Indoor Rheological Test and Creep Model Analysis of Soft Soil in Qingyi River region in Wuhu Anhui

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Abstract: The shear strength and the failure deviatoric stress of the Wuhu soft soil under different confining pressures were determined by indoor undrained consolidation triaxial rheological tests. Selecting 20%, 40%, 60% and 80% of the failure deviatoric stress as deviatoric stress and 100kPa, 200kPa and 300kPa as confining pressures, the rheological tests were conducted by separate loading method. Based on the creep curves obtained from the rheological tests, the related model parameters were determined after modifying the stress-strain and strain-time relation of Singh-Mitchell and Mesri creep model. And the empirical creep model was obtained, of which the stress-strain and strain-time relation were expressed in the form of power function. The analysis indicated that the creep characteristics of Wuhu soft soil was described more accurately by the new empirical creep model than Singh-Mitchell and Mesri creep model.

1. Introduction
In engineering practice, soil rheology mainly includes creep, relaxation, flow and long-term strength changing with the load history\textsuperscript{[11]}. The key of soil rheological study is to establish the rheological model. The soil rheological constitutive model is mainly divided into element model, empirical model, yield surface model and internal time model\textsuperscript{[2]}. The empirical model is based on the indoor tests and field measured data to get the rheological equation by data fitting. This method is widely used in engineering due to its simple expression, convenience of use and high specificity. Generally, the empirical model uses two functions to describe the stress-strain and strain-time relation. The empirical model can be obtained by combining these two functions.

Many scholars at home and abroad have put forward many empirical rheological models by summarizing and studying the rheological test results. Singh & Mitchell(1968) \textsuperscript{[3]} summarized the test results of stress-strain and strain-time characteristics under shear stress and put forward famous Singh-Mitchell model, which was only applicable to the stress level above 20% and less than 80%. Hereafter, many scholars verified and modified Singh-Mitchell empirical equation. 1981, Mersi\textsuperscript{[4]} modified Singh-Mitchell empirical equation based on the test results. He used Kondner hyperbolic curve instead of exponential curve to express the stress-strain relation and put forward Mesri model, making it suitable within the whole stress level. Li Shijun et al.\textsuperscript{[5]} studied the creep characteristics of silty clay in Shanghai. It was found that the stress-strain-time relation of silty clay in Shanghai could be more accurately and conveniently described by Singh-Mitchell creep equation. Wang Chen et al.\textsuperscript{[6-8]} used...
Singh-Mitchell and Mesri model to study the creep characteristics of soil in Sliding Zone of Xietan Landslide in the Three Gorges, and improved Singh-Mitchell and Mesri creep model. Deng Zhibin[9] adopted a power function to describe the stress-strain relation and a hyperbolic function to describe the strain-time relation to simulate the rheological characteristics of the subgrade soft soil of zhucheng highway subgrade. Tian Shuangzhu et al. [10] conducted creep tests on typical mucky clay and silty clay in Tianjin Port. The creep parameters of mucky clay and silty clay based on Singh-Mitchell model were obtained, which was a good match to the actual test results. Lai Huahui[11] adopted a hyperbolic function to describe the stress-strain relation and a power function to describe the strain-time relation when building soft soil creep empirical model of Ningbo.

This paper chose Qingyi River project as the research object and conducted indoor undrained consolidation triaxial rheological test in separate loading method under different confining pressures and deviator stresses. The Creep curve under different deviator stresses was obtained, which could be used to analyze the stress-strain and strain-time relation. Then the empirical creep model of the stress-strain and strain-time relation expressed in the form of power function was established.

2. Indoor Rheological Test of Soft Soil

2.1. Basic mechanical properties of soft soil

Three typical fault surfaces and nine holes were selected to study the basic mechanical properties of the soft soil in Qingyi River Project, as shown in table 1. According to the test results, the soil in Qingyi River region in Wuhu Anhui was a typical soft soil with high compressibility, low strength and low permeability.

| Moisture content (%) | Wet density (g/cm³) | Liquid limit (%) | Plastic limit (%) | Compression coefficient (MPa⁻¹) | Compression modulus (MPa) | Cohesive force (KPa) | Internal friction angle (°) |
|----------------------|--------------------|------------------|------------------|-------------------------------|--------------------------|----------------------|--------------------------|
| Maximum value        | 40.8               | 2.00             | 38.9             | 24.1                          | 0.58                     | 7.94                 | 32.7                    | 16.4                     |
| Minimum value        | 20.3               | 1.81             | 30.5             | 20.2                          | 0.22                     | 3.14                 | 10.7                    | 4.8                      |
| Average value        | 31.2               | 1.91             | 35.0             | 22.3                          | 0.38                     | 4.91                 | 23.7                    | 8.8                      |
| Quantity             | 143                | 143              | 34               | 34                            | 53                       | 53                   | 24                      | 24                       |

2.2. Triaxial compression test of soft soil

The diameter of triaxial sample was 39.1mm and the height was 80mm. After being consolidated under the confining pressures of 100kpa, 200kpa and 300kpa, the samples were sheared under undrained conditions until the axial strain reached 16%. The shear rate was 0.08mm/min. According to the data collected in the test, the relation curve between principal stress difference and axial strain of soil samples was shown in figure 1, and undrained triaxial consolidation test results were shown in table 2. The test results were used as the basis for the following triaxial undrained rheological test.

![Figure 1. Stress-strain curves of triaxial tests under different confining pressures.](image)
Table 2. Summary of undrained triaxial compression tests results.

| Dry density | Cohesive force | Internal friction angle | Effective Cohesive force | Effective internal friction angle | Peak strength |
|-------------|----------------|-------------------------|--------------------------|----------------------------------|---------------|
| g/cm$^3$ | kPa             | °                       | kPa                      | °                                | 100kPa 200kPa 300kPa |
| 1.67 | 23               | 21.1                    | 7                        | 28.8                             | 228            368   433 | kPa |

2.3. Triaxial rheological test of soft soil

Separate loading method which met the requirements of the rheological test best was used in this test. There was no need to process data using this method and it could reflect the creep phenomenon more directly. The tests were conducted under the same confining pressure and the same soil samples but 20%, 40%, 60% and 80% of the failure deviatoric stress. At present, there is no standardized standard for the creep stability of soil. According to the experience, the sample is considered to be stable until the deformation is less than 0.01mm within 10000 seconds. In order to determine the right rate of strain rate, the total observed duration is generally set to 7 ~ 14 days. The test in this paper lasted for 7 days.

The samples were performed on a fully automatic three-axis machine, and the sample size was 39.1mm in diameter and 80mm in height. The test confining pressures were 100kPa, 200kPa and 300kPa. The rheological tests under four stress states were carried out under each confining pressure, and the result was shown in table 3.

Table 3. Summary of rheological tests results.

| Confining pressure kPa | Dry density g/cm$^3$ | Deviator stress kPa | Rheological deformation % |
|------------------------|---------------------|---------------------|--------------------------|
|                        | 1.67                | 45                  | 0.11                     | 1.43                      |
|                        |                     | 90                  | 0.22                     | 1.91                      |
|                        |                     | 135                 | 0.32                     | 2.22                      |
|                        |                     | 180                 | 0.40                     | 2.62                      |
|                        |                     | 70                  | 0.17                     | 1.58                      |
|                        | 1.67                | 140                 | 0.29                     | 2.02                      |
|                        |                     | 210                 | 0.36                     | 2.54                      |
|                        |                     | 280                 | 0.51                     | 2.91                      |
|                        |                     | 80                  | 0.27                     | 1.76                      |
|                        | 1.67                | 160                 | 0.34                     | 2.45                      |
|                        |                     | 240                 | 0.49                     | 2.82                      |
|                        |                     | 320                 | 0.61                     | 3.04                      |

Firstly, a series of triaxial creep curves under different confining pressures were obtained, as shown in figure 2 ~ figure 4. It could be seen that the deformation value increased with stress level under a certain confining pressure. And instantaneous deformation occurred in a relatively short period of time under different confining pressures and stress levels. When the deviator stress remained small, instantaneous deformation reached 50%. When the deviator stress increased, instantaneous deformation reached 80%. And the deformation time is very short. After that the soil develops into decay creep and a period of time later, it developed into steady-state creep stage and continued for a long time.

