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Dynamic properties of composite cemented clay*

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Abstract: In this work, the dynamic properties of composite cemented clay under a wide range of strains were studied considering the effect of different mixing ratio and the change of confining pressures through dynamic triaxial test. A simple and practical method to estimate the dynamic elastic modulus and damping ratio is proposed in this paper and a related empirical normalized formula is also presented. The results provide useful guidelines for preliminary estimation of cement requirements to improve the dynamic properties of clays.

Key words: Composite cemented clay, Dynamic triaxial test, Dynamic elastic modulus, Damping ratio

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INTRODUCTION

Soft soils are widely distributed in China's coastal areas. The 1985 earthquake that inflicted great damage to Mexico City sited on soft soil foundations greatly attracted attention of researchers and engineers and moved them to study the dynamic properties of soft soils. Many researches have been dedicated to the study of dynamic properties of soft soils. In China, deep cement mixing methods have been widely used in the coastal areas. The mechanical properties of these composite foundation soils are not the same as that of undisturbed soft soils or other kinds of artificial foundations (such as pile foundations). The soil and reinforced column may exhibit much more complex interaction than natural foundations under dynamic loads. However, few researches on the dynamic properties of cemented mix piles foundations have been reported.

The dynamic properties of different kinds of soils have been reported in literature. Theirs and Seed (1968) studied the effect of strain and load circles on the parameters of the hyperbola model with San Francisco Bay mud. Based on a large number of tests, Hardin and Black (1968; 1969), and Hardin and Drnevich (1972a; 1972b) presented some empirical equations to evaluate the dynamic modulus and damping ratio of soft clay. Kim and Novak (1981), Kokusho *et al.*(1982), Kagawa (1992), Xin and Wang (1995), He (1997), Bao and Ma (2000), Teachavorasinskun *et al.*(2001) conducted numerous tests on many kinds of soil samples taken from different places. Vucetic and Dobry (1991) proposed that the plasticity index (I_p) is the key factor influencing the dynamic modulus and damping ratio of both normally consolidated and overconsolidated soils. The normalized dynamic modulus increased and the damping ratio decreased with the increase of I_p. Curves showing the influence of the plasticity index (I_p) on the normalized

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dynamic modulus and damping ratio with different strain levels were plotted. Yuan and Sun (2000) tested six soil samples using resonant column and listed the recommended values of dynamic modulus and damping ratio. Lanzo *et al.*(1997) studied the trend of the dynamic modulus and damping ratio under small strains through cyclic simple shear test. Assimaki *et al.*(2000) proposed a four-parameter model for estimating the dynamic modulus and damping ratio for granular soil, in which the input parameters were confining pressure and density. Researches on the dynamic properties of composite cemented clay are relatively new. Some results had been obtained: Fahoum (1996) studied the dynamic properties of three kinds of clays treated with lime; Chen *et al.*(2000) tested cemented clay through dynamic triaxial and resonant column test. Hou *et al.*(2001) studied the effect of cyclic stress ratio on the axial strain of composite cemented clay. As described above, there were a lot of research on the dynamic properties of clay and cemented clay; however, few studies were focused on cemented clay as a whole body. In engineering practice, the cemented mixing method is widely adopted in economically advanced and densely populated areas where earthquakes may cause great damage. It is very important to study the dynamic stress and strain, seismic response and soil foundation superstructure interaction of composite cemented soil, which is meaningful for seismic design of structures (Hadjian, 1991). This paper presents the testing and a simple equation to estimate the dynamic properties of composite cemented soils, which could serve as guidelines for determining whether cement would be an effective additive to improve the dynamic properties of soft clay soils.

SOILS TESTED AND TEST PROCEDURE

The triaxial test equipment in the testing procedure was improved and calibrated to test prepared soil samples (6.2 cm in diameter, 14 cm in height). The cement-mixing ratio (a) of cement soil core was 15% and the replacement ratio (m) of the composite cemented clay was set to be 5.7%, 10.8%, 19.5% respectively. At the same time, the pure clay samples were also prepared for comparison purpose.

A commercially available soil from Xiaoshan County and a commonly-used cement (425#) were used in the test. The major properties of undisturbed soil samples and remolded soil samples are listed in Table 1. The remolded soil samples were prepared according to Specifications of Soil Test (DT-92, 1993).

