NOTE

Influence of fines content and initial shear stress on dynamic properties of hydraulic reclaimed soil

L.-K. Chien and Y.-N. Oh

Abstract: The hydraulic placement of sand fill is one of the most important methods of land reclamation. During the reclamation process, losses of fines in sand are induced by the transportation of soil which affects the dynamic properties of the soil materials. In this study, the reclaimed soil in the Yunlin area of Taiwan is adopted as the test material. Different fines contents, different relative densities, and initial stress ratio were taken as test conditions. Resonant column tests were performed to evaluate the shear modulus and damping ratio of the reclaimed soil under initial shear stress. The results show that the maximum shear modulus decreases as the fines content increases. The influences of initial shear stress are discussed. A prediction method for maximum shear modulus under different fines content and initial shear stress is proposed based on empirical equations obtained. The results can be helpful for land reclamation design and assessment.

Key words: reclaimed soil, fines content, initial shear stress, dynamic properties.

Résumé : Le remblayage hydraulique du sable est une des plus importantes méthodes de réhabilitation des terrains. Au cours du processus, la perte de particules fines dans le sable se produit au cours du transport du sol. Ceci va influencer les propriétés dynamiques des sols. Dans cette étude, on a utilisé le sol réhabilité de la région de Yunlin de Taiwan comme échantillons d'essais. Différentes teneurs en particules fines, différentes densités relatives et différents rapports de contraintes initiales ont été utilisés comme conditions d'essai. Des essais à la colonne résonnante ont été réalisés pour évaluer le module de cisaillement et le rapport d'amortissement du sol réhabilité sous la contrainte initiale de cisaillement. Comme le montrent les résultats, le module maximum de cisaillement décroît avec l'augmentation de particules fines. On discute également l'influence de la contrainte initiale de cisaillement. On propose une méthode de prédiction du module maximum de cisaillement avec différentes teneurs en particules fines et différentes contraintes initiales de cisaillement sur la base des équations empiriques obtenues. Les résultats peuvent être utiles pour la conception et l'évaluation de la réhabilitation de terrains.

Mots clés : sol réhabilité, teneur en particules fines, contrainte de cisaillement initiale, propriétés dynamiques.

[Traduit par la Rédaction]

Introduction

The hydraulic placement of sand fill is one of the most important methods of land reclamation in nearshore areas of west Taiwan. The land is reclaimed for industrial development (Sinotech Engineering Consultants, Inc. 1990). The materials for hydraulic sand fill are obtained from the seabed or river mouth using a cutter and pump. According to Sladen and Hewitt (1989) from studies of manmade islands in the Beaufort Sea, Canada, the relative density of hydraulic placed soil ranges from 10 to 70% and is normally below 50%. As shown from field standard penetration tests (SPT) in the reclamation area, the initial relative density of reclaimed soil ranges from 35 to 65% (Sinotech Engineering Consultants, Inc. 1990). By understanding the mechanisms involved in the dynamic behavior of soils, the reclamation in the coastal area can be improved. The purpose of this study is to evaluate the dynamic properties of the reclaimed soil.

Resonant column tests were conducted on specimens prepared by the moist-tamping method. The influences of relative density (void ratio), confining pressure, fines content, and initial stress ratio (initial shear stress) are discussed.

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Testing procedure

Test materials

Soil samples were obtained from the offshore area at Yunlin on the west coast of Taiwan (as shown in Fig. 1). The

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

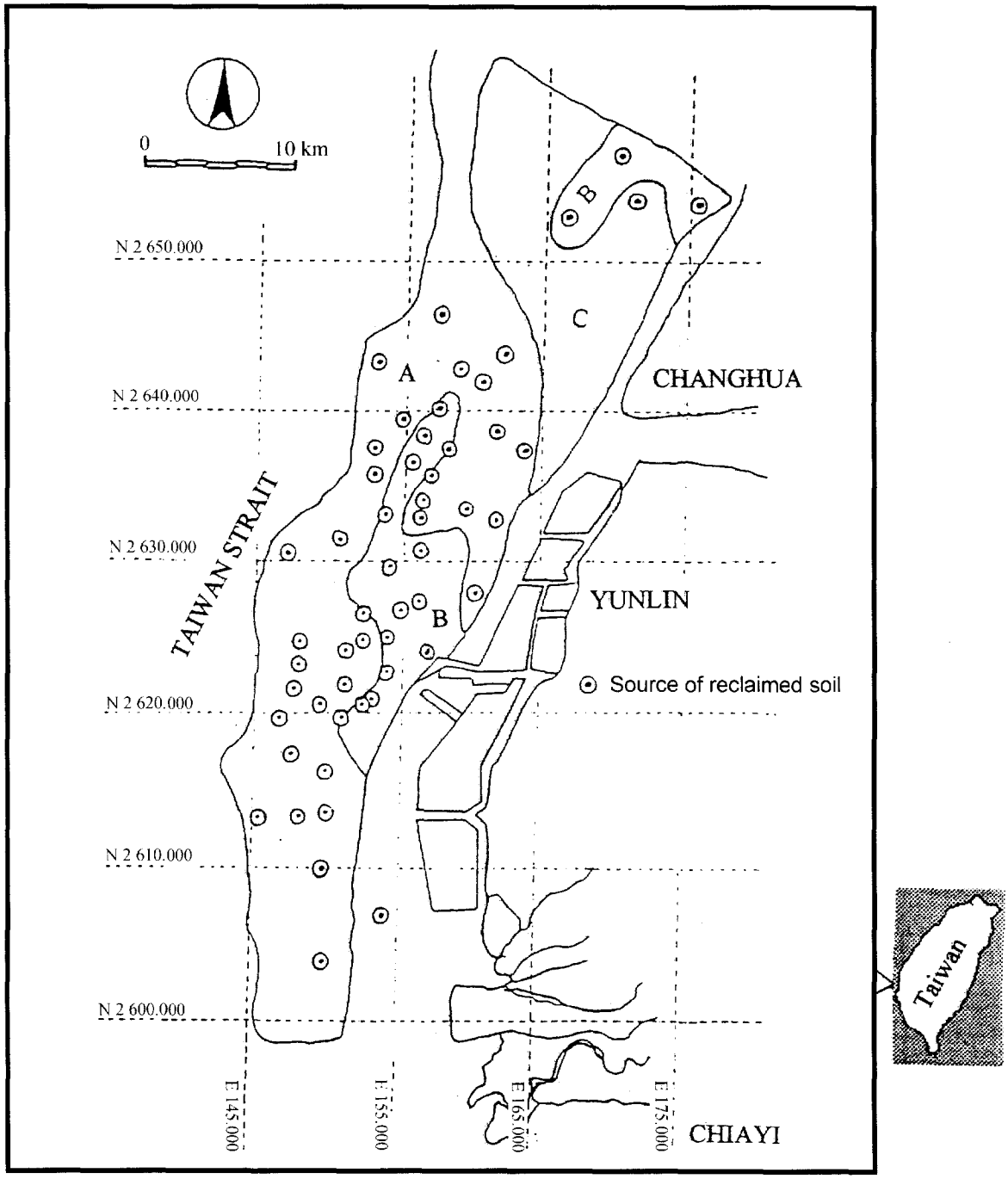

Table 1. Basic soil properties of the test samples.