According to the test data obtained, the isochronous curves between stress and strain under different confining pressures and deviator stresses were shown in figure 5~ figure 7. When the confining pressure remained small, the stress-strain curves were concentrated and diverged outward with the increase of deviatoric stress. When the confining pressure increased, the stress-strain curves were dispersed and gradually diverged outward with the increase of deviator stress. Moreover, when the stress level was low, the stress-strain curves were approximately straight lines, which reflected
linear rheological characteristics. With time going by, the stress level increased and the curve showed nonlinear characteristics. Therefore, the traditional linear viscoelastic plastic element model is not suitable for the creep equation.

3. The study of soft soil constitutive model
The key of constitutive model is to determine the parameters. The parameters of geotechnical engineering include those directly measured by tests, those deduced by simple physical relations and those in complex models. It can be solved by finite element analysis, parameter optimization and regression inversion. Compared with theoretical model, empirical model lacks the corresponding
theoretical derivation, and the expression is more simple and clear, and easy to determine the parameters through tests.

3.1. The verification of Singh-Mitchell creep model

Singh A and Mitchell J.K. raised the extensive Singh-Mitchell creep model in 1968. And it can be expressed as:

\[
\varepsilon = A \exp (\alpha D) \left( t/t_1 \right)^m
\]  

(1)

Where \( \varepsilon \) is the strain rate at any time \( t \); \( t_1 \) is unit time; \( A = \varepsilon \left( t_1, D_h \right) \) is the strain rate of \( t_1 \) when deviator stress \( D = \sigma_1 - \sigma_3 = 0 \); \( \alpha \) is the slope of the linear segment in the logarithm of strain rate-shear stress curve; \( D_1 = (\sigma_1 - \sigma_3)/(\sigma_1 - \sigma_3)_1 \); \( m \) is the absolute value of the slope of the line of \( \ln \varepsilon - \ln t \) curve, and the value of \( m \) is between 0.75–1.0, and it will change because of consolidation and over consolidation.

There are two situations when integrating the above equation—\( m = 1 \) and \( m \neq 1 \):

1) \( m = 1 \)

\[
\varepsilon = A \exp (\alpha D) t_1 \ln t
\]

(2)

2) \( m \neq 1 \)

\[
\varepsilon = B e^{\alpha D} \left( t/t_1 \right)^n
\]

(3)

According to equation (3)

\[
\varepsilon = \varepsilon_1 \left( t/t_1 \right)^n
\]

(4)

Calculate the logarithm of equation (4)

\[
\ln \varepsilon - \ln \varepsilon_1 = n \left( \ln t - \ln t_1 \right)
\]

(5)

Parameter \( n \) is the slope of straight segment of \( \ln \varepsilon - \ln t \) curve. According to the result of triaxial rheological test, \( \ln \varepsilon - \ln t \) curves of different situations could be fitted as shown in figure 8. The values of slope \( n \) after fitting \( \ln \varepsilon - \ln t \) curves of different situations were shown in table 4. The average value of \( n \) was: \( n = 0.054475 \).

| Deviator stress/kPa | 70  | 140 | 210 | 280 |
|---------------------|-----|-----|-----|-----|
| \( n \)             | 0.0918 | 0.0588 | 0.0316 | 0.0357 |

The values of \( D_1 \) under different confining pressures were as 0.2, 0.4, 0.6 and 0.8. Take \( t = 1d \) and \( \ln \varepsilon - D_1 \) curve was shown in figure 9.

So, the equation of Singh-Mitchell model was
\[ \varepsilon = 0.212e^{3.0805D_t \left( \frac{t}{86400} \right)^{0.054475}} \]  \hfill (6)

The calculated curves of Singh-Mitchell creep model when \( t_1 = 1 \text{d} \) were compared with the test curves as shown in figure 10. It could be seen from the figure that two curves were nearly the same or had a small error when the deviatoric stress was small. With the increase of deviator stress, the error grew up gradually. Especially when the stress level reached 80%, there was a large error between the real data and the one fitted by Singh-Mitchell equation, which met with the application of the equation. It was concluded that the reason why the error was large was that the exponential function was selected to describe stress-strain curve and the power function to describe strain-time curve in Singh-Mitchell model. However, there was a certain gap between the stress-strain curve obtained from the triaxial rheological test and the exponential function in the Singh-Mitchell model.

3.2. The verification of Mesri creep model
Mesri uses the power function to describe the stress-strain curve and the hyperbolic curve to describe the stress-strain curve under the condition of constant velocity axial deformation. Thereby, Mesri creep model under undrained condition is:

\[ \frac{\varepsilon}{D_r} = \left( \frac{2}{E_u/S_u} \right)_1 + (R_1)_{\varepsilon} \]  \hfill (7)

When \( S_u = \frac{1}{2} (\sigma_1 - \sigma_3)_1 \): \( \left( \frac{2}{E_u/S_u} \right)_1 \) is the intercept of \( \frac{\varepsilon}{D_r} \cdot \varepsilon \) curve when \( t = t_1 \); \( (R_1)_{\varepsilon} \) is the slope.

The method to determine parameter \( n \) was the same as Singh-Mitchell model, and the result was \( n=0.054475 \). Take \( t = t_1 \) and \( \frac{\varepsilon}{D_r} \cdot \varepsilon \) curve was shown in figure 11.

So, the equation of Mesri model was:

\[ \varepsilon = 1.588 \cdot \frac{D_t}{1 - 0.5597D_t \left( \frac{t}{t_1} \right)^{0.054475}} \]  \hfill (8)

Comparing the calculated curves of Mesri creep model when \( t_1 = 1 \text{d} \) and the test curves, the result was shown as figure 12. It could be seen that two curves were nearly the same when the stress remained small. With the increase of stress level, there was a certain error between two curves, but the error was lower than that of Singh-Mitchell model. Moreover, Mesri model curves went through test curves, which illustrated that the error between Mesri model and test was small but would increase
with time. So Mesri model cannot describe the rheological properties of soft soil perfectly. The error was from the functions chose to describe stress-strain and strain-time curves.

Figure 11. $e/\Delta e - e$ curve under under 200kPa confining pressure.

Figure 12. Comparison between curves calculated by Mesri model and test results.

3.3. The establishment and verification of modified empirical creep model

According to above results, both Singh-Mitchell model and Mesri model were based on the stress-strain and strain-time curves. Therefore, it is necessary to fit stress-strain and strain-time curves to find out the creep law of soft soil in wuhu. It has been proved that stress-strain relation can be expressed by power functions and hyperbolic functions, and that strain-time relation can be expressed by power functions, logarithmic functions, exponential functions and hyperbolic functions.

According to the stress-strain isochronous curves in figure 13, the axial strain increases with deviatoric stress. In this case, the stress-strain isochronous curves were fitted by power functions, exponential functions and hyperbolic functions, and it turned out that a power function was the most appropriate one to describe the strain-stress relation. According to the strain-time curves in figure 14, the deformation increases slowly with time going by when the soil samples entered into the stage of steady creep from attenuation creep. When fitting the strain-time curves, a power function was considered to be the best one to describe strain-time relation. Therefore, a power function was adopted to fit stress-strain and strain-time relation.

Therefore, the creep equation established was as follows:

$$\varepsilon = AD_m \left( \frac{t}{t_i} \right)^n$$

(9)
When $t = t_1$, $\varepsilon_1 = AD^{n}$. Take $t_1 = 1d$, stress-strain isochronous curve was shown as figure 15. According to the fitting result, $A = 2.9486$, $m = 1.3377$. The method to determine parameter $n$ was the same as Singh-Mitchell model, and the result was $n = 0.054475$.

![Figure 15. $\varepsilon$-$D_t$ curves under 200kPa confining pressure.](image)

So, the creep equation was:

$$\varepsilon = 2.9486D_t^{1.3377}(\frac{t}{t_1})^{0.054475}$$ \hspace{1cm} (10)

3.4. The verification of modified empirical creep model

Comparing the calculated curves of modified empirical creep model, Singh-Mitchell creep model, Mesri creep model with the test curves when $t_1 = 1d$, the result was shown in figure 16. From the figure, it could be found that compared with other two models, the modified empirical creep model curves could reflect the creep characteristics of the soft soil in this area best. Especially when deviatoric stress was larger, the error between Singh-Mitchell creep model curves and the test curves became larger and larger, while Mesri model was similar to the test curves at the beginning, but the later deformation grew larger than the test curves gradually. On the contrary, the modified empirical creep model curves had a certain error with the test curves in the initial stage. However, it could be found that two curves kept consistent in the later age as shown in figure 16. Therefore, the modified empirical creep model could reflect creep characteristics of the soft soil in this area perfectly.

![Figure 16. Comparison of creep curves.](image)
Figure 16. Comparison between curves calculated by three creep models and test result under 200kPa confining pressure.

4. Conclusions

This paper chose Qingyi River project as the research object and obtained the creep curves by indoor undrained consolidation triaxial rheological tests. A new constitutive model was established based on stress-strain and strain-time relation. The main conclusions were as follows:

1. According to the test curves, the deformation of soil samples could be divided into three stages: instantaneous deformation stage, attenuation creep stage and steady creep stage. Since the deviatoric stress in this test did not exceed the yield strength, there was no accelerating creep stage in the creep curves. The strain would increase with stress level. When the stress level was low, the stress-strain isochronous curves were linear. And the curves became nonlinear with the stress level increasing.

2. Fit the curves of triaxial rheological test by Singh-Mitchell and Mesri model. The result showed that the curves fitted by Singh-Mitchell model was almost consistent with the rheological characteristics of soft soil in the region at the initial stage. But the error between two curves became larger with the increase of deviatoric stress. And Mesri model adopted in test of deviatoric stress range almost accorded with the rheological characteristics with a certain error.

3. The stress-strain isochronous and strain-time creep curves were fitted and finally the power function was used to describe the stress-strain and strain-time relation. And it was proved that the modified empirical model could reflect the rheological characteristics of soft soil in this region.

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References

[1] LU, T.H., LIU, Z.D., CHEN, X.G. (2006) Advanced Soil Mechanics[M]. 1st Edition. China Machine Press, Beijing.

[2] YUAN, J., GONG, X.N., YI, D.Q. (2001) A Comparative Study of the Geotechnical Rheological Model[J]. Chinese Journal of Rock Mechanics and Engineering, 20: 772-772.

[3] Singh A., Mitchell J.K. (1968) General stress-strain-time functions for soils[J]. Journal of the Soil Mechanics and Foundations Division, 94:406-415.

[4] Castro A., Shields D.R., Mesri G., Febres-Cordero E. (1981) Shear stress-strain time behavior of clays[J]. Géotechnique, 31:537-552.

[5] LI, J.S., LIN, Y.M. (2000) Singh-Mitchell creep model of Shanghai very soft clay[J]. Rock and Soil Mechanics, 21:363-366.
[6] WANG, C., TANG, M., LIU, H.E., et al. (2003) Creep Tests of sliding zone soils of Xietan Landslide in Three Gorges[J]. Journal of Sichuan University (Engineering Science Edition), 35: 93-95.

[7] WANG, C., LIU, H.W., XU, Q. (2004) Modified Mesri’s Creep Model for Soils in Sliding Zone of Xietan Landslide in the Three Gorges[J]. Journal of Southwest Jiaotong University, 39: 15-19.

[8] WANG, C., ZHANG, Y.L., LIU, H.W, (2005) A modified Singh-Mitchell’s creep function sliding zone soils of Xietan landslide in Three Gorges[J]. Rock and Soil Mechanics, 26: 415-418.

[9] DENG, Z.B.(2007) Creep Test on Soft Clay and the Identification of Constitutive Model Study and Its application[D]. Central South University, Changsha.

[10] TIAN, S.Z., LI, Y.S., JI, C.N. (2009) Creep Tests Study of Typical Soft Clay in Tianjin Port[J]. Journal of Waterway and Harbor, 30: 440-443.

[11] LAI, H.H. (2013) Study on Pheological Property of Silt Clay and Its Application[D].: Shanghai Jiao Tong University, Shanghai.

[12] Du, J.C., LU, Z.Z. (1999) A new method to determine the parameters of structural planes in rock masses-the weighted displacement back analysis[J]. Chinese Journal of Geotechnical Engineering, 21:74-77.

[13] SUN, J., HUANG, W. (1992) An Optimization Method for the Elastoplastic Inversion of Parameters in Rock Mechanics[J]. Chinese Journal of Rock Mechanics and Engineering, 11:221-229.

[14] XU, H.F., QIAN, Q.H., WU, H.J., et al. (2003) A polynomial regressive inverse method to determine rheologic parameters of soft soil[J]. Chinese Journal of Geotechnical Engineering, 25:365-367.