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Effects of Types of Additives on Dynamic Properties of Cement Stabilized Soils

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Abstract: The variation of dynamic properties of soils (shear modulus and damping ratio) as a function of shearing strain is an important input for solving geotechnical problems involving dynamic loading. In this paper, the dynamic properties of cement stabilized soil were studied using resonant column test. Three types of stabilized soil were studied. They are cement stabilized soil, slag cement stabilized soil, and cement with sodium silicate stabilized soil. The amount of cement admixed, the magnitude of confining pressure, and shearing strain amplitude were the parameters considered in this study. Test results show that the maximum shear modulus of cement stabilized soil increases with increasing confining pressure, the minimum damping ratio decreases with increasing confining pressure. However, the relationship between the maximum shear modulus and the confining pressure varies with the type of additive. The shear modulus of cement stabilized soil decreases with increasing shearing strain while the damping ratio increases with increasing shearing strain. The relationship of shear modulus versus shearing strain was fitted into the Ramberg-Osgood equations using regression analysis. The results also indicate that the cement with sodium silicate stabilized soil is able to sustain larger shearing strain before stiffness degradation occurring than other types of additive.

Keywords: Cement stabilized soil; resonant column test; shears modulus; damping ratio.

1. Introduction

Dynamic soil properties are essential for the analysis of soil behavior under dynamic loads such as machine vibration, traffic loads, earthquake and construction loading. Subsurface soft soils, such as those existed in the Taipei city of Taiwan, is always necessary to improve for the control of stability and settlement reason. Mixing soft soil with cement can be a method to improve the engineering properties of soft soil. The dynamic properties of cement stabilized soil must be studied in order to take into account the cement stabilized soil as a material for foundation soils. In spite of the higher strain under earthquake, the response is still calculated by using the equivalent linear method in the dynamic response analysis. In the equivalent linear method, the strain-dependent shear modulus and damping represent the dynamic non-linear deformation characteristics of soil. Therefore, for most soil dynamic problems, the dynamic stress-strain properties of soils or cement stabilized soils are important key factors. Two dynamic parameters were investigated in this study. The shear modulus represents effective

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stiffness of cement stabilized soil, and damping ratio indicates the dissipating of energy within the cement stabilized soil. Cyclic loadings result in degradation of stiffness and evolution of damping ratio with increasing in shearing strain amplitude. The dynamic properties in dynamic analysis are the shear modulus and damping ratio under smaller shearing strain, the trend of shear modulus reduction and damping ratio increase with increasing shearing strain amplitude. The shear modulus under very small shearing strain, G_{max}, is one of the important parameters of soil deformability and plays a significant role in soil dynamic analysis. A number of experimental researches have been carried out in the last few decades to study the dynamic properties of soils, such as Stokoe and Richart [1], Iwasaki et al. [2], Kokusho, [3], Seed. et al. [4], Wang and Kuwano [5]. Researchers (Anderson and Richart [6], Kokusho et al. [7], Dobry and Vucetic [8], Okur and Ansal [9]) considered that plastic index effects significantly on dynamic properties of fine grained soil. Only a few studies about dynamic properties of grouted sand were studied (e.g. Maher et al. [10], Ribay et al. [11]). The clay mixing with cement is seemed as one of the best method for soil stabilization. The mechanical properties of cement stabilized clay were studied by Kamaluddin and Balasubramaniam [12], Uddin et al. [13], Yin and Lai [14], Miura et al. [15]. However, the dynamic characteristics of cement stabilized clay have not yet been fully investigated particularly with respect to the strain-dependent shear modulus and damping ratio.

In this study, three stabilized soils were studied. They are soil mixing with normal Portland cement, and soil mixing with cement and sodium silicate or slag. All of these soil modifications are admixed with cement, so called cement stabilized soils. In order to study the dynamic properties of cement stabilized soil, the resonant column tests were used in this study.

To study the effect of influent factors on the low-amplitude shear modulus, G_{max}, and the low-amplitude damping ratio, D_{min}, some parametric studies were performed in low amplitude resonant column tests. The parameters of cement stabilized soil are the type of additive, cement content, and the magnitude of confining pressure. The shear modulus decreases markedly with increases in shearing strain amplitude, and the damping ratio increases with increasing in shearing strain amplitude as its threshold is exceeded. To study the shearing strain effects on the dynamic properties, the high amplitude resonant column tests were implemented, too. The Ramberg-Osgood model was used to describe the relationship between shear modulus and shearing strain from the results of high amplitude resonant column tests.

2. Tested material and testing program

2.1. Tested materials

Three additives of stabilized soil were investigated in this study. There were regular Portland cement, slag cement, and cement with sodium silicate. The geology of Taipei city had been reported in more detail in other publications (e.g. Moh and Ou (1979)[16], Woo and Moh (1990)[17]). In this study, the soils tested were obtained at a depth of 15m in the Taipei Basin. The soil is a layer of deep gray silty clay with very little sand, and can be classified as low plastic clay (CL) by the United Soils Classification System. The engineering properties of this soil are as follows: liquid limit LL=40%, plastic limit PL=22%, unit weight γ_t=17.2 kN/m^3, natural water content W_n=37%, undrained shear strength s_u=30 kN/m^2, and compression index C_c=0.4.

