Research on creep characteristics of sand with different fine content

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Abstract: The storage yard in port terminal project is generally is formed by backfilling. If the backfill contains high content of fine particle, on the one hand, it will cause difficulty in foundation treatment, on the other hand, excessive settlement will occur during the operation period, which will affecting the normal operation of the project. In this paper, through experimental research on the creep settlement of sandy soils with different fine content, the relevant parameters of sandy soils with different fine-grained contents and different types of fine-grained soils are obtained, and through the analysis and fitting of commonly used rheological element models, the settlement calculation parameters of sandy soil with different fine contents are obtained.

1. Preface
In recent years, with the implementation of the "One Belt One Road" initiative, more and more port engineering projects along the route have been launched. Port engineering projects in some regions have very high requirements for foundations, especially oil terminal projects in the Middle East, such as the Kuwait project, the project's backfill material is mostly sand with less fine grain content. According to on-site particle size test data, the fine content is about 6%, while a small part of the soil samples are 15% or even 35%, and the fine content is mainly silt. The post-construction settlement requirement of the project is 10 mm 20 years. The high standards and strict requirements pose a severe challenge to engineering construction.

The high fine content not only poses a challenge for foundation reinforcement, but also increases post-construction settlement. The post-construction settlement is mainly the creep settlement of the fine-grained sandy soil. At present, there are many researches on the creep test of pure sand. However, there are few studies on the creep settlement of fine-grained sands with different fine-grain content or even different types of fine-grained sands.

Zhang Yun et al.¹,² conducted indoor unidirectional compression tests on saturated Shanghai sand and saturated Changzhou sand, respectively, and showed that sand has obvious creep properties, and the relationship between stress and strain, strain and time of Shanghai sand and Changzhou sand can be described by a power function. Shi Xiaoqing et al.³ selected undisturbed sand samples of the Changzhou aquifer system for one-dimensional creep tests, analyzed the sand creep curves, and compared the applicability of the Burgers model and the Merchan model; Wang Fei⁴ proposed to use Singh clay creep equation for sand creep calculation, and obtained the m value range of the creep
equation in sand calculation, and verified it by settlement calculation examples in Changzhou and Shanghai; Sun Xiaohan\cite{5} used a self-developed high-pressure consolidation instrument to conduct a one-dimensional creep test study on fine sand in Xi’an aquifer to study the relationship between groundwater level changes and sand creep, and explored the microscopic mechanism of sand creep with laser particle size and electron microscope scanning, which observed that sand particles slip and break during the creep process, and the creep behavior is simulated by a 5-element generalized Kelvin model. Wang Yanfang\cite{6} studied the drainage creep characteristics of saturated sand using a stress-controlled triaxial instrument modified indoors, and found that the creep characteristics of sand are greatly affected by the confining pressure and relative density, and the creep deformation becomes larger as the stress level increases. Cai Guojun\cite{7} studied the effects of different densities, different grading methods, and different loading methods on the creep characteristics of sand through confined high-pressure unidirectional compression tests, and used a power function to fit the creep curve well.

This paper intends to carry out creep tests on sandy soils with different types of fine grains and different content of fine grains to study the creep settlement of sandy soils containing fine grains for reference during the construction of this type of project.

2. Test conditions and program
In this paper, remolded soil was used as the test soil sample with different fine content. The coarse aggregate of the test soil sample was taken from Zhuhai, and the fine particles were quartz silt and Nansha clay. The coarse particles and fine particles are mixed in proportion, and the fine content is configured to be 0, 15%, 25% and 35% respectively, and the relative density is 80%. The particle gradation details are shown in Table 1.

| Sample NO. | fine content (%) | fine type | Minimum dry density $\rho_{\text{min}}$ (g/cm$^3$) | Maximum dry density $\rho_{\text{max}}$ (g/cm$^3$) | Initial void ratio $e$ |
|------------|------------------|-----------|---------------------------------------------|---------------------------------------------|-------------------|
| 1          | 0                | \         | 1.60                                        | 1.90                                        | 0.454             |
| 2          | 15               | silt      | 1.66                                        | 2.11                                        | 0.341             |
| 3          | 25               | silt      | 1.56                                        | 2.14                                        | 0.353             |
| 4          | 35               | silt      | 1.40                                        | 2.09                                        | 0.417             |
| 5          | 15               | clay      | 1.66                                        | 1.97                                        | 0.413             |
| 6          | 25               | clay      | 1.56                                        | 1.92                                        | 0.469             |
| 7          | 35               | caly      | 1.40                                        | 1.96                                        | 0.488             |
It can be seen from Figure 1 that the void ratio of pure sand is 0.454. With the gradual increase of the fine content, the void ratio gradually decreases, that is, the pores between coarse particles are gradually filled by fine particles, and the void ratio is the smallest at about 15% of the fine content, and then with the fine content increases, the void ratio gradually increases.

