A study on the shear modulus and damping ratio of reclaimed soil in Yun-Lin nearshore area
台湾西部外海回填土壤剪切模量与阻尼比之研究

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Abstract　In this study，using the filled material in Yun-Lin nearshore area as test samples，a series of resonant column test has been performed to evaluate the dynamic properties of filled material. From the test results，the relation curve of normalized shear modulus （G/G_{max}）vs. shear strain （γ）lies on the upper bound of the curve suggested by Seed and Idriss，and the damping ratio （D）vs. shear strain （γ）lies on the lower bound of the suggested curve. The influence of confining pressure，different fines contents and relative densities on dynamic properties of reclaimed soil were discussed. Based on the equations suggested by Seed and Idriss，a new proposed method was established to evaluate the shear modulus of reclaimed soil under different fine contents and relative densities. Using the resonant column triaxial test and static triaxial test results，and based on elastic theory for 1% of axial strain，the deviator stress and G_{max} are found to be related. The results shown in this paper can be used as a reference for foundation and structure design in land reclamation area.
Key words　reclaimed soil，resonant column test，shear modulus，damping ratio.
Lien－Kwei Chien　Male，born in 1957，Ph.D.（geotechnical engineering）and associate professor. Recent research topics are focus on nearshore and offshore geotechnical engineering，reclamation geotechnical problem （as liquefaction behavior，and dynamic properties），and undersea technology.
文　摘　本研究采用云林外海的土壤进行共振柱试验，以求得回填土壤之剪切模量与阻尼比。试验资料正规化（G/G_{max}）与剪应变振幅（γ）关系曲线位于 Seed 和 Idriss 所建议曲线的上限范围，而阻尼比与剪应变振幅关系曲线则位于其下限范围。采用 Seed 和 Idriss 评估土壤剪力数模的方式，建立不同细粒含量回填土壤于不同相对密度下，所对应的 K_2 值之相关图表，以提供作为回填造地工程规划之参考。同时本研究利用静力三轴试验结果，以弹性理论推求于轴应变为 1% 时所对应之偏应力与最大剪切模量具有相关联性。利用本研究所建立之回填土壤动态特性相关评估方式及图表可作为回填土壤造地时有关承受动态荷重基础及结构物之参考。
关键词　回填土壤，共振柱试验，剪切模量，阻尼比。
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1　Introduction

Hydraulic fill method is one of important reclamation methods in nearshore areas of West Taiwan. The materials for hydraulic fill were obtained from the seabed or river mouth by use of cutter and pump，and transferred to the land reclamation area using the pressure pipe and barge. The reclamation land has multiple-purpose. So，this construction method is very economical and beneficial. The earthquake loading should be considered in the nearshore reclamation area of West Taiwan. The effects of wave forces and wind forces were also considered as the main factors affecting the stability of foundation structure in nearshore reclamation area. According to Sladen and Hewitt's [1] studies on the Beaufort man-made island in Canada. The relative density of hydraulic fill soil ranges from 0% to 70%，the relative density is difficult to be controlled and is normally below 50%. Thus，the possible factors of influence，such as fines content，particle fabric，void ratio，effective confining pressure and shear strain，are taken into consideration in the laboratory test to evaluate the dynamic properties of reclaimed soil. This is very important for the safety and stability of reclamation engineering. Therefore，the purpose of this paper is to evaluate the dynamic properties of reclaimed soil.

In this study，a successful hydraulic fill method is developed to prepare specimens and to simulate packing properties of the in-situ reclaimed sand. Resonant test is conducted to discuss the properties （such as shear modulus and damping ratio） of reclaimed soil. The traditional moist tamping method is used to prepare specimens. The influences of different confining pressures，different fines contents，different relative density and specimen preparation methods are discussed.

2　Previous related studies

The dynamic properties of soil are influenced by factors [2] such as strain amplitude，effective mean principle stress，void ratio，cyclic number，saturation degree，overconsolidation ratio，effective confining pressure，soil fabric （specimen preparation method） and others. The main influence factors include shear strain，effective mean principle stress，void ratio and soil fabric.

Hardin and Drenvich [2] presented that the relationship between shear stress and shear strain of sand is nonlinear，namely the shear modulus decreases nonlinearly as the strain amplitude increases. Hall and Richart [3] showed that the damping ratio increases as the shear strain amplitude increases for dry Ottawa sand.