Three cement contents of 5%, 15% and 25% by weight of soil were used in this study to investigate the effect of cement contents on cyclic deformation characteristics of cement stabilized soil. Three different types of additive including Portland cement, cement with 6% sodium silicate, and slag cement were studied the influence of the type of additive on the dynamic properties.

For soil stabilization purpose, three types of additive were used:

Normal Portland cement: It is the most commonly used additive for soil stabilization. The normal Portland cement is the main admixing material for stabilizing soil in the study. The water/cement ratio was fixed at 0.5.

Portland cement with sodium silicate: Sodium silicate is known as water glass. It is used to reduce the plasticity index of clay and rapidly solidify soil. For comparison reason, 6% sodium silicate addition and 15% cement content were admixed into the soil.

Blast furnace slag cement: The blast furnace slag was recently used to develop new geological improvement hardener for soil improvement purpose in Taiwan. The cement is made from granulated slag, gypsum, and not more than 5% of Portland cement clinker. It is finer than normal Portland cement. In this study, slag cement content was still considered as 15% and the water to slag cement ratio was fixed at 0.5 for comparing with the improvement results of Portland cement.

2.2. Experimental method

The fixed-free type resonant column device was used to measure the dynamic properties of cement stabilized soil. The device was developed by Professor Stokoe II of the University of Texas at Austin, as shown in Figure 1. The sample was applied a torsional vibration to find its resonant frequency or period during the resonant column tests. A harmonic signal with excitation frequencies from 2Hz to 690Hz and very low strain amplitude was applied to the top of the specimen using the electromagnetic drive system, which locates at the top of specimen, leading to a distortion of the specimen.

Figure 1. Resonant column device

Each measurement consisted of taking reading of the frequency response curve, accelerometer output voltage, and free vibration decay curve. From frequency response curve, the resonant frequency was found from the corresponding maximum response in frequency response curve. The shear modulus and shearing strain can be obtained from resonant frequency and accelerometer output, respectively.

The shear modulus was determined from searching for the corresponding resonant frequency and it was calculated by the following relation:

$$\frac{\rho\pi r^4 L}{2I_0} = \frac{\omega L}{V_s}\tan\frac{\omega L}{V_s} \tag{1}$$

where ω=the measured resonant circular frequency; L=sample height; ρ=sample density; V_s = the velocity of the propagating shear wave; r=radius of sample; and I_0= mass polar moment of inertial of driving system. The velocity of shear wave V_s can then be calculated from Equation (1), and shear modulus will be determined by the following equation:

$$G = \rho V_s^2 . \tag{2}$$

The shearing strain was determined by the accelerometer output, read by AC voltage meter in root mean square (rms) volts. So that the shearing strain of sample was calculated by:

$$\gamma = 73.9912 \frac{rV_{rms}}{L\omega^2} . \tag{3}$$

where V_{rms} is the accelerometer output voltage in root mean square volts.

After the resonant frequency was established, the excitation power was abruptly shut off, and the specimen was allowed to vibrate freely. The damping ratio was determined from the free vibration curve by the logarithmic decrement method.

$$D = \frac{1}{2n\pi} \ln\left(\frac{A_0}{A_n}\right). \tag{4}$$

where A_0 is the vibration amplitude of the first cycle after the excitation has been shut off; A_n is the vibration amplitude of the nth cycle; and n is the number of cycle in the free vibration curve.

The damping ratio was also determined from the frequency response curve based on half-power bandwidth method. In the half-power bandwidth method, the soil damping ratio was calculated by measuring the frequencies at $1/\sqrt{2}$ of the maximum amplitude and the resonant frequency from the frequency response curve.

2.2.1. Test procedures

The clay with natural water content and cement agent in water/cement ratio of 0.5 were mixed. The mixing time was fixed at 10 min. Then these pastes were filled into cylindrical containers. After 24 hours the samples were dismantled and put into a curing pool. All of the specimens were performed by the resonant column tests after 7 days of curing period. Before testing, specimens were trimmed to the dimensions of 50mm in diameter and 100mm in height.

First, the sample was applied an isotropic pressure in the cell. In the procedure, a hydrostatic confining pressure was applied to the specimen, and measurement was made in 50 minute after application of the confining pressure. The confining pressure used are 27kPa, 55kPa, 110kPa and 220kPa. And then, low-amplitude resonant column tests were performed to study the effect of confining pressure on G_{max} and D_{min}. In these tests, shearing strain of specimen is less than the threshold shearing strain, about 0.001%. At these strain level, the dynamic properties of cement stabilized soil are independent of shearing strain and are a function of confining pressure.

