NOTE

Effects of fines content on liquefaction strength and dynamic settlement of reclaimed soil

Lien-Kwei Chien, Yan-Nam Oh, and Chih-Hsin Chang

Abstract: In this study, the reclaimed soils in the Yunlin area of west Taiwan are adopted as test samples. The specimens were prepared by moist tamping at different relative densities and fines contents. Triaxial liquefaction tests were performed to evaluate the liquefaction strength and liquefaction-induced settlement. The test results show that the liquefaction strength of reclaimed soil increases as the relative density increases. In addition, under constant relative density, the liquefaction strength decreases as the fines content increases. Based on the test results and one-dimensional consolidation theory, the volumetric strain and settlement can be evaluated by dry density and fines content of the reclaimed soil. The results show that the settlement ratio decreases as the relative density increases. The figures and results can be references for the evaluation of liquefaction strength and liquefaction-induced settlement. The results are useful for liquefaction strength and settlement analysis for planning, design, and related research on land reclamation engineering.

Key words: reclaimed soil, liquefaction resistance, fines content, settlement.

Résumé : Dans cette étude, les sols réhabilités dans la région de Yunlin à l'ouest de Taiwan ont été adoptés comme échantillons d'essais. Les spécimens ont été préparés par la méthode de damage humide avec différentes valeurs de densité relative et de teneurs en particules fines. Des essais triaxiaux de liquéfaction ont été réalisés pour évaluer les augmentations de la résistance à la liquéfaction et du tassement induit par la liquéfaction. Comme le démontrent les résultats, la résistance à la liquéfaction du sol réhabilité augmente avec l'augmentation de la densité relative. De plus, à une densité relative constante, la résistance à la liquéfaction décroît avec les diminutions de la teneur en particules fines. En partant des résultats de la théorie de consolidation unidimensionnelle, la déformation volumétrique et le tassement peuvent être évalués sur la base de la densité sèche et de la teneur en particules fines du sol réhabilité. Comme le montrent les résultats, le rapport de tassement décroît lorsque la densité relative décroît. Les figures et les résultats peuvent servir de références pour évaluer la résistance à la liquéfaction et le tassement induit par liquéfaction. Les résultats sont utiles pour l'analyse de la résistance au cisaillement et du tassement pour la planification, la conception et les recherches en rapport avec l'ingénierie de la réhabilitation de terrains.

Mots clés : sol réhabilité, résistance à la liquéfaction, teneur en particules fines, tassement.

[Traduit par la Rédaction]

Introduction

Liquefaction is one of the most important, interesting, complex, and controversial topics in geotechnical earthquake engineering. Taiwan is located at the center of the west circumpacific earthquake zone, and lies between the Philippine plate and the Eurasia plate. When plates move with respect to each other, relative deformation between the plates occurs. Therefore, earthquakes occur in Taiwan and cause severe damage.

An earthquake of magnitude 7.3 on the Richter scale hit Taiwan on 21 September 1999 at 1:47 a.m., with its epicenter 12.5 km west of Sun Moon Lake. The earthquake was caused by crust dislocations between the Che Lungpu fault and the Da Maupu-Shuang Tong fault, both located in the southwestern part of the island. Tai-Chung harbor on the west coast in central Taiwan was seriously damaged. Earthquakes have produced spectacular examples of liquefaction-induced damage to structures in land reclamation areas, including slope failures, bridge and building foundation failures, and flotation of buried structures.

Liquefaction of reclaimed soil can be influenced by earthquake loading, cyclic loading, relative density, and fines content. Seed and Idriss (1967) illustrated that relative

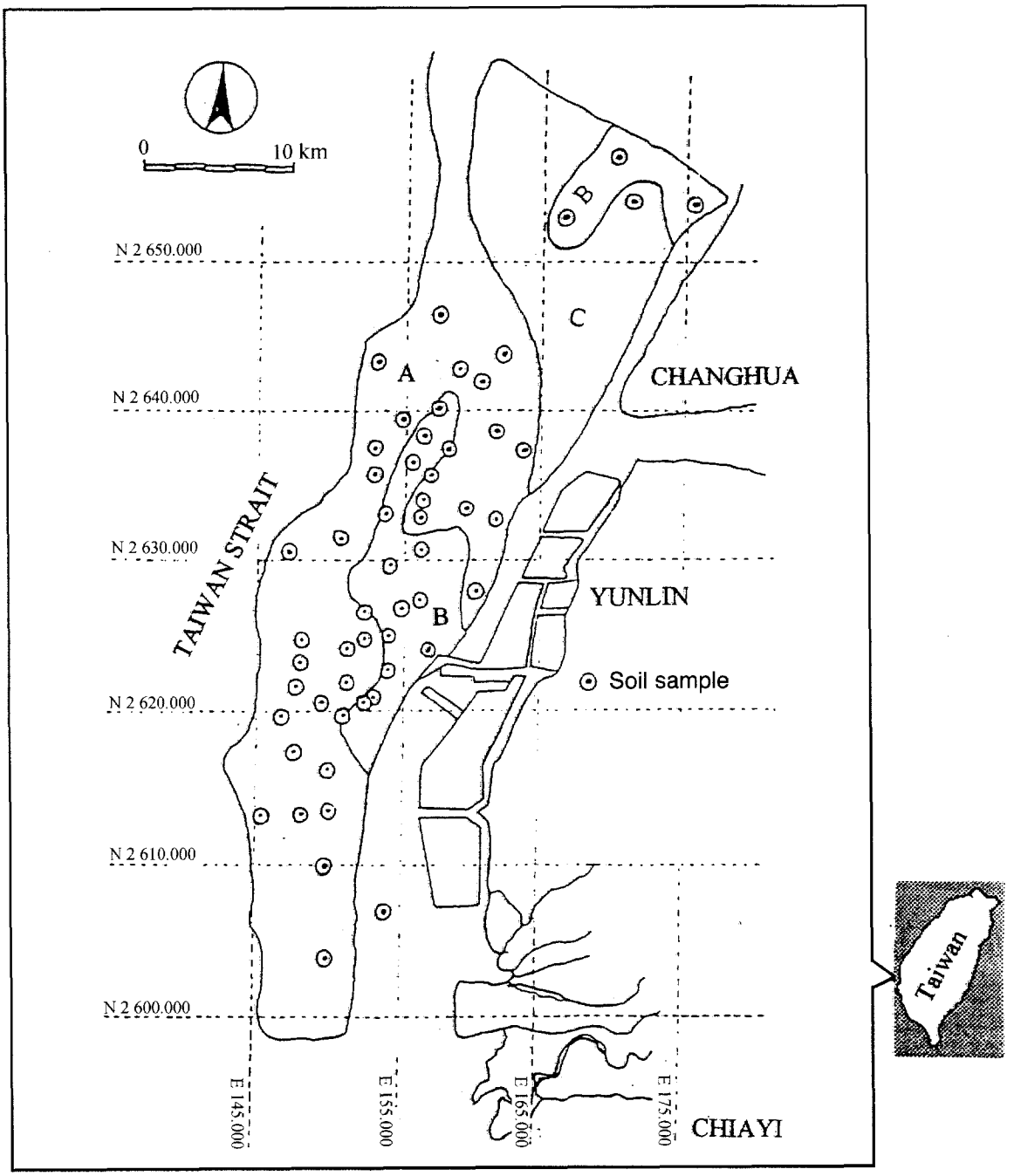
Received 2 May 2000. Accepted 20 April 2001. Published on the NRC Research Press Web site at http://cgj.nrc.ca on 22 February 2002.