Fines content (%)	0	10	20	30
Specific gravity, G_s	2.691	2.696	2.698	2.701
Maximum dry density (g/cm^3)	1.590	1.680	1.760	1.790
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, C_u	1.688	2.232	3.393	6.306
Coefficient of curvature, C_c	1.347	1.353	1.630	1.477

Table 2. Experiment conditions.

Sample preparation method	Moist tamping (MT)
Fines content, FC (%)	0, 10, 20, 30
Initial relative density, D_r (%)	40, 60, 80
Initial stress ratio, K	1.0, 1.5, 2.0, 2.5, 3.0
Total no. of tests	75
Total no. of repeated tests	17

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Fig. 2. Grain-size distribution of the test samples.

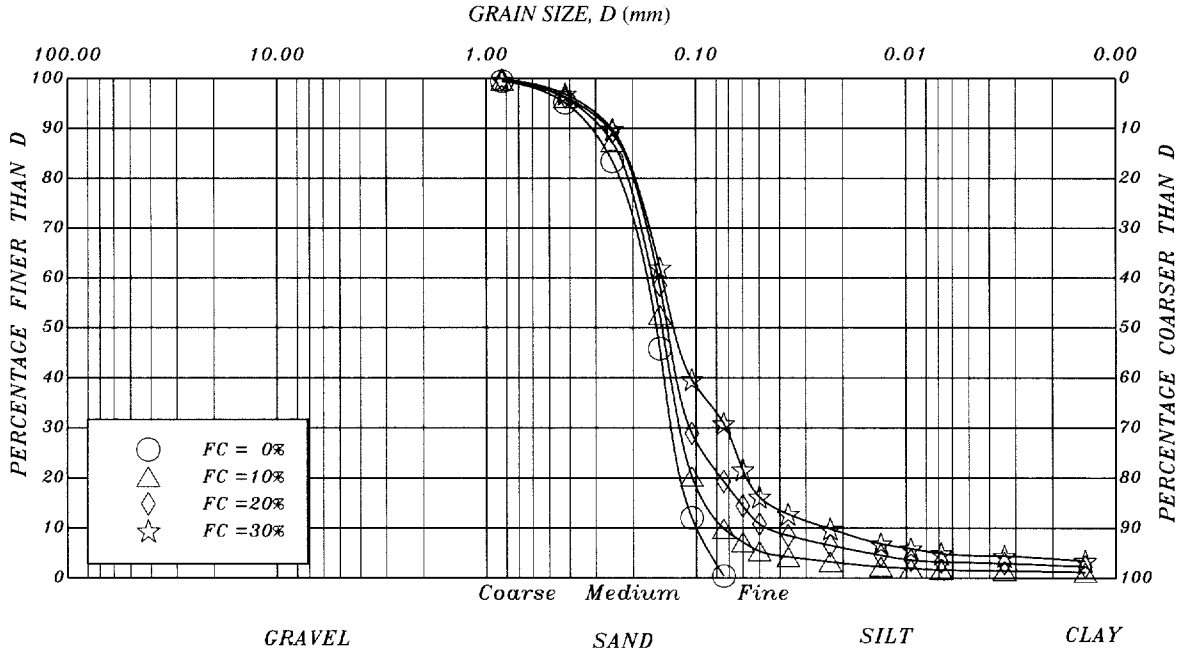
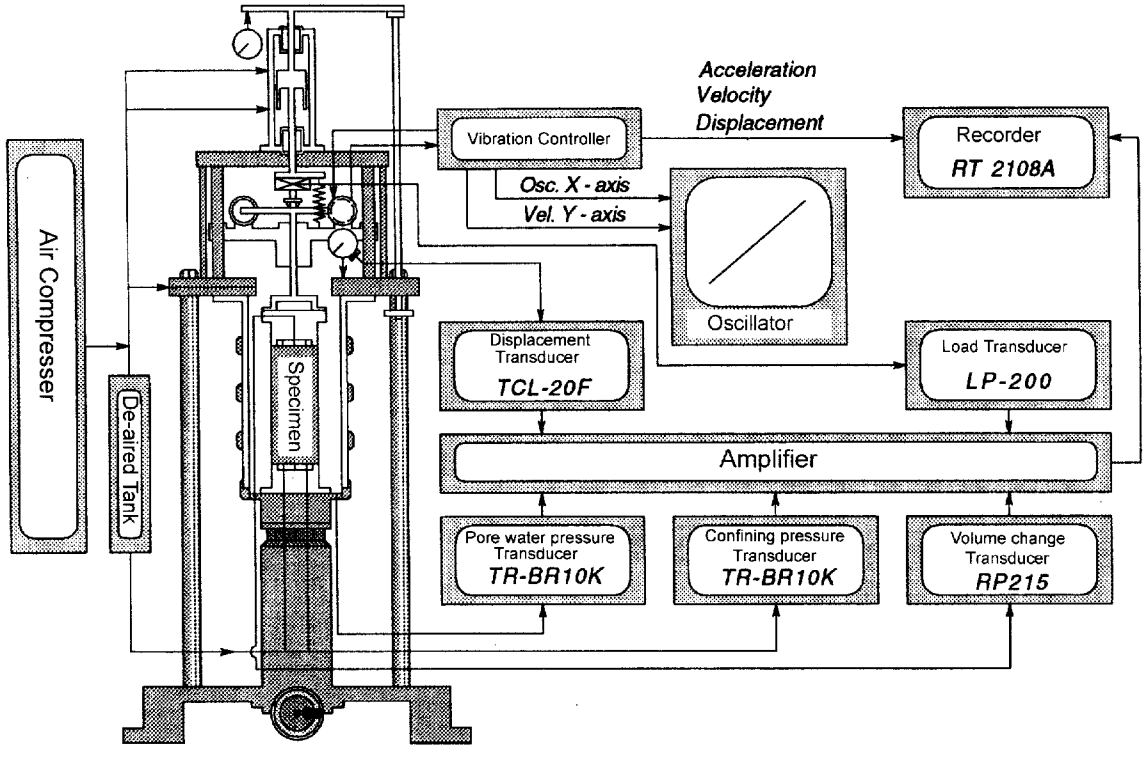


Fig. 3. Sketch of the resonant column test apparatus.



soil is a uniform, round grained, fine, black sand and is classified as SP according to the Unified Soil Classification System (USCS). Grain size of the reclaimed soil indicates 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 an effective diameter D_{10} = 0.06–0.15 mm. The soil properties and grain-size distribution of the sand used are shown in Table 1 and Fig. 2, respectively. Fines content was obtained from the soil samples passing through the No. 200 sieve (<0.075 mm). Sieve analysis and specific gravity tests were conducted according to the American Society for Testing and Materials (ASTM) standard methods D452-85 and D854-83, respectively. The maximum and minimum dry density tests were conducted based on the standard JSF-T26-81T of the Japanese Society of Soil Mechanics and Foundation Engineering (1979).

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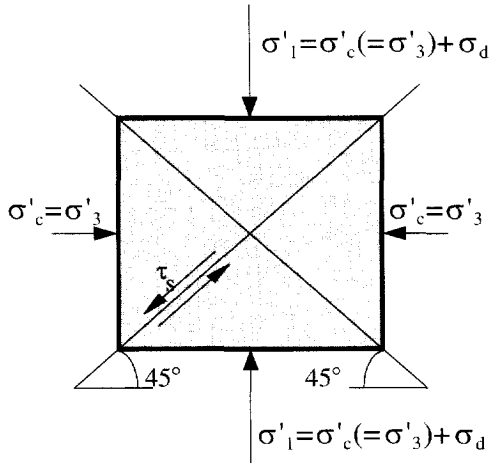
Fig. 4. Illustration sketch of initial shear stress in the soil element.



