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Experimental Research on Dynamic Parameters of Unit Cell of Deep Mixed Column-Reinforced Soft Clay at Different Stress Levels

Guanbao Ye[1, 2], Liangkai Qin[1, 2], Zhen Zhang[1, 2*], Wenqiang Zheng[1, 2, 3] and Yong Chen[1, 2]

[1]Department of Geotechnical Engineering, Tongji University, Shanghai, China;
Email: ygb1030@126.com, 973026959@qq.com, zhenzhang@tongji.edu.cn, zweqia@163.com, 1005636953@qq.com
[2]Key Laboratory of Geotechnical and Underground Engineering of Ministry of Education, Tongji University, Shanghai, China;
[3]SGIDI Engineering Consulting (Group) Co., Ltd., Shanghai, China

Abstract: Composite soil with deep mixed column is widely used in strengthening soft soil subgrade. This paper carries out the multistage and cyclical loading–unloading dynamic triaxial tests, with the large static and dynamic triaxial equipment (GCTS-STX600), on composite soil with deep mixed column under different confining pressures. The results show that: During the loading stage process of composite soil with deep mixed column, the difference of dynamic elastic modulus under different confining pressures does not change much. The dynamic elastic modulus increases and the damping ratio decreases slightly with increasing the confining pressure. In the process of unloading staged, the difference of dynamic elastic modulus under different confining pressure is more obvious. The dynamic elastic modulus increases and the damping ratio decreases slightly with increasing the confining pressure; the gradual unloading causes the degradation of the dynamic parameters of composite soil with deep mixed column. In the process of grading loading and unloading, the difference of dynamic parameters decreases as the confining pressure increases. Under the same confining pressure, as the dynamic stress ratio *CSR* increases, the difference of dynamic parameters gradually decreases, and the standard deviation of the corresponding dynamic parameters also decrease. The coefficient of variation of dynamic elastic modulus of Composite soil with deep mixed column is 0.51%~4.89%, the coefficient of variation of damping ratio is 3.55%~13.9%, and the coefficient of variation of damping ratio is larger than that of the corresponding dynamic elastic modulus, that is, damping is more obvious than volatility.

Keywords: Composite soil with deep mixed column; cyclic loading–unloading; large-scale triaxial test; dynamic elastic modulus; damping ratio

1 Introduction

Cement-soil mixed piles has been widely used in the practice of soft soil foundation reinforcement in my country due to its flexible pile layout, mature construction technology, and economical cost (Huang et al., 2009). The treated soft soil roadbed has withstand long-term reciprocating traffic loads, so the dynamic characteristics of cement-soil pile composites have also attracted much attention.

Liu Songyu et al. (2009) conducted a field study of nail-shaped cement-soil piles in conjunction with a certain expressway project. Ye Guanbao et al. (2016) established a theoretical calculation formula for the pile-soil stress ratio of the cored cement-soil pile composite foundation based on the deformation mode of the soil, cement-soil and composite pile elements. Bai Shunguo et al. (2006) used indoor model tests to find that as the cyclic stress ratio increases, the settlement rate of the cement-soil composite foundation increases. Liu (2019) investigated the static and dynamic characteristics of the composite soil with cemented soil core, a series of experiments were carried out by using the cyclic simple shear test. The result shows that, the static shear strain showed strain hardening, cemented soil core can improve static shear strength of composite soil, vertical stress can enlarge reinforcement of cemented soil core. Cai et al. (2004), Lyu Chengwei (2016) and Kazemian et al. (2012) analyzed the static and dynamic characteristics of composite soil with deep mixed column. However, most of the current researches focus on the static characteristics of cement-soil pile composite foundations (Cai et al. 2020; Chai et al. 2019) and the dynamic characteristics of cement-soil (Liu et al. 2019). There are few studies on the dynamic characteristics of cement-soil pile composites under cyclic loading.

This paper uses the GCTS-STX600 large-scale triaxial apparatus to carry out a large-scale dynamic triaxial test of cement-soil pile composites, to study the influence of the graded loading and unloading paths on its dynamic parameters under different confining pressures, and to analyze the volatility of dynamic parameters.

