specimens would produce distortion after soil initial liquefaction. Post-liquefaction volumetric strain decreased with relative density increased. [4] concluded the test results of cyclic simple shear tests to indicate that post-liquefaction volumetric strain was affected most by the maximum shear strain $\gamma_{\text{max}}$, and the secondary factor was relative density, initial effective confining pressure was the minimal impact factor. [5] concluded the test results from [4] to indicate that post-liquefaction volumetric strain of sand was related to its relative density and shear strain. In addition, the relationship between post-liquefaction volumetric strain ($e$), cyclic stress ratio (CSR) and corrected standard penetration test value, $(N_1)_{60}$, was proposed. [6] proposed the relationship between maximum shear strain and post-liquefaction volumetric strain from cyclic loading tests results. The post-liquefaction volumetric strain of sand layer was about 3~10%, which was related to relative density and maximum shear strain under cyclic loading condition.

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 WuFeng, NanTou, and YuenLin areas. 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. 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.

HsinHwa area, HH01, which locates at south Tainan, is the major research site in this study, non-plastic silty sand layer and non-plastic clay layer interbedded in this site. There had severe soil liquefaction occurred by JiaSian earthquake in 2010, therefore this soil liquefaction area which near the Taiwan High Speed Rail (THSR) was selected to investigate the post-liquefaction volumetric strain behavior of non-plastic silty sand. In this study, undisturbed specimens of non-plastic silty sand who obtained from GP sampler and comparative remolded specimens were both used for soil dynamic triaxial test. The variation of void ratio ($e$), cyclic stress ratio (CSR), and number of cycle (Ne) were recorded. On the basis of the research by [7] and [8], this research needs three investigated categories as follow. First, to discussion the influence of void ratio on post-liquefaction volumetric strain behavior of non-plastic silty sand was concluded. Besides, according to the variation of characteristics and percentage of fines content to investigate the influence of fines content was necessary. Finally, effect of disturbance on post-liquefaction volumetric strain properties was proposed. Finally, a more easy and direct preliminary assessment method of post-liquefaction settlement was proposed in this study.

2. Research Site

The magnitude 6.4 of JiaSian earthquake occurred in southern Taiwan in 2010, the epicenter is located 17.1
km south-east of JiaSian station (station ID: KAU047), and the focus depth of about 22.6 km below the surface as shown in Figure 1. Although the magnitude of JiaSian earthquake was weaker than Chi-Chi earthquake, it caused severe soil liquefaction in HsinHwa area of Tainan. Figure 2 shows the ground acceleration history of regional seismic station (station ID: CHY063). Because of the amplification effect of soft soil, the peak ground acceleration of HsinHwa area was 385 gal. The soil profile of HsinHwa area was shown as Figure 3, the ground water level located below the surface 1.38 m, and SPT-N value was between 3 to 20, the soil layers within 20 m below the surface were composed of non-plastic silt and non-plastic clay, and soil liquefaction zone adjacent to the...
piers of high-speed rail as shown in Figure 4.

For investigating the post-liquefaction volumetric strain behavior of non-plastic silty sand in Hsinhwa area, this study obtained the representative specimens by utilizing the Gel Push sampling technique. Table 1 shows the basic physical properties of HH01 specimens, and the grain size distribution curve of HH01 specimens is shown in Figure 5. As shown in the Table 1, the soil type of HH01 specimens belongs to SM or ML in USCS system, and the average grain size ($D_{50}$) is about 0.1–0.19 mm, fines content ($F_c$) is 9.0–29.1% and plastic grain content ($P_G$) is less than 7.7%. Comparing the grain size distribution curve of HH01 specimens with easy liquefied grain size distribution curve of Japan Society of Civil Engineers (JSCE), it points out that specimens of HH01 have higher liquefaction potential. The site moisture content ($\omega$) of this kind soil is higher than liquid limit (LL), and the fines particles are non-plastic, it means that HH01 specimens are influenced by disturbance easily than other kind soil.

