EVALUATION OF LIQUEFACTION RESISTANCE AND LIQUEFACTION INDUCED SETTLEMENT FOR RECLAIMED SOIL

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SUMMARY

In this study, the filled material in Yun-Lin near shore in west Taiwan is adopted as testing samples. Using moist tamping method, the specimens were prepared with different relative densities and fine contents. A series of triaxial liquefaction test was performed to evaluate the liquefaction resistance and liquefaction-induced settlement of reclaimed soil. Based on the proposed evaluation method and combined the one-dimensional consolidation theory, the volumetric strain and settlement of reclamation land would be predict by dry density and fines content of reclaimed soil. From the figures and results analysis, it can be a reference evaluation method for liquefaction resistance and liquefaction-induced settlement behavior of the reclaimed soil. This result is very useful to predict the liquefaction potential analysis and settlement for planning, design and related research of reclamation engineering.

Key Words: Reclaimed soil, Liquefaction resistance, Fines content, Settlement.

INTRODUCTION

Liquefaction is one of the most important, interesting, complex, and controversial topics in geotechnical earthquake engineering. Taiwan is located at the center of west circumpacific earthquake zone, and between Philippine plate and Eurasia plate. When plates move with respect to each other. The relative deformation between plates occurs near their boundaries, and could be induced earthquakes. Therefore, Taiwan has 1 to 2 major earthquakes per year and would cause severe damages. Earthquakes produced spectacular examples of liquefaction-induced damage for structures in land reclamation area, including slope failures, bridge and building foundation failures, and flotation of buried structures.

The liquefaction of reclaimed soil is influenced by factors such as earthquake loading, cyclic loading, relative density and fines content. Seed and Idriss (1967) illustrated that relative density is the main factor affecting the liquefaction strength of soil. The major earthquakes of Niigata in 1964 have illustrated that soil below 50% of relative density would liquefy. As for soil with 70% or higher relative density, the soil remains unchanged. By using dynamic triaxial tests, Seed (1979) showed that, for soil with 0% to 70% of relative density, the shear stress ratio for initial liquefaction would increase as the relative density increases. Seed et al. (1985) showed the influence of fines content on $(N_1)_{60}$ values and 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 earthquake are conducted in laboratory testing subjected to cyclic triaxial test. Finn and Barsty (1970) showed that, for soil under cyclic loading, the liquefaction strength of soil would increase with 0.5% of initial strain. By using moist tamping method with saturated specimen, Chien and Oh (1998) showed that, there is distinct influence of fines content on the dynamic properties of reclaimed soil.

Summarizing the above, for specimen under pre-cyclic loading, the soil aggregate would become denser and would increase the soil strength. In this study, the specimens are prepared with different relative densities (as 35%, 55% and 75%) and different fines content (as 5%, 10%, 20% and 30%). The cyclic triaxial tests are

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conducted with pre-cyclic loading to discuss the influence of initial earthquake on soil strength and liquefaction induce dynamic settlement of reclaimed soil.

In recent years, in order to promote development and utilization of marine resources and ocean space, the land reclamation is important to solve the lack and development of industrial estate. In general, the basic properties of reclaimed soil are low strength, low relative density and low SPT-N values with high water contents (Sladen and Hewitt (1989)). Therefore, the reclaimed soil would easily liquefied under earthquake loading and wave forces. Thus, in this paper, the different relative densities (as 35%, 55%, and 75%) and fines content (as 5%, 10%, 20%, and 30%) are considered to evaluate the liquefaction resistance and liquefaction-induced settlement. The results are very useful as reference for earthquake designs and ensure the safety and stability reclamation engineering.

Test Materials

The reclamation soil used in this investigation was obtained from Yun-Lin area. It is uniform, fine, black sand and classified as SP according to the Unified Soil Classification System (USCS). Grain-size data of the reclaimed soil (as Fig. 1) indicate a mean diameter D_{50} = 0.22 mm~0.29mm, a coefficient of uniformity C_u = 2.3~4.7, a coefficient of curvature C_c = 0.60~1.42, and an efficient diameter D_{10} = 0.06 mm~0.15mm. The index properties are shown in Table 1 respectively.