2 Test plan and sample preparation

2.1 Test equipment and scheme

The static and dynamic test of composite soil with deep mixed column adopts a large static and dynamic triaxial apparatus, as shown in Figure 1. The GCTS large-scale dynamic and static triaxial testing machine can generate sine waves, square waves, triangle waves and user-defined waveforms with an axial loading frequency of 0~10 Hz. The axial force loading accuracy is ±0.01 kN, and the confining pressure accuracy is ±0.1 kPa.

The test plan mainly considers the influence of the confining pressure and dynamic stress grading loading and unloading on the dynamic characteristics of composite soil with deep mixed column. The loading form is divided into multi-stage loading and multi-stage unloading: the dynamic stress of stepped loading is divided into 5 grades, each cycle is 2500 times, and the dynamic stress ratio is 0.25, 0.30, 0.35, 0.40 and 0.45 in sequence; the order of the stepped unloading dynamic stress ratio is reversed. Relevant studies have shown (Hyodo et al., 1988; Pham et al., 2020) that the frequency of the dynamic stress generated by the traffic load in the roadbed is generally 0.1 Hz to 5 Hz, and the low frequency component is mainly about 1 Hz, so it can be used half sine wave is used to describe the dynamic stress in the foundation soil under traffic load. Therefore, this experiment uses a 1 Hz half sine wave to simulate the dynamic stress in the foundation soil under the traffic load. The schematic diagram of loading (unloading) is shown in Figure 2. The confining pressure adopts 40 kPa, 60 kPa and 80 kPa, respectively.

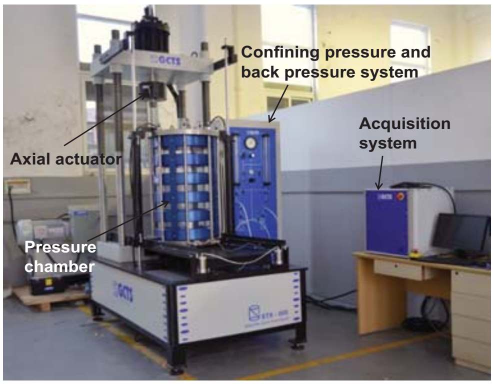
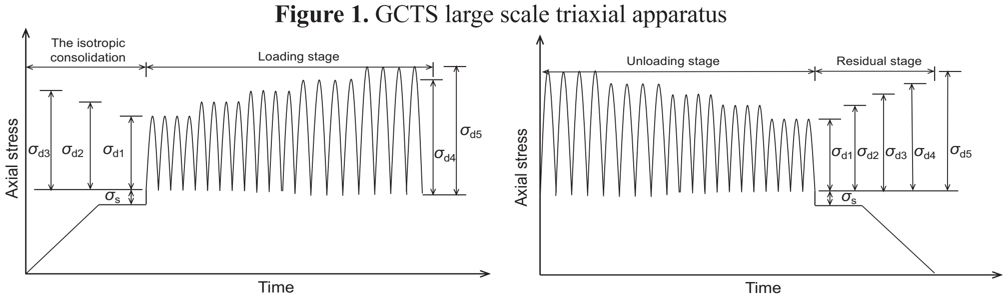


Figure 1. GCTS large scale triaxial apparatus



(a) (b)

Figure 2. Schematic of staged cyclic loading: (a) loading; (b) unloading

2.2 Experimental material

The test materials include soil, cement and water. The basic physical and mechanical parameters of the silty clay used in the test are as follows: the density is 1.66 g/cm^3, the water content is 25.0%, the liquid limit is 36.3%, and the plastic limit is 21.2%. The cement uses ordinary Portland cement (P.O 32.5), and the water uses tap water. The diameter of the cement-soil model pile is 100 mm, and the replacement ratio is 11.1%. The cement-soil model pile has a cement content of 10%, and the water-cement ratio is 1. The prepared cement-soil slurry was placed in the model pile mold and vibrated, and the molds were removed after standing for 48 hours, and placed in a standard curing room for 60 days of immersion in water. The peak strength of the cement-soil was measured to be 0.93 MPa.