3. Post-liquefaction Volumetric Strain

The dynamic triaxial test apparatus used in this research was designed by Chan & Mulilis in 1976. Undisturbed specimens of non-plastic silty sand who obtained from GP sampler and comparative remolded specimens

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>4–4.9 m</th>
<th>5–5.9 m</th>
<th>6–6.9 m</th>
<th>7–7.9 m</th>
<th>8–8.9 m</th>
<th>9–9.9 m</th>
<th>10–10.9 m</th>
</tr>
</thead>
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<tr>
<td>Effective confining pressure (kPa)</td>
<td>50</td>
<td>68</td>
<td>75</td>
<td>85</td>
<td>100</td>
<td>105</td>
<td>115</td>
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<tr>
<td>Initial void ratio, $e$</td>
<td>0.620–0.699</td>
<td>0.675–0.730</td>
<td>0.663–0.805</td>
<td>0.813–0.857</td>
<td>0.861–0.886</td>
<td>0.690–0.765</td>
<td>0.711–0.813</td>
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<tr>
<td>Specific gravity, $G_s$</td>
<td>2.60</td>
<td>2.63</td>
<td>2.61</td>
<td>2.63</td>
<td>2.62</td>
<td>2.62</td>
<td>2.69</td>
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<tr>
<td>Moist unit weight, $\gamma_m$ (g/cm$^3$)</td>
<td>1.85–2.03</td>
<td>1.87–1.93</td>
<td>1.71–1.96</td>
<td>1.85–1.87</td>
<td>1.85–1.88</td>
<td>1.94–2.03</td>
<td>1.89–1.98</td>
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<tr>
<td>Dry unit weight, $\gamma_d$ (g/cm$^3$)</td>
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<td>1.52–1.57</td>
<td>1.44–1.56</td>
<td>1.41–1.45</td>
<td>1.39–1.40</td>
<td>1.48–1.55</td>
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<td>Moisture content, $\omega$ (%)</td>
<td>21.1–23.9</td>
<td>22.7</td>
<td>17.0–28.9</td>
<td>29.6–30.8</td>
<td>33.49</td>
<td>30.69</td>
<td>25.7–27.4</td>
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<tr>
<td>Liquid limit, LL (%)</td>
<td>25.36</td>
<td>19.81</td>
<td>24.54</td>
<td>26.49</td>
<td>15.41</td>
<td>18.76</td>
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were both used for soil dynamic triaxial test. Ignition of liquefaction was set as double amplitude (DA) of axial strain exceeds 5%. The variation of void ratio (e), cyclic stress ratio (CSR), and number of cycle (Nc) were recorded. After the destruction of test soil specimens, the initial test condition was restored, and then the below drainage gate was opened to exhaust pore water pressure. The discharges of water and maximum axial strain were recorded until pore water pressure equal to zero to calculate the post-liquefaction volumetric strain (\(\gamma_{rv}\)) and maximum shear strain (\(\gamma_{max}\)).

Figure 6 summarizes the test results of post-liquefaction volumetric strains, where the volume of water was measured from the dissipation of excess pore water pressure after liquefaction was identified in each cyclic triaxial test. As shown in the figure, remolded specimens clearly possess larger volumetric strains than undisturbed ones. Post-liquefaction volumetric strains of remolded specimens would be as high as 8 to 10%, whereas those of undisturbed specimens remain between 2 and 5%.

This test results of triaxial test were distinguished to three categories: In-situ undisturbed specimens, in-situ remolded specimens, and series remolded specimens. According to the research conclusion proposed by [8], the dynamic engineering properties of non-plastic silty sand were investigated. When fines content (FC) was similar, the cycle stress ratio (CSR) of non-plastic silty sand increased with relative density (Dr) increasing, it means that CSR of non-plastic silty sand increased with void ratio (e) decreased. For the influence of fines content on dynamic properties of non-plastic silty sand, the CSR had higher value when FC equal to 20%, and it had lower value when FC equal to 0 under similar Dr condition. Therefore, when Dr was similar, CSR_{20} would increase then decrease with FC increasing. In addition, for the influence of disturbance effect, the CSR of remolded specimens was lower than it of undisturbed specimens obviously under similar test condition; it means that soil liquefaction resistance of undisturbed non-plastic silty sand specimens was higher than it of remolded specimens.