From the in-situ exploration data, the fines content distribution of reclaimed soil ranges very large from small fines content is 0% ~10% to high fines content is 20%~40% below –20m soil layers. The average fines content is about 10%~20%. In this study, in order to understand the influence of the fines content of reclaimed soil, the different fine contents were adopted as 0%, 5%, 10%, 20%, and 30% to evaluate liquefaction resistance and liquefaction-induced settlement. Fines content was obtained from the soil samples passing through the #200 sieve (<0.075mm). The weight of specimen is provided as a component to control the fines content of the specimen (Chien (1994)).

Test Procedure

The specimens are prepared by moist tamping method with different relative densities and fines content to discuss the influence of soil fabric properties for the liquefaction resistance of the reclaimed soil.

In this study, the automatic triaxial test system is adopted to conduct the cyclic triaxial liquefaction test. The automatic triaxial test system was developed by Mulils and Chan (1977) in University of California at Berkeley. The test system has great advantages in stress, strain and stress path control.

After the specimen was prepared and consolidated, a series of liquefaction test is performed. In order to understand the liquefaction-induced settlement, the volume changes induced by the dissipation of pore water pressure of specimens after liquefaction-induced consolidation is measured to evaluate the volumetric strain and settlement.

Table 1 Physical properties of reclaimed soil samples

Properties	Values				
Fines content (%)	0	5	10	20	30
Max. Dry Density (g/cm^3)	1.604	1.686	1.739	1.784	1.806
Min. 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)	0.15	0.105	0.077	0.073	0.06
D_{30}(mm)	0.217	0.204	0.183	0.162	0.1
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_d	0.91	1.21	1.42	1.21	0.60
Dry Dr=35% (g/cm^3)	1.34	1.39	1.43	1.46	1.47
Dry Dr=55% (g/cm^3)	1.41	1.47	1.51	1.55	1.56
Dry Dr=75% (g/cm^3)	1.49	1.56	1.60	1.64	1.66
Void Ratio (Dr=35%)	1.016	0.945	0.892	0.885	0.851
Void Ratio (Dr=55%)	0.916	0.839	0.792	0.747	0.744
Void Ratio (Dr=75%)	0.813	0.733	0.691	0.651	0.639

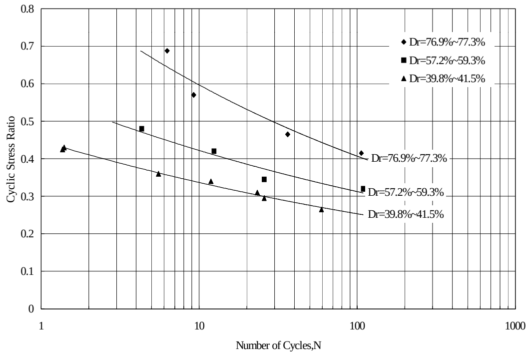

Fig.2 Relation between number of cycle and cyclic stress ratio under different relative density (F.C.=0%)

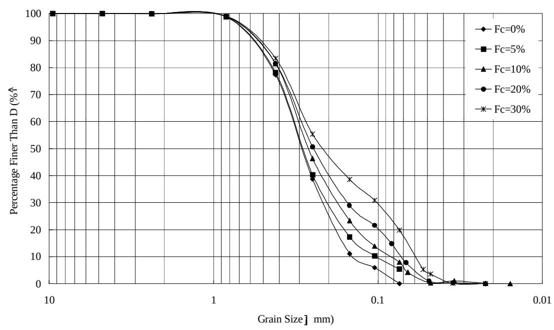

Fig. 1 Grain size distribution of reclaimed soil samples.

EXPERIMENT ANALYSIS AND RESULTS

Influence of fines content on liquefaction resistance for reclaimed soil

According to previous related study about influence of relative density on liquefaction resistance for reclaimed soil, the dense relative density of sand has higher liquefaction strength than loose relative density of sand. However, from in-situ data analysis, different relative densities of sands also possible have same liquefaction strength. Fines content of reclaimed soil is one of most influence factors. Therefore, in this study, in order to understand the influence of fines content, a series of liquefaction test was performed with different fine contents (as FC = 0% to 30%) and different relative densities (as Dr 35%, 55%, and 75%).

