Experimental study of five element creep model for high salt saturated fine sand soil

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Abstract: A series of creep tests on high salt saturated fine sand under different stress and salt content were carried out by uniaxial compression test. Based on the classical K-H body model of three elements and the Bu body model of four elements on the linear viscoelastic plasticity theory, a creep model of five elements under the consideration of the comprehensive effect of salt water soil is proposed combined with the experimental analysis results under different stresses and salt content. The analysis results show that the creep model of the five element can fit well the creep law of high salinity fine sand under different stress and salt content, and the validity of the model is proved by comparing the three models and comparing the experimental data with the fitting results.

1. Introduction
The stress and strain of soil in creep show a non-linear relationship with time. This process is affected by many factors, such as load size, time, temperature and humidity conditions. Scholars at home and abroad have studied the properties of different soils and put forward some constitutive models which can better describe the rheological behavior of soils [1-10]. These studies show that the strain of soil is not only a function of stress and time, but also closely related to other factors. Therefore, when summing up the creep law of soil, researchers should consider a series of characteristics of soil itself, so as to make the theoretical solution of soil close to its field properties fundamentally.

Creep law of saturated sandy soil has been studied by scholars. Creep constitutive relationship of this kind of soil is described based on empirical function or model theory [11-13]. However, there is not much discussion about the mineral composition in soil (such as salt content) and its influence on the model. On this basis, a series of laboratory uniaxial compression tests were carried out on a high salt saturated fine sand roadbed of a newly built railway in Qinghai Province through laboratory uniaxial compression tests to study the creep law of saturated fine sand under different stress levels and different salt contents. Based on the widely used linear viscoelastic-plastic model theory, the influence of salt content on the model is analyzed from the micro-level, and the creep constitutive relationship of this special type of soil is summarized.

2. Test method
In this paper, a double low-pressure consolidation apparatus is used in the laboratory. The sample is cut into a cylindrical cake with a base area of 30 cm² and a height of 2 cm according to the ring knife
characteristics. In order to unify the test conditions, the dry density of the specimens is 1.8g/cm³ according to the field test results and conforms to the field gradation conditions. The salt content of field soil samples is 28.6%~33.2%. Table 1 shows the soil parameters and soluble salt content obtained from three sampling points. In order to cooperate with the test method, indirect elution and desalination were carried out on the field soil samples. After drying, the collected salt blocks were ground and mixed in proportion of 0%, 1%, 5%, 10%, 20% and 30%. Water treatment was done every day seven days before sample preparation to make them fully crystalize and harden. After one week or so, the samples were formed and cut in the form of ring knife, the test could be carried out.

Table 1  Soil parameters and soluble salt content at each sampling point

| Sampling point | Soluble salt content /% |
|---------------|-------------------------|
|               | CO³⁻ | HCO³⁻ | Cl⁻ | So⁴⁻ | Ca²⁺ | Mg²⁺ | Na⁺ | Total content |
| 1             | 0.021 | 0.131 | 18.97 | 0.872 | 0.117 | 0.078 | 10.651 | 30.840 |
| 2             | 0.019 | 0.128 | 19.73 | 0.698 | 0.124 | 0.083 | 10.776 | 31.558 |
| 3             | 0.018 | 0.134 | 20.11 | 0.710 | 0.130 | 0.062 | 9.775  | 30.939 |

The filter paper and pervious stone were placed on the top and bottom of the sample, and the pressure grading was 100 kPa, 200 kPa, 400 kPa and 800 kPa, respectively. The same concentration of brine is poured into the tank at the moment of initial loading and saturated soil samples are kept at any time during subsequent tests. Three sample points were sampled for comparative test. The temperature was controlled at 20±2℃. Generally, a group of tests lasted about 7-10 days. The group of tests ended when the daily strain hardly changed in the later period.

3. Test results and analysis

Fig. 1 shows the strain curves of saturated soils under different loads when the salt content is 5% and 20%. Fig. 2 shows the strain curves of saturated soils with different salt content under the loading levels of 200 kPa and 800 kPa. Fig. 3 shows the stress-strain isochronal curves under the condition of 20% salt content. Fig. 4 shows the salt content-strain isochronal curves under the loading levels of 800kPa. From these curves we can see that:

Fig.1 saturated soil sample strain curve with varying salt content

Fig.2 Saturated soil sample strain curve of variable stress level
(1) The strain curves under various loads and salinity show a decaying creep process, and instantaneous deformation occurs immediately after loading, then the deformation develops slowly, and the deformation rate tends to zero in the range of stress and salinity. This may be related to its lower load level and the proportion of salt in soil samples. Correspondingly, the deformation value tends to a stable value under the corresponding load or salt content. Figures 1-2 show that the strains in both cases are the sum of the instantaneous deformation and the decaying deformation with the development of time.