Liu (1991) described in detail the preparation procedure of composite cement clay samples and testing procedure. In this paper, some of the procedures were modified.

Table 1 Major properties of undisturbed soil samples and remolded soil samples

	Specific gravity (g/cm^3)	Water content (%)	Density (g/cm^3)	Plasticity index	Dry density (g/cm^3)	Void ratio
Undisturbed soil	2.73	50.4	1.73	19.8	1.15	1.37
Remolded soil	2.73	36	1.768	17.5		1.10

Sample preparation

This procedure was divided into three stages: (1) Preparation of cement soil core (1.48 cm, 2.04 cm, 2.74 cm in diameter respectively corresponding to m = 5.7%, 10.8%, 19.5%). According to standard lab procedure, three thin-wall (0.1 cm in thickness) tubes with different inner diameters 2.04 cm, 2.74 cm) were designed and made specially. The dry soil was pulverized into powder and sieved (with mesh less than 0.2 cm in diameter sieve). The required amount of cement (a=15%) was first mixed with the dry soil, and then water was added. After being thoroughly mixed, the mixture was pressed into the tubes. (2) Preparation of remolded pure soil samples. The standard preparation method

(SL237-002-1999) was adopted as the compaction procedure to prepare all pure soil samples. The compaction was done in 7 layers. (3) Preparation of composite soil samples. After the preparation of remolded pure soil samples, a hole (about 1 cm in diameter) was drilled in the center of the samples. Three different thin-wall tubes daubed with vaseline were driven into these samples respectively according to the replacement ratio in them. The thin-wall tubes were driven slowly and vertically to a certain depth into soil samples, then pulled out slowly and soils in the tubes were removed. This step was repeated 3−5 times until the tubes reached the bottom of soil samples. The tubes were then pulled out and substituted by another exactly similar tube with cement soil core inside the hole at the center of the samples. A tailor-made plastic stick (with diameter equal to the inner diameter of the corresponding tube) was inserted into the tubes and pressed down; then the tube was pulled out from the soil sample at constant speed. Then the cement soil core was left in the clay soil sample and a composite soil sample was made (Fig.1). The samples were wrapped in water-proof plastic bags and cured in water for 180 days, after which, a portion of the samples was selected randomly and cut to observe whether the cement soil cores had good contact with the surrounding clay soil.

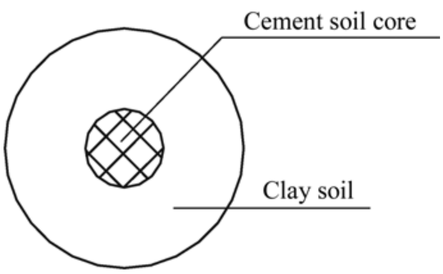

Fig.1 The plan view of composite cemented clay

Test procedure

Isotropic consolidation of the cured samples was done under three different confining pressures: 100 kPa, 200 kPa, 300 kPa. The confining pressure during consolidation was applied in several stages. After consolidation, cyclic loading was applied using a staged-testing procedure in which cyclic stress was applied in sequences starting from low to high.

Although the procedure for preparation of composite cemented clay samples was somewhat different from field construction condition of mixing cement piles, there was still reasonably good similarity between the composite soil and the onsite mixing cement piles. The composite cemented soil behavior was similar to that of cement mixing pile foundation under cyclic loading, in which the loading was shared by both piles and soils.

DATA CALCULATION AND ANALYSIS

The dynamic properties of composite cemented soil can be represented by the stress-strain curve of soils under cyclic loading: the dynamic elastic modulus shows the relation between dynamic stress and recoverable dynamic strain while the damping ratio can be measured from the area of a hysteresis loop related by stress and strain. A typical stress-strain curve forming a hysteresis loop during cyclic loading is shown in Fig.2. From such a loop, two parameters can be determined (the dynamic elastic modulus E_d and the damping ratio D). The dynamic elastic modulus E_d can be calculated using the following equation:

$$E_d = (\sigma_{d1} + \sigma_{d2}) / (\varepsilon_1 + \varepsilon_2) \quad (1)$$

where σ_{d1} and σ_{d2} are axial dynamic compression and tension stresses respectively; and ε_1 and ε_2 are the corresponding vertical strains. The damping ratio