The typical test results between cyclic stress ratio and number of cycles are shown in Fig. 2. From the figures shows that the liquefaction resistance of dense relative density soil has greater than the loose relative density soil under the same fines content. In order to evaluate the increment of cyclic stress amplitude with different fine contents, by use of the 10,15, 20 number of cycles correspond to cyclic stress ratio is conducted. Based on the cyclic stress ratio of loose soil, the percent increment of cyclic stress ratio is defined, and shown in Table 2. The cyclic stress ratio has decreasing as fines content increasing tendency. The percent increment of cyclic stress ratio is not significant with number of cycles. For media density, the percent increment of cyclic stress ratio ranges from 1.25 (as FC is 0%) to 1.12 (as FC is 30%). In addition, for dense density, the percent increment of cyclic stress ratio ranges about from 1.75 (as FC is 0%) to 1.55 (as FC is 30%). In higher fines content, the percent increment of cyclic stress ratio has significant decreasing.

Table 2 Increment of relative density under different fines content induced by cyclic stress ratio.

Fines Content=0%							Fines Content =10%						
Relative Density (%)	$(SR)_{10}$	Increment (%)	$(SR)_{15}$	Increment (%)	$(SR)_{20}$	Increment (%)	Relative Density (%)	$(SR)_{10}$	Increment (%)	$(SR)_{15}$	Increment (%)	$(SR)_{20}$	Increment (%)
76.9□77.	0.60	1.77	0.56	1.74	0.53	1.72	77.3□77.	0.54	1.69	0.50	1.69	0.48	1.70
57.2□59.	0.42	1.25	0.40	1.25	0.39	1.25	56.5□59.	0.42	1.31	0.39	1.31	0.37	1.31
39.8□41.	0.34	1.00	0.32	1.00	0.31	1.00	38.4□40.	0.32	1.00	0.30	1.00	0.28	1.00
Fines Content =20%							Fines Content =30%						
Relative Density (%)	$(SR)_{10}$	Increment (%)	$(SR)_{15}$	Increment (%)	$(SR)_{20}$	Increment (%)	Relative Density (%)	$(SR)_{10}$	Increment (%)	$(SR)_{15}$	Increment (%)	$(SR)_{20}$	Increment (%)
76.2□77.	0.49	1.76	0.45	1.77	0.41	1.71	76.2□77.	0.42	1.69	0.37	1.60	0.34	1.55
57.3□58.	0.33	1.18	0.30	1.19	0.29	1.20	60.3□60.	0.28	1.12	0.26	1.12	0.24	1.11
41.3□42.	0.28	1.00	0.26	1.00	0.24	1.00	41.8□42.	0.25	1.00	0.23	1.00	0.22	1.00

When the relative density keeps constant (as initial relative density is 35%) and changes the fines content (as 0% to 30%), the relationship between number of cycles and cyclic stress ratio is presented in Fig. 5. From the figures shows that the liquefaction resistance of reclaimed soil has decreased as the fines content increases tendency under constant relative density. The fines content ranges from 0% to 10%, the liquefaction curve is not distinctive for initial relative density 35% and 55%. The variable range values are very closely. When the fines content is greater than 10%, the influence of liquefaction curve has significant reducing. For 75% of initial relative density, the liquefaction resistance uniform decreases as the fine content increases. When Nc = 10, 15, and 20, for specimen with different fine contents, the cyclic stress ratio can be obtained. As shown in Fig. 6, the ratio of cyclic stress ratio with clean reclaimed soil without fines content for 38.4% to 42.9% after consolidated relative density related with Nc under different fine contents. From the figures shows that the linear relationship is well. In general, the ratio values are small than 1.0, and difference of ratio value increases as the Nc increases. The Dr = 56.5% ~60.7% also has similar behavior. For dense relative density (as Dr = 76.0% ~77.9%), the ratio of liquefaction resistance curve has small increasing under fines content is 5%. Other curves are steady decreasing with fines content increasing.