Seed and Idriss [4] proposed an equation for the relationship between shear stress and effective confining pressure as follows

$$G = 22 \cdot K_2 \cdot (\sigma'_m)^{0.5} \qquad (1)$$

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where σ'_m is average effective confining pressure (kgf/cm^2), and K_2 is a parameter depending upon the void ratio and shear strain amplitude of sand.

Hardin and Richart[5] presented that when the shear strain is below 10^{-6}, the shear modulus of sand almost keeps a maximum constant value. The relationship between void ratio and maximum shear modulus can be shown as follows

$$G_{max} = A \cdot F(e) \cdot (\sigma'_m)^n \quad (2)$$

where

$$F(e) = \frac{(2.97 - e)^2}{(1 + e)}, \text{for angular grained sand} \quad (3)$$

$$F(e) = \frac{(2.17 - e)^2}{(1 + e)}, \text{for round grained sand} \quad (4)$$

A is a dimensionless parameter of soil, and n is a parameter.

Iwasaki and Tatsuoka[6] obtained a formula of the maximum shear modulus for different clean sand as follows:

$$G_{max} = 900 \cdot F(e) \cdot (\sigma'_m)^{0.4} \quad (5)$$

where $F(e) = \frac{(2.71 - e)^2}{(1 + e)}$.

The above equation shows that the shear modulus increases as the effective confining pressure increases. From the previous studies, the maximum shear modulus is related to the effective confining pressure with a power of n. When the shear strain amplitude ranges from small to large strain, n ranges from 0.5 to 1.0. The G_{max} is influenced by void ratio, and decreases as the void ratio increases.

Summarizing all of the previous studies, the liquefaction evaluation studies for earth dam are extensively discussed, but the dynamic properties of reclaimed soil are not completely studied. Thus, in this paper, the filled material in Yun-Lin nearshore area is adopted as test samples, and resonant column tests are conducted to discuss the dynamic properties of reclaimed soil in the West Taiwan offshore area. A successful simulation method of hydraulic fill sand was developed by author to simulate the packing properties of the reclaimed soil condition. The empirical relations are newly developed and evaluation methods are revealed for the dynamic properties of the offshore hydraulic fill soil in West Taiwan area.

3 Experimental investigation

3.1 Test material and equipment

In this study, the soil samples were obtained from the offshore-reclaimed soil by vibration coring method in the Yun-Lin industrial estate area (as shown in Fig. 1). The sand is composed of subangular grains. The index properties and grain size distribution of reclaimed soil with different fines contents is shown in Table 1. The resonant column triaxial tests were successfully used for testing specimens by using the resonant column apparatus, Model DTC -158 developed by Seiken Inc. (Japan). Air supply control system, oscillation control system, measurement system and triaxial cell are included in the main apparatus.

3.2 Sample preparation

In this study, the moist tamping method (M.T.), the multi-sieve pluviation (through water) method (M.P.) and the hydraulic fill method (H.F.) were adopted to prepare specimens.