L.-K. Chien[1] **and C.-H. Chang.** Coastal Disaster Prevention Research Center, Department of Harbor and River Engineering, National Taiwan Ocean University, No. 2, Pei-Ning Road, Keelung, Taiwan 202, R.O.C.
Y.-N. Oh. School of Engineering, Griffith University Gold Coast Campus, PMB50, Gold Coast Mail Centre, QLD 9726, Australia.

[1]Corresponding author (e-mail: lkchien@mail.ntou.edu.tw).

 DOI: 10.1139/T01-083

Fig. 1. Location of the Yunlin reclamation area in west Taiwan (Sinotech Engineering Consultants, Inc. 1990).



density is the main factor affecting the liquefaction strength of soil. The major earthquakes of Niigata, Japan, in 1964 have illustrated that soil below 50% relative density would liquefy. Soil with a relative density of 70% or higher will not liquefy. By using dynamic triaxial tests, Seed (1979) showed that for soil with a relative density of 0–70% the shear stress ratio for initial liquefaction increases as the relative density increases. Seed et al. (1985) showed the influence of fines content on standard penetration test (SPT) blow count values ($(N_1)_{60}$) and the liquefaction strength of soil. The results showed that the $(N_1)_{60}$ value decreases as the fines content increases.

Much of the early works related to soil liquefaction induced by earthquakes were conducted in the laboratory using cyclic triaxial tests. Lee and Albaisa (1974) showed that the settlement of sands was caused by dissipation of excess pore-water pressures developed during cyclic loading. Tatsuoka et al. (1984) studied the volumetric strain after liquefaction and found that the amount of settlement can be significantly influenced by the maximum shear strain developed in the soil.

In recent years, land reclamation has been developed to provide additional land for industrial development. In general, the basic properties of reclaimed soil are low

Fig. 2. Grain-size distribution of reclaimed soil samples.

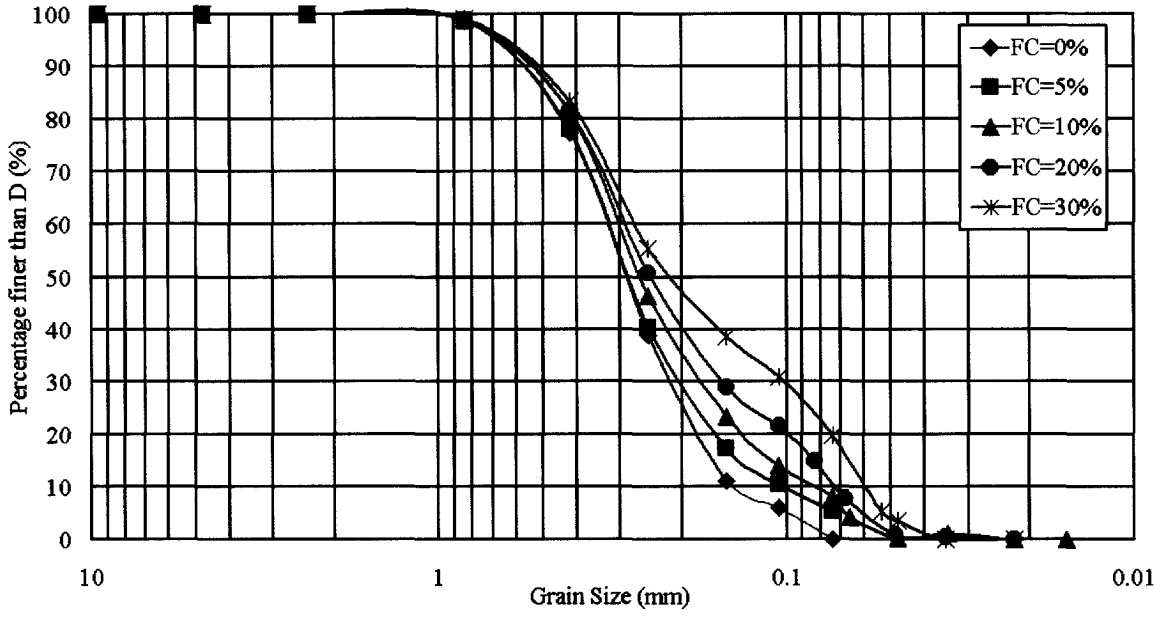


Table 1. Physical properties of reclaimed soil samples.

Fines content, FC (%)	0	5	10	20	30
Maximum dry density (g/cm^3)	1.604	1.686	1.739	1.784	1.806
Minimum dry density (g/cm^3)	1.233	1.270	1.303	1.330	1.340
Specific gravity, G_s	2.701	2.702	2.703	2.706	2.708
D_{50} (mm)	0.292	0.290	0.271	0.254	0.221
D_{10} (mm)	0.150	0.105	0.077	0.073	0.060
D_{30} (mm)	0.217	0.204	0.183	0.162	0.100
D_{60} (mm)	0.344	0.328	0.306	0.293	0.279
Coefficient of uniformity, C_u	2.3	3.1	4.0	4.1	4.7
Coefficient of curvature, C_c	0.91	1.21	1.42	1.21	0.60
Dry density at D_r = 35% (g/cm^3)	1.34	1.39	1.43	1.46	1.47
Dry density at D_r = 55% (g/cm^3)	1.41	1.47	1.51	1.55	1.56
Dry density at D_r = 75% (g/cm^3)	1.49	1.56	1.60	1.64	1.66
Void ratio at D_r = 35%	1.016	0.945	0.892	0.885	0.851
Void ratio at D_r = 55%	0.916	0.839	0.792	0.747	0.744
Void ratio at D_r = 75%	0.813	0.733	0.691	0.651	0.639

Table 2. Experiment conditions.

Sample preparation method	Moist tamping (MT)
Fines content, FC (%)	0, 5, 10, 20, 30
Relative density, D_r (%)	35, 55, 75
Total number of tests	70

strength, low relative density (D_r), and low SPT N values with high water contents (Sladen and Hewitt 1989). Therefore, reclaimed soil would readily liquefy under earthquake loading and wave forces. Thus, in this paper, different relative densities (35, 55, and 75%) and fines contents (FC) (5, 10, 20, and 30%) are considered to evaluate liquefaction resistance and liquefaction-induced settlement. The results are very useful as a reference for earthquake designs and ensure the safety and stability of reclamation engineering.

Test materials

The reclamation soil used in this investigation was obtained from the Yunlin area in west Taiwan (see Fig. 1). It is a uniform, fine, black sand classified as SP according to the Unified Soil Classification System (USCS). Grain-size data for the reclaimed soil (as Fig. 2) indicate a mean diameter D_{50} = 0.22–0.29 mm, a coefficient of uniformity C_u = 2.3–4.7, a coefficient of curvature C_c = 0.60–1.42, and effective diameter D_{10} = 0.06–0.15 mm (see Table 1).

From the in situ data, the fines content distribution of reclaimed soil ranges from 0 to 40%, with an average of about 10–20%. In this study, to understand the influence of the fines

Fig. 3. Sketch of the triaxial test system. LVDT, linear variable displacement transducer.