After the low-amplitude resonant column tests had finished, the high-amplitude resonant column tests were performed under a fixed confining pressure of 220kPa. High-amplitude testing is defined as shearing strains of between 0.001% ~0.1%. In the range of strain investigated, the specimens are not essentially destructive. The high-amplitude resonant column tests were designed to assess the effect of shearing strain on dynamic shearing modulus and damping ratio.

3. Low-amplitude test results

A low-amplitude resonant column test was performed with untreated soil speciman to compare with the results of cement stabilized soil. The G_{max} of the untreated speciman is about 80MPa at the confining pressure of 220kPa. The measured G_{max} value is close to that obtained by Lee, et al. [18]. It thus indicates that the test procedure adapted in this study is valid.

3.1. Effect of confining pressure on the maximum shear modulus

The effect of confining pressure on the G_{max} value of cement stabilized soils is shown in Figure 2. It can be seen that G_{max} value slightly increases with increasing of the confining pressure for the cement stabilized soils. The G_{max} value of cement stabilized soil at cement content of 5% and 15% seems to be constant and independent of the confining pressure. The void ratios of cement stabilized specimen of 5%, 15% and 25% cement content were 0.38, 0.40 and 0.48, respectively. And the void ratios of specimen of cement with sodium silicate and slag cement were 0.46 and 0.50, respectively. Therefore, the samples of 5% and 15% cement contents had few voids than others. It could be that the above both samples have less porosity, so the denseness of particle cannot build up due to confining pressure increasing.

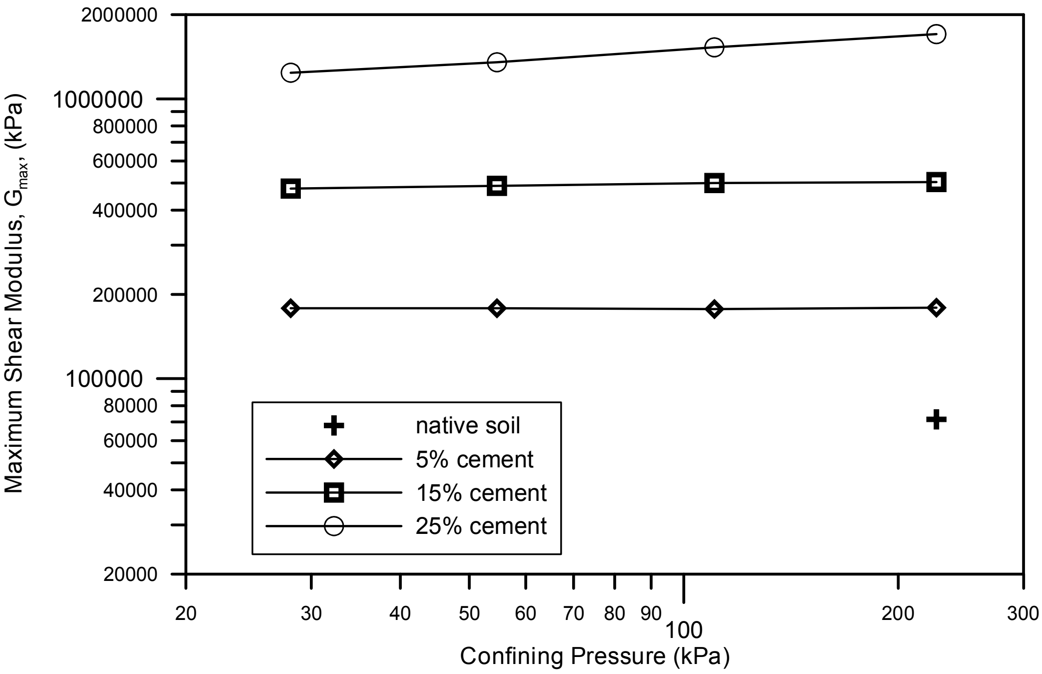

Figure 2. Influence of cement content on G_{max}

The approximation equations of the relationship between the G_{max} value and confining pressure for the cement stabilized soil can be expressed as follow:

$$G_{max} = K_G \sigma_0^n. \tag{5}$$

where K_G is the modulus constant; n is the modulus exponent; σ_0 is the confining pressure. The n value implies the extent of influence of confining pressure on the G_{max} value. The K_G and n values for the stabilized soils were obtained by using regression method from the test results. The results are listed in Table 1. As shown in the table, the n value of stabilized soil is about 0.002~0.231, which value could depend on the porosity of sample.