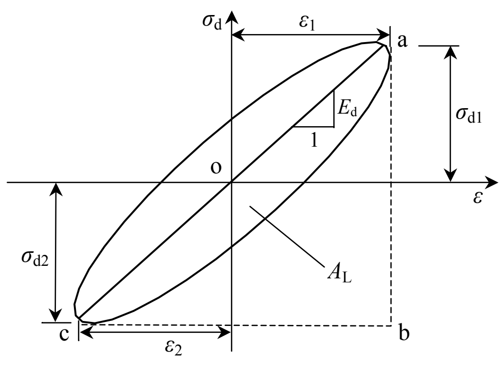

Fig.2 Typical idealized loop produced by cyclic loading

D can be calculated from Fig.2 using:

$$D = A_L / (\pi \times S_{\Delta abc}) \quad (2)$$

where A_L is the area of the hysteresis loop, and $S_{\Delta abc}$ is the area of the triangle abc.

EFFECT OF STRAIN

Two sets of curves are presented: dynamic elastic modulus (E_d) versus the axial strain ε ($=\varepsilon_1+\varepsilon_2$) and the damping ratio (D) versus the axial strain ε. Fig.3−Fig.6 show the effect of strain level ε on E_d and D with cement-mixing ratio of 15% and different replacement ratio (5.7%, 10.8%, 19.5%). All figures show that E_d decreases and D increases with the increase of ε, which agree well with the actual behavior of soils during dynamic loading due to the nonlinear characteristics of soils. The composite cemented clay samples with replaced cement soil core behave more rigidly than the untreated pure clay soil samples, which means higher values of E_d. Damping is an index representing of the amount of energy dissipated during cyclic loading. As the soil particles slide upon adjacent particles under cyclic loading, the strain energy released during the unloading stage is less than the strain energy accumulated during the loading stage. Therefore, at higher strain levels, more slippage and rearrangement of particles occurs and higher damping ratio would be expected. This explains the increase of D with the change of strain shown in these figures showing that E_d decreases very rapidly when the strain level ε ranges from 10^{-3} to10^{-2}. When ε is less than 10^{-3}, E_d

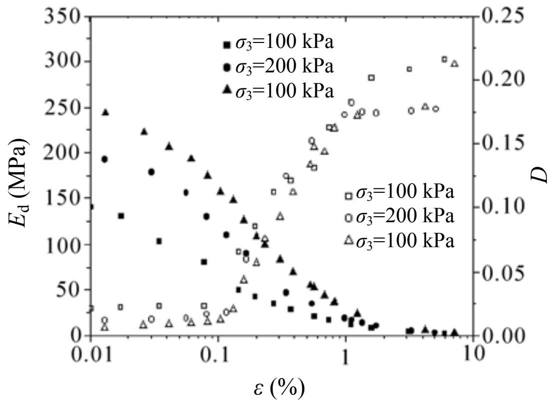

Fig.3 Curves of E_d and D versus ε (pure clay soil)

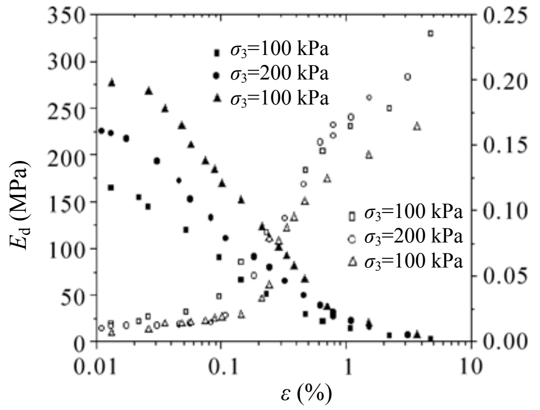

Fig.4 Curves of E_d and D versus ε (composite cemented soil, m=5.7%)