Test procedure

To control the required test conditions, the specimens were prepared using the moist-tamping method (MT) with different fines contents (0, 10, 20, and 30%) and different initial relative densities, D_r (40, 60, and 80%). The soil sample is divided into five layers. Each layer is determined by the weight and relative density of a similar volume of the soil. To eliminate the consolidation effects of the soil layer, the relative density for each layer is different. From the top to the bottom of the soil sample, the relative density (in %) of each layer is $D_r + 2$, $D_r + 1$, D_r, $D_r - 1$, and $D_r - 2$. After the specimen was prepared, a vacuum of 19.6 kPa was applied through the top drainage line to the specimen. Carbon dioxide was allowed to pass through the specimen under vacuum for about 2 h. For carbon dioxide to be fully dissolved, water was allowed to pass through the specimen for about 3 h. A back-pressure of 196 kPa was applied to ensure 100% saturation. Saturation occurs when the Skempton B value is greater than 0.99. Considering the in situ properties (as the thickness of reclaimed soil is about 15 m), different confining pressures (98, 147, 196, and 294 kPa) were applied. The specimens were consolidated to their desired consolidation pressure before testing commenced. The resonant column tests were then carried out using the apparatus schematically shown in Fig. 3.

Fines content (FC) is defined as

$$[1] \qquad \mathrm{FC} = \frac{\text{weight of fines (passing No. 200 sieve)}}{\text{weight of specimen}}$$

The initial shear stress, τ_s, is defined as follows (as shown in Fig. 4):

$$[2] \qquad \tau_s = \frac{\sigma_1' - \sigma_3'}{2} = \frac{\sigma_d}{2}$$

where σ_1' is the effective major principal stress, σ_3' is the effective confining pressure (or the minor principal stress), and σ_d is the deviator stress.

The initial stress ratio, K, adopted in this paper can be expressed as follows:

$$[3] \qquad K = \frac{\sigma_1'}{\sigma_3'}$$

Based on eqs. [2] and [3], the relation between initial shear stress and initial stress ratio can be illustrated as follows:

$$[4] \qquad \tau_s = \frac{\sigma_3'(K-1)}{2}$$

In this study, mean effective confining pressure, σ_m', is adopted for analysis and is illustrated as follows (Hardin and Drnevich 1972):

$$[5] \qquad \sigma_m' = \frac{\sigma_1' + \sigma_2' + \sigma_3'}{3}$$

where σ_1', σ_2', and σ_3' are the major, intermediate, and minor effective principal stresses (or effective confining pressure), respectively.

The test conditions and factors considered are listed in Table 2. The stress ratio is added at different stages by using the pressure transducers in the apparatus. Resonant test results are presented in Fig. 5 for a fines content of 10% and initial relative density of 60%.

Experimental results and analysis

Hardin and Richart (1963) demonstrated that for a shear strain below 10^{-3}%, the shear modulus of sand is nearly constant. The relationships among σ_m', void ratio (e), and maximum shear modulus (G_{max}) are shown by the following equation:

$$[6] \qquad G_{max} = AF(e)(\sigma_m')^n$$

where

$$[7] \qquad F(e) = \frac{(2.97 - e)^2}{1 + e}$$

for angular sand, and

$$[8] \qquad F(e) = \frac{(2.17 - e)^2}{1 + e}$$

for round sand, where A is a constant reflecting soil fabric formed through various stress and strain histories, and n is a dimensionless parameter approximately equal to 0.5.

Relationship between fines content and void ratio

The relationships between fines content, maximum void ratio, and minimum void ratio are shown in Fig. 6. For fines contents less then 20%, the maximum void ratio does not change with respect to fines content. This is attributed to the arching effects in loose sands (Lambe and Whitman 1987). The minimum void ratio decreases as the fines content increases. This showed that fines are replacing the voids in the specimen.

Influence of void ratio and mean effective confining pressure on maximum shear modulus

Figure 5 presents test results with FC = 10%. Figure 7 plots effective confining pressure versus $G_{max}/F(e)$. By regressing the results in Fig. 7, parameters A and n in eq. [6] can be obtained as 87.296 and 0.553, respectively. Therefore, the maximum shear modulus, G_{max}, of the reclaimed soil can be expressed as follows:

$$[9] \qquad G_{max} = 87.296F(e)(\sigma_m')^{0.553} \quad (\mathrm{FC} = 10\%;\ K = 1)$$

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Fig. 5. Typical results of resonant column tests of reclaimed soil ($\sigma_c' = 98$ kPa): (*a*) relationship between shear modulus and shear strain; (*b*) relationship between damping ratio and shear strain.

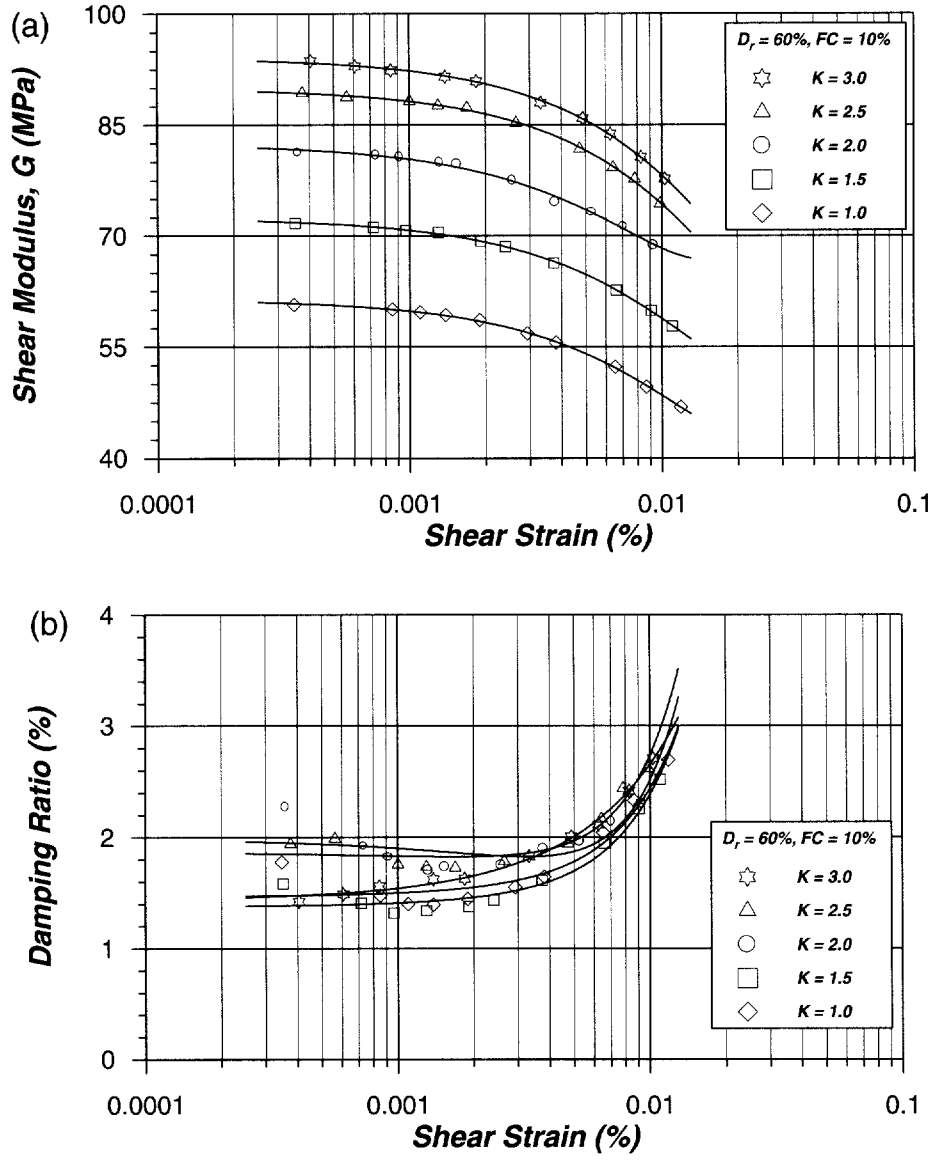
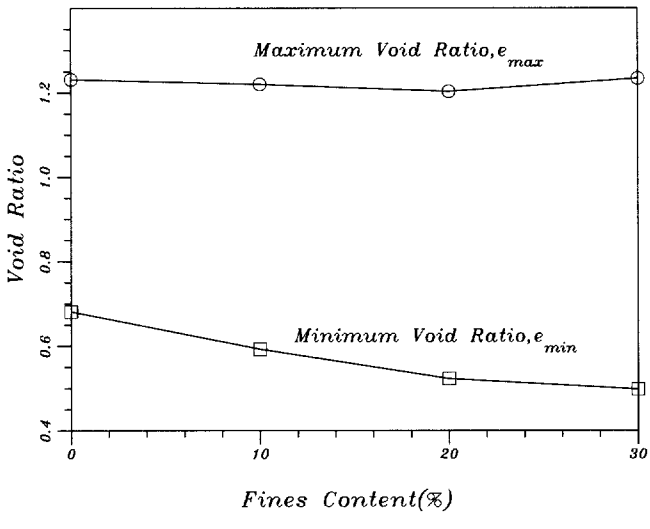