Figure 3 is a schematic diagram of a large-scale triaxial test sample of a cement-soil pile composite unit body. The diameter of the large triaxial test specimen is 300 mm and the height is 600 mm. When making the sample, place the cement-soil model pile in the center of the mold; weigh the fully stirred soft soil in batches according to the natural density of the soft soil, fill it into the mold layer by layer, and compact to the specified height; repeat the operation to the mold fill the soft soil; scrape the top surface of the sample to be flush, spread a layer of filter paper, and then gently place the loading top cover on the top of the sample. The finished sample is shown in Figure 4. Place the sample in the instrument and consolidate it under the corresponding confining pressure. After the volume change stabilizes (in this test, let it stand for 12 hours), perform the GCTS dynamic triaxial test.

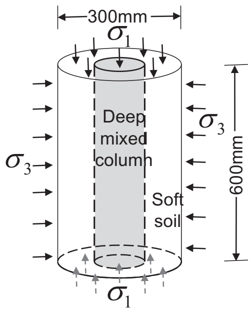


Figure 3. Schematic of unit cell of composite soil with DM column

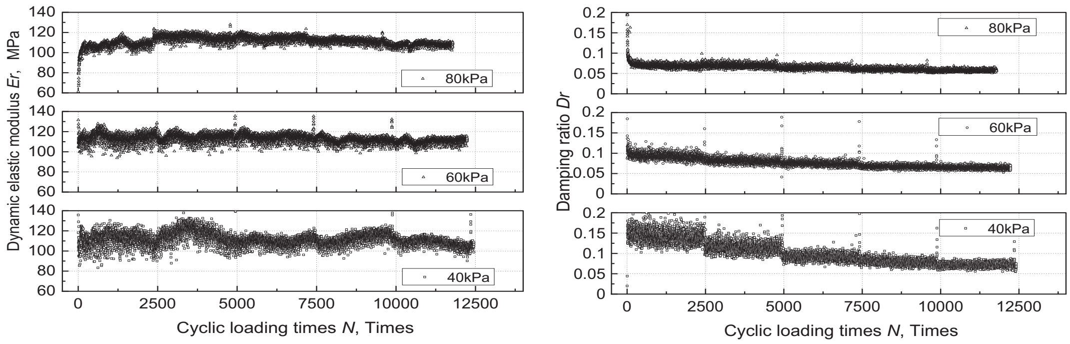
(a) (b)

Figure 4. Specimen preparation of GCTS large-scale triaxial test: (a) sample preparation; (b) flatness calibration of sample top surface

3 Analysis of dynamic parameters of composite soil with deep mixed column

3.1 The effect of dynamic stress multi-stage loading

Figure 5 shows the relationship curves of dynamic parameters of cement-soil pile composites with gradual loading under different confining pressures. It can be seen from Figure 5(a) that under the step-by-step loading, the difference in the effect of confining pressure on the dynamic elastic modulus is not obvious. As the dynamic stress ratio increases, the dynamic elastic modulus decreases slightly, but within the same dynamic stress vibration level range, the dynamic elastic modulus does not change much with the vibration frequency. This may be because the dynamic stress level is lower than its strength. Figure 5(b) shows the variation curve of damping ratio with vibration frequency under different confining pressures. As the confining pressure increases, the damping ratio under the same vibration frequency becomes smaller; as the dynamic stress amplitude increases, the damping ratio decreases slightly. Within the range of test confining pressure and dynamic stress ratio, the stable dynamic modulus value is 100~130 MPa, and the stable value of damping ratio is 0.05~0.15.