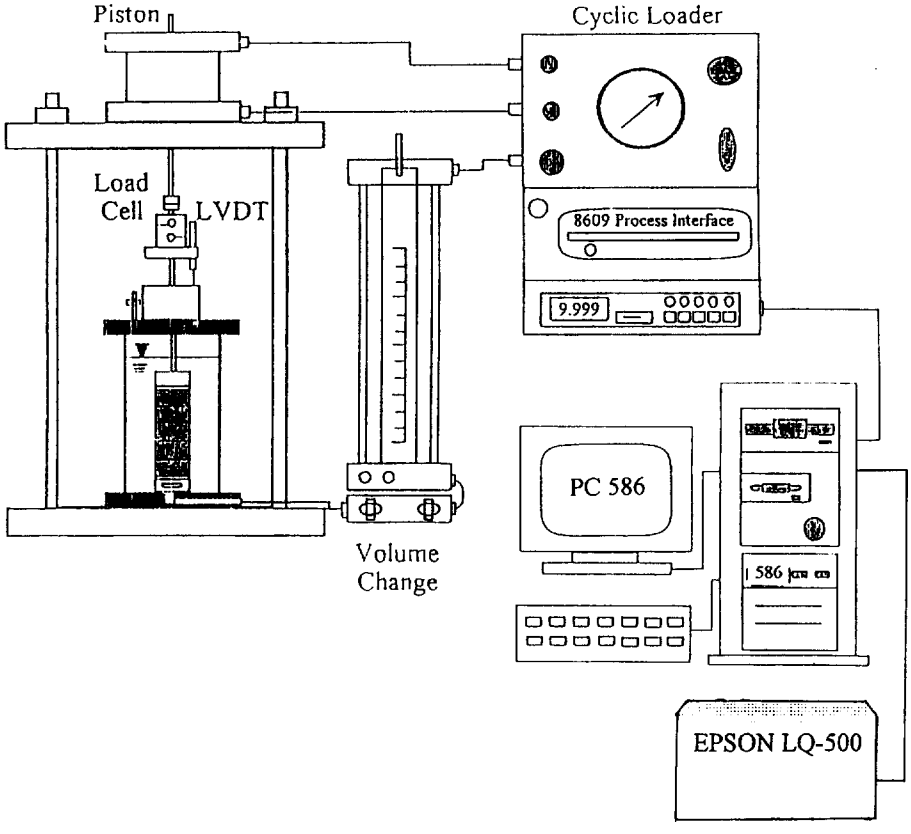


Table 3. Increment of relative density for different fines contents induced by the cyclic stress ratio.

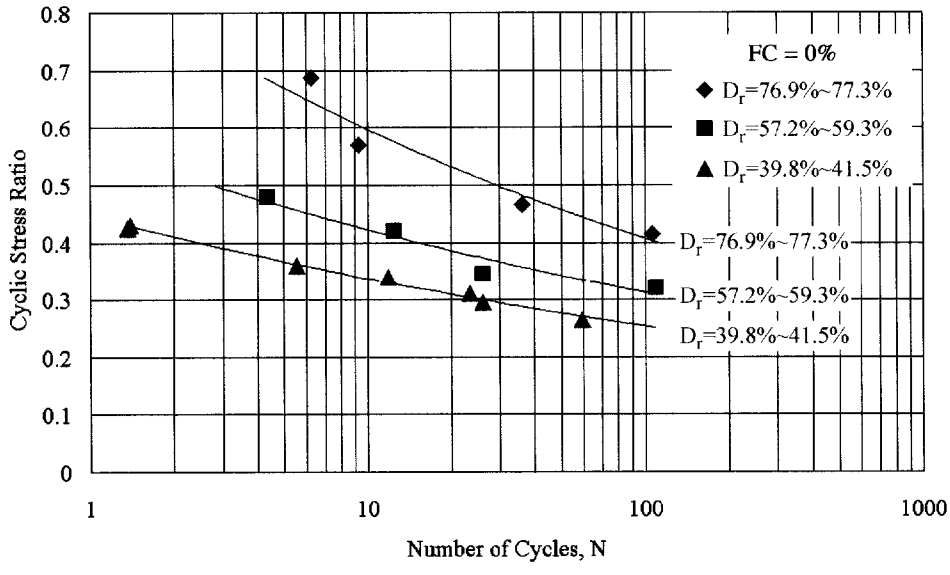
Relative density (%)	$(SR)_{10}$	Increment	$(SR)_{15}$	Increment	$(SR)_{20}$	Increment
Fines content = 0%						
76.9–77.3	0.60	1.77	0.56	1.74	0.53	1.72
57.2–59.3	0.42	1.25	0.40	1.25	0.39	1.25
39.8–41.5	0.34	1.00	0.32	1.00	0.31	1.00
Fines content = 5%						
76.0–76.8	0.57	1.74	0.54	1.76	0.51	1.77
57.3–58.0	0.42	1.29	0.39	1.30	0.38	1.30
39.7–40.2	0.33	1.00	0.30	1.00	0.29	1.00
Fines content = 10%						
77.3–77.6	0.54	1.69	0.50	1.69	0.48	1.70
56.5–59.2	0.42	1.31	0.39	1.31	0.37	1.31
38.4–40.0	0.32	1.00	0.30	1.00	0.28	1.00
Fines content = 20%						
76.2–77.4	0.49	1.76	0.45	1.77	0.41	1.71
57.3–58.1	0.33	1.18	0.30	1.19	0.29	1.20
41.3–42.4	0.28	1.00	0.26	1.00	0.24	1.00
Fines content = 30%						
76.2–77.9	0.42	1.69	0.37	1.60	0.34	1.55
60.3–60.7	0.28	1.12	0.26	1.12	0.24	1.11
41.8–42.9	0.25	1.00	0.23	1.00	0.22	1.00

content, different fines contents were adopted (0, 5, 10, 20, and 30%) to evaluate liquefaction resistance. Fines content was determined as the percent passing through the No. 200 sieve (<0.075 mm). The weight of the specimen is provided as a component to control the fines content of the specimen (Chien and Oh 1998). The test conditions are listed in Table 2.

Table 4. Relationship between volumetric strain and settlement ratio.

D_r (%)	FC (%)	SR	ΔV (cm^3)	ΔH (cm)	ε_v (%)	S_r(%)
Initial D_r = 35%						
40.8	0	0.2650	44.25	1.15	7.80	0.77
40.4	0	0.2950	48.78	1.27	8.60	0.85
41.0	0	0.3100	34.61	0.90	6.11	0.61
40.8	0	0.3400	45.34	1.18	8.17	0.79
40.7	0	0.3600	34.99	0.91	6.17	0.61
41.5	0	0.4250	41.25	1.07	7.29	0.72
39.8	0	0.4300	45.86	1.19	8.07	0.80
Initial D_r = 55%						
58.9	0	0.3200	33.23	0.86	5.84	0.58
59.3	0	0.3450	33.87	0.88	5.95	0.59
59.3	0	0.4200	32.93	0.86	5.79	0.57
58.8	0	0.4800	34.34	0.89	6.03	0.60
Initial D_r = 75%						
77.3	0	0.4150	21.57	0.56	3.77	0.38
77.2	0	0.4650	22.06	0.57	3.86	0.38
77.2	0	0.5700	22.77	0.59	3.98	0.40
76.9	0	0.6875	20.20	0.52	3.53	0.35

Fig. 4. Relationship between number of cycles and cyclic stress ratio for different relative densities.