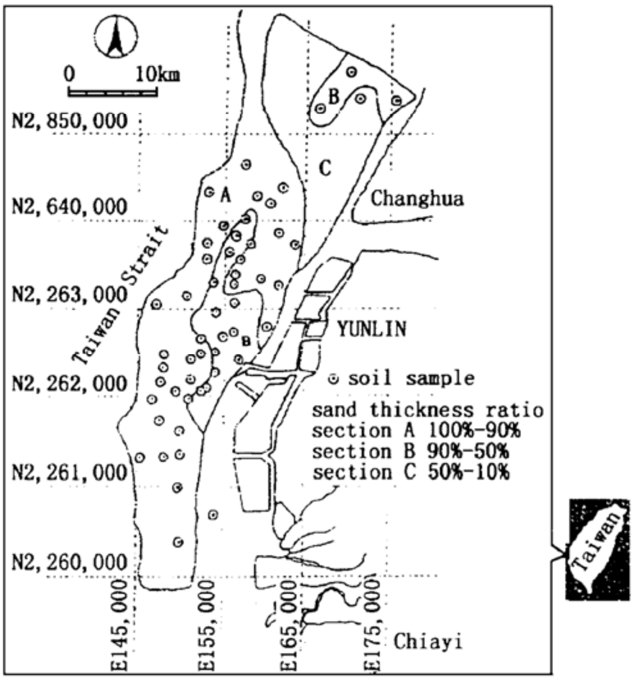

Fig.1 Sketch of reclaimed soil in Yun-Lin offshore area

Table 1 General properties of different fines content soil

Physical index	Fines content (%)			
	0	10	20	30
Specific gravity, *Gs*	2.691	2.696	2.698	2.701
Maximum dry density (g/cm^3)	1.59	1.68	1.76	1.79
Minimum dry density (g/cm^3)	1.199	1.205	1.214	1.197
D_{50} (mm)	0.164	0.155	0.146	0.137
D_{60} (mm)	0.169	0.165	0.157	0.155
D_{30} (mm)	0.138	0.129	0.109	0.074
D_{10} (mm)	0.100	0.074	0.046	0.025
Coefficient of uniformity, *Cu*	1.688	2.232	3.393	6.306
Coefficient of curvature, *Cc*	1.347	1.353	1.630	1.477

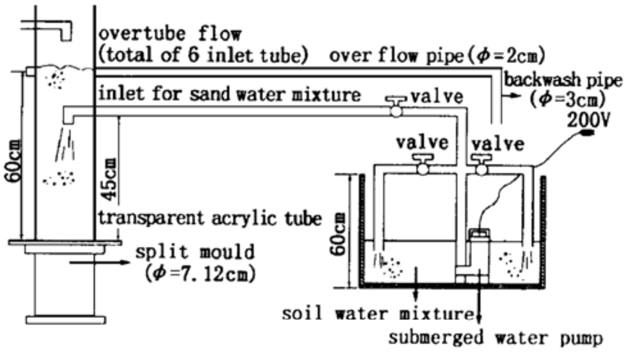

Fig. 2　Sketch of hydraulic fill sand system

A new simulation method of hydraulic fill was developed to simulate the in-situ filling procedure of the reclaimed materials (as shown in Fig. 2). In this method, a water pump with a diameter of 50mm and a flow of 0.15 m^3/min is submerged in a uniform mixture of sand and water. Three pipes are connected to pump. The specimen prepared by the hydraulic fill method has an initial relative density ranging from 32% to 47%.

3.3　Test procedure

A series of resonant column triaxial test were performed to discuss the dynamic properties of reclaimed soil. The factors of influence such as fines content, sample preparation method, relative density, confining pressure and shear strain are taken into consideration. The specimens were prepared by three specimen preparation methods (M. T., M.P., H.F.) with different fines content. After the specimen was prepared, a vacuum pumping with 19.6 kPa was applied on the top drain lead of the cell. The mould were then taken apart. Carbon dioxide and water were allowed to pass through the specimen for about 30min. Back pressure of 196 kPa was applied to the specimen in order to obtain a saturation degree of 95%. According to Mulilis [7], the sand specimens consolidated for 24h and for 30min have similar strength. For sake of convenience, the consolidation process extended only for 30 minutes. Considering the in-situ properties, different confining pressure (98kPa, 147 kPa, 196 kPa and 294 kPa) were applied for different stages in the consolidation process. Finally, a series of resonant column triaxial test were performed.

From a series of resonant column triaxial test, the oscillation frequency and the decaying condition of vibration amplitude are measured when the applied force is taken off. The shear strain and the related shear modulus and damping ratio of reclaimed soil were calculated by related equations. In order to reduce the time of data process, a Q-basic program is developed by Chien [8] for interpreting measured data.

4　Experiment results and analysis

The soil samples of experiment are obtained from reclaimed zone A and B in Yun-Lin industrial estate by vibration coring. A series of the resonant column test has been performed to evaluate the dynamic properties of the reclaimed soil. According to the basic physical properties of the in-situ samples obtained by vibration coring, the dry density of the offshore filled material is about 14.7 kN/m^2, and the relative density is about 80%. The test specimen is used of sand mixture of zone A and B. The basic properties are shown in Table 1 and the fines content ranges about from 6% to 10 %. The specimen was prepared by the moist tamping method. Considering different confining pressure, a series of triaxial column test were performed to discuss the influence of factors, such as grain fabric general properties of soil dredged from material source area to reclamation land, on the dynamic properties of soil. Meanwhile, by use of the hydraulic fill system developed by auther, the influence of soil grain fabric on the dynamic properties of reclaimed soil are discussed.