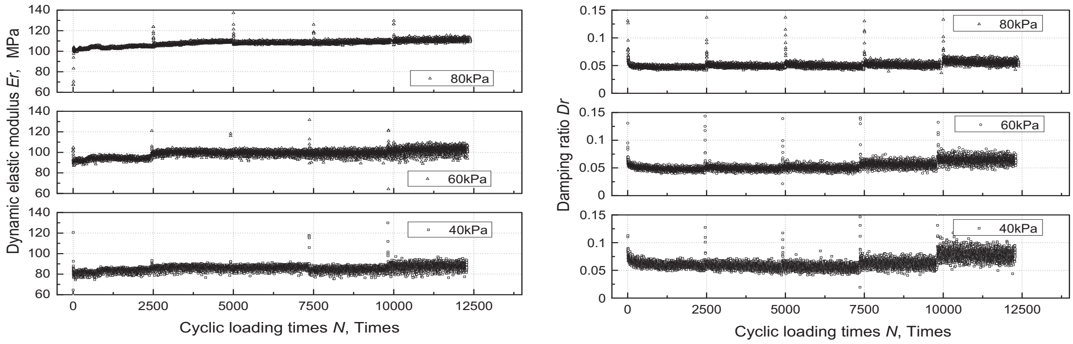


(a) (b)

Figure 5. Dynamic parameter versus cyclic loading times under loading stage: (a) dynamic elastic modulus; (b) damping ratio

3.2 The effect of dynamic stress multi-stage unloading

Figure 6 shows the relationship curves of dynamic parameters of cement-soil pile composites with gradual unloading under different confining pressures. It can be seen from Figure 6(a) that, in the case of unloading, the effect of confining pressure on the dynamic elastic modulus is more obvious. As the vibration frequency increases, the dynamic elastic modulus increases, but within the same dynamic stress vibration level range, the dynamic elastic modulus does not change much with the vibration frequency. Figure 6(b) shows the variation curve of the damping ratio with the order of vibration under different confining pressures. As the confining pressure increases, the damping ratio under the same vibration frequency is approximately the same, and the fluctuation of the damping ratio becomes smaller; as the amplitude of the dynamic stress decreases, the damping ratio increases slightly. Within the range of test confining pressure and dynamic stress ratio, the dynamic elastic modulus has a stable value of 80~110 MPa, and the damping ratio has a stable value of 0.05~0.10.

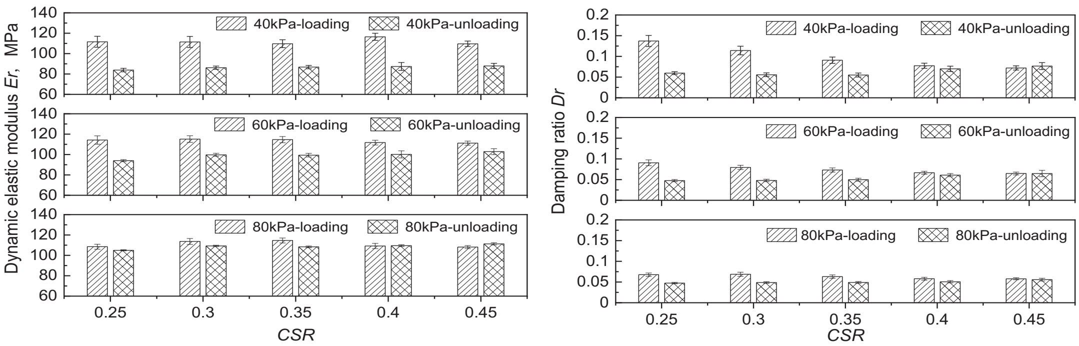


(a) (b)

Figure 6. Dynamic parameter versus cyclic loading times under unloading stage: (a) dynamic elastic modulus; (b) damping ratio

3.3 Analysis of dynamic parameters at different stress levels

Figure 7 shows the comparison of the difference in dynamic elastic modulus and damping ratio for each level of dynamic stress ratio of the cement-soil pile composite body. The dynamic parameter of each level of dynamic stress ratio is the average value after the dynamic parameter is stabilized, and the standard deviation of the corresponding dynamic parameter is marked. It can be seen from Figure 7(a) that in the process of dynamic stress hierarchical loading and unloading, the difference in dynamic elastic modulus between the two decreases as the confining pressure increases, and the standard deviation of the corresponding dynamic parameters also decreases as the confining pressure increases; Under the same confining pressure, with the increase of the dynamic stress ratio CSR, the difference in dynamic elastic modulus between staged loading and staged unloading gradually decreases, and the standard deviation of the corresponding dynamic parameters also decreases. It can be seen from Figure 7(b) that in the process of dynamic stress grading loading and unloading, the difference in damping ratio between the two decreases as the confining pressure increases.