Test procedure

The specimens were prepared using the moist tamping method with different relative densities and fines contents to investigate the liquefaction resistance of the reclaimed soil. The automatic triaxial test system was adopted to conduct the cyclic triaxial testing. The automatic triaxial test system was developed by Mulilis et al. (1977) at the University of California at Berkeley (as shown in Fig. 3). The test system has great advantages in stress, strain, and stress path control.

The soil samples were divided into five layers, with each layer determined by the weight and relative density of soil with the same volume. To eliminate the consolidation effects of the soil layer, the relative density for each layer is different. From top to the bottom of the soil sample, the relative density of each layer is $D_r + 2$, $D_r + 1$, D_r, $D_r - 1$, and $D_r - 2$%. After the specimens were prepared and consolidated, the liquefaction tests were performed. To evaluate the liquefaction-induced settlement, the volume changes induced by the dissipation of pore-water pressure were measured.

Experiment analysis and results

Liquefaction resistance of reclaimed soil with different fines contents

The liquefaction resistance of soil is expressed in terms of cyclic stress ratio τ_{av}/σ_0', where τ_{av} is the average cyclic stress, and σ_0' is the initial effective pressure. According to a related study of the influence of relative density on liquefaction resistance, dense sand has a higher liquefaction strength than loose sand. Therefore, to understand the influence of fines content, liquefaction tests were performed with different fines contents (FC = 0–30%) and different relative densities (D_r = 35, 55, and 75%).

Fig. 5. Relationship between number of cycles and cyclic stress ratio for different relative densities.

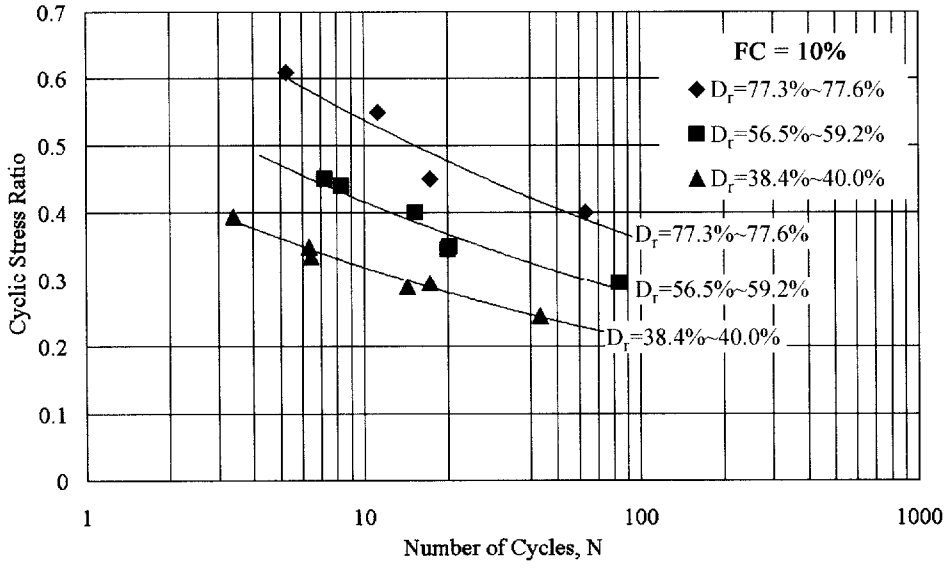
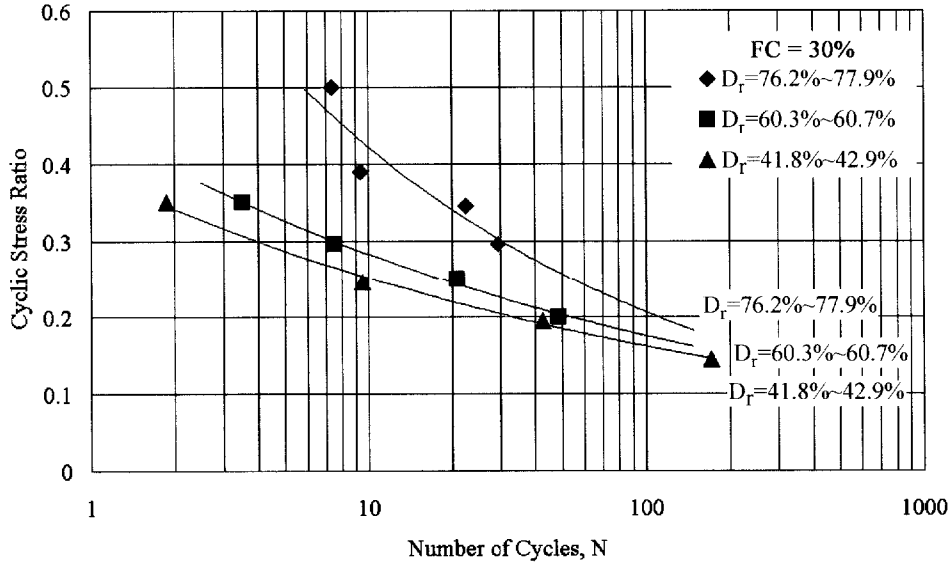


Fig. 6. Relationship between number of cycles and cyclic stress ratio for different relative densities.



The test results for the relationship between cyclic stress ratio and number of cycles are shown in Figs. 4–6, which show that the liquefaction resistance of dense soil is greater than that of loose soil. To evaluate the increment of cyclic stress with different fine contents, different numbers of cycles (N = 10, 15, and 20) and different cyclic stress ratios ($(SR)_{10}$, $(SR)_{15}$, and $(SR)_{20}$) were adopted. Based on the cyclic stress ratio of loose soil, the increment of cyclic stress ratio is defined and shown in Table 3. The cyclic stress ratio decreases as fines content increases. For soil with a moderate relative density, the increment of cyclic stress ratio ranges from 1.25 (FC = 0%) to 1.12 (FC = 30%). In addition, for soil with a high relative density, the increment of cyclic stress ratio ranges from about 1.75 (FC = 0%) to 1.55 (FC = 30%).

The relationship between number of cycles and cyclic stress ratio for different fines contents is presented in Fig. 7, which shows that the liquefaction resistance decreases as the fines content increases. For a fines content greater than 10%, the liquefaction curve reduces significantly. For an initial relative density of 75%, the liquefaction resistance decreases as the fines content increases. When N = 10, 15, and 20, the cyclic stress ratio can be obtained. As shown in Fig. 8, the ratios are less than 1.0 and decrease as N increases. For D_r = 76.0–77.9%, the ratio of liquefaction resistance curve increases for FC = 5%.

Liquefaction strength of reclaimed soil

Figures 9–11 present the relationship between cyclic stress ratio and void ratio, e. For N = 10, 15, and 20, the liquefaction resistance curves illustrate a linear relationship. For soil with a high relative density and low fines content, the void ratio is lower. As shown in

Fig. 7. Relationship between number of cycles and cyclic stress ratio for different fines contents.