Table 1. Values of K_G, n, K_D, m and void ratio

Stabilized soil type		K_G	n	K_D	m	void ratio
Portland cement stabilized soil	5%	177011	0.002	2.159	-0.012	0.38
	15%	438530	0.026	1.837	-0.028	0.40
	25%	734852	0.155	1.208	-0.067	0.48
Cement with sodium silicate stabilized soil		267178	0.231	2.087	-0.048	0.46
Slag cement stabilized soil		558470	0.188	2.972	-0.241	0.50

3.2. Effect of the cement content on the maximum shear modulus

Test results (Figure 2) also show that the G_{max} value is higher for samples with higher cement content. The results of this study show that enough cement content is necessary to obtain the higher stiffness for cement stabilized soil.

3.3. Effect of the type of additive on the maximum shear modulus

To study the effect of the type of additive on the G_{max} value, the cement content was fixed at 15%. As shown in Figure 3, at the same confining pressure, the slag cement stabilized soil has highest G_{max} value. The G_{max} value of soil cemented with sodium silicate ranks the second. And the soil stabilized with normal Portland cement yields the lowest G_{max} value. As expected, there is little influence of confining pressure on the G_{max} value of cement stabilized soil with sodium silicate or blast furnace slag in this study. It could be the reason that blast furnace slag is able to facilitate cement hydrating and pozzolanic reaction to cause the strength and stiffness of stabilized soil increasing. To have better visualizing the effect of the type of additive, results are expressed in term of a stiffness improvement factor which is defined as the ratio between the G_{max} value of stabilized soil and that of native soil.The stiffness improvement factor is higher as the effectiveness of improvement is greater, as shown in Table 2. The average stiffness improvement factors are 7.1, 22.0 and 13.5 for the normal Portland cement stabilized soil, slag cement stabilized soil, and cement admixed with sodium silicate stabilized soil, respectively. The stiffness improvement factor for the normal Portland cement has a weaker stiffness than the other two types of additive.

3.4. Effect of confining pressure on the minimum damping ratio

Typical behavior of low-amplitude viscous damping ratio as a function of the confining pressure is shown in Figure 4. It can be seen from the Figure 4 that the trend of reduction of D_{min} with confining pressure increasing is not obvious for cement stabilized soils. In this figure, confining pressure effects on the D_{min} value could be neglected. Ribay et al. (2004)[11] have drawn the same conclusions on sand grouted with silicate grout. This could be the reason that sample is denser due to confining pressure.

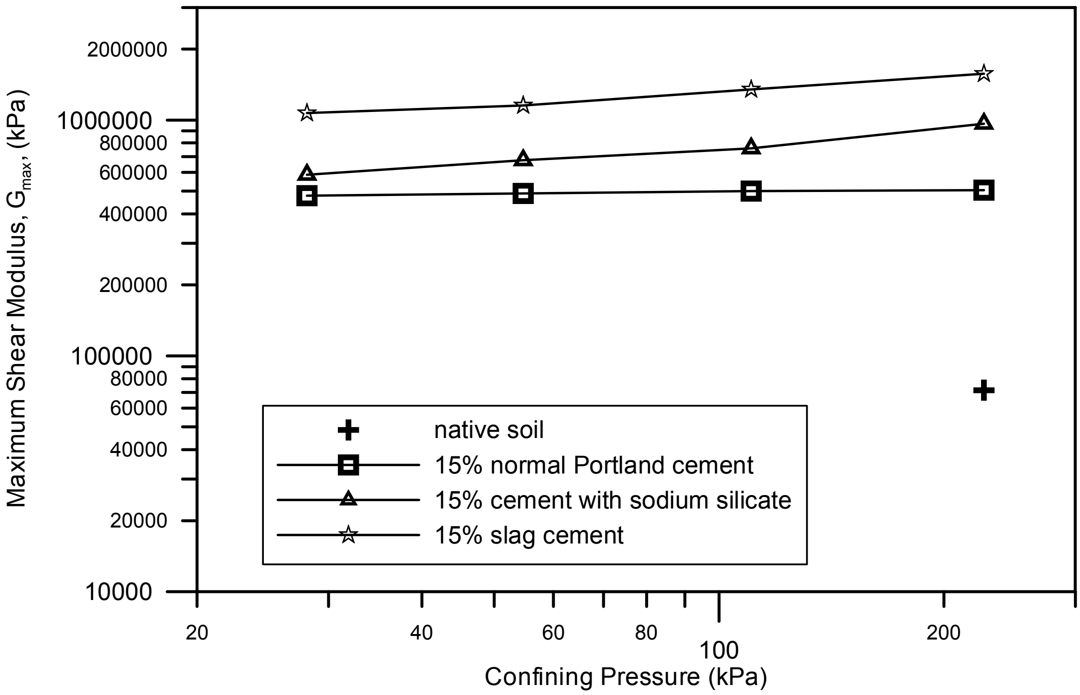

Figure 3. Influence of the type of additive on G_{max}

Table 2. Average stiffness improvement factor

Stabilized soil type		G_{max} (kPa)	Improvement factor
		71490.9	—
Portland cement stabilized soil	5%	179230	2.5
	15%	504180	7.1
	25%	1704100	23.8
Cement with sodium silicate stabilized soil		965230	13.5
Slag cement stabilized soil		1571200	22.0