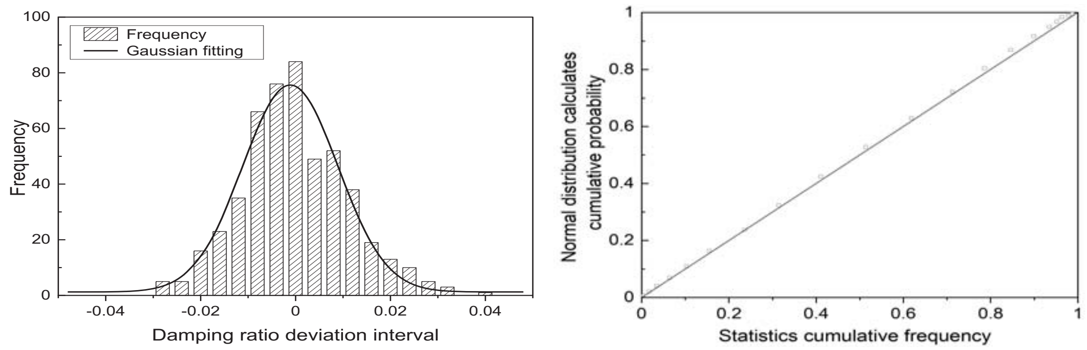
(a) (b)

Figure 7. Difference of dynamic parameters of composite soil with deep mixed column: (a) dynamic elastic modulus; (b) damping ratio

4 Analysis of volatility of dynamic parameters

4.1 Volatility distribution

It can be seen from the test results that under cyclic loading, the dynamic elastic modulus and damping ratio of the composite soil with deep mixed column fluctuate in a certain range. If the volatility of the parameters is large, it is not rigorous to only represent the design parameters with a certain value. For study the volatility of the dynamic parameters of the specimen, the last 500 times under each level of dynamic stress, that is, the dynamic parameters after the strain is stabilized, are selected for analysis. Figure 8(a) is a histogram of the frequency distribution of the damping ratio deviation under the condition of 40 kPa confining pressure and staged loading, and Gaussian fitting is used to obtain its mean value, variance and other related parameters. Normal distribution is used to check the fitting parameters. If the data shows a good normal distribution, as shown in Figure 8(b), the mean, standard deviation and coefficient of variation of the test data of this group are calculated. Based on this, the degree of volatility of the dynamic parameters of the composite soil with deep mixed column is analyzed.

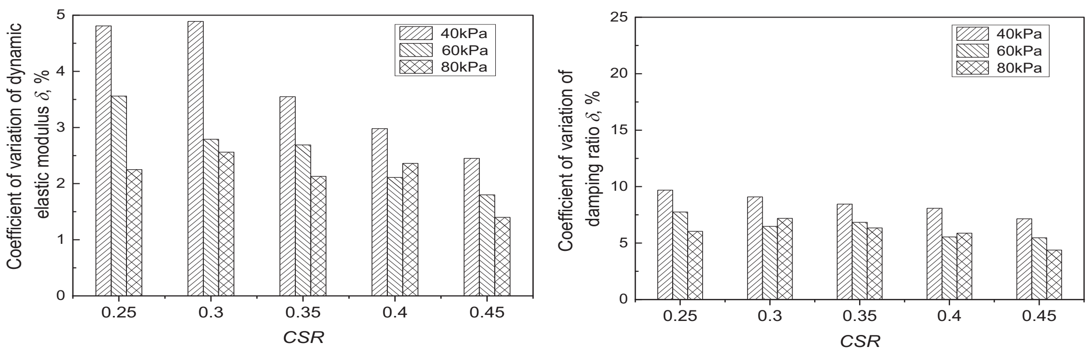


(a) (b)