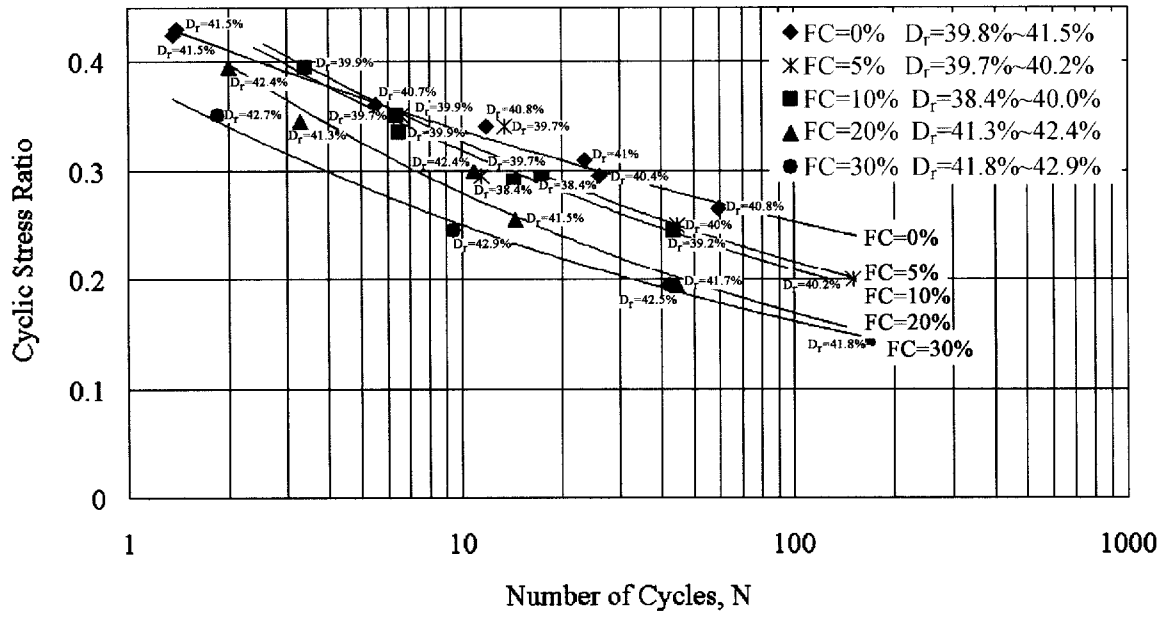


Fig. 8. Comparison curves for a specimen of clean sand (D_r = 38.4–42.9%) with different fines contents.

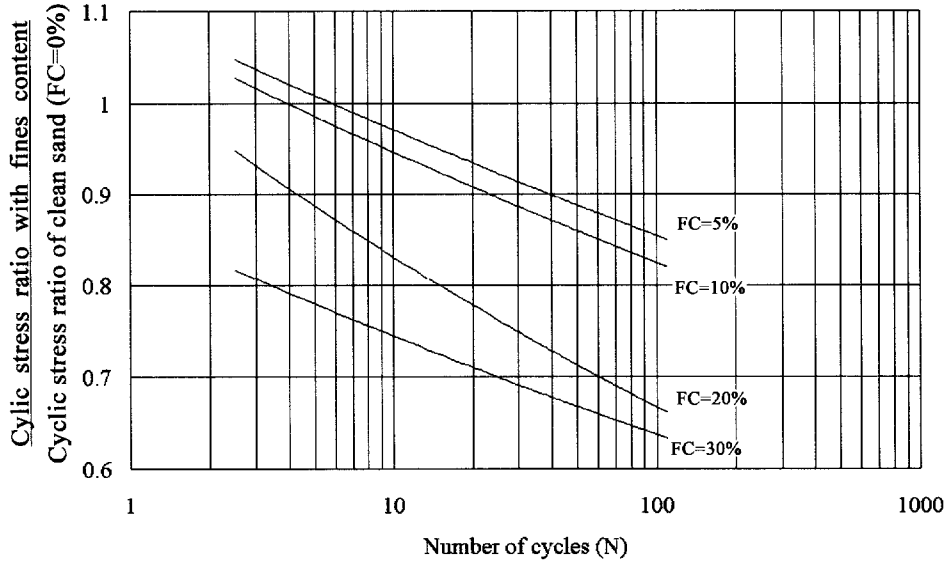


Fig. 12–14, the average relative density is approximately 40.59, 58.51, and 76.94%. The relationship between void ratio and cyclic stress ratio can therefore be obtained.

For a void ratio of 0.8 and N = 10, the cyclic shear stress ratio $(SR)_{10}$ is 0.59 (FC = 0%), and $(SR)_{10}$ is 0.24 (FC = 30%). For N = 20, the cyclic shear stress ratio $(SR)_{20}$ is 0.53 (FC = 0%), and $(SR)_{20}$ is 0.22 (FC = 30%). For different fines contents, the liquefaction strength of reclaimed soil decreases as the void ratio increases.

Liquefaction-induced settlement in reclaimed soil

In this study, to understand liquefaction-induced settlement, liquefaction tests were performed and volume change was measured (as shown in Table 4). Based on one-dimensional consolidation theory, the dynamic settlement of reclaimed soil is evaluated and discussed in the following sections.

Relationship between relative density and settlement of reclaimed soil

The relationship between relative density and consolidated volumetric strain after liquefaction is shown in Fig. 15. When the relative density increases, the volumetric strain decreases. Assuming the cross-sectional area of the test specimen is kept constant after liquefaction-induced consolidation, the vertical axial settlement (as the settlement induced by liquefaction) can be calculated from the volume changes and can be expressed as follows:

Fig. 9. Relationship between void ratio and cyclic stress ratio for different fines contents (N = 10).

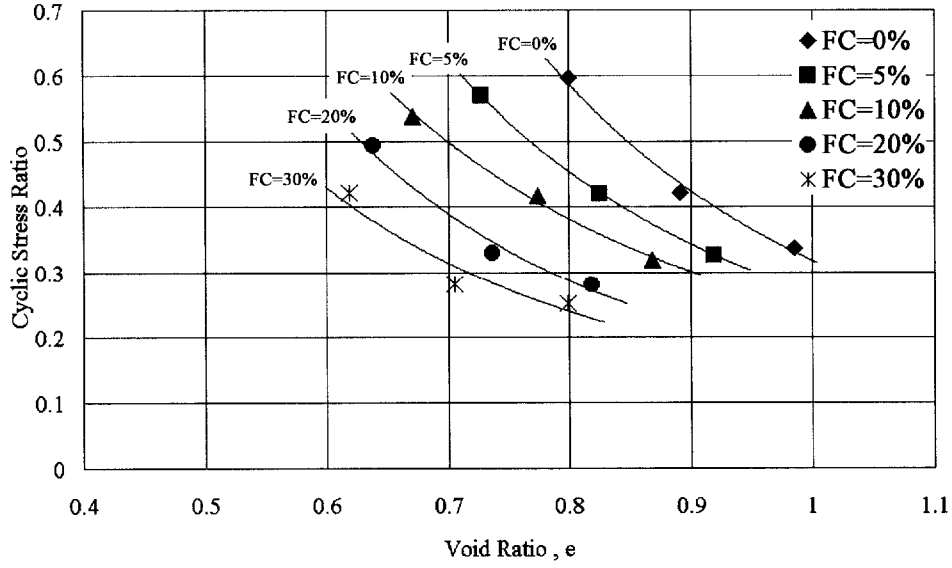
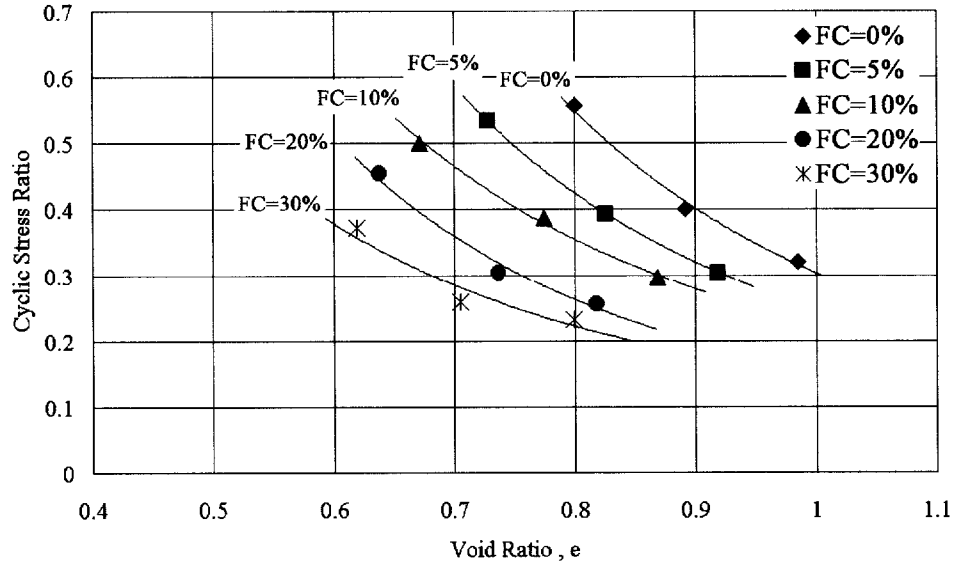