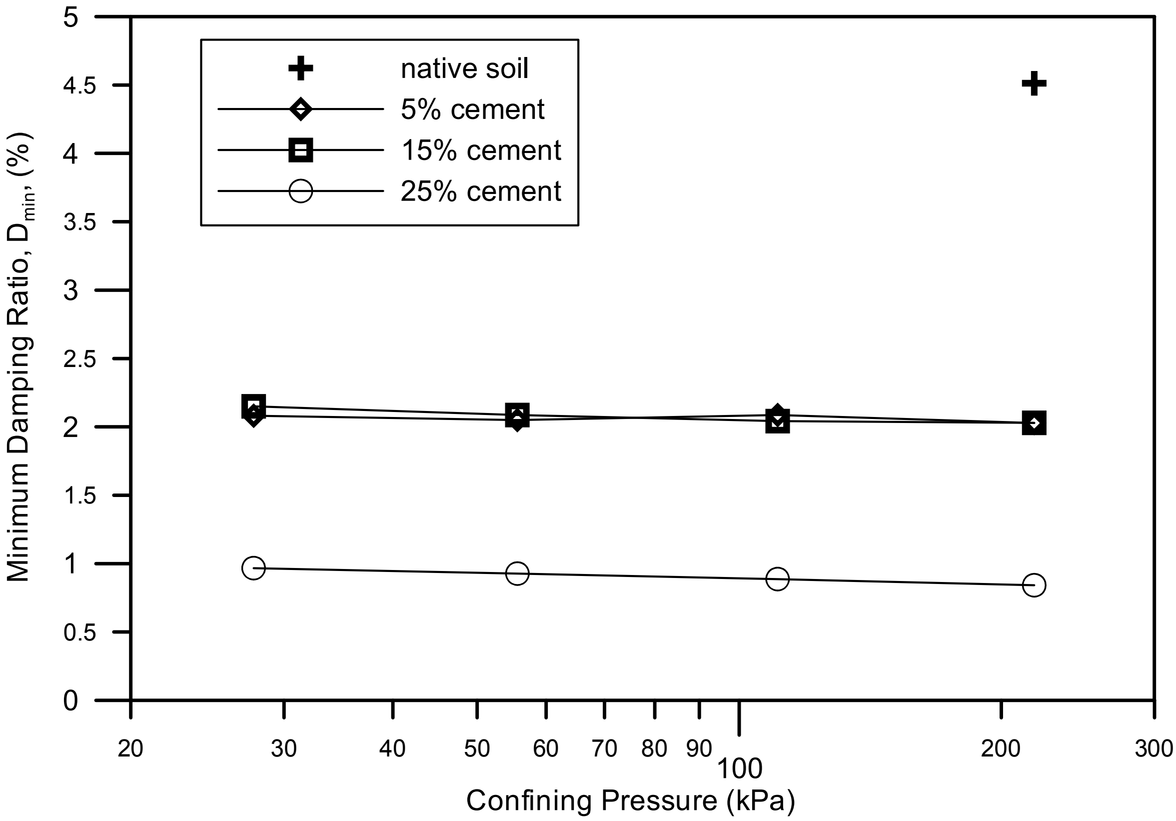

Figure 4. Influence of cement content on D_{min}

The approximation equations of the D_{min} value versus confining pressure for the cement stabilized soil were used as follow:

$$D_{min} = K_D \sigma_0^m . \tag{6}$$

where K_D is the modulus constant; m is the modulus exponent; σ_0 is the confining pressure. The K_D and m values for the stabilized soils were obtained by using regression method, which are also listed in Table 1. The m value of stabilized soils are about -0.012 ~ -0.241.

3.5. Effect of the cement content on the minimum damping ratio

For the stabilized soil, the confining pressure is also not a significant factor for the D_{min} value (Figure 4). The figure also shows that the D_{min} values for the 5% and 15% of cement content are close. The D_{min} value of 25% cement content is significantly lower than those of the above both cement contents.

3.6. Effect of the type of additive on the minimum damping ratio

It can be seen from Figure 5 that the D_{min} of the slag cement stabilized soil is lower than others. Therefore, it could be the reason that blast furnace slag is able to help cement hydrating and pozzolanic reaction to cause damping of stabilized soil decreasing. However, the functions result from sodium silicate is less than those of blast furnace slag.

4. High-amplitude test results

4.1. Effect of shearing strain on normalized shear modulus

The high-amplitude data obtained cover a range of shearing strains from 0.001% to 0.1% in this study. The results as shown in Figure 6 and Figure 7 are in a normalized shear modulus versus shearing strain plot.