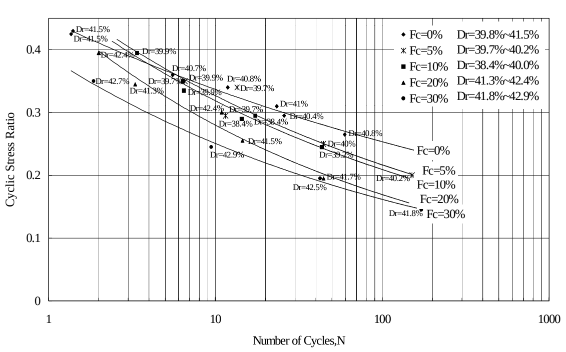

Fig.3 Relation between number of cycles and cyclic stress ratio under different fines content. (Initial Dr=35%)

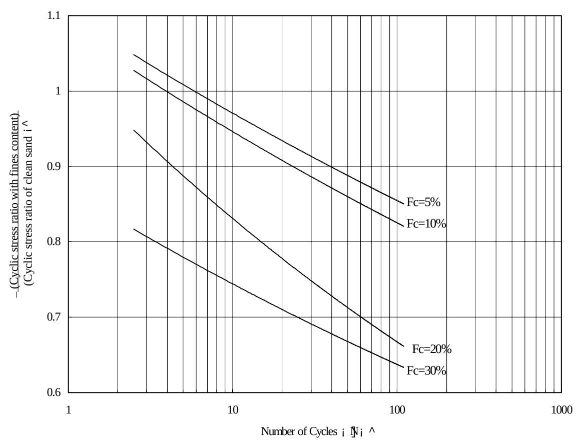

Fig.4 Comparison curve for specimen with fines content and clean sand (Dr=38.4%～42.9%).

The liquefaction resistance of the reclaimed soil

As shown in Fig. 5, the relationship between the cyclic stress ratio and void ratio of reclaimed soil with different fine contents is presented. Under number of cycles (Nc) is 10, considering the void ratio of the reclaimed soil cyclic stress ratio of liquefaction, the linear relationship of liquefaction resistance curves is well. It very clear can be compared with different fine contents.

When considering the fines content added the increment of fines content would be equal to the decrement of large grain material of specimen. Therefore, for high density with low fines content of specimen, the void ratio is possible lower than low density with high fines content of specimen, as shown in Fig.6. From the figures without considering the fines content, under after consolidated the average relative density is 40.59%, 58.51%, and 76.94%, the relationship between void ratio of reclaimed soil and the cyclic stress ratio can be obtained.

When number of cycles from 10 increases to 20 with different relative densities, cyclic shear stress require to cause liquefaction has decreasing tendency. For example, considering void ratio 0.8, and Nc = 10, for FC = 0%, the cyclic shear stress ratio required liquefaction $(SR)_{10}$ is 0.59. For FC = 30%, $(SR)_{10}$ is 0.24. When number of cycles increases to 20, for FC =10%, the cyclic shear stress ratio required liquefaction $(SR)_{20}$ is 0.53. For FC = 30%, $(SR)_{20}$ is 0.22. The liquefaction resistance has small decreasing tendency. Summarizing the above, under different fine contents, the liquefaction strength of reclaimed soil decreasing with the void ratio increasing.

On the other hand, combined the above results, under same number of cycles, the Fig.7 and Fig.8 can be obtained. According to initial liquefaction curve correspond to Nc = 20 and double axial amplitude strain (DA) reach to 5%, the liquefaction strength $(SR)_{20}$ is adopted to evaluate the properties of liquefaction strength. Between void ratio, dry density and liquefaction strength is presented in Fig.9 and Fig.10. In practice engineering, by use of fines content and dry density of soil layer, the liquefaction strength and relative density can be evaluated. From the regression analysis, the dry density related to liquefaction strength $(SR)_{20}$ with different fine contents can determine as follows:

For FC = 0%, $(SR)_{20} = 0.059 \times (\gamma_d)^{5.31}$ $R^2=0.994$ (1)

For FC = 5%, $(SR)_{20} = 0.046 \times (\gamma_d)^{5.30}$ $R^2=1.000$ (2)

For FC = 10%, $(SR)_{20} = 0.053 \times (\gamma_d)^{4.50}$ $R^2=0.995$ (3)

For FC = 20%, $(SR)_{20} = 0.027 \times (\gamma_d)^{5.40}$ $R^2=0.987$ (4)

For FC = 30%, $(SR)_{20} = 0.038 \times (\gamma_d)^{4.13}$ $R^2=0.924$ (5)

Combined above equation (Eq.(1) to Eq. (5)) and regression analysis, it can be obtained the dry density(γ_d) related with $(SR)_{20}$ under different fine contents as follows:

$$(SR)_{20} = a_1 \times (\gamma_d)^{b_1} \quad (6)$$

Where, a_1 and b_1 are function of fine content, a_1 = 0.059-0.0078 FC + 0.0015 FC^2, and b_1 = 5.311+0.0247 FC - 0.0714 FC^2. From the above test results analysis, considering the relative density and fine content to evaluate the liquefaction strength, it can be obtained good agreement. The results are very useful to provide the reference of liquefaction strength evaluation of the land reclamation engineering.

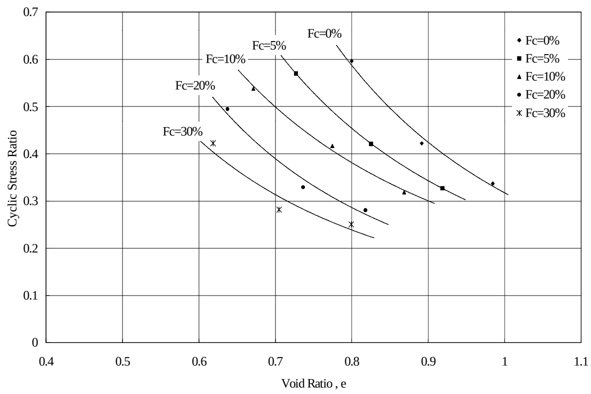

Fig.5 Relation between void ratio and cyclic stress ratio under different fines content (No. of cycle=10).

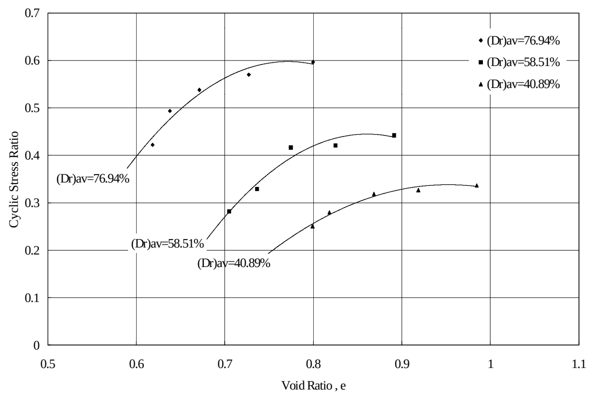

Fig.6 Relation between void ratio and cyclic stress ratio under different relative densities (No. of cycle=10).

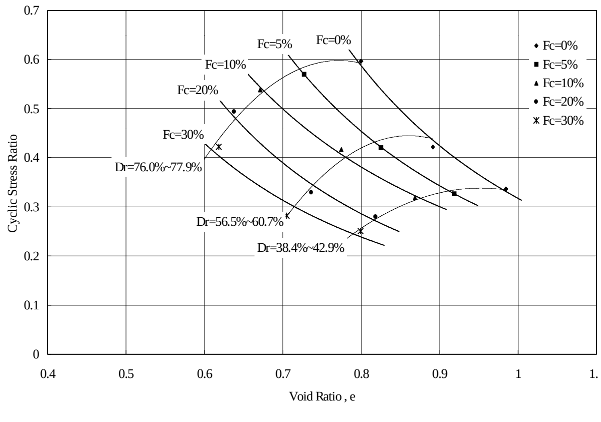

Fig.7 Relation between void ratio and cyclic stress ratio under different fines content and relative densities (No. of cycle=10).