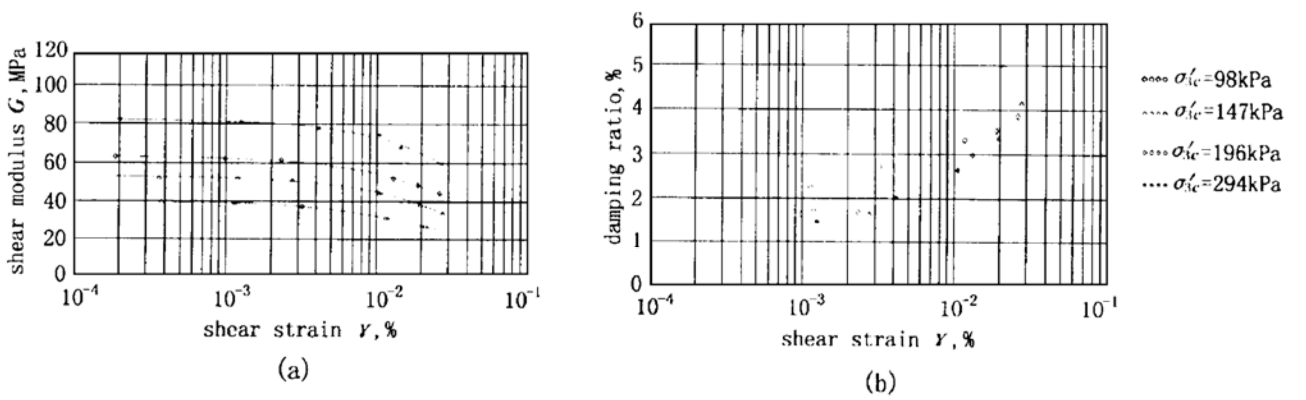

Fig. 3　Typical results of resonant column tests (D_r = 60%)

Table 2　The suggested shear modulus for Yun-Lin nearshore soil

Effective confining pressure (kPa)	Shear modulus of zone A, G (MPa)			Shear modulus of zone B, G (MPa)		
	5×10^{-6}	1×10^{-4}	5×10^{-4}	5×10^{-6}	1×10^{-4}	5×10^{-4}
98	53.2	43.6	22.9	58.7	47.9	21.7
196	84.2	75.4	49.3	82.6	72.9	44.3
294	108.2	97.14	64.3	108.5	97.9	67.1

4.1 Influence of shear strain amplitude

The reclaimed soil of Yun-Lin offshore area was prepared by the moist tamping method. The triaxial resonant column test was conducted. The typical test results presented in Fig.3 clearly show that the shear modulus of the reclaimed soil decreases as the shear strain amplitude increases. This is mainly due to the nonlinear stress-strain relationship of soil. In order to evaluate the relationship between shear modulus (G) and shear strain (γ) conveniently and to compare with the curve G/G_{max} vs. γ suggested by Seed and Idriss, the results were normalized (where G_{max} is defined at shear strain 5×10^{-6}). The results show that the shear modulus decreases as the shear strain amplitude increases, and the related curve lies on the upper bound of the curve suggested by Seed and Idriss. The suggested shear modulus for Yun-Lin nearshore soil under resonant column test shown in Table 2 could be provided as a reference for planning and designing in reclamation engineering. The damping ratio of reclaimed soil ranges from 1% to 12%, and increases as the shear strain increases.

4.2 Effects of confining pressure and void ratio

The typical results of shear modulus and shear strain were presented in Fig. 3. As shown in Fig. 3 (a), the shear modulus of the reclaimed soil increases as the effective confining pressure increases, while the damping ratio of the reclaimed soil decreases as the effective confining pressure increases (Fig.3 (b)). As the effective confining pressure increases, the void ratio of specimen becomes smaller and the relative density becomes larger. Thus, the contact points between the soil aggregates increase. This would cause the stress wave to transmit faster and induce the shear modulus to increase.

According to the evaluation method of maximum shear modulus proposed by Hardin and Richard[5] (as shown in Eq. (2) to Eq. (4)), the resonant column test results were analyzed. Therefore, the particle shape of Yun-Lin offshore soil is subangular by SEM, and the Eq. (3) is used for $F(e)$. Thus, Eq. (3) can be provided to evaluate the influence of void ratio on G_{max}. The relationship between effective confining pressure and $G_{max}/F(e)$ is shown in Fig. 4. Based on regression analysis, the parameters of A and n for Eq. (2) are found to be 208.9 and 0.57, respectively.