(2) As can be seen from Fig. 1, the deformation of samples with different salt content increases with the increase of stress level. The higher the stress, the greater the non-linearity of the initial deformation, and the higher the deformation level of the stable attenuation stage. By comparing the two diagrams, it can be found that the increase of salt content has a significant effect on the instantaneous deformation and plastic deformation of soil. From Figure 3, it can be seen that the stress-strain isochronal curve under a certain salt content is not a straight line, which shows the non-linear characteristics of rheology. The higher the stress level, the greater the deviation of the isochronal curve from the straight line, indicating that the degree of non-linearity increases with the increase of the stress level.

(3) As can be seen from Figure 2, the deformation of specimens with different salt content increases with the increase of salt content under various loads. The higher the salt content, the larger the deformation of soil sample, which shows the creep characteristics of salt-water-soil interaction. When the salt content is low, the sample will enter the attenuation deformation and tend to a stable value in a short time. With the increase of salt content, the strain decreases obviously with time, which makes the time for the sample to reach a stable value gradually prolonged at the high salt content level. By comparing the two maps, it can be found that under the combined influence of high stress and high salinity, the deformation of soil samples and the time of attenuation and stability have increased significantly. It can be seen from Fig. 4 that the salt content-strain isochronal curve under a certain stress level is not linear either. With the increase of salt content, the non-linearity of the isochronal curve increases, and the non-linearity increases with the increase of time. These experimental characteristics further indicate the non-linear influence of salt content on soil creep, and the influence of this factor should be fully considered in subsequent models.

4. Introduction of Contrast Model and Establishment of Five-element Model
The rheology of materials can be described by linear viscoelastic-plastic theory. The model theory is simple and intuitive. It can fully reflect all rheological properties of rheological media by connecting elastic elements, viscous pot models and friction elements in series and parallel. According to the previous research results, this paper refers to the K-H volume model of three elements and the Bu volume model of four elements. Based on the test results under different stress and salinity, a five-element comprehensive model considering salt-water-soil interaction is established to analyze and compare the creep characteristics of this kind of saturated fine sandy soil with high salinity.

The K-H body model of three elements is composed of H body and K body in series. As shown in Fig. 5, its differential constitutive equation is as follows:

\[ E \Delta \sigma = D \Delta \epsilon + C \epsilon \]

where \( E \) is the elastic modulus, \( \Delta \sigma \) is the change in stress, \( \Delta \epsilon \) is the change in strain, \( D \) is the viscous modulus, and \( C \) is the plastic modulus.
\[ \sigma + \frac{\eta_1}{E_1+E_2} \dot{\varepsilon} = \frac{E_1 E_2}{E_1+E_2} \sigma + \frac{E_2 \eta_1}{E_1+E_2} \dot{\varepsilon} \quad (1) \]

Formulas \( \sigma \) and \( \varepsilon \) are stress and strain, \( E_1 \) and \( E_2 \) are elastic modulus and \( \eta_1 \) are compressive viscous coefficient. When the stress is constant value \( \sigma_0 \), the creep equation can be obtained by inverse Laplace transformation on both sides of the formula.

\[ \varepsilon(t) = \frac{\sigma_0}{E_2 \eta_1} + \frac{\sigma_0}{E_1} (1 - e^{-\frac{E_2}{\eta_1}}) \quad (2) \]

Fig. 5 three element K-H body model

Fig. 6 four element Bu body model

The Bu-body model of four elements is composed of M-body of two elements and K-body of two elements in series. As shown in Fig. 6, the differential constitutive equation of the Bu-body model is as follows:

\[ \sigma + \frac{E_1 E_2}{E_1+E_2} \sigma + \frac{E_2 \eta_1}{E_1+E_2} \dot{\varepsilon} = \eta_1 \dot{\varepsilon} + \eta_2 \dot{\varepsilon} \quad (3) \]

When the stress is a constant value of \( \sigma_0 \), the creep equation can be obtained by inverse Laplace transformation on both sides of the equation.

\[ \varepsilon(t) = \frac{\sigma_0}{E_2 \eta_1} + \frac{\sigma_0}{E_1} (1 - e^{-\frac{E_2}{\eta_1}}) \quad (4) \]

In this test, instantaneous strain occurs under different loads and salinity at the initial stage of loading, which reflects the elastic deformation characteristics of soil. The latter stage experienced the stable stage of attenuation creep, which reflected the viscoelastic deformation characteristics, and its gradual coefficient was determined by K body. The strain of soil sample is affected by stress level and salt content, and it is affected by soluble salt content and stress level under saturation state. The strain increases gradually with the increase of both, reflecting the rheological comprehensive characteristics of M body. To sum up, a creep model of five elements can be formed by parallel connection of a three-element K-H body and a two-element M body. As shown in Figure 7, the differential constitutive equation can be written as follows:

\[ \sigma + p_1 \sigma + p_2 \dot{\sigma} = q_0 \varepsilon + q_1 \dot{\varepsilon} + q_2 \ddot{\varepsilon} \quad (5) \]