From the figures, the normalized shear modulus is constant as shearing strain below 0.001% and decreases with increasing shearing strain. In the figures, the normalized shear modulus versus shearing strain curve is composed of two linear phases. At shearing strains less than threshold shear strain, shear moduli do not experience any cyclic degradation. The elasticity zone, where strains of materials are still reversible, can be identified. It corresponds to the zone where shear modulus is constant. The second phase, as its threshold shearing strains is exceeded, result in cyclic degradation of shear modulus. The Ramberg-Osgood curve fittings were performed for all of the high-amplitude test data. The Ramberg-Osgood parameters found are listed in Table 3. The shear modulus is decreased due to cyclic loading degradation.

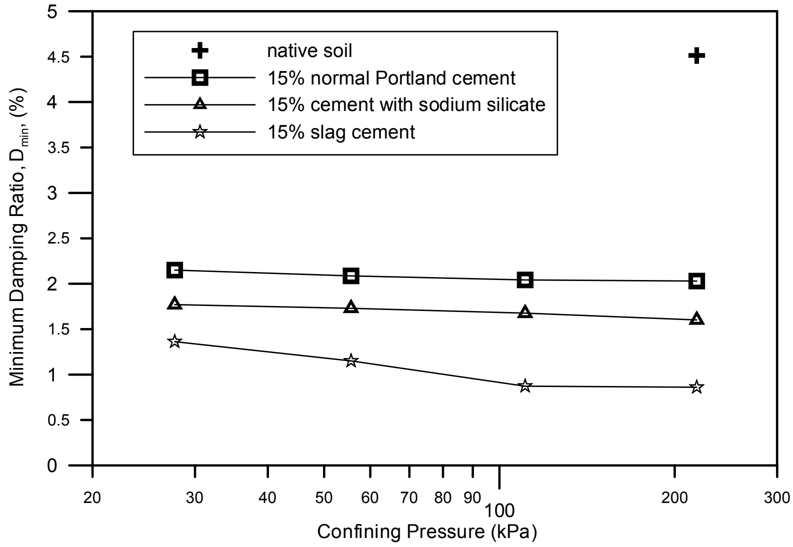

Figure 5. Influence of the type of additive on D_{min}

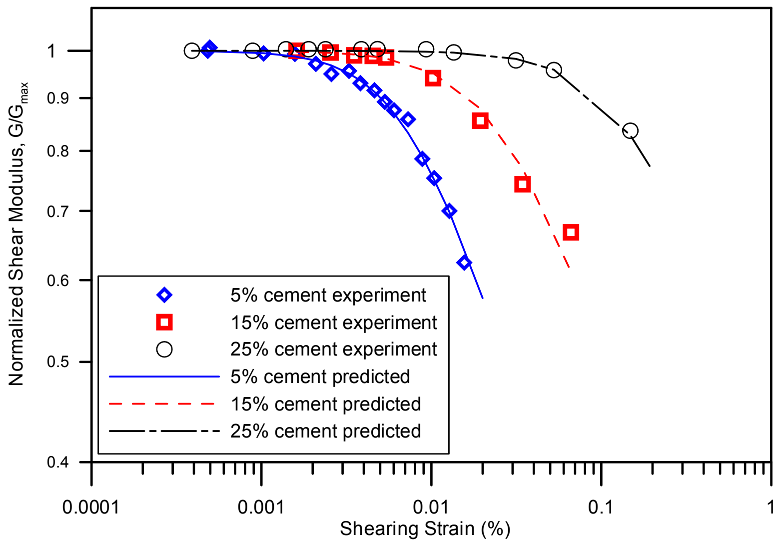

Figure 6. Influence of cement content on G/G_{max} versus γ curve

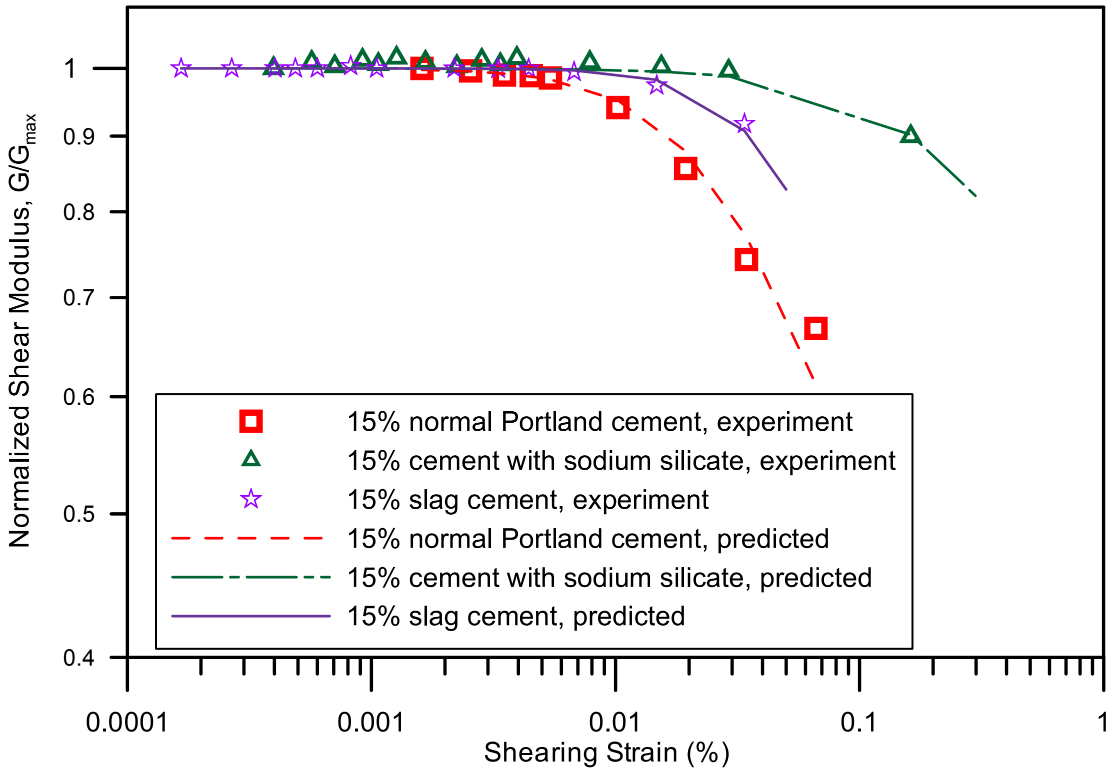

Figure 7. Influence of the type of additive on G/G_{max} versus γ curve

Table 3. Values of C and R

Stabilized soil type		C	R
	5%	6150	3.024
Portland cement stabilized soil	15%	184	2.768
	25%	8.43	2.766
Cement with sodium silicate stabilized soil		1.48	2.358
Slag cement stabilized soil		354	3.338

The high-amplitude test result presented by the Ramberg-Osgood stress strain relationship was using a least-square curve-fitting technique. For the stabilized soil studied, the variation of shear modulus with strain was satisfactorily represented by a following Ramberg-Osgood equation.

$$\gamma = \left(\frac{G}{G_{max}}\right)\gamma + C\left(\frac{G}{G_{max}}\gamma\right)^R = \left(\frac{\tau}{G_{max}}\right) + C\left(\frac{\tau}{G_{max}}\right)^R \quad (7)$$

where G is the shear modulus; γ is the shearing strain; C and R are the constant. Constants C and R determined for each material are listed in Table 3.

The normalized shear modulus for high-amplitude test measured and those predicted by the Ramberg-Osgood model were plotted as a function of shearing strain for comparison, as shown in Figure 6 and Figure 7. These figures show that the Ramberg-Osgood model can adequately describe the shear modulus for a wide range of shearing strain. The predicted curves of shearing stress versus shearing strain by the Ramberg-Osgood model are shown in Figure 8.