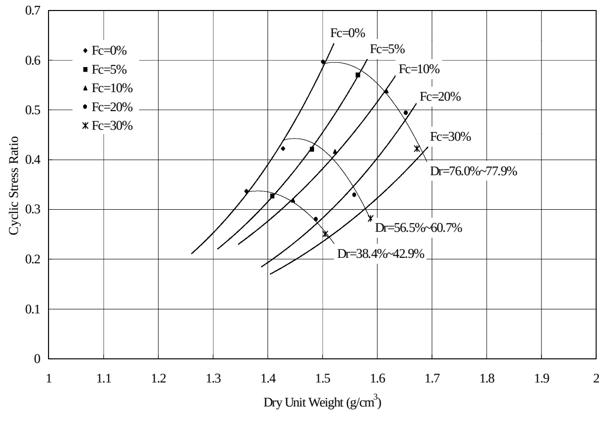

Fig.8 Relation between dry unit weight and cyclic stress ratio under different fines content and relative densities (No. of cycle=10).

Liquefaction-induced settlement in reclaimed soil

In this study, in order to understand the liquefaction induced settlement on reclaimed soil, a series of liquefaction test was performed and the volume change after liquefaction-induced consolidation was measured. Based on one-dimensional consolidation theory, the dynamic settlement of reclaimed soil can be evaluated and is discussed as follow:

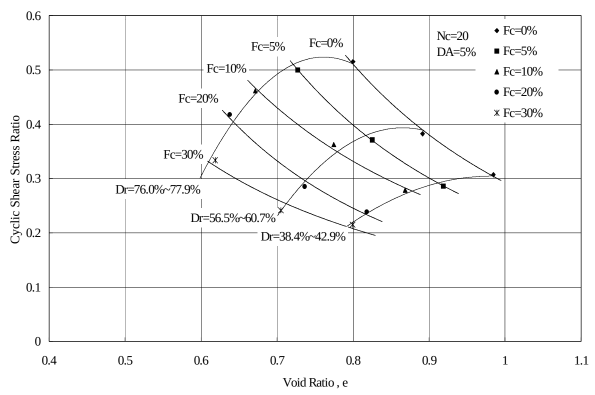

Fig.9 Relation between void ratio and cyclic stress ratio under different fines content and relative densities (No. of cycle=20, DA=5%).

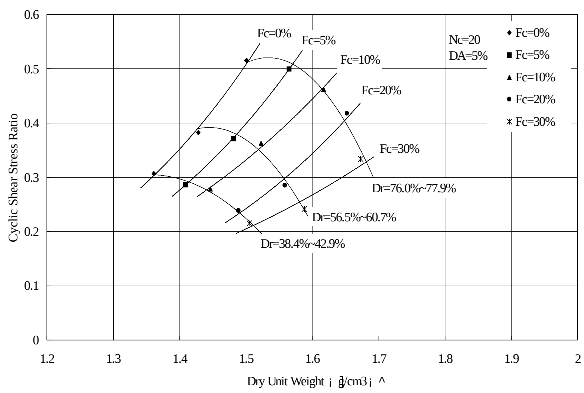

Fig.10 Relation between dry unit weight and cyclic stress ratio under different fines content and relative densities (No. of cycle=20, DA=5%).

(1) The relationship between relative density and settlement of reclaimed soil

The relations between relative density and consolidated volumetric strain after liquefaction are shown in Fig.11. When the relative density increases, the volumetric strain of reclaimed soil decreases. For sake of convenience the settlement induced by liquefaction, the concept of one-dimensional consolidation is adopted. Assume the cross section area of tests specimen kept constant after liquefaction induced consolidation, the vertical axial settlement (as the settlement induced by liquefaction of reclaimed soil) could be calculated from the volume changes, and can be expressed as follows:

$$\Delta H = \frac{\Delta V}{A} \qquad (7)$$

Where, ΔV is the volume changes induce by liquefaction drainage, A is the section area of tests specimen, and ΔH is the settlement changes of specimen based on the concept of one-dimensional consolidation.