Fig. 10. Relationship between void ratio and cyclic stress ratio for different fines contents (N = 15).



$$[1] \qquad \Delta H = \frac{\Delta V}{A}$$

where ΔV is the volume change induced by liquefaction drainage, A is the cross-sectional area of the test specimen, and ΔH is the settlement change of the specimen.

Using the volume change, settlement changes are divided by the consolidated volume and specimen height. The volumetric strain (ε_v) and settlement ratio (S_r) are defined and the results are shown in Figs. 15 and 16. The volumetric strain ranges from about 3.5 to 9.5% and the settlement ranges from about 0.35 to 0.95%. For D_r = 40%, the average settlement is 0.78. For D_r = 60 and 75%, the average settlement is 0.58 and 0.42, respectively. These results indicate that the settlement ratio of reclaimed soil increases as the relative density decreases. Using regression analysis, the relationship between volumetric strain, settlement ratio, and relative density can be determined as follows:

$$[2] \qquad \varepsilon_v \text{ (in \%)} = -0.10D_r \text{ (in \%)} + 11.84 \qquad R^2 = 0.88$$

$$[3] \qquad S_r \text{ (in \%)} = -0.01D_r \text{ (in \%)} + 1.17 \qquad R^2 = 0.89$$

The relationships between volumetric strain and fines content and settlement ratio and fines content are presented in Figs. 17 and 18, respectively. The distribution range of volumetric strain and settlement ratio are influenced by relative density.

Influence of fines content on settlement

As shown in Fig. 19, the linear relationship between fines content and settlement is presented for different dry densities and fines contents. For the same dry density, the settlement ratio increases as the fines content increases. The settlement

Fig. 11. Relationship between void ratio and cyclic stress ratio for different fines contents (N = 20).

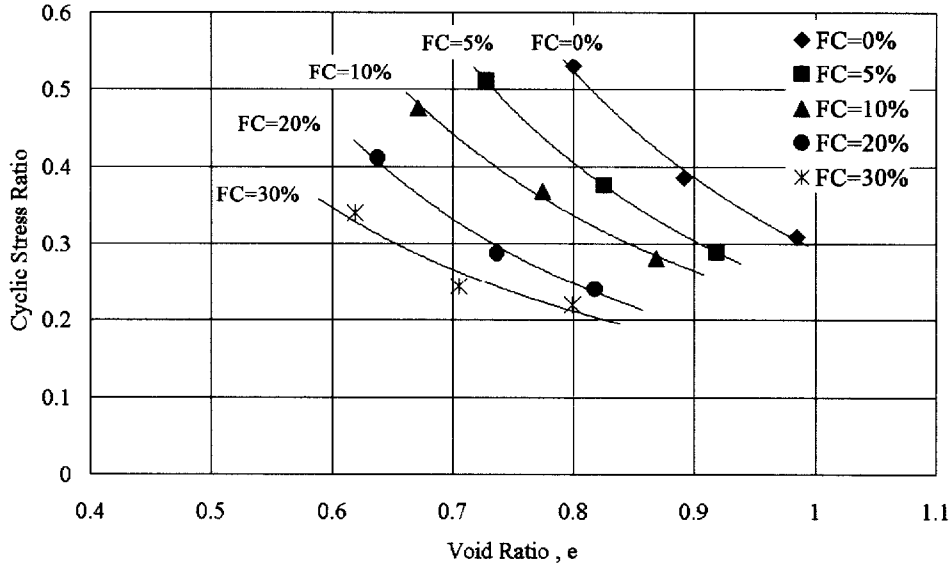
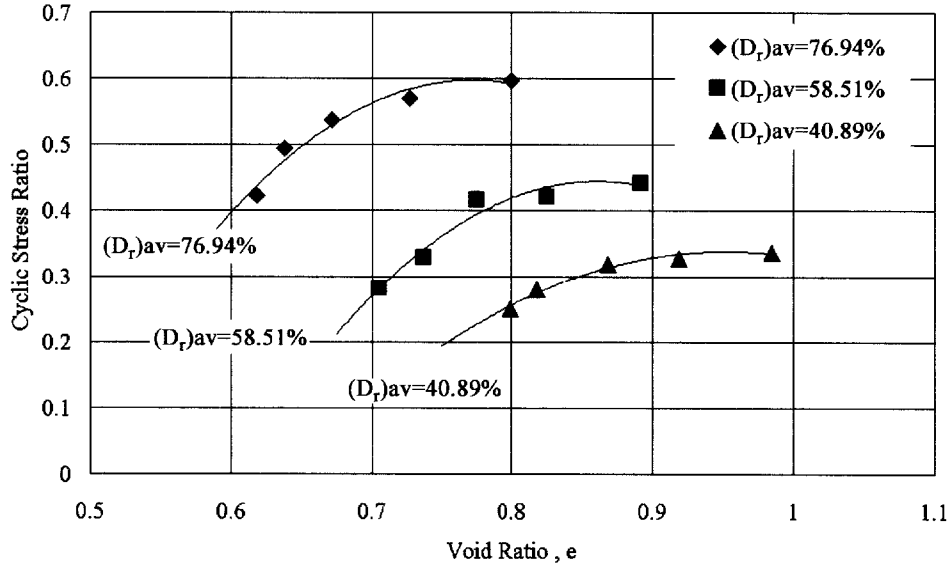


Fig. 12. Relationship between void ratio and cyclic stress ratio for different relative densities (N = 10).



ratio has the largest value for FC = 10%. This shows the influence of fines content on the settlement behavior of reclaimed soil.

Conclusions

In this study, which considered different relative densities and fines contents for reclaimed soil in the Yunlin nearshore area of west Taiwan, liquefaction tests were performed to evaluate the liquefaction strength and liquefaction–induced settlement. Based on the results of laboratory tests, the following observations were obtained:

(1) For the same fines content, the liquefaction strength of reclaimed soil increases as the relative density increases. In addition, for a constant relative density, the liquefaction strength decreases as the fines content increases.