Sand with silt and clay show two different patterns. Except when the fines content is 15%, the void ratio is smaller, while the clay content is bigger than 25%, the void ratio becomes bigger with the increase of clay content. While for sand with silt, the void ratio of pure sand with silt all smaller than sand silt.

3.2. Creep test results

The creep curve is shown in Figure 2. The test results show that the creep curve shape of each fine content is similar. The stability time of the slit sample and the clay sample is significantly longer than sand without fine, and the larger the fine content, the longer the creep stability time.
4. Research on creep settlement of sand with fine

4.1. The correlation between creep settlement and load

Figure 3 is the stable creep value curve under different fine content and different load, the abscissa is the logarithmic coordinate of the load with 10 as the base, and the ordinate is the stability value of the creep test under different loads (the stability criterion is the settlement less than 0.005mm/d). It can be seen from Figure 3 that the creep stability settlement curve under different loads is linear in the semi-logarithmic coordinate. The relationship between the slope and intercept of the load-creep relationship curve under different fine content is shown in figure 4 and figure 5.

It can be seen from figure 4 and figure 5 that the relationship between the fine content and the slope and intercept of the load-creep curve is linear, and the correlation coefficients are all above 92%. The relevant formulas are shown below.

\[ \varepsilon = A \times \ln(P) + B \]

- \( A = 0.00216 \times F_c + 0.0183 \) (sand with clay)
- \( A = 0.00216 \times F_c + 0.0183 \) (sand with silt)
- \( B = -0.00222 \times F_c - 0.01626 \) (sand with clay)
- \( B = -5.72486E^{-4} \times F_c - 0.02375 \) (sand with silt)
In it, A is slope; B is intercept; Fe is fine content.

5. Creep constitutive model
The creep constitutive model of sand is roughly divided into three categories: empirical model, rheological model and viscoelastic-plastic model. The rheological element model is a basic mechanical model composed of elastic springs, plastic sliders and viscous dampers. The rheological element models commonly used in soil mechanics are Maxwell model, Kelvin model and Burgers model.

In this paper, the 5-element generalized Kelvin model is composed of two Kelvin bodies and a Hook body in series. The creep equation is shown in the following equation.

$$\varepsilon(t) = \frac{\sigma}{E_H} + \frac{\sigma}{E_{K1}} \left(1 - e^{-\frac{t}{\eta_{K1}}}\right) + \frac{\sigma}{E_{K2}} \left(1 - e^{-\frac{t}{\eta_{K2}}}\right)$$

$E_H$ is the modulus of elasticity, $E_{K1}$, $E_{K2}$ is the modulus of the creep stage, and, $\eta_{K1}$, $\eta_{K2}$ is the modulus of the deformation of the creep stage.

5.1. Creep constitutive calculation model and parameters

| Soil sample | Normal stress /kPa | $E_{K1}$ /MPa | $\eta_{K1}$/MPa-min | $E_{K2}$ /MPa | $\eta_{K2}$/MPa-min | $E_H$ /MPa | Correlation coefficient |
|-------------|---------------------|--------------|---------------------|--------------|---------------------|------------|------------------------|
| Pure sand   |                     |              |                     |              |                     |            |                        |
| 50          | 12                  | 9.1          | 44.6                | 7560.3       | 5                   | 0.992      |                        |
| 100         | 39.1                | 71.8         | 46.9                | 10775.9      | 5.9                 | 0.966      |                        |
| 200         | 128.2               | 2832.4       | 79.4                | 93075.9      | 7.3                 | 0.989      |                        |
| 400         | 231.2               | 1675.8       | 140.8               | 89743.5      | 11.3                | 0.993      |                        |
| 600         | 337.1               | 4035.6       | 205.5               | 136061.7     | 14.5                | 0.984      |                        |
| 800         | 442                 | 5253.7       | 233.9               | 201469       | 17.2                | 0.982      |                        |
| 15% silt    |                     |              |                     |              |                     |            |                        |
| 50          | 17.9                | 58.3         | 25.4                | 54747.7      | 5.1                 | 0.964      |                        |
| 100         | 32.4                | 328.8        | 28.3                | 53444.3      | 7.3                 | 0.973      |                        |
| 200         | 105.8               | 2281.6       | 56.5                | 107812.2     | 9                   | 0.997      |                        |
| 400         | 256.4               | 3784.8       | 137                 | 164527.3     | 13.7                | 0.99      |                        |
| 600         | 363.6               | 5655.3       | 229.9               | 294715.4     | 17.9                | 0.994      |                        |
| 800         | 615.4               | 12791        | 266.7               | 526627       | 21.3                | 0.996      |                        |
| 25% silt    |                     |              |                     |              |                     |            |                        |
| 50          | 17.4                | 74.4         | 16                  | 14135.7      | 5.8                 | 0.987      |                        |
| 100         | 25.2                | 149.5        | 20.7                | 18333        | 8.6                 | 0.981      |                        |
| 200         | 71.2                | 710.2        | 68.3                | 45358.1      | 9.2                 | 0.978      |                        |
| 400         | 130.7               | 1257.7       | 120.8               | 67163        | 13.3                | 0.988      |                        |
| 600         | 204.1               | 2240.8       | 161.3               | 107081.3     | 16.8                | 0.989      |                        |
| 800         | 310.1               | 4327.9       | 215.6               | 217165.4     | 19.6                | 0.989      |                        |
| 35% silt    |                     |              |                     |              |                     |            |                        |
| 50          | 10.4                | 36.4         | 6.8                 | 6423         | 1.9                 | 0.994      |                        |
| 100         | 12.9                | 53.6         | 9.5                 | 8842.5       | 3.3                 | 0.991      |                        |
| 200         | 44.8                | 615.1        | 33.9                | 35615.1      | 4                   | 0.989      |                        |
| 400         | 73.1                | 1425         | 66.7                | 106499.6     | 6.2                 | 0.989      |                        |
| 600         | 108.1               | 2715.3       | 104.5               | 205430.4     | 8.2                 | 0.986      |                        |
| 800         | 172.4               | 7311.2       | 144.9               | 355082.3     | 9.9                 | 0.993      |                        |
| 15% clay    |                     |              |                     |              |                     |            |                        |
| 50          | 13.4                | 32.8         | 49.5                | 206161.6     | 3.6                 | 0.977      |                        |
| 100         | 17.7                | 55.3         | 37.9                | 30052.9      | 5.6                 | 0.978      |                        |
| 200         | 54.5                | 548.8        | 49.8                | 96146.7      | 6.9                 | 0.981      |
5.2. Correlation between five element parameters and load and fine content