By use of original volume changes and settlement changes are divided by the consolidated volume and specimen height, the percent of volumetric(ε_v) and settlement ratio (S_r) are defined. The typical results are shown in Fig.11. The percent of volumetric ranges about from 3.5% to 9.5% and the settlement ratio ranges about from 0.35% to 0.95%. When relative density is 40%, the average settlement ratio is 0.78. For the soil with relative density 60% and 75%, the average settlement ratio are 0.58 and 0.42, respectively. These results indicated that the settlement ratio of reclaimed soil has increased as the relative density decreases. Thus, also shows the denser sand is not easy to induce the settlement. According to regression analysis, the relationship between percent of volumetric, settlement ratio, and relative density can be determined as follows:

$$\varepsilon_v\ (\%) = -0.10\ Dr\ (\%) + 11.84,\ R^2 = 0.88 \qquad (8)$$

$$S_r\ (\%) = -0.01\ Dr\ (\%) + 1.17,\ R^2 = 0.89 \qquad (9)$$

The typical results between percent of volumetric, settlement ratio, and fines content presented in Fig.12. It is clearly show that the influences of different fine contents on variable change values is not distinctive for different relative densities. But, considering the same fines content, and taking the average value of distribution ranges, could be found from F_c=0% to F_c=5% has decreasing tendency. When fines content is greater than 5% has increasing tendency. But when fines content is greater than 10% has decreasing tendency. In general, the average percent of volumetric strain ranges from 4% to 8%, and the settlement ratio ranges from 0.4% to 0.8%. Therefore, the distribution ranges of percent of volumetric strain and the settlement ratio are always influenced by relative density. When the high relative density was adopted, it could be obtained lower values tendency. If the low relative density was adopted in testing, it could be obtained great values. Hence, the distribution ranges of percent of volumetric strain and the settlement ratio can be increased.

(2) Influence of fines content on settlement

Considering the different fines contents such as 0%, 5%, 10%, 20%, 30%, the effects of fines content was considered. The typical test results were presented in Fig.13. As shown in the figure, the linear relationship is well under different dry density of reclaimed soil. It very clear can be compared with different fine contents and the curve with different fine contents right-hand side moving with fine content increasing. This is expressed the settlement ratio of reclaimed soil decreases as the dry density increases. For the settlement ratio, the distribution ranges about from 0.4% to 0.8%. The settlement ratio increases as the fines content increasing. Under the same dry density of reclaimed soil, the more fine content easy to induce settlement tendency. In order to understand the effect of fines content, the case of γ_d = 1.5 g/cm^3 is discussed. From the Fig.13 shown that, when the fines content from 0% increases to 30%, the settlement ratio of reclaimed soil from 0.39% increases to 0.8%.

Based on regression analysis, the reclaimed soil of dry density(γ_d) related with settlement ratio(S_r) can be expressed under different fines content(F_c) as follows:

$$FC = 0\%,\ S_r\,\% = -2.56\gamma_d + 4.22,\ R^2 = 0.86 \tag{10}$$

$$FC = 5\%,\ S_r\,\% = -2.14\gamma_d + 3.76,\ R^2 = 0.96 \tag{11}$$

$$FC = 10\%,\ S_r\,\% = -2.26\gamma_d + 4.04,\ R^2 = 0.83 \tag{12}$$

$$FC = 20\%,\ S_r\,\% = -2.20\gamma_d + 4.05,\ R^2 = 0.92 \tag{13}$$

$$FC = 30\%,\ S_r\,\% = -2.21\gamma_d + 4.11,\ R^2 = 0.99 \tag{14}$$

Combined above equations (Eq.(10) to Eq.(14)) and regression analysis, it can be obtained the relationship between dry density(γ_d) and settlement ratio(S_c) as follows:

$$S_c(\%) = a\gamma_d + b \tag{15}$$

Where, a and b are function of fines content, a=-2.56+0.19 FC –0.03 FC^2 , and b=4.22-0.25 FC +0.04 FC^2.