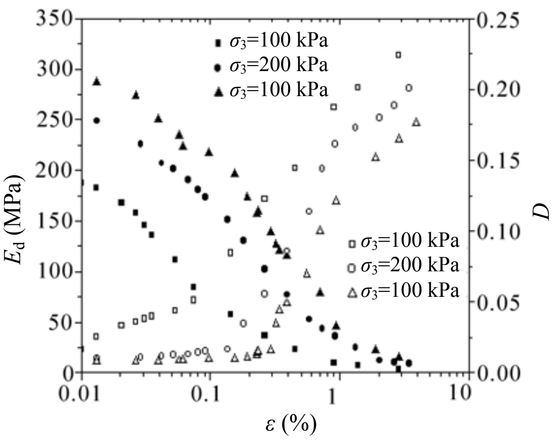

Fig.5 Curves of E_d and D versus ε (composite cemented soil, m=10.8%)

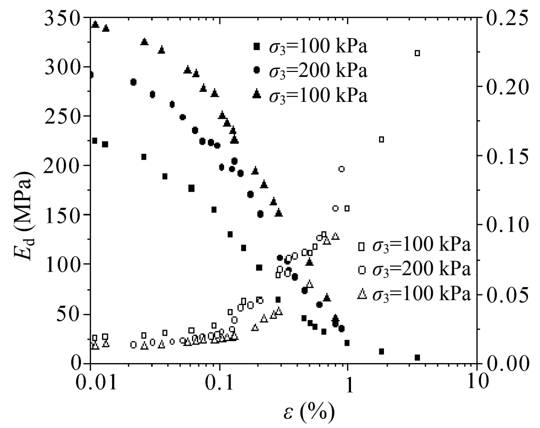

Fig.6 Curves of E_d and D versus ε (composite cemented soil, m=19.5%)

decreases slowly; when ε is greater than 10^{-2}, the residual dynamic elastic modulus remains almost constant. However, D shows reverse trend. It increases rapidly when the strain level ε ranges from 10^{-3} to 10^{-2}. When ε is less than 10^{-3}, D remains almost unchanged; when ε is greater than 10^{-2}, the increment of D becomes smooth.

EFFECT OF CONFINING PRESSURE

Fig.3 shows the effect of confining pressure on E_d and D of pure clay soil samples. Under a certain strain level, with the increase of confining pressure, D increases while E_d decreases. Fig.4−Fig.6 show similar trend. This can be explained as follows: when the confining pressure increases, the contact of adjacent particles in composite cemented soil samples becomes tighter; thus there are more wave pathways, which will lead to less energy dissipation; so the composite cemented clay samples have higher E_d and lower D.

EFFECT OF REPLACEMENT RATIO

The composite cemented clay samples' replacement ratio (m) is a very important factor affecting E_d and D. When other parameters remain unchanged, E_d increases while D decreases when m increases at a certain strain magnitude. The dynamic modulus of cemented soil core is much higher than that of the surrounding clay soil. When m increases, the resulting increase of the dynamic modulus of cemented soil core increases the integral dynamic modulus (E_d).

DETERMINATION OF MAXIMUM DYNAMIC ELASTIC MODULUS (E_{dmax}) AND DAMPING RATIO (D_{max})

Hardin and Black (1968) obtained an empirical equation for estimating the maximum dynamic shear modulus G_{dmax}:

$$G_{\mathrm{dmax}} = \frac{326(2.97-e)^2}{1+e}(OCR)^a(\sigma_{\mathrm{m}})^{\frac{1}{2}} \tag{3}$$

where e is void ratio; OCR is the over consolidation ratio; σ_m is the confining pressure σ_3 (isotropic consolidation) in 10^5 Pa; and a is a function of Plastic Index I_p. Eq.(3) can be used to calculate G_{dmax} of pure soil. With Eq.(4), E_{dmax} can be obtained as:

$$G_{\mathrm{dmax}} = \frac{E_{\mathrm{dmax}}}{2(1+\mu)} \tag{4}$$

Lambe and Whitman (1969) reported that μ has a relatively small effect on the dynamic shear modulus in most civil engineering projects. For fully-saturated soils, μ is 0.5, and for weakly-saturated soils, μ is 0.35. It is suggested that for lime-stabilized soils, a value of 0.31 be used (Lime Stabilization, 1987). Hicher *et al.*(1987) proposed a value of 0.3 in their dynamic tests with 90% saturated cohesive soils. Because of the lack of special research on μ of cemented soils, based on the work of the above researchers, a value of 0.4 selected as Poisson ratio in this study was reasonable.