(2) The relationship between dry density, void ratio, and liquefaction strength of reclaimed soil is established. The linear relationship demonstrates the influence of void ratio and fines content.

(3) For the liquefaction-induced settlement, the settlement ratio of reclaimed soil decreases as the relative density increases. For the same dry density, the settlement ratio increases as the fines content increases.

The results in this paper can be used for liquefaction resistance and settlement analysis and as a reference for planning, design, and related research in land reclamation engineering.

Fig. 13. Relationship between void ratio and cyclic stress ratio for different relative densities (N = 15).

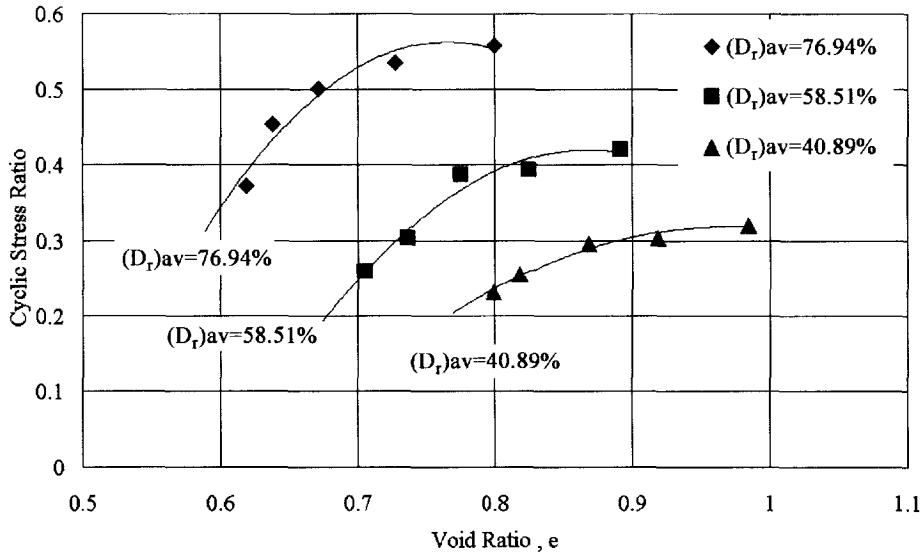


Fig. 14. Relationship between void ratio and cyclic stress ratio for different relative densities (N = 20).

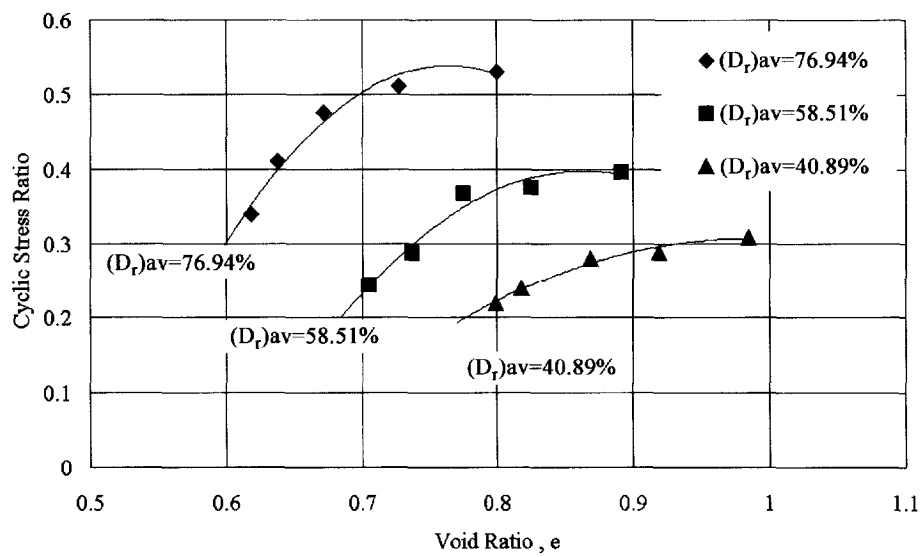


Fig. 15. Volumetric strain induced by liquefaction for different relative densities.

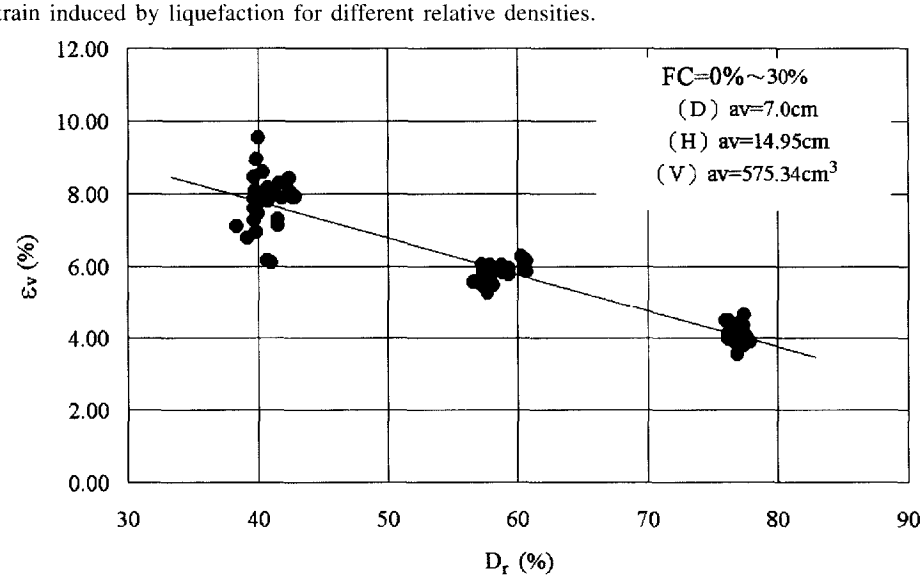


Fig. 16. Settlement ratio induced by liquefaction for different relative densities.

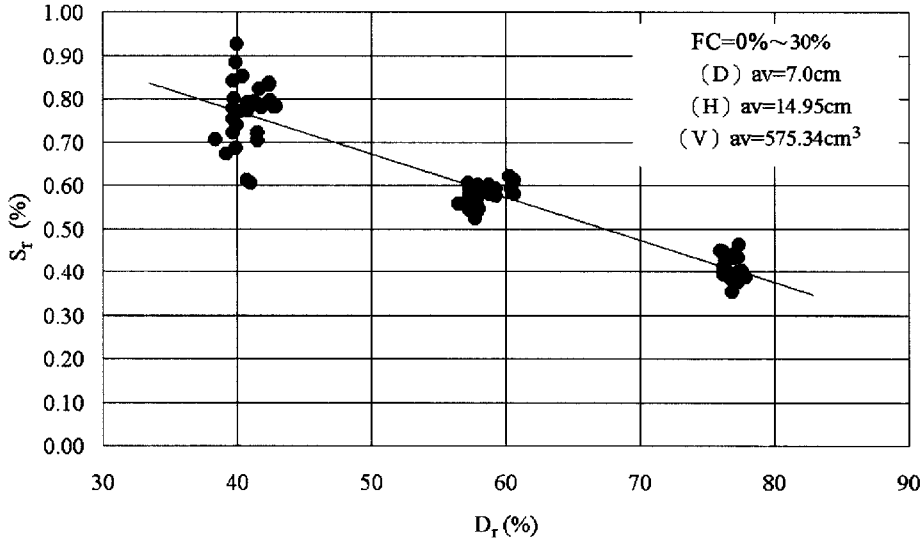


Fig. 17. Percentage of volumetric strain induced by liquefaction for different fines contents.

