A Study on Constitutive Model of the Cohesive Soil Considering Soil-Structure Interactions

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Abstract. Transformer is key equipment in the power transmission and transformation system. When the seismic calculation is carried out, the foundation soil is generally considered to be absolutely rigid, and the bottom of the structure is considered as the fixed end, the soil-structure interaction is ignored. This paper is aimed to study the soil-structure interaction’s impact on the seismic performance of the transformer and other power facilities by carrying out cyclic shear test on cohesive soil, simulating the dynamic response of clay soil under the seismic load, and get the nonlinear dynamic characteristics parameters of the soil in the loading process of seismic cycles. On the basis of the study, the fitting equation of the dynamic shear modulus and damping ratio of the soil is put forward through analyzing the cohesive soil dynamic hysteresis constitutive model.

Keywords. Cyclic shear, constitutive model, cohesive soil, seismic effect.

1. Introduction

Extra-high voltage transformers, transforming voltage levels and reducing power energy losses in the power transmission system, are the key equipment in the power transmission system. The destruction of power facilities caused by earthquake will also cause inconvenient for earthquake relief and post-disaster reconstruction work besides the economic loss it caused.

At president, many researches on the seismic performance of electrical equipment has been carried out and fruits have been made at home and abroad [1-9]. But most of these researches take the foundation and the structure separately, assuming that the foundation performs absolute rigidity and the base of the upper structure performs the fixed end, ignoring the influence of the interaction between the foundation and the transformer structure. Actually, the foundation material has the non-absolute rigidity and even has much stronger non-linear deformation property compared to the structural material. There is both a force interaction and a mutual constraint of deformation between the object and the foundation, which in turn causes the mutual transmission and exchange of vibration energy, making a big difference on the dynamic response of the structure between the real practice and the assumption of a rigid foundation.

Many in-depth researches that carried out by scholars at home and abroad proved that the upper structure, the base and the foundation interactions between each other should be taken as a whole, and the dynamic interaction between the three should not be neglected when carrying out structural seismic calculation [10]. Researches includes the shaking table tests of the structure and the overall structural system of the soil in consideration of soil-structure dynamic interaction made by Konagai K [11], and the three-dimensional finite element model of the Shaanxi Information Building in
consideration of soil-structure dynamic interaction advanced by Tao Lei in 2009. Professor Chen in Nanjing Tech University proposed a simplified analysis method to assist in calculating the soil-structure dynamic interaction, the calculation accuracy of this method cannot meet the requirements of seismic calculation as a kind of seismic simplification method, but it can be used to check the results of seismic calculation as a reference [12]. Using Goodman units on the SuperFLUSH software platform and then using an equivalent linear model to represent the nonlinear characteristics of soil, Yin established and made an analysis of the nuclear island model considering the dynamic interaction of soil-structure, but the pile-soil-nuclear island calculation model used for the calculation is a two-dimensional simplified model, which cannot reflect the real reaction of complex nuclear island structures in earthquakes [13]. In summary, scholars at home and abroad believe that the dynamic interaction between the upper structure, the foundation and soil cannot be neglected when performing seismic calculations [14-18]. As the improvement of computer performance, the overall finite element method to analyze the influence of soil-structure interaction is often used in large engineering projects, which treats the structure and the foundation soil body within a certain range as a whole structural system, and then uses the finite element method to discretize the structure and the foundation soil and then analyzes the seismic response of the input ground shaking of the whole structural system, so that the seismic response in anytime under seismic action and the complex nonlinear problems can be solved more conveniently. But the disadvantage is that the amount of the set of equations to be solved will increase dramatically as the overall structure's degrees of freedom increase, and the preparation work required by the computer is large and computationally intensive.

In this paper, the cyclic shear test on cohesive soil, is carried out and the dynamic response of clay soil under the seismic load is simulated, and get the nonlinear dynamic characteristics parameters of the soil in the loading process of seismic cycles. On the basis of the study, the fitting equation of the dynamic shear modulus and damping ratio of the soil is put forward through analyzing the cohesive soil dynamic hysteresis constitutive model.

2. Cyclic Shear Test Studies on Cohesive Soils

2.1. Test Apparatus and Soil Specimens

Soil dynamics test is the basis of the study on dynamic properties of soil, and only through the test under specific conditions can we reveal the different mechanical properties of different types and states of soil for specific soil specimens. Due to the strong nonlinearity of soil, the dynamic characteristics obtained at one strain stage cannot be simply extrapolated to another strain stage, we need to conduct a soil dynamic constitutive test.

Data show that the shear strain of soil in strong earthquakes ranges from about $2 \times 10^{-4}$ to $2.0 \times 10^{-3}$, and the strain of soil at the point of contact with a soil structure will be greater. Therefore, the strain amplitude is usually larger when the dynamic characteristics of the soil are tested indoors, and the cyclic single shear test is an appropriate way to simulate the ideal seismic stress of soil units in the laboratory.

The cyclic single shear system consists of single shear instrument, a sensor and a PC system are showed in figure 1. The single shear instrument includes a servo-controlled brake, a control and data acquisition system, a compressor and specimen preparation equipment. The sensors include a vertical sensor ($\pm 5.0$ kN), pressure sensor (1000 kPa), horizontal sensor ($\pm 5.0$ kN) and displacement sensor ($\pm 25$ mm), and the PC is connected to the data collection system. The thin, laminated copper rings were used to simulate the boundary conditions of the soil specimens, it can bring the shear force with fixed volume and fixed vertical pressure, strain control and stress control. The accuracy of the displacement sensor is 1 μm and that of the force sensor is 0.001 kN. 50 measurement points are recorded for each cycle in the test.
Both in-situ and disturbed soils were tested. Both in-situ and disturbed soils for the same condition were taken from the same layer of silty clay. The disturbed specimens were prepared in accordance with the Specification of Soil Test requirements that the specific natural moisture content and natural density of the silty clay, the specimens should with a diameter of 70 mm and a height of 20 mm, and the specimens were compacted in two layers to ensure the density and uniformity of the specimens. Some of the specimens are showed in figure 2:

2.2. Testing Method
In order to study the dynamic constitutive model of cohesive soil, a cyclic single shear test for cohesive soil was designed.

The test conditions are shown in table 1. Each sample is tested only under primary load amplitude, and the load amplitude of each specimen is gradually increased, and the test results of all specimens in the group are combined to obtain the dynamic stress - dynamic strain curve of the soil under study over the full range of strain.

| Specimen number | Applied load (strain) | Number of cycles | Number of specimens |
|-----------------|-----------------------|------------------|---------------------|
| I-1             | 1×10^{-3}            | 10               | 3                   |
| I-2             | 2×10^{-3}            | 10               | 3                   |
| I-3             | 4×10^{-3}            | 10               | 3                   |
| I-4             | 6×10^{-3}            | 10               | 3                   |
| I-5             | 8×10^{-3}            | 10               | 3                   |
| I-6             | 2×10^{-2}            | 10               | 3                   |
| I-7             | 4×10^{-2}            | 10               | 3                   |
| I-8             | 6×10^{-2}            | 10               | 3                   |
| I-9             | 8×10^{-2}            | 10               | 3                   |
To minimize the influence of human factors in the test, the consistency of all soil samples and the standard operation should be ensured. At the same time, except for the different applied load in the above table, other test conditions should be ensured same. The test conditions were as follows: consolidation pressure 50 kPa, loading in the form of equal amplitude sinusoidal, vibration frequency 1 Hz, consolidation drainage conditions is consolidation without drainage, loading control mode is strain control, and 50 measurement points recorded in each cycle.

The physical property parameters of the soil samples in situ and disturbed soil are shown in tables 2 and 3 respectively.

### Table 2. Indicators of physical properties of in-situ soil samples.

| Working Conditions | Natural water content w (%) | Natural density ρ(g/cm³) | Porosity ratio e | Plasticity index Ip | Liquidity index IL |
|--------------------|-----------------------------|--------------------------|------------------|---------------------|-------------------|
| I-1                | 30.9                        | 1.85                     | 0.932            | 13.8                | 0.43              |
| I-2                | 30.9                        | 1.86                     | 0.881            | 14.2                | 0.43              |
| I-3                | 31.3                        | 1.83                     | 0.922            | 12.9                | 0.41              |
| I-4                | 31.2                        | 1.86                     | 0.869            | 13.4                | 0.38              |
| I-5                | 30.6                        | 1.84                     | 0.853            | 14.5                | 0.43              |
| I-6                | 31.2                        | 1.83                     | 0.944            | 15.4                | 0.41              |
| I-7                | 31.0                        | 1.86                     | 0.957            | 16.5                | 0.42              |
| I-8                | 30.6                        | 1.86                     | 0.960            | 14.1                | 0.36              |

| Working Conditions | Natural water content w (%) | Natural density ρ(g/cm³) | Porosity ratio e | Plasticity index Ip | Liquidity index IL |
|--------------------|-----------------------------|--------------------------|------------------|---------------------|-------------------|
| I-1                | 30.5                        | 1.82                     | 0.885            | 11.72               | 0.66              |
| I-2                | 30.4                        | 1.83                     | 0.846            | 13.29               | 0.45              |
| I-3                | 30.6                        | 1.83                     | 0.863            | 12.83               | 0.63              |
| I-4                | 30.8                        | 1.83                     | 0.849            | 12.91               | 0.57              |
| I-5                | 30.5                        | 1.82                     | 0.842            | 13.17               | 0.42              |
| I-6                | 30.9                        | 1.82                     | 0.825            | 11.82               | 0.68              |
| I-7                | 30.8                        | 1.83                     | 0.877            | 12.84               | 0.57              |
| I-8                | 30.5                        | 1.83                     | 0.849            | 11.79               | 0.43              |
| I-9                | 30.8                        | 1.82                     | 0.857            | 12.37               | 0.58              |

### 2.3. Analysis of Test Results

In the cyclic single shear test, the shear strain $\gamma_d$ and shear stress $\tau_d$ are measured and a hysteresis loop can be made to reflect the relationship between dynamic shear stress and dynamic shear strain at each moment in the cycle, as shown in figure 3. The dynamic shear modulus $G_d$ and damping ratio D can be defined as equation (1) and equation (2), respectively.

$$G_d = \frac{\left| \tau_{d1} \right| + \left| \tau_{d2} \right|}{\left| \gamma_{d1} \right| + \left| \gamma_{d2} \right|}$$  \hspace{1cm} (1)

$$D = \frac{A_0}{\pi A_T}$$  \hspace{1cm} (2)

In the equation (1) and equation (2), $\tau_{d1}$, $\tau_{d2}$ represents the maximum dynamic shear stress in both positive and negative direction, Where $A_0$ is the area of the hysteresis loop, which represents the energy consumed by the soil body during the cycle week, and $A_T$ is the area of the triangle abc.
According to equation (1) and equation (2), the dynamic shear modulus and damping ratio of clay at each shear strain, can be obtained, cyclic single shear test conditions in-situ and disturbed soil test results data are shown in Table 4 and Table 5 respectively.

**Table 4.** Data log sheet for cyclic single shear test conditions for in-situ soil.

| Specimen number | Positive maximum shear strain γ_{d1} (kPa) | Negative maximum shear strain γ_{d2} (kPa) | Positive maximum shear stress τ_{d1} (kPa) | Negative maximum shear stress τ_{d2} (kPa) | Hysteresis area A₀ | Triangle abc area Aₜ | Dynamic shear modulus Gd(kPa) | Damping ratio D |
|-----------------|------------------------------------------|------------------------------------------|------------------------------------------|------------------------------------------|-------------------|---------------------|----------------------------|-----------------|
| I-1             | 7.02E-04                                 | -7.02E-04                               | 4.152                                    | -4.152                                   | 0.001             | 0.006               | 5912.177                   | 5.580E-02       |
| I-2             | 1.86E-03                                 | -1.86E-03                               | 9.735                                    | -9.735                                   | 0.009             | 0.036               | 5246.469                   | 8.247E-02       |
| I-3             | 3.81E-03                                 | -3.81E-03                               | 16.924                                   | -16.924                                  | 0.042             | 0.129               | 4437.752                   | 1.044E-01       |
| I-4             | 5.73E-03                                 | -5.73E-03                               | 20.656                                   | -20.656                                  | 0.100             | 0.237               | 3604.649                   | 1.344E-01       |
| I-5             | 7.70E-03                                 | -7.70E-03                               | 24.989                                   | -24.989                                  | 0.181             | 0.385               | 3243.633                   | 1.499E-01       |
| I-6             | 1.96E-02                                 | -1.96E-02                               | 33.779                                   | -33.779                                  | 0.670             | 1.323               | 1724.572                   | 1.611E-01       |
| I-7             | 3.96E-02                                 | -3.96E-02                               | 40.742                                   | -40.742                                  | 2.003             | 3.226               | 1029.176                   | 1.976E-01       |
| I-8             | 5.96E-02                                 | -5.96E-02                               | 45.333                                   | -45.333                                  | 3.701             | 5.401               | 761.081                    | 2.182E-01       |
| I-9             | 7.95E-02                                 | -7.95E-02                               | 50.318                                   | -50.318                                  | 5.701             | 8.003               | 632.728                    | 2.267E-01       |

**Table 5.** Recording of cyclic single shear test data for disturbed soil under cyclic single shear test conditions.

| Specimen number | Positive maximum shear strain γ_{d1} (kPa) | Negative maximum shear strain γ_{d2} (kPa) | Positive maximum shear stress τ_{d1} (kPa) | Negative maximum shear stress τ_{d2} (kPa) | Hysteresis area A₀ | Triangle abc area Aₜ | Dynamic shear modulus Gd(kPa) | Damping ratio D |
|-----------------|------------------------------------------|------------------------------------------|------------------------------------------|------------------------------------------|-------------------|---------------------|----------------------------|-----------------|
| I-1             | 7.002E-04                                 | -7.002E-04                               | 3.484                                    | -3.484                                   | 0.001             | 0.005               | 4974.918                   | 7.833E-02       |
| I-2             | 1.880E-03                                 | -1.880E-03                               | 7.898                                    | -7.898                                   | 0.009             | 0.030               | 4201.670                   | 9.394E-02       |
| I-3             | 3.896E-03                                 | -3.896E-03                               | 12.260                                   | -12.260                                  | 0.036             | 0.096               | 3146.945                   | 1.205E-01       |
| I-4             | 5.829E-03                                 | -5.829E-03                               | 14.617                                   | -14.617                                  | 0.073             | 0.170               | 2507.773                   | 1.358E-01       |
| I-5             | 7.793E-03                                 | -7.793E-03                               | 15.563                                   | -15.563                                  | 0.096             | 0.243               | 1997.049                   | 1.261E-01       |
| I-6             | 1.979E-02                                 | -1.979E-02                               | 15.970                                   | -15.970                                  | 0.413             | 0.632               | 807.155                    | 2.078E-01       |
| I-7             | 3.971E-02                                 | -3.971E-02                               | 16.247                                   | -16.247                                  | 1.111             | 1.290               | 409.137                    | 2.741E-01       |
| I-8             | 5.958E-02                                 | -5.958E-02                               | 17.630                                   | -17.630                                  | 2.325             | 2.101               | 295.889                    | 3.523E-01       |
| I-9             | 7.955E-02                                 | -7.955E-02                               | 20.094                                   | -20.094                                  | 3.903             | 3.197               | 252.592                    | 3.886E-01       |
Next, the test data are processed and analyzed, and the hysteresis curves of in-situ soil and disturbed soil at shear strains of $1 \times 10^{-3}$ to $8 \times 10^{-3}$, $2 \times 10^{-2}$ to $8 \times 10^{-2}$, and $1 \times 10^{-3}$ to $8 \times 10^{-2}$ can be obtained. The hysteresis curves of the original soil and the disturbed soil in the shear strain range of $1 \times 10^{-3}$ to $8 \times 10^{-2}$ are shown in figure 4 and figure 5, respectively.

![Figure 4](image1.png)  ![Figure 5](image2.png)

Figure 4. Hysteresis curves for primary soils-shear strain range $1\times 10^{-3} \sim 8\times 10^{-2}$

When the shear strain is $1\times 10^{-3}$ to $8\times 10^{-3}$, the hysteresis curve of the original soil is elliptical; when the shear strain is greater than $2\times 10^{-2}$, the hysteresis curve is an inverse S. As the strain amplitude increases, the hysteresis circle becomes more and more inclined, the enclosed area increases, and the stress-strain relationship of the soil shows strong nonlinearity and hysteresis. Compared with undisturbed soil, when the shear strain range is $1\times 10^{-3}$ to $8\times 10^{-2}$, the shear stress of disturbed soil is less than that of undisturbed soil. The loop of the disturbed soil becomes flatter and flatter as the shear strain increases.

When the control shear strain is loaded with equal amplitude, the shear modulus $G$ of the cohesive soil gradually decreases with the increase of the control shear strain $\gamma$ under the same cycle, and the decrease rate of shear modulus becomes smaller and smaller, and the trend of the dynamic shear modulus of this cohesive soil is consistent with the general feature that of the cohesive soil dynamic shear modulus becomes smaller and smaller with the increase of its shear strain.

3. Selection of the Cohesive Soil Constitutive Model

3.1. The Shear Modulus Fit

The dynamic shear modulus of the soil is expressed using the Darendeli model of the geodynamic constitutive model, it dynamic characteristic curve expressed as equation (3).

$$
\frac{G_d}{G_{d,\text{max}}} = \frac{1}{1 + (\gamma_d / \gamma_{\text{ref}})^{\alpha}}
$$

(3)

where $\alpha$ is the modulus curve attenuation parameter; $\gamma_d$ is the shear strain amplitude; $\gamma_{\text{ref}}$ is the reference shear strain amplitude; $G_{d,\text{max}}$ is the maximum shear strain; and $G_d$ is the dynamic shear modulus when the dynamic strain amplitude is equal to $\gamma_d$.

According to the test data recording sheet, the dynamic shear modulus corresponding to each level of strain is pooled into a dynamic shear modulus-shear strain scatter plot, and the dynamic shear modulus scatter is fitted according to equation (3), and the in-situ and disturbed soils are shown in figures 6 and 7 respectively.
Figure 6. Fit curve for shear modulus of in-situ soil.

Figure 7. Fit curve for disturbed soil shear modulus.

As a result, the dynamic shear modulus parameters for in-situ and disturbed soils are shown in Table 6 below.

| Test soil samples | $G_{d_{\text{max}}}$ (kPa) | $\gamma_{\text{ref}}$ (%) | $\alpha$ |
|-------------------|-----------------------------|--------------------------|---------|
| in situ soil      | 6480                        | 0.76                     | 1.011   |
| disturbed soil    | 5425                        | 0.51                     | 1.226   |

### 3.2. Damping Ratio Fit

The damping ratio model of the soil uses the Darendeli model of the soil dynamic characteristic model with the following dynamic characteristic curve shown in equation (4)

$$D = b \left( \frac{G_d}{G_{d_{\text{max}}}} \right)^{0.1} \text{Dmasing} + D_{\text{min}}$$

where $D$ is the damping ratio, $D_{\text{masing}}$ represents the expected damping ratio of the Masing hysteresis criterion, $D_{\text{min}}$ represents the small strain damping ratio, and $b$ is the damping ratio curve parameter.

According to the test data recording table, the damping ratios corresponding to each level of strain are assembled into a dynamic damping ratio-shear strain scatter plot, and the damping ratio scatter is fitted according to equation (4). The damping ratio curves of the Darendeli model fitted to the in-situ soil and disturbed soil are shown in Figure 8 and Figure 9, respectively, and Table 7 shows the damping ratio parameters of the Darendeli model.
Fit curve of the damping ratio of in-situ soil.

Figure 8. Fit curve of the damping ratio of in-situ soil.

Damping ratio fit curve for disturbed soil.

Figure 9. Damping ratio fit curve for disturbed soil.

Table 7. Damping ratio parameters for in-situ and disturbed soils.

| Test soil samples       | b     | D\(_{\text{max}}\) (%) |
|------------------------|-------|------------------------|
| in situ soil           | 0.467 | 6.490                  |
| disturbed land         | 0.573 | 4.053                  |

From the above figure, it can be seen that the Darendeli model can better represent the relationship between dynamic shear modulus and damping ratio with dynamic shear strain of the cohesive soil specimen, which reflects the nonlinear dynamic characteristics of the cohesive soil.

4. Conclusion

By carrying out cyclic shear tests on the cohesive soil, the dynamic characteristics of the original soil and disturbed soil parameters were obtained, the hysteresis curve characteristics of the original soil and disturbed soil were analyzed, with the increase of the control shear strain \(\gamma\), the shear modulus \(G\) of the cohesive soil gradually decreases, and the rate of shear modulus reduction is becoming smaller and smaller. (2) Using the dynamic constitutive Darendeli model, the equation for calculating the dynamic shear modulus and damping ratio of the in-situ and disturbed soil and the values of the relevant parameters were obtained.

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