On the basis of the research by [7] and [8], this research needs three investigated categories. First, to discussion the influence of void ratio on post-liquefaction volumetric strain behavior of non-plastic silty sand was concluded. Besides, according to the variation of characteristics and percentage of fines content to investigate the influence of fines content was necessary. Finally, effect of disturbance on post-liquefaction volumetric strain properties was proposed. The post-liquefaction volumetric strain behavior of non-plastic silty sand was illustrated mainly by the relationship between maximum shear strain (\(\gamma_{max}\)) and post-liquefaction volumetric strain (\(\gamma_{rv}\)) as follow. Where \(\gamma_{max}\) denotes maximum shear strain, it calculated from axial strain (\(\varepsilon_{a}\)) of triaxial test, hence, \(\gamma_{max}\) is equivalent to 1.5 \(\varepsilon_{dmax}\). According to the research results from [7], the shear strain \(\gamma\) is equivalent to 1.5 \(\varepsilon_{a}\), where \(\varepsilon_{a}\) is the axial strain. When double amplitude (DA) of axial strain exceeds 5%, it was defined as initial liquefaction. Therefore, DA axial strain of 5% is equivalent to the maximum shear strain \(\gamma_{max}\) = 3.75%, as discussed above as \(\gamma_{max} = 1.5 \varepsilon_{a} = 1.5 \times (5/2) = 3.75\%\).

3.1 The Influence of Void Ratio
In this research, a series of remolded soil specimens, with fines content was equal to 0, 10, 20, 30 and 40%, was utilized to investigate the influence of void ratio to post-liquefaction volumetric strain behavior of non-plastic silty sand. The initial void ratio (e) was about 0.55–0.94, and relative density (Dr) was controlled at 60 and 90%. In the Figure 7, the post-liquefaction volumetric strain, \(\varepsilon_{rv}\), was plotted in the ordinate, and maximum shear strain, \(\gamma_{max}\), was plotted as abscissa. Post-liquefaction volumetric strain would increase with maximum shear strain increased, and then achieve a constant value as maximum.
shear strain was about 15%. When fines content was similar, post-liquefaction volumetric strain increased with void ratio increasing.

3.2 The Influence of Fines Content

As shown in the Figures 8–9, when void ratio and relative density of test specimens were similar, the post-liquefaction volumetric strain, $\varepsilon_v$, increased with fines content increasing, and then achieved a constant value. This phenomenon occurred because of the soil particle structure; moreover, soil specimen with greater relative density has smaller post-liquefaction volumetric strain. In the Figure 10, the maximum and minimum void ratio of Hsinhwa soil specimens decreased and then increased with fines content increased, it was due to the influence of soil fabric phase transition proposed by [9]. The phase transition zone was located in fines content equal to about 25 to 35%. It means that when soil specimen has lower fines content, the main soil fabric was controlled by coarse particles. When particle size of silty sand was smaller than structure void, silty sand easily filled into the void between the coarse particles after soil liquefaction. Therefore, post-liquefaction volumetric strain increased with fines content increased. Behind the phase transition zone, soil fabric would control by fine particles when soil specimen has higher fines content. Void and soil particle size were similar, soil particles difficult to move to fill the void, therefore post-liquefaction volumetric strain would not influence by fines content under this condition.

3.3 The Influence of Disturbance Effect

In the same test boundary condition, the influence of disturbance effect to post-liquefaction volumetric strain,
\( \varepsilon_v \) was investigated by comparing the difference of test results between undisturbed and remolded specimens. As shown in the Figure 11, post-liquefaction volumetric strain increased with maximum shear strain increasing. When void ratio and fines content were similar, post-liquefaction volumetric strain of remolded specimens was higher than it of undisturbed specimens. The post-liquefaction volumetric strain increased with void ratio increased for remolded specimens, but this phenomenon was not evident for undisturbed ones. In addition, the influence of fines content to post-liquefaction volumetric strain of undisturbed specimens was unobvious as well.

4. Post-liquefaction Settlement Estimation

[10] performed the laboratory shear tests of Fuji-kawa clean sand specimens. The relationship between maximum shear strain and post-liquefaction volumetric strain under different relative density condition was proposed, and assessment curve of post-liquefaction volumetric strain and analysis method were developed as well. [7] concluded the test results of post-liquefaction volumetric strain on clean sand and soil with fines \( (F_C = 0 \sim 43.3\%) \) to propose the relative assessment curves and analysis processes of Toyoura sand \( (F_C = 0\%) \). This post-liquefaction settlement estimated methods were calculated indirectly. According to the assessment methods used in the past, a more direct settlement estimated method was proposed as shown in Figure 12–14. [9] collected various types of soil test results to propose the relationship between void ratio range, fines content, \( (N_1)^{18} \) and relative density shown as Figures 12–13. The test re-
sults of Hsinhwa specimens were consistent in these figures, fines content and \( (N_t)_{35} \) could be used to calculate the void ratio range and relative density by these formulas. And then the test results of Taiwan Hsinhwa and Bengal Padma undisturbed specimens were collected to propose the relationship between post-liquefaction volumetric strain of Hsinhwa specimens.