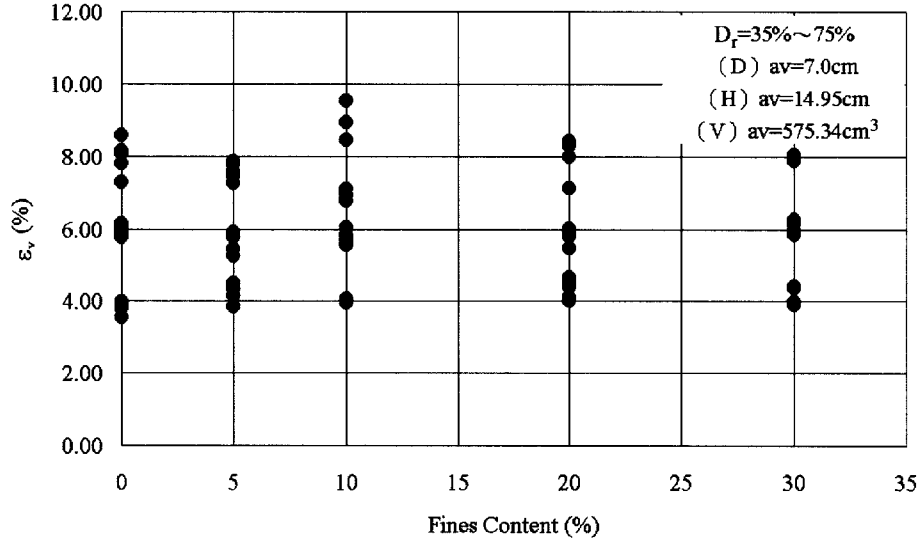


Fig. 18. Settlement ratio induced by liquefaction for different fines contents.

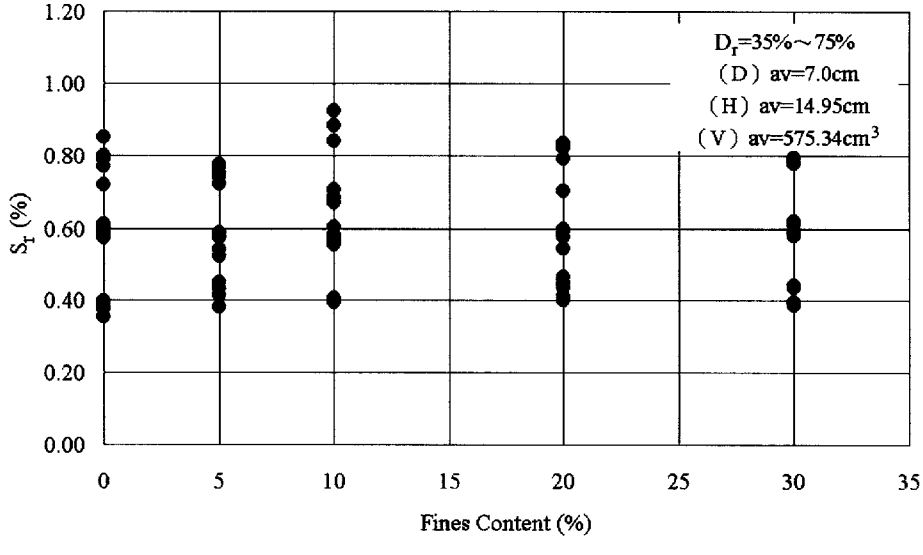
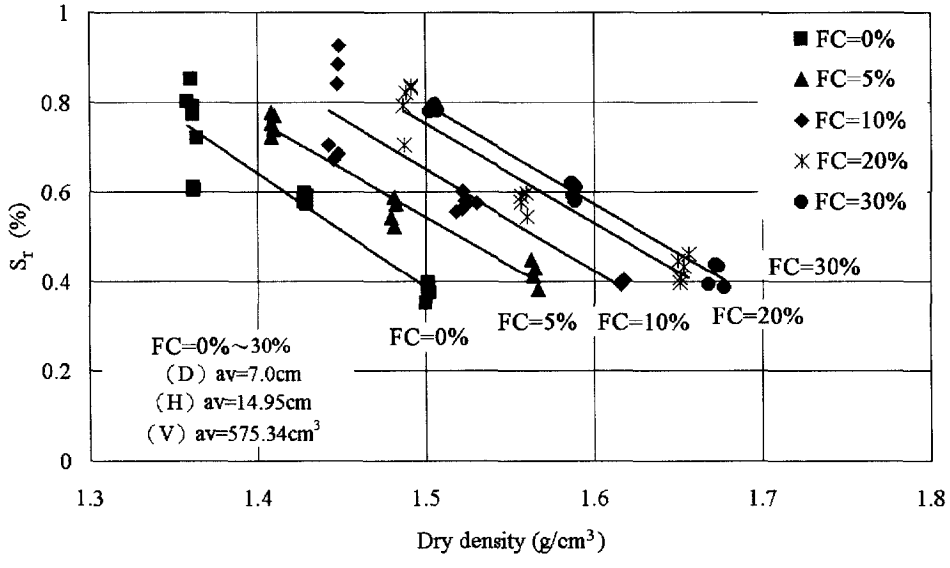


Fig. 19. Settlement ratio induced by liquefaction for different fines contents and dry unit weights.



Acknowledgment

This research was supported by the National Science Council of Taiwan under Grant No. NSC 87-2621-P019-002. This support was greatly appreciated.

References

Chien, L.K., and Oh, Y.N. 1998. Influences on the shear modulus and damping ratio of hydraulic reclaimed soil in west Taiwan. International Journal of Offshore and Polar Engineering, **8**(3): 228–235.

Lee, K.L., and Albaisa, A. 1974. Earthquake-induced settlements in saturated sands. Journal of the Soil Mechanics and Foundations Division, ASCE, **100**(SM4): 387–400.

Mulilis, J.P., Seed, H.B., Chan, C.K. 1977. Resistance to liquefaction due to sustained pressure. Journal of the Geotechnical Engineering Division, ASCE, **103**(GT7): 793–797.

Seed, H.B. 1979. Soil liquefaction and cyclic mobility evaluation for level ground during earthquakes. Journal of the Geotechnical Engineering Division, ASCE, **105**(GT2): 201–255.

Seed, H.B., and Idriss, I.M. 1967. Analysis of soil liquefaction: Niigata earthquake. Journal of the Soil Mechanics and Foundations Division, ASCE, **93**(SM3): 83–108.

Seed, H.B., Tokimatsu, K., Harder, L.F., and Chung, R.M. 1985. Influence of SPT procedures in soil liquefaction resistance evaluations. Journal of Geotechnical Engineering, ASCE, **111**(12): 1425–1445.

Sinotech Engineering Consultants, Inc. 1990. Yunlin offshore development project: morphological baseline studies. Sinotech Engineering Consultants, Inc., Taipei, Taiwan. (In Chinese.)

Sladen, J.A., and Hewitt, K.J. 1989. Influence of placement method on the in situ density of hydraulic sand fills. Canadian Geotechnical Journal, **26**: 453–466.

Tatsuoka, F., Sasaki, T., and Yamada, S. 1984. Settlement in saturated sand induced by cyclic undrained simple shear. *In* Proceedings of the 8th World Conference on Earthquake Engineering, San Francisco, Calif., pp. 95–102.