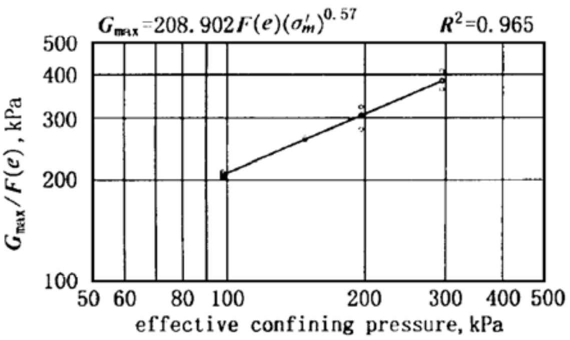

Fig.4 The relationship between $G_{max}/F(e)$ and mean effective confining pressure

From the above analysis, the maximum shear modulus of Yun-Lin reclaimed soil can be expressed as follows:

$$G_{max} = 208.9 \cdot F(e) \cdot (\sigma'_m)^{0.57} \quad (6)$$

where G_{max} is the maximum shear modulus (kPa), σ'_m is effective confining pressure (kPa), and $F(e) = \frac{(2.17-e)^2}{(1+e)}$.

By use of the Eq. (6), the G_{max} of offshore-reclaimed soil at different depths with different relative densities is evaluated to provide with the reference for planning and designing.

In order to investigate the influence of effective confining pressure on the shear modulus of the reclaimed soil with different fines contents, the evaluation method proposed by Seed and Idriss[4] is adopted.

According to Eq. (1), the test results were calculated to obtain the related curves of K_2 value with different relative densities, fines contents and shear strain amplitudes. Taking the corresponding value of K_2 at the shear strain 5×10^{-6}, K_{2max} is defined. The values of K_{2max} with different relative densities and fines contents are shown in Table 3 and Fig.5. From Table 3, we can see that K_{2max} does not make a great difference as the fines content increases for soil with relative density 40%. For soil with relative density 60% and 80%, K_{2max} varies remarkably as the fines content increases, ranging from 20 to 27 and 30 to 22 respectively. From Table 3, we can also see that the influence of fines content on K_{2max} is not distinctive for low density, and the influence of the fines content is clear for denser specimens with relative density 60% to 80%. The influences of different fines content and shear strain amplitude on K_2 are shown in Fig. 6. When fines content is greater than 10%, G_{max} decreases as the fines content increases, and K_2 value decreases as the shear strain amplitude increases.

Table 3 The K_{2max} values of different fines contents and relative densities

Relative density (%)	K_{2max} (%)				
	0	10	16	20	30①
40	20.27	21.74	20.56	20.05	19.42
60	24.02	26.72	24.10	22.18	20.24
80	26.95	29.97	29.21	26.19	21.65

Note: ①This item is the fines contents of soil.

4.3 Influence of soil fabric

In order to evaluate the properties of particle settling and depositing of the reclaimed soil, the specimens were prepared by the hydraulic simulation method developed by the author, and compared with the specimens prepared by the moist tamping method. A series of the resonant column test have been performed to evaluate the influence of soil fabric on the dynamic properties of the reclaimed soil. The results show that the loss of the fines content is very significant by use of H.F. method. The fines content of in-situ reclaimed soil is about 6%, while the fines content of specimen prepared by H.F. reduces to 1% - 2%. The coarse gains and fine gains of specimen dispose anisotropically and most of the fine grains deposit on upper layer of specimen.

Hardin and Richart [5] proposed Eq. (2) to express G_{max}. Based on the analysis and test, the G_{max} of Yun-Lin offshore area reclaimed soil prepared by hydraulic fill method can be determined as follows (Fig.7):

$$G_{max} = 234.4 \cdot F(e) \cdot (\sigma'_m)^{0.55} \quad (7)$$

where G_{max} is the maximum shear modulus of the reclaimed soil (kPa), and σ'_m is the effective confining pressure (kPa).