4.2. Effect of the cement content on normalized shear modulus vs. shearing strain curve

It can be observed from Figure 6 that the curve of normalized shear modulus, G/Gmax, versus shearing strain, γ, moves to the right as the cement content increasing. This could be explained that threshold shearing strain of stabilized soil increases with the cement content, the specimen of higher cement content is able to sustain a larger torsional vibration before stiffness degradation occurring. As can also be seen in Figure 6, the stiffness degradation curves are close to parallel. It indicates that the nonlinear stress-strain behavior of the cement stabilized soils for various cement content are the same.

4.3. Effect of the type of additive on normalized shear modulus vs. shearing strain curve

In Figure 7, the threshold strain of the cement stabilized soil with sodium silicate is greater than those of other types of cement stabilized soil in this study. Therefore, the cement stabilized soil with the sodium silicate has larger threshold shearing strain. As shearing strains larger than threshold shearing strain, the trend of the stiffness degradation of these stabilized soil are still the same.

4.4. Effect of shearing strain on normalized damping ratio

The cement stabilized soils presents an evolution of damping ratio with shearing strain: the normalized damping ratio is constant as shearing strain below 0.001% and increases with increasing shearing strain. (Figure 9)

4.5. Effect of the cement content on normalized damping ratio vs. shearing strain curve

Figure 9 illustrates the influence of the cement content on the curve of damping ratio versus shearing strain. It can be seen that if the cement content increases, the shearing strain is higher to hold damping ratio constant. This implies that the cement stabilized soil for higher cement content can sustain larger shearing strain before damping ratio increasing.

4.6. Effect of the type of additive on normalized damping ratio vs. shearing strain curve

Figure 10 presents a comparison of the curves of damping ratio versus shearing strain from various types of cement stabilized soil. As expected with the damping ratios of normal Portland cement stabilized soil is larger than those of the slag cement or the cement with sodium silicate stabilized soil.