Fig. 6. Relationship between fines content and void ratio.



where $F(e) = (2.17 - e)^2/(1 + e)$ for round sand.

Influence of initial stress ratio on maximum shear modulus

By using eq. [9] and considering the soil with different initial stress ratio (K = 1.5, 2.0, 2.5, 3.0), the predicted and test values of G_{max} are shown in Fig. 8 for a relative density of 60%. The predicted G_{max} obtained by eq. [9] is different compared with those obtained from the test results. The difference is more obvious as the initial stress ratio (K) increases. In this study, to analyze the influences of effective confining pressure on maximum shear modulus, an increment of maximum shear modulus is defined as $\Delta G_{max(s)}$. As shown in Fig. 9, $\Delta G_{max(s)}$ increases as the initial stress ratio (K) increases. Therefore, the relations between increments of maximum shear modulus ($\Delta G_{max(s)}$) and initial stress ratio (K) can be expressed and simplified as follows:

$$\Delta G_{max(s)} = 8K \quad [10]$$

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

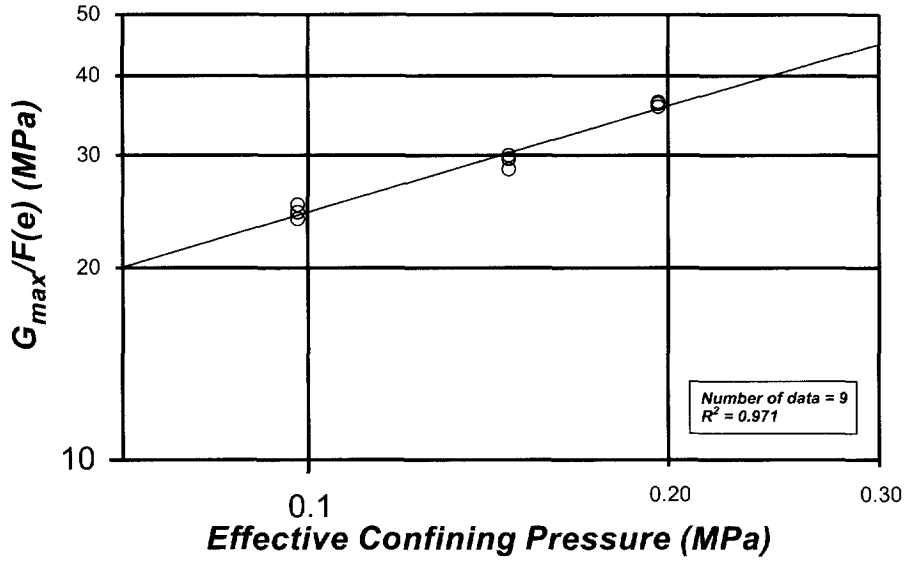
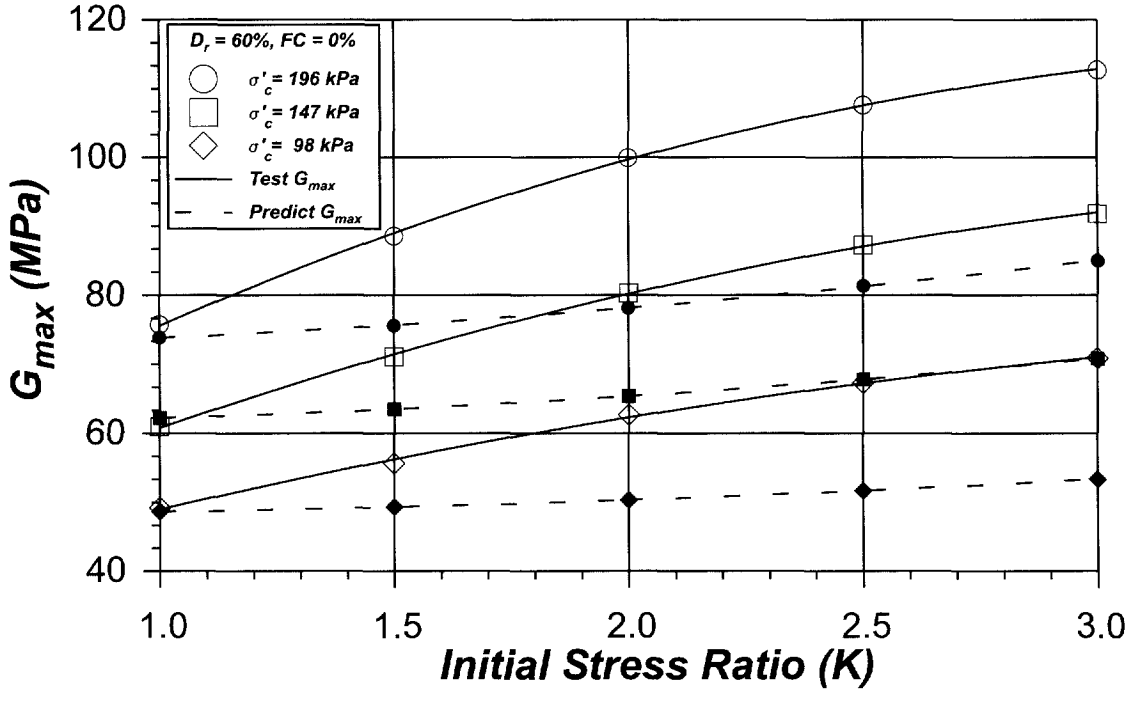


Fig. 8. Comparison between G_{max} predicted from eq. [9] (Hardin and Richart 1963) and from test results (this study) (D_r = 60%).