Figure 8. Damping ratio deviation results under the confining pressure is 40kPa: (a) frequency distribution histogram; (b) normal distribution test

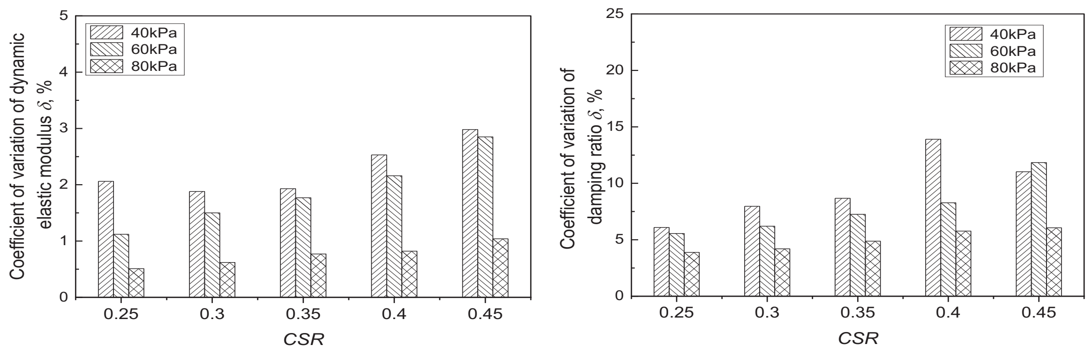
4.2 Analysis of volatility of dynamic parameters

Figures 9 and 10 show the calculation results of the coefficient of variation of dynamic parameters of composite soil with deep mixed column under the condition of stepped loading and stepped unloading, respectively. Under gradual loading, the composite soil with deep mixed column shows that the coefficient of variation of dynamic elastic modulus and the coefficient of variation of damping ratio gradually decrease with the increase of dynamic ratio. Under gradual unloading, the coefficient of variation of dynamic parameters of the composite unit body increases step by step with the dynamic load. And it also shows that under the same dynamic stress ratio, the greater the confining pressure, the smaller the coefficient of variation of dynamic parameters, that is, the volatility decreases. The coefficient of variation of dynamic elastic modulus of cement pile composite unit body is 0.51%~4.89%, the coefficient of variation of damping ratio is 3.55%~13.9%, and the coefficient of variation of damping ratio is larger than that of the corresponding dynamic elastic modulus, that is, damping is more obvious than volatility.



(a) (b)

Figure 9. Coefficient of variation of dynamic parameter under loading stage: (a) dynamic elastic modulus; (b) damping ratio



(a) (b)

Figure 10. Coefficient of variation of dynamic parameter under unloading stage: (a) dynamic elastic modulus; (b) damping ratio

5 Conclusions

(1) During the stepped loading process of composite soil with deep mixed column, the difference in dynamic elastic modulus under different confining pressures does not change much. Within the range of test

confining pressure and dynamic stress ratio, the stable dynamic modulus value is 100~130 MPa, and the stable value of damping ratio is 0.05~0.15. In the stepped unloading process, the difference in dynamic elastic modulus under different confining pressures is more obvious; the gradual unloading causes the dynamic parameters of the composite unit to deteriorate. The stable value of dynamic elastic modulus is 80~110 MPa, and the stable value of damping ratio is 0.05~0.10.

(2) In the process of dynamic stress stepped loading and unloading, the difference of dynamic parameters decreases with the increase of confining pressure. Under the same confining pressure, as the dynamic stress ratio CSR increases, the difference of dynamic parameters gradually decreases, corresponding to the difference of dynamic parameters and the standard deviation is also reduced.

(3) The volatility of dynamic parameters of staged unloading is obviously weaker than that of multi-stage loading, and this kind of volatility has an obvious relationship with the amplitude of dynamic stress. The coefficient of variation of dynamic elastic modulus of composite soil with deep mixed column is 0.51%~4.89%, the coefficient of variation of damping ratio is 3.55%~13.9%, and the coefficient of variation of damping ratio is larger than that of the corresponding dynamic elastic modulus, that is, damping is more obvious than volatility.

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