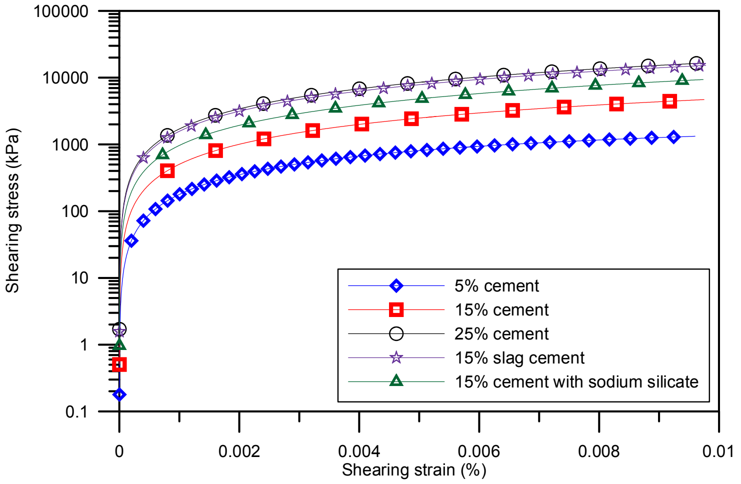

Figure 8. Predicted shearing stress versus shearing strain curve by Ramberg-Osgood equations

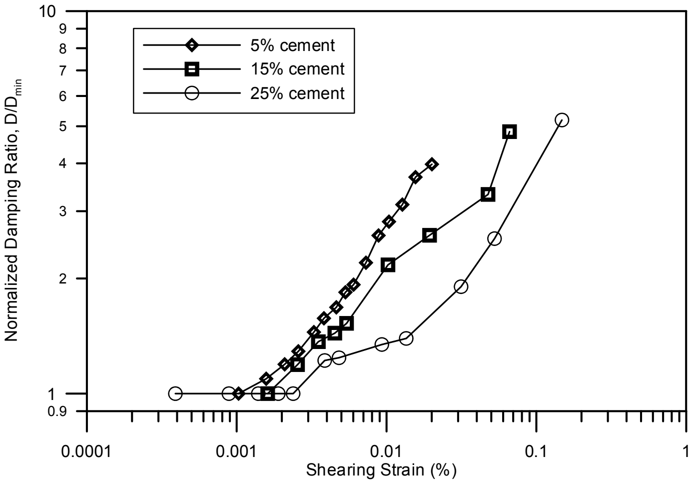

Figure 9. Influence of cement content on D/D_{min} versus γ curve

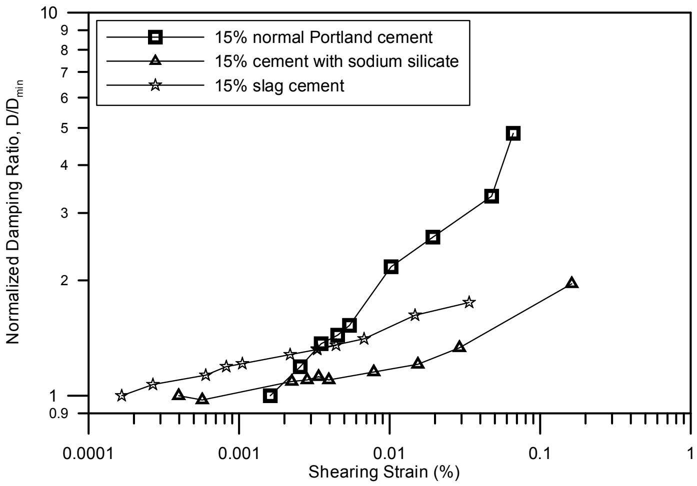

Figure 10. Influence of the type of additive on D/D_{min} versus γ curve

5. Conclusions

In this study, the dynamic properties for the cement stabilized soil from Taipei city were measured using the resonant column device. The effects of the cement content, the type of additive, the confining pressure, and the shearing strain on the shear modulus and the damping ratio were studied. The results are summarized as follows:

a) The slope of logarithmic low-amplitude shear modulus of the cement stabilized soil versus logarithmic confining pressure is ranging from 0.002 to 0.231, while the slope of logarithmic low-amplitude damping ratio of the cement stabilized soil versus logarithmic confining pressure is ranging from -0.012 to -0.241. The variation in confining pressure for the cement stabilized soil is not a significant factor on shear modulus and damping ratio.
b) The G_{max} value increases and the D_{min} value decreases as cement content increases for the cement stabilized soil.
c) The greatest stiffness improvement factor is about 22 for the additive of slag cement. Other stiffness improvement factors are 7.1 and 13.5 for the normal Portland cement and the cement admixed with sodium silicate, respectively.
d) The threshold shearing strain distinguished between strain-dependent and strain-independent modulus. The threshold shearing strain of the stabilized soils is larger for higher cement content. That is, the specimen of higher cement content is able to sustain a larger shearing strain before stiffness degradation occurring.
e) The soil stabilized with sodium silicate is able to sustain a larger threshold shearing strain than the other types of additive.

Acknowledgements

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