Summarizing and considering the influence of anisotropic consolidation, the prediction equation in eq. [9] for maximum shear modulus of reclaimed soil can be rewritten as follows:

$$[11] \quad G^*_{max} = 87.296F(e)(\sigma_m')^{0.553} + 8K$$

where G^*_{max} is the maximum shear modulus (in MPa) of reclaimed soil under anisotropic consolidation.

By using the proposed eq. [11], the maximum shear modulus of the reclaimed soil can be predicted. Using the analyzed results and substituting different fines contents into eq. [11], the predicted maximum shear modulus is different compared with that obtained from the test. Therefore, the influence of fines content should be discussed.

Influence of fines content on maximum shear modulus

To evaluate the influence of fines content, specimens were prepared with different fines contents. As shown in Fig. 10, under different fines contents, the maximum shear modulus increases as the initial stress ratio increases. For specimens with a fines content of less than 20%, the maximum shear modulus increases as the fines content increases. For specimens with a fines content of greater than 20%, the maximum shear modulus decreases as the fines content increases.

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Fig. 9. Relationship between maximum shear modulus and initial stress ratio.

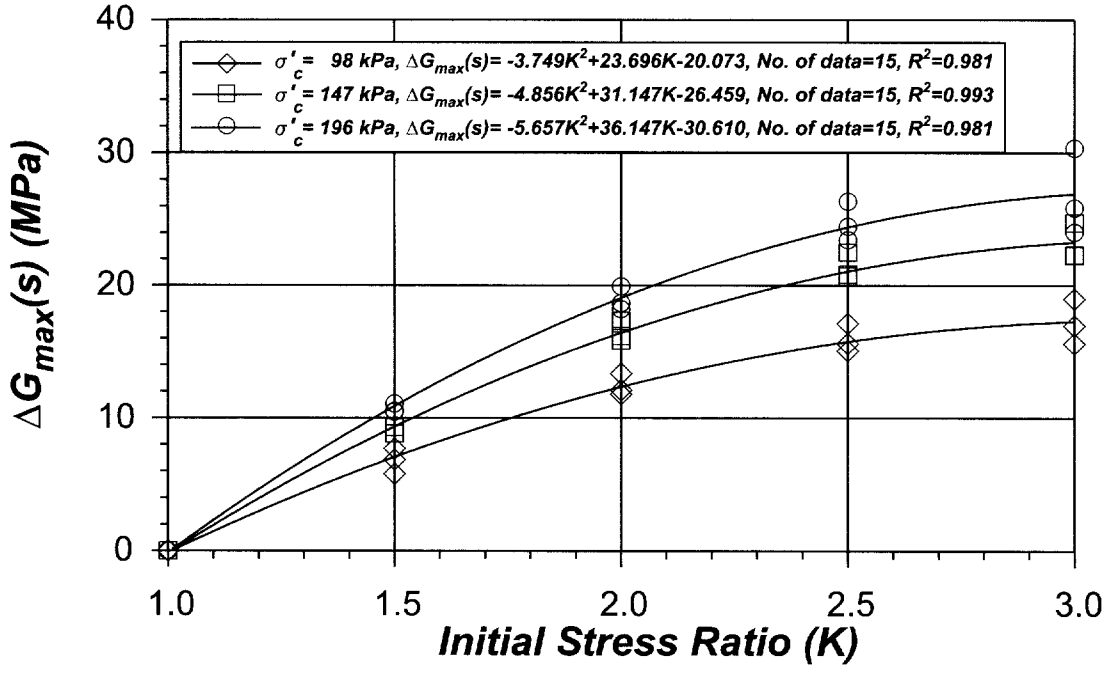
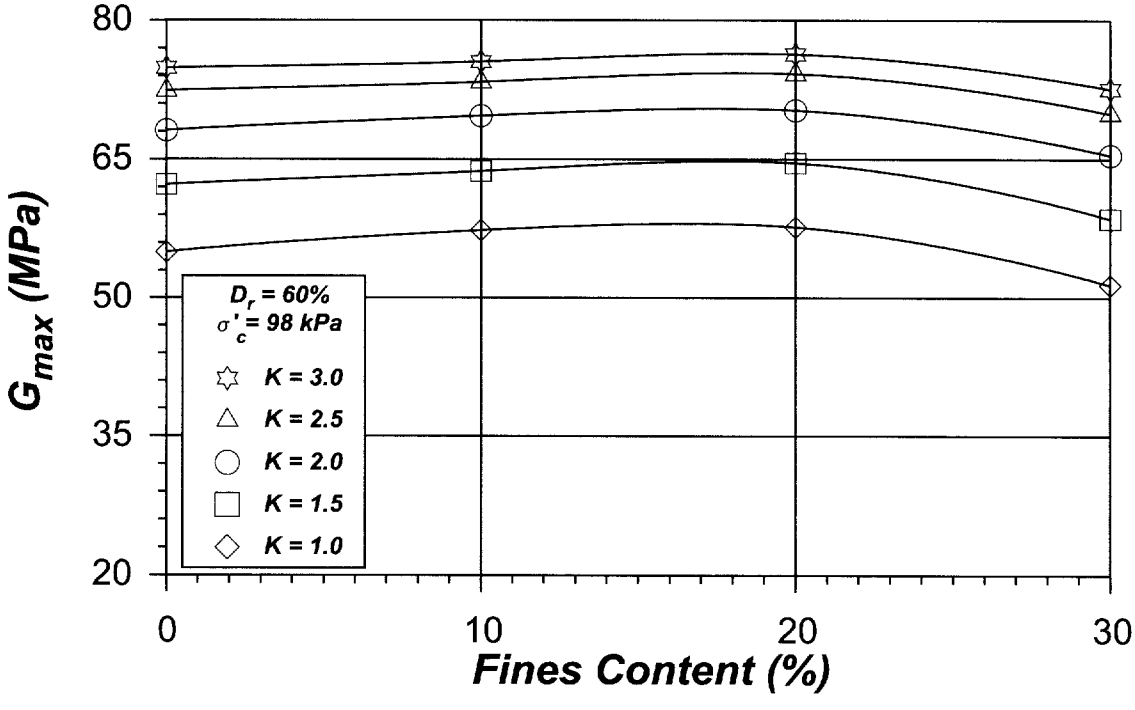


Fig. 10. Relationship between fines content and maximum shear modulus with different initial stress ratios.



Considering the changes in void ratio induced by fines content, the influence of fines content on maximum shear modulus can be evaluated. Based on the test results conducted with fines content, comparisons are made with results predicted using eq. [11]. As shown in Fig. 11, the test results differ from the predicted results (using eq. [11]). Significantly, the differences between the test and predicted results increase as the fines content increases. Therefore, in this study, the increment in maximum shear modulus induced by fines contents is defined as $\Delta G_{\max(FC)}$. The maximum shear modulus with a different fines content and initial stress ratio can be defined as $G^{**}_{\max}$ and illustrated as follows:

$$[12] \quad G^{**}_{\max} = G^{*}_{\max} + \Delta G_{\max(FC)}$$

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Fig. 11. Comparison of test results (with fines content) with results obtained from eq. [11].