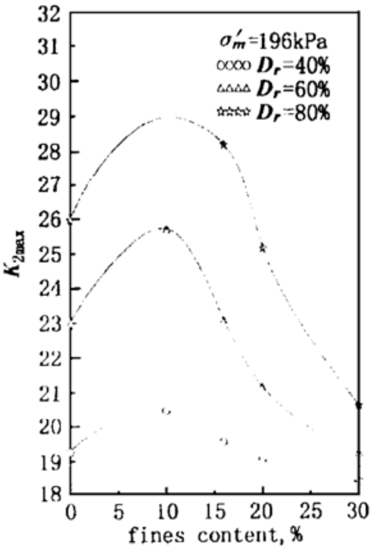

Fig.5　Relationship between K_{2max} and fines contents under different relative density

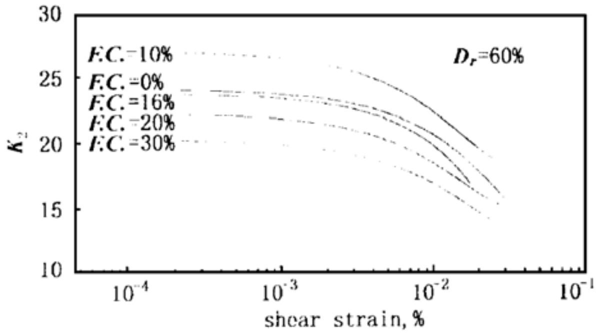

Fig.6　Relationship between K_2 and shear strain under different fines contents

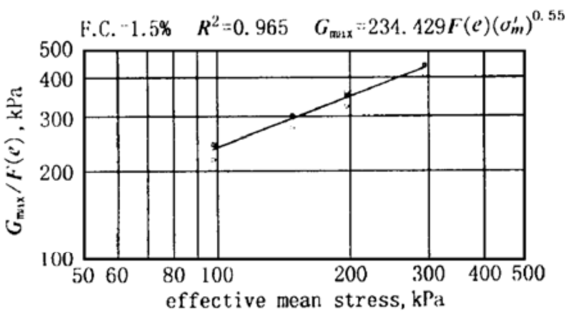

Fig.7　The relationship between $G_{max}/F(e)$ and mean effective confining pressure

From the results shown, the G_{max} for the specimen prepared by hydraulic fill method is higher than for the specimen prepared by moist tamping method. The possible reason may be that the grain orientation of the specimen prepared by hydraulic fill method is parallel with horizontal axis, and that of the specimen prepared by the moist tamping method rotates from horizontal axis to some angles. Thus, the contact points at the same horizontal plane in the hydraulic fill method are more than those in the moist tamping method. This induces more available transmission of stress versus strain wave, and then induces higher G_{max} value.

A series of resonant column test have been performed in order to compare with the specimen prepared by different method and to study the influence of the soil fabric on the dynamic properties of the reclaimed soil.

(1) The multi-sieve pluviation through water method

By use of the multi-sieve pluviation through water method to prepare the specimen of different fines contents, the resonant column tests were conducted. From the preparing process, it could be found the coarse and fine grains have been segregated, and the fine grain can induce the coarse grain to settle to a stable position. The study results agree with those presented by Tatsuoka [9] and Aiba [10]. The relative density of specimen ranges from 36% to 48%.

(2) The hydraulic fill method

By use of the hydraulic fill method to prepare the specimen, the loss of fine is very serious, and the relative density ranges from 32% to 47%. The segregation could be induced in coarse and fine grains. The fine grains always deposit on the upper layer of the specimen.

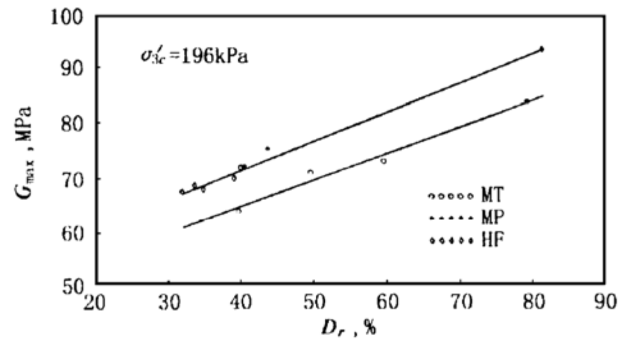

Fig.8　Comparison of G_{max} of reclaimed soil specimen prepared with different methods

(3) Comparison between different preparation methods

The results of specimens prepared with different methods and tested under different effective confining pressure are compared as shown in Fig. 8. From the Fig. 8, the specimens prepared by multi-sieve pluviation through water method and hydraulic fill method have the similar G_{max} value, which is larger than that of other methods. The possible reason is the orientation of the grain is parallel with the horizontal axis and there are more intergrain contacts, which are more helpful for transmission of the stress wave and induce the higher G_{max} values.