In a definite strain range, with the relationship presented in Fig.7, E_{dmax} can be obtained. Table 2 shows E_{dmax} for the soil samples.

With Eq.(4), G_{dmax} of clay soil are 54, 77, 93 MPa, while using Eq.(3), the corresponding G_{dmax} is 50, 68, 86 MPa. These two sets of values agree well.

The determination of D_{max} is more complicated. Hardin and Black (1968) presented empirical equations for evaluating D_{max} of several kinds of clays and sands. D_{max} can be easily determined at hi-

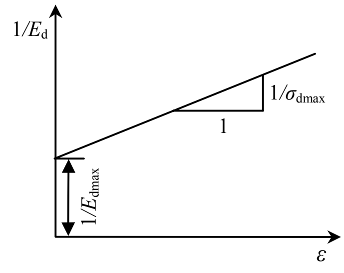

Fig.7 Curve of dynamic stress and strain

gher strain and the increase of D becomes slow. In Fig.3−Fig.6, the curves of D−ε become flatter in the upper right corner and then approach to a constant, D_{max}.

Table 2 E_{dmax} with different confining pressure and replacement ratio

E_{dmax} (MPa)	σ_3=100 kPa	σ_3=200 kPa	σ_3=300 kPa
Clay soil	145	196	250
Composite cemented soil (m=5.7%)	172	233	286
Composite cemented soil (m=10%)	196	263	300
Composite cemented soil (m=19%)	244	313	357

Table 2 shows that the E_{dmax} of the treated soils is obviously higher compared with untreated soils. The replacement ratio m shows more significant influence on E_{dmax} with lower confining pressure σ_3. When σ_3 is 100 kPa, E_{dmax} increases 68% as m increases from 5.7% to 19.5%; while when σ_3 is 300 kPa, E_{dmax} increases 43% as m increases from 5.7% to 19.5%. σ_3 is more significant to E_{dmax} when m is smaller. When m is 5.7%, E_{dmax} increases 66% as σ_3 increases from 100 kPa to 300 kPa; When m is 19.5%, E_{dmax} increases 46% as σ_3 increases the same percent. Data in Table 2 are plotted in Fig.8 and Fig.9.

Regression analysis of the relevant data yielded an empirical equation for estimating the maximum

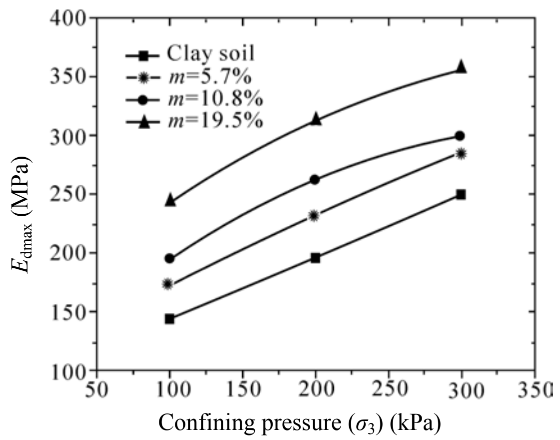

Fig.8 Plot of E_{dmax} for different confining pressures

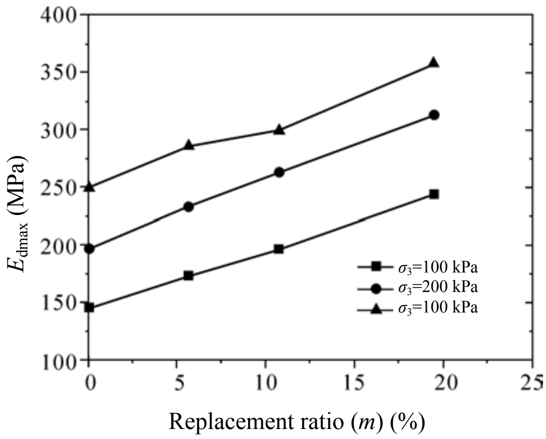

Fig.9 Plot of E_{dmax} for different replacement ratio

dynamic elastic modulus E'_{dmax} of composite cemented soil with different replacement m under various confining pressures:

$$E'_{dmax} = E_{dmax}[1 + m(\frac{3.524 - A}{1 + \xi^{\frac{\sigma_3 - 2.825}{0.425}}} + A)] \tag{5}$$

where E_{dmax} is the maximum dynamic elastic modulus of pure clay soils, which can be calculated through Eq.(3); E'_{dmax} is the maximum dynamic elastic modulus of composite cemented soils; σ_3 is in 10^5 Pa and ξ is the Napierian base (ξ=2.718). A (=1.738) is a parameter obtained from the test data. In this way, E'_{dmax} of composite cemented soils with different replacement ratio can be estimated through Eq.(5).

Fig.10 of the normalized plot of E_d/E'_{dmax} versus ε for different kinds of treated and untreated soils shows that the distribution of most data agrees well with the fitting solid curve, which can be expressed as:

$$\frac{E_d}{E'_{dmax}} = \frac{A_1 - A_2}{1 + \xi^{\frac{\varepsilon + 0.6}{0.24}}} + A_2,$$

where A_1 and A_2 are constants obtained from test, with A_1=15, A_2=0.05.

Fig.11 of the normalized plot of D/D'_{max} versus ε for different kinds of treated and untreated soils

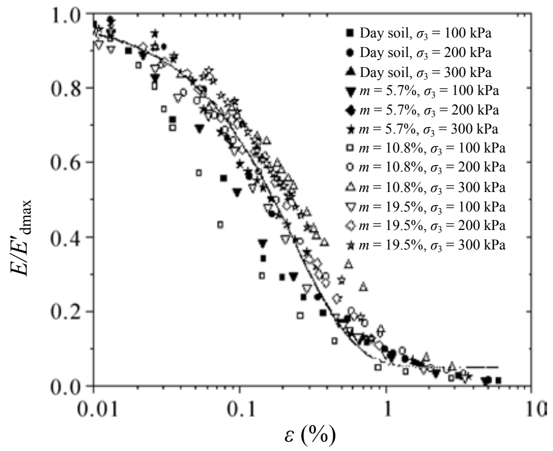

Fig.10 Normalized plot of E_d/E'_{dmax} versus ε

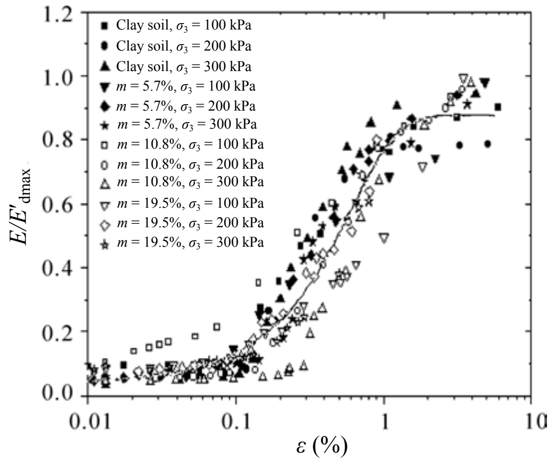

Fig.11 Normalized plot of D/D'_{max} versus ε

shows the distribution of most data agrees well with the fitting solid curve, which can be expressed as:

$$\frac{D}{D'_{max}} = \frac{A_3 - A_4}{1 + \xi^{\frac{\varepsilon - 0.135}{0.35}}} + A_4,$$

where A_3 (=−0.54) and A_4 (=0.88) are also constants obtained from test.

CONCLUSION

Parameters (E_d and D) indicating the dynamic properties of soil are fundamental to the seismic design of structures. However, few reports of researches on the dynamic properties of composite cemented soils are found in literature. Curves presented in this paper can provide useful reference for estimating dynamic parameters of cement-mixed pile foundations. This work leads to the following conclusions:

1. The dynamic properties of composite cemented soils are obviously improved; the maximum dynamic elastic modulus increased and the maximum damping ratio decreased after replacement.

2. E_d increased and D decreased with the increased confining pressure in the same strain level. When the strain level ε increased, E_d decreased and D increased.

3. After normalization, the test data agreed well with the fitting curves. For clay soils treated with a definite cement-mixing ratio (15%), the dynamic parameters can be determined, which may be important for the seismic design of structures.

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