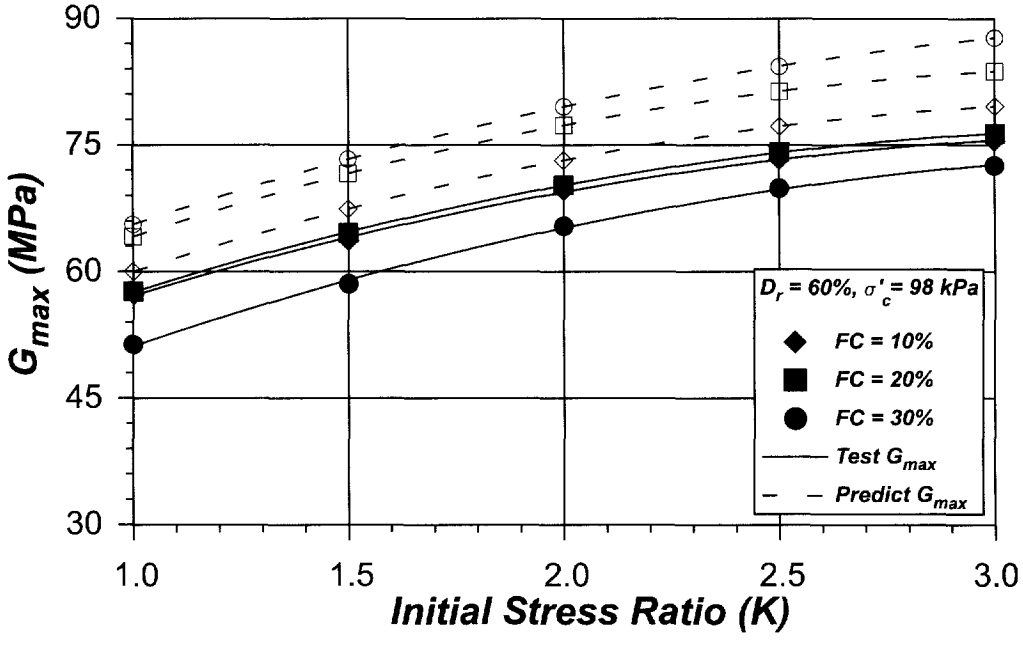
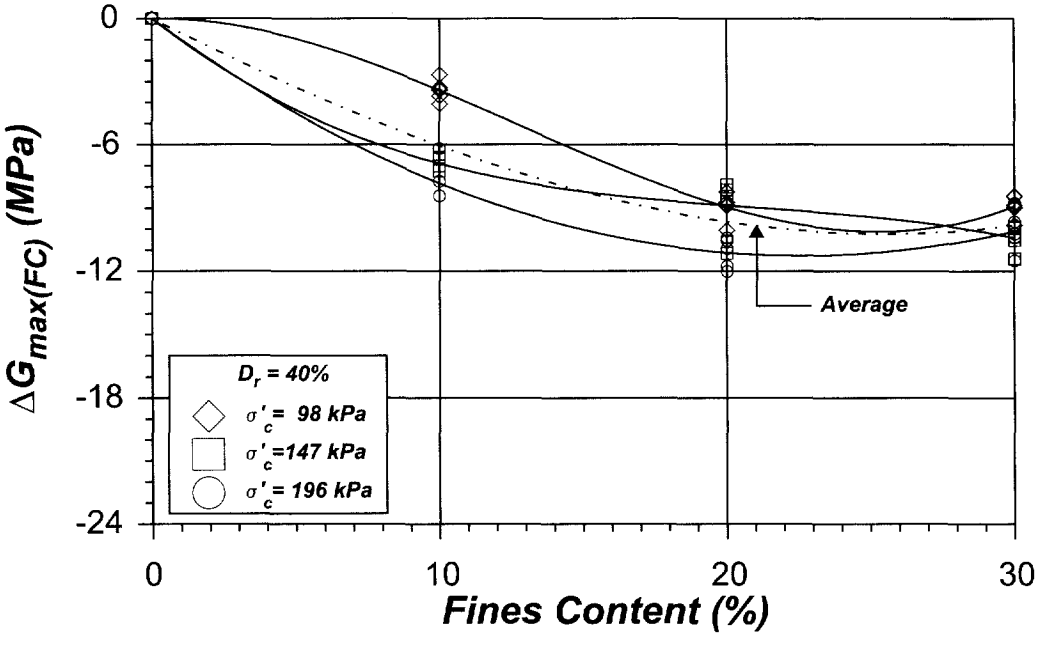


Fig. 12. Relationship between reduction in maximum shear modulus and fines content (D_r = 40%).



By using eq. [12], the increment in maximum shear modulus induced by fines content, $\Delta G_{max(FC)}$, can be expressed as

$$[13] \quad \Delta G_{max(FC)} = G^{**}_{max} - G^{*}_{max}$$

where G^{*}_{max} is obtained from eq. [11].

As shown in Figs. 12–14, an increase in fines content results in a decrease in $\Delta G_{max(FC)}$. By using linear regression analysis, the relationship between fines content and increments in maximum shear modulus induced by fines content ($\Delta G_{max(FC)}$) can be expressed as follows:

$$[14] \quad \Delta G_{max(FC)} \approx 0.5\text{FC}$$

By considering the influence of fines content and initial stress ratio, eq. [11] can be rewritten as follows:

$$[15] \quad G^{**}_{max} = 87.296F(e)(\sigma_m')^{0.553} + 8K + 0.5\text{FC}$$

where G^{**}_{max} is the maximum shear modulus with different fines content under anisotropic consolidation (MPa).

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Fig. 13. Relationship between reduction in maximum shear modulus and fines content (D_r = 60%).