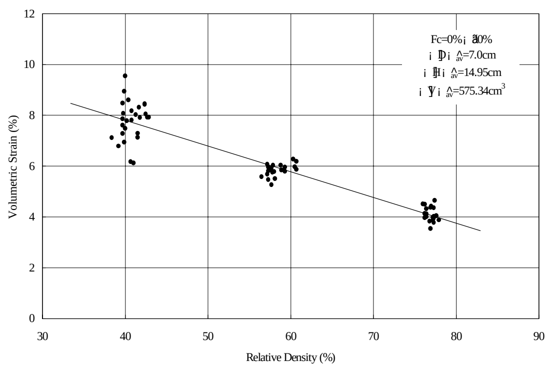

Fig.11 Percentage of volumetric strain induced by liquefaction under different relative density

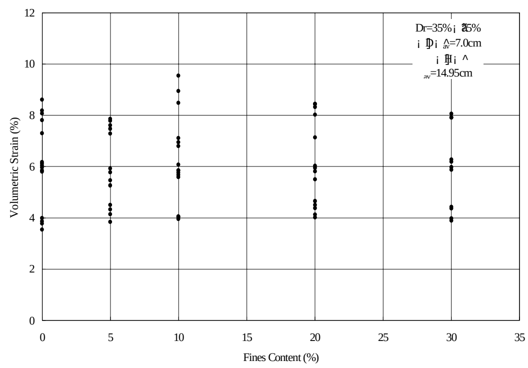

Fig.12 Percentage of volumetric strain induced by liquefaction under different fines content.

Summarizing the above analysis, it could be found that only considering the relative density to evaluate the settlement of after liquefaction for reclaimed soil, is not completely response the effects of the fine content. On basis of the soil dry density and fines content, a new proposed method is established to evaluate the liquefaction induced settlement of reclaimed soil, and good agreements are obtained.

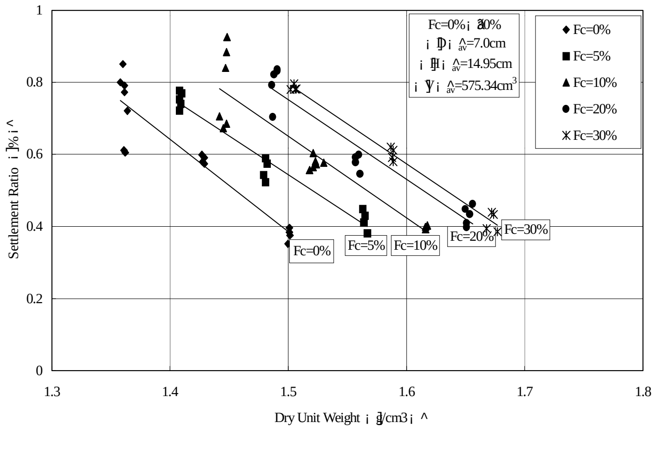

Fig.13 Settlement ratio induced by liquefaction under different fines content and dry unit weight.

CONCLUSIONS

In this study, considering different relative densities and fine contents for reclaimed soil in Yun-Lin nearshore area in west Taiwan. A series of liquefaction test was performed to evaluate the liquefaction strength and liquefaction –induced settlement. Based on the results of laboratory tests, the following conclusions can be drawn.

1. Under the same fines content, the liquefaction strength of reclaimed soil increases as the relative density increases tendency. In addition, under the 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, and the linear relationship is well.
3. For the liquefaction induced settlement analysis, the settlement ratio of reclaimed soil increases as the relative density increases. Under the same dry density, the settlement ratio increases as the fines content increases.
4. On the basis of the reclaimed soil dry density and fines content, a new proposed method is established to evaluate the liquefaction resistance and liquefaction induced settlement.
5. For the liquefaction induced settlement analysis, the results indicated that, the settlement ratio of reclaimed soil increases as the relative density increases. Under the same dry density, the settlement ratio increases as the fines content increases. Based on the reclaimed soil dry density and fines content, a new proposed method is established to evaluate the liquefaction induced settlement.

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

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