4.4　Dynamic properties of the soil in the west coast of

Taiwan

In order to verify the reliability of these results and provide as a reference for the design of the reclamation engineering, this paper has prepared some other results of dynamic properties of the soil in the west coast of Taiwan. The analysis shows that the results of the reclaimed soil in Yun-Lin offshore area by resonant column tests agree with those in Hsin Chu offshore (CBK) area. The normalized shear modulus of the reclaimed soil lie at upper bound of the curves suggested by Seed, and the damping ratio lies near the lower bound curve.

4.5 Correlation between resonant column tests and static triaxial tests

Resonant column tests are costly and complicated; where as conventional triaxial compression tests are very common and easy to conduct. In order to understand the variable properties of the shear modulus of the reclaimed soil at large strains, the results of static triaxial tests are used to estimate the variation of shear modulus at large strain and the maximum shear modulus, expecting to establish the correlations of dynamic modulus obtained from resonant column tests with the results of triaxial tests. By use of the results of large triaxial tests presented by Tsai [11] and the results of the maximum shear modulus obtained by resonant column tests, the related analysis is conducted.

The results of the resonant column tests and the triaxial tests with the similar initial test condition were adopted to evaluate the relationship between maximum shear modulus and deviator stress. The triaxial test results of the stress versus strain show that the maximum deviator stress almost lies within the axial strain range of 2% to 3%. A correlation between G_{max} and σ_d of static triaxial drained tests at axial strain 1% has been obtained from Fig. 9 as follows:

$$\frac{G_{max}}{\sigma'_m} = 299.398 \cdot \frac{\sigma_d}{\sigma'_m} + 125.894 \qquad (8)$$

The proposed correlation is dimensionless. Based on regression analysis, the G_{max} could be evaluated from the σ_d of static triaxial test at axial strain 1%.

The Eq. (8) can be written as follows

$$G_{max} = 299.398 \cdot \sigma_d + 125.894 \cdot \sigma_m' \qquad (9)$$

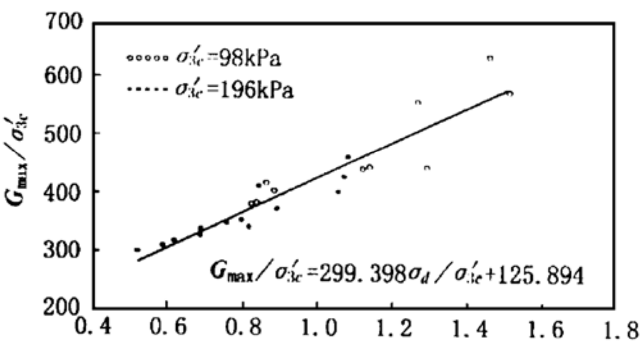

Fig.9 The relationship between G_{max} and deviator stress in triaxial test

By using Young's modulus E of the static triaxial tests with different axial strain ε and according to the elastic theory, the relationship between shear strain and shear modulus at large strain is obtained as follows:

$$G = \frac{E}{2(\mu + 1)} \qquad (10)$$

$$\gamma = \varepsilon \cdot (\mu + 1) \qquad (11)$$

in which E is Young's modulus of the reclaimed soil (kPa), G is shear modulus of the reclaimed soil (kPa), μ is Poisson's ratio, and ε is axial strain (%). Therefore, with help of the above proposed equation, the shear strains and shear modulus of the reclaimed soil can be estimated by the results of the static triaxial tests.

The Poisson's ratio can be adopted as 0.5 for the consolidated undrained triaxial test. Thus, the Eq. (11) can be simplified as follows

$$G = \frac{E}{3} \qquad (12)$$

$$\gamma = 1.5 \cdot \varepsilon \qquad (13)$$

On the basis of the Eq. (12) and Eq. (13), the variation of the shear modulus with γ in an extended strain range can be obtained, as shown in Fig. 10. The G values of static triaxial tests are tangent modulus values and are compatible with G determined by resonant column tests. It may be observed that the "smooth" extension exists. Hence, the relativity between the results of triaxial test and the results of the resonant column test is good.