| Load (kPa) | EH (MPa) | EK1 (MPa) | EK2 (MPa) | k1 (MPa) | Load (kPa) |
|-----------|----------|-----------|-----------|----------|------------|
| 50        | 3.4      | 3.6       | 2.9       | 4.6      | 50         |
| 100       | 5.4      | 10.4      | 3.6       | 8.2      | 100        |
| 200       | 24.4     | 10.4      | 10.4      | 41.1     | 200        |
| 400       | 53.3     | 23.3      | 23.3      | 92.1     | 400        |
| 600       | 84.0     | 37.2      | 37.2      | 145.1    | 600        |
| 800       | 104.0    | 77.1      | 77.1      | 443.7    | 800        |

5.3. Creep parameter EH changes with the normal stress

5.4. Creep parameter EK1 changes with the normal stress

5.5. Creep parameter EK2 changes with the normal stress

5.6. Creep parameter ηK1 changes with normal stress
Figure 10. Creep parameter $\eta_{K2}$ changes with normal stress

Through the figures 6 to figure 10, it can be found that under the double logarithmic coordinates, the generalized Kelvin parameter has a linear relationship with the load under different silt content and fine particle types. By fitting all data points, the correlation between different parameters is obtained, as shown in the table 4. The data points of 15% and 35% silt at 50kPa were removed during the $E_{K2}$ fitting process.

Table 4. Equation of five elements parameters

| Equation | log10(y) = a + b*log10(x) |
|----------|---------------------------|
| Type of soil | Pure sand | 15% silt | 25% silt | 35% silt | 15% clay | 25% clay | 35% clay |
| $E_{K1}$ Slope b | 0.506 |
| Intercept a | -0.242 | -0.165 | -0.155 | -0.521 | -0.302 | -0.716 | -0.797 |
| $E_{K2}$ Slope b | 1.179 |
| Intercept a | -0.754 | -0.716 | -0.905 | -1.155 | -1.035 | -1.420 | -1.664 |
| $\eta_{K1}$ Slope b | 0.868 |
| Intercept a | -0.058 | -0.144 | -0.237 | -0.509 | -0.262 | -0.494 | -0.587 |
| $\eta_{K2}$ Slope b | 1.877 |
| Intercept a | -1.666 | -1.290 | -1.639 | -1.714 | -1.791 | -2.297 | -2.808 |

5.3. parameter discussion

Figure 11 and Figure 12 is the different values of $\eta_{K1}$ and $\eta_{K2}$ to show comparison between the creep curve and the original test curve. By comparison, it can be seen that $\eta_{K1}$ mainly affects the initial slope of the creep curve. When nk1 takes the maximum and minimum values, the second half of the creep curve basically coincides, and the slope of the initial stage is different, the smaller of the nk1, the steeper the initial stage of creep, the larger of the $\eta_{K1}$, the slower the initial stage of creep. The situation of $\eta_{K2}$ is similar to the $\eta_{K1}$, the smaller of the $\eta_{K2}$ value, the steeper, the larger the slower. $\eta_{