Figure 11. The influence of disturbance effect to post-liquefaction volumetric strain of Hsinhwa specimens.

Figure 12. The relationship between void ratio range and fines content of Hsinhwa undisturbed specimens (after \([9]\)).

Figure 13. The relationship between relative density and void ratio range of Hsinhwa undisturbed specimens (after \([9]\)).
volumetric strain ($e_{\text{max}}$), void ratio range ($e_{\text{max}} - e_{\text{min}}$) and relative density ($D_r$) as shown in the Figure 14. In the figure, soil specimens were grouped according to the relative density, and the dash lines were drawn along the edge of each group. It could be used to estimate the post-liquefaction volumetric strain directly, as long as there has fines content and N-value in the drilling data. It also means that the post-liquefaction settlement could be calculated easily in the future.

5. Conclusions

In this study, high quality undisturbed soil specimens were provided for laboratory tests to investigate the post-liquefaction volumetric strain behavior of non-plastic silty sand. Results of laboratory tests indicate that higher the void ratio, fines content and disturbance effect of the non-plastic silty sand would have a larger post-liquefaction volumetric strain. This phenomenon is considered to be very important in understanding time sequence of silty sand liquefaction. Void ratio (or relative density) would have deterministic effect on the silty sand post-liquefaction volumetric strain. The post-liquefaction volumetric strain becomes greater as the maximum shear strain increases, and decreases when its relative density increases for the same sort specimens. According to the research results proposed by [8] and [11], a phase transition zone of soil structure was appeared at fines content equal to 20~35%, the soil structure and dynamic properties of soil specimens would vary obviously. In this study, if the fines content of soil specimens was equal to 15~35%, they located in this phase transition zone. Because of the influence of phase transition, the effects of fines content are significant in the range of 15%~35%, the soil structure and dynamic properties of soil specimens would vary obviously.

Post-liquefaction volumetric strain of non-plastic silty sand increased with void ratio, fines content and disturbance effect increased, it indicated that non-plastic silty sand was a sensitive and susceptible to soil disturbance. The definition and judgment of disturbance degree on non-plastic silty sand are pivotal for post-liquefaction volumetric strain behavior of non-plastic silty sand; it will depend on the experience and wisdom of the geotechnical engineers. Besides, a more easy and direct settlement estimated method was proposed in this study, the test results of undisturbed specimens were collected to propose the relationship between post-liquefaction volumetric strain, void ratio range and relative density. The post-liquefaction settlement could be calculated as long as there has fines content and N-value in the drilling data, however it needs to be further verified by the actual case in the future.

![Figure 14. The relationship between post-liquefaction volumetric strain, void ratio range and relative density of Hsinhwa specimens.](image-url)
Nomenclature

CSR cyclic stress ratio
CSR$_{20}$ cyclic stress ratio with number of cycle equal to 20
$D_{50}$ average grain size
DA double amplitude
Dr relative density
e void ratio
$e_{\text{max}} - e_{\text{min}}$ void ratio range
F$_C$ fines content
LL liquid limit,
$(N_1)_{60}$ corrected standard penetration test value
Nc number of cycle
PG plastic grain content
$\gamma_{\text{max}}$ maximum shear strain
$e_{d_{\text{max}}}$ maximum axial strain
$e_{v_{\text{post}}}^\text{v}$ post-liquefaction volumetric strain
$e_{v_{\text{max}}}^\text{v}$ maximum post-liquefaction volumetric strain
$m$ moisture content

Acknowledgements

The authors would like to thank Prof. Kenji Ishihara (CHUO University, Tokyo, Japan) for his guidance and correction.

References


Manuscript Received: Apr. 29, 2016
Accepted: Sep. 5, 2016