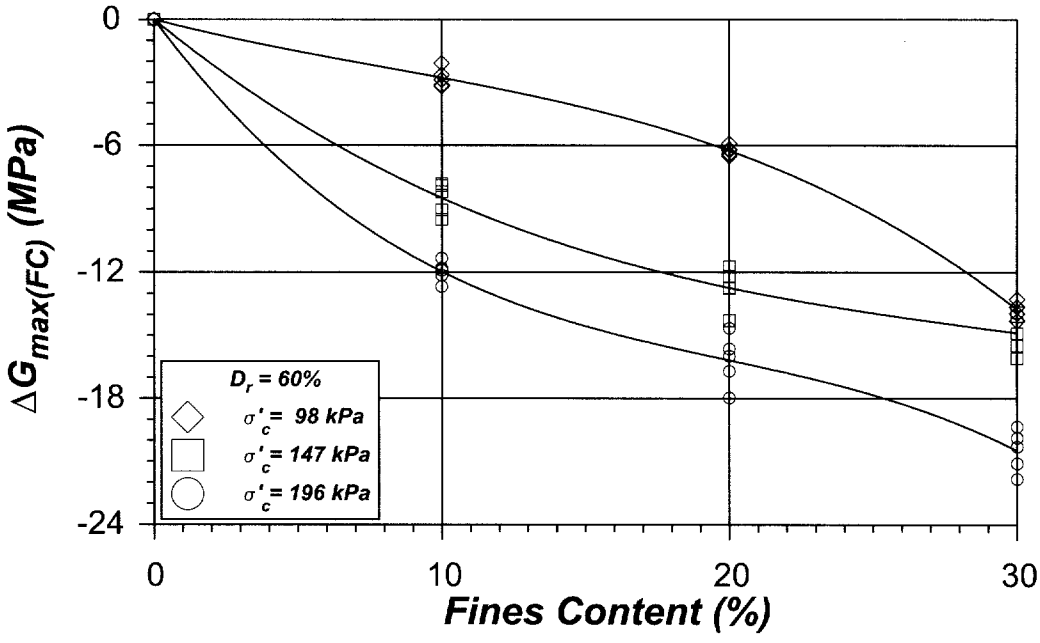
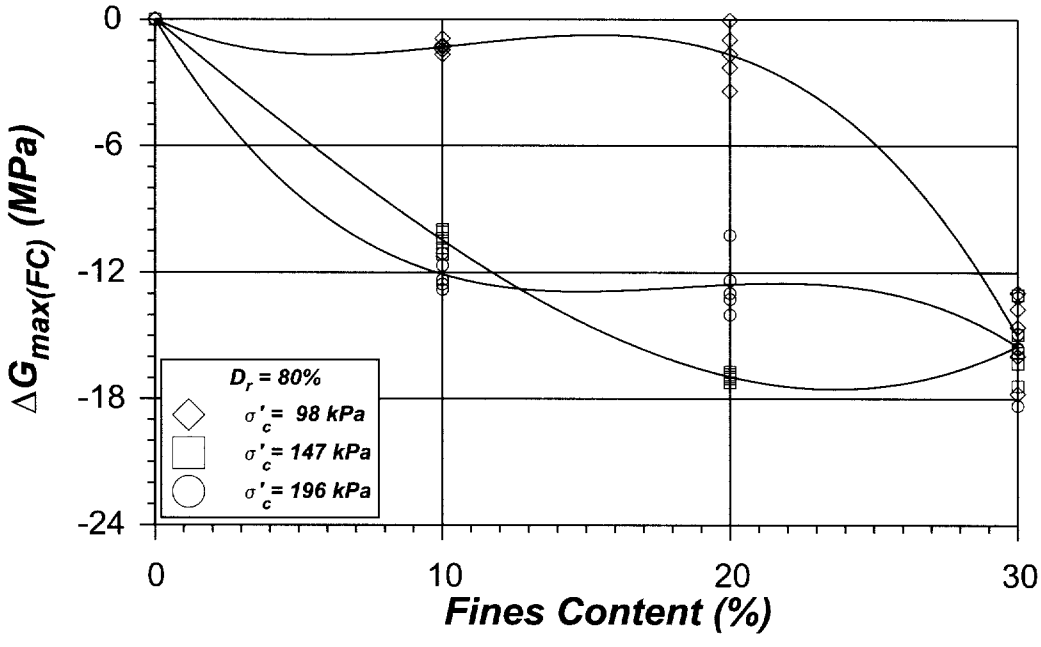


Fig. 14. Relationship between reduction in maximum shear modulus and fines content (D_r = 80%).



Influence of fines content on damping ratio

Typical results of resonant column tests on reclaimed soil with a fines content of 10% are shown in Fig. 5*b*. Figure 15 presents a comparison between the damping ratio of reclaimed soil under different fines contents and curves suggested by Seed and Idriss (1970). The damping ratio of reclaimed soil lies on the lower bound of the curve suggested by Seed and Idriss (1970). Figure 16 shows the relationship between damping ratio and shear strain with different fines contents. The damping ratio increases as the shear strain increases. Based on the tests on damping ratio, the average damping ratio for the reclaimed soil is presented in Fig. 17. By using regression analysis, the regression curve for average values of the damping ratio, D (in %), can be expressed as

$$[16] \quad D = 6350\gamma^2 + 50\gamma + 1.5$$

where γ is the strain amplitude (in %).

As shown in Fig. 17, the upper and lower bound curves are +20% and –20% of the average values. As shown in Figs. 16 and 17, the damping ratio of soil with different

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Fig. 15. Comparison between the damping ratio of reclaimed soil and the curve suggested by Seed and Idriss (1970).

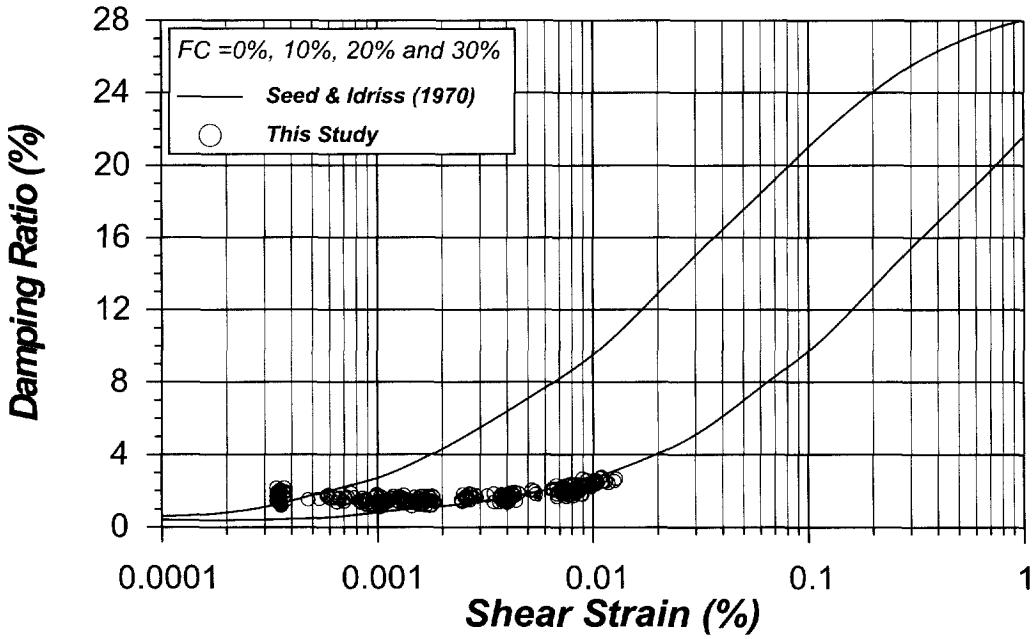
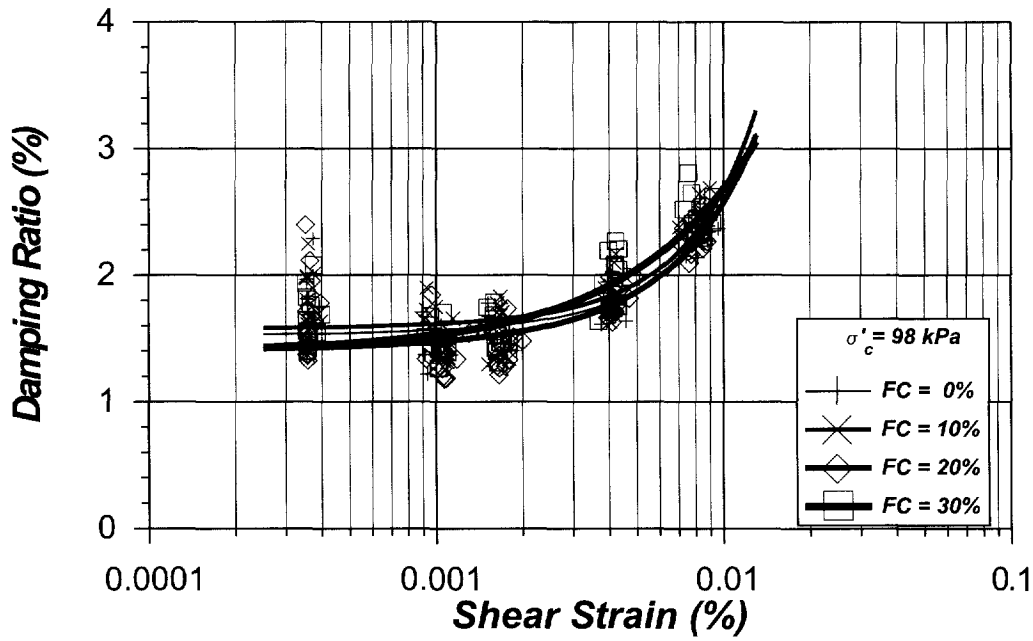