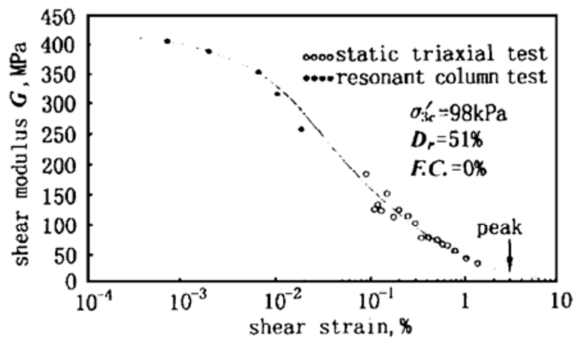

Fig.10 Relation between shear modulus obtained by triaxial test and resonant column test

5 Conclusions

The objective of this paper is to discuss the dynamic properties of the reclaimed soil. Thirty-six sets of resonant column test were performed to evaluate the influence of factors, such as the different relative densities, sample preparation methods and effective confining pressures. Summarizing the results, the following conclusion can be obtained.

On the basis of the suggested equation, the maximum shear modulus of offshore soil in Taiwan with different relative densities at different depths could be evaluated to provide a reference for seismic planning and designing of reclamation land projects. The shear modulus of reclaimed soil with different fines contents decreases as the shear strain amplitude increases, and the damping ratio increases as the shear strain amplitude increases. The related curve of normalized shear modulus (G/G_{max}) vs. shear strain (γ) lies at the upper bound of the curve suggested by Seed and Idriss, and the damping ratio (D) vs. shear strain (γ)

lies at the lower bound of the suggested curve.

The shear modulus of reclaimed soil increases as the effective confining pressure increases. The damping ratio also shows similar trends, but is not significantly affected by the effective confining pressure. By comparison between specimens prepared by the multi-sieve pluviation through water method and the hydraulic fill method on the similar initial condition (such as void ratio, fines content and effective confining pressure), the shear modulus of reclaimed soil has similar value. And the shear modulus of the specimen prepared by the moist tamping method is the lowest.

Based on the equations suggested by Seed and Idriss, and considering the influence of the effective confining pressure, relative density and fines content, a new method was proposed. For a fines content above 10%, G_{max} decreases as the fines content increases. In general, the K_2 value decreases as the shear strain amplitude increases. The idea of correlating static triaxial tests with resonant column tests may be objectionable in view of their fundamental difference, however, such correlation are helpful in crude estimation of maximum dynamic modulus at low strain. Combining the elastic theory, the related curve of the shear modulus and shear strain at large shear strain could be evaluated. It is very useful as reference for the evaluation of the dynamic properties of reclaimed soil.

References

1 Sladen J A. Hewitt K J. Influence of placement method on the in site density of hydraulic sand fills. Canadian Geotechnical Journal, 1989, **26** (3): 453 ~ 466.

2 Hardin B O, Drenvich V P. Shear modulus and damping in soils: Design equation and curves. Journal of the Soil Mechanics and Foundation Division, ASCE, 1972, **98** (SM7): 603 ~ 624.

3 Hall R T, Richart F E. Dissipation of elastic wave energy in granular soils. Journal of the Soil Mechanics and Foundations Division, ASCE, 1973, **89** (SM6): 27 ~ 56.

4 Seed H B, Idriss I M. Soil modului and damping factors for dynamic respose analyses, EERC 70 – 10. Berkeley: Earthquake Engineering Research Center, University of California, 1970.

5 Hardin B O and Richart F E. Elastic wave velocities in granular soils. Journal of the Soil Mechanics and Foundations Division, ASCE, 1963, **89** (SM1): 603 ~ 624.

6 Iwasaki T, Tatsuoka F. Effect of grain size and grading on dynamic shear modulus of sands. Soils and Foundations, 1977, **17** (3): 19 ~ 35.

7 Mulilis J P, Clarence K Chan, Bolton Seed H. The effect of method of sample preparation on the cyclic stress-strain behavior of sand, EERC 75 – 18. Berkeley: Earthquake Engineering Research Center, University of California, 1975.

8 Chien L K, A study on the dynamic properties of reclaimed soil in West Taiwan, NSC – 83 – 0414 – P – 019 – 001B. Taiwan: National Science Council, 1994.

9 Tasuoka F, Murammatsu M, Sasaki T. Cyclic undrained stress-strain behavior of dense sands by torsional simple shear test. Soils and Foundations, 1982, **22** (2): 55 ~ 70.

10 De Albe, P K, Baldwin V, Janoo G. Elastic-wave velocities and liquefaction potential. Geotechnical Testing Journal, ASTM, 1984, **7** (2): 77 ~ 78.

11 Tsai Y M. A study on the steady state parameter and engineering properties of reclaimed soil in west coast Taiwan [Master Thesis]. Keelung, Taiwan: National Taiwan Ocean University, 1994.