In style:

\[ p_1 = \frac{\eta_2}{E_1} + \frac{\eta_1}{E_1+E_2}, \quad p_2 = \frac{\eta_1 \eta_2}{E_1(E_1+E_2)}, \quad q_0 = \frac{E_1 E_2}{E_1+E_2}, \quad q_1 = \frac{E_2(\eta_1 + E_2 \eta_2)}{E_1(E_1+E_2)} + \eta_2, \quad q_2 = \frac{E_1 \eta_2}{E_3(E_1+E_2)} \]

When the stress is a constant value of \( \sigma_0 \), the creep equation can be obtained by inverse Laplace transformation on both sides of the equation.
5. Creep Model Analysis and Verification

According to the creep model, the parameters can be fitted. It is noteworthy that the creep tests of saturated fine sand with high salinity conducted in this paper show that the strain is not only a function of stress, but also varies with the change of salinity. Therefore, in the analysis of creep parameters, the rheological parameters are analyzed according to different stress and salt content. Nonlinear fitting and multiple iterations were carried out using 1stOpt software to analyze the coincidence and correlation between model results and experimental data. On this basis, the influence of stress and salt content on model parameters was further discussed and analyzed. Table 2 shows the fitting results of rheological parameters of saturated soils with 20% salt content under three models and the corresponding fitting conditions.

Table 2 shows that the rheological fitting parameters of saturated soils under the three models exhibit certain regularity with the increase of stress level at a certain salt content. With the increase of the number of model elements, the sum of squares of residual fitted by the models decreases. This shows that the fitting results of the five-element creep model are more accurate than those of the three-element K-H model and the four-element Bu model. However, the sum of residual squares of the first two models increases gradually with the stress level. The value of the model in this paper shows the opposite trend, which shows that the model can more accurately fit the test results at a higher stress level.

Fig. 8 shows the comparison between the test results and the fitting results of the three models at a certain stress level when the salt content is 5% and 20%. Figure 8 (a) shows the situation of low salt content and high stress level, and figure 8 (b) shows the situation of high salt content and low stress level. Five-element creep model is better than four-element Bu model in the initial stage of creep process, while three-element K-H model is weaker than the first two models. Five-element creep model fitting results are obviously better than the other two models in the middle stage of the test (3000-8000 min). In the stable creep stage, the fitting results of the three models are close. By comparing (a) and (b) diagrams, it can be found that with the increase of salt content, the coincidence of the initial creep test results fitted by the five-element model in this paper increases correspondingly, and the fitting of the stable creep stage under high stress level is better than that under low stress level.
Table 2 the fitting results of rheological parameters of saturated soil under three models (salt content 20%)

| Stress /kPa | $E'_1$/MPa | $E'_2$/MPa | $E'_3$/MPa | $\eta_1$/MPa·min | $\eta_2$/MPa·min | Sum of squares of residuals (SSE) |
|-------------|-------------|-------------|-------------|------------------|------------------|---------------------------------|
| 100         | 0.917       | 2.751       | -           | 1.465.648        | -                | 2.523x10^{-3}                  |
| 200         | 1.383       | 4.822       | -           | 3.442.121        | -                | 3.635x10^{-3}                  |
| 400         | 2.290       | 10.119      | -           | 4.379.981        | -                | 4.882x10^{-3}                  |
| 800         | 5.592       | 18.596      | -           | 6.575.782        | -                | 1.282x10^{-2}                  |
| 100         | 0.904       | 8.519       | -           | 1.254.508        | 4.063            | 2.034x10^{-3}                  |
| 200         | 1.271       | 13.558      | -           | 3.159.363        | 7.484            | 3.117x10^{-3}                  |
| 400         | 2.088       | 20.576      | -           | 4.183.054        | 19.909           | 4.295x10^{-3}                  |
| 800         | 5.286       | 38.840      | -           | 6.423.618        | 35.066           | 0.967x10^{-2}                  |
| 100         | 0.723       | 5.936       | 3.906       | 872.431          | 134.576          | 3.878x10^{-4}                  |
| 200         | 1.089       | 10.882      | 5.623       | 1.349.770        | 285.010          | 2.959x10^{-4}                  |
| 400         | 1.672       | 17.045      | 8.665       | 2.630.503        | 482.507          | 2.108x10^{-4}                  |
| 800         | 3.455       | 22.117      | 11.702      | 4.389.012        | 672.118          | 1.573x10^{-4}                  |

Fig.8 Comparison of experimental results and model fitting

6. Conclusion
In this paper, the uniaxial creep tests of saturated fine sand with high salinity are carried out, and the results of soil tests with different stress levels and salinity are analyzed by using model theory. The following conclusions are drawn:

1. Based on the linear viscoelastic-plastic model theory, the creep law of saturated soils can be fitted by a five-element creep model. The comparison shows that the fitting accuracy and accuracy of the five-element creep model are higher than those of the three-element K-H model and the four-element Bu model.

2. By comparing the fitting results with the experimental data, it is further proved that the five-element creep model proposed in this paper can better reflect the creep law of high salt saturated fine sand.

3. The parameters of the model change regularly with the stress level and salt content. The nonlinear creep characteristics should be taken into account in the follow-up study, and the model should be improved and revised.

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