Fig. 16. Relationship between damping ratio and shear strain for different fines contents.



fines contents would increase as the shear strain increases. For $\gamma = 3 \times 10^{-3}\%$, the average damping ratio is approximately 1.5%. For $\gamma = 1 \times 10^{-2}\%$, the average damping ratio is approximately 2.6%. Figure 18 shows the relationship between damping ratio and shear strain: the damping ratio increases as the shear strain increases.

Conclusions

In this study, resonant column tests were carried out on samples of reclaimed soil in the Yun-Lin area of west Taiwan. Based on the in situ conditions, different test conditions (different fines contents, relative densities, effective confining pressures, and initial stress ratios) are considered.

The test results show that the maximum shear modulus (G_{max}) increases as the relative density increases. For specimens with high density, the contact surface of soil particles increases and would increase the transmission of the shear wave in soil. Tests were conducted with different effective confining pressures and initial stress ratios. The maximum

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Fig. 17. Relationship between damping ratio and shear strain of reclaimed soil, showing the average and upper and lower bound curves of damping ratio.

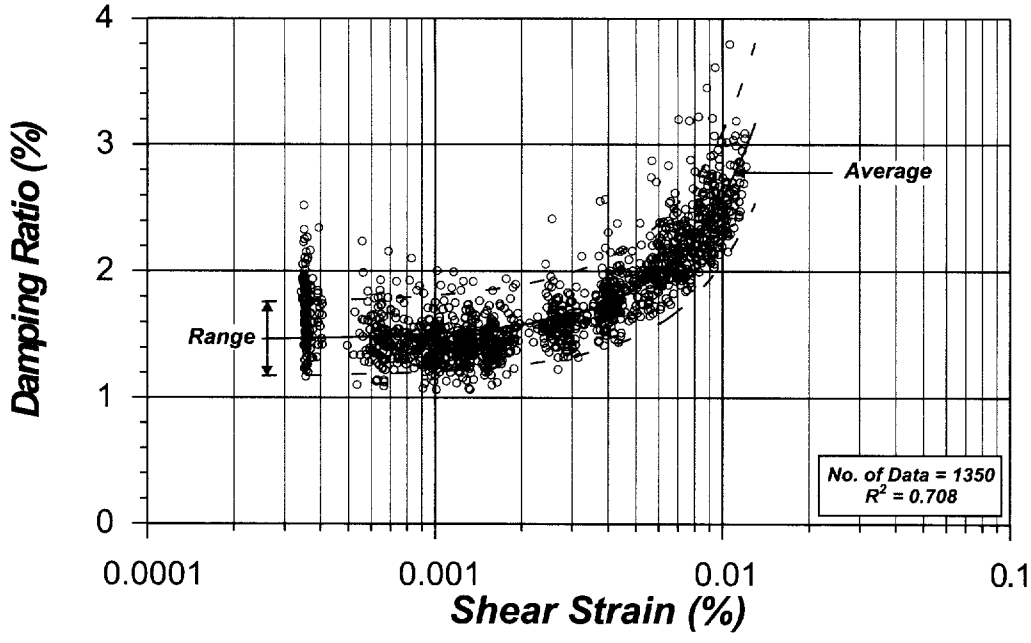
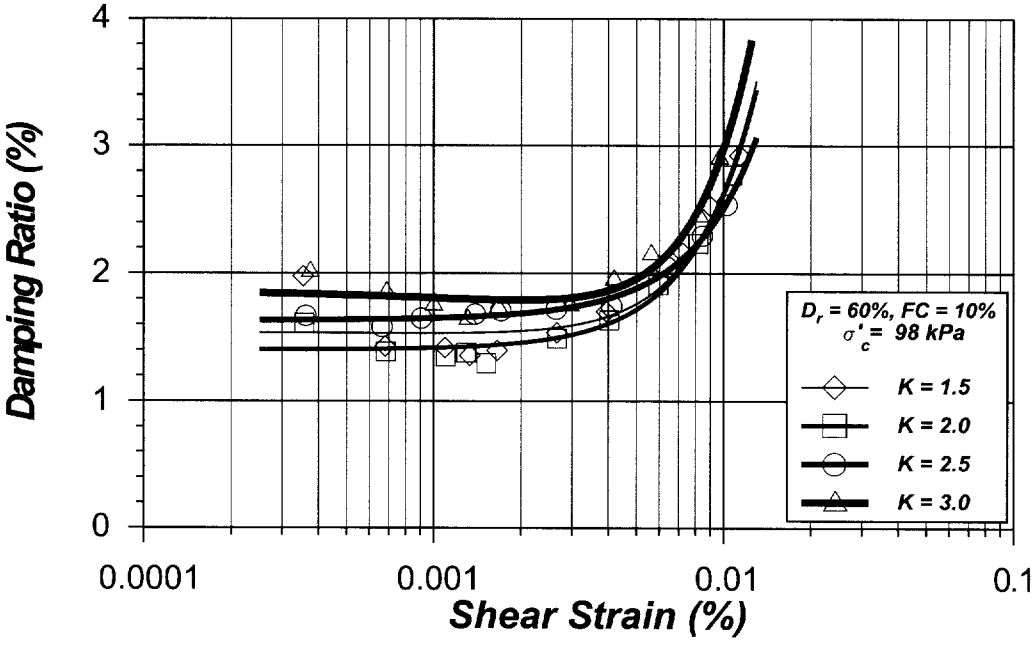


Fig. 18. Relationship between damping ratio and shear strain for different values of K.



shear modulus (G_{max}) increased as the effective confining pressure and initial stress ratio increased.

For different relative densities (40, 60, and 80%) and fines contents (10, 20, and 30%), the increment of maximum shear modulus induced by fines content ($\Delta G_{max(FC)}$) decreased as the fines content increased. The reduction is approximately 25% (for specimen with D_r = 60% and FC = 30%). For specimens with D_r = 60 and 80%, the influence of fines content on maximum shear modulus increases as the effective confining pressure increases. The addition of fines to the specimen would fill the voids between soil particles and reduce the contact surface of soil particles. Equations are proposed and can be used to predict the maximum shear modulus (G^{**}_{max}) for different fines contents.

A comparison between the damping ratio of reclaimed soil and the curve suggested by Seed and Idriss (1970) is presented. The damping ratio of reclaimed soil lies on the lower bound of the curve suggested by Seed and Idriss. By using regression analysis, the regression curve for average values of damping ratio can be presented.

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This paper discussed the influences on dynamic properties of reclaimed soil. Empirical equations for the prediction of maximum shear modulus are proposed based on the results, and the results can be used as a reference for related studies and the evaluation of soil properties in land reclamation.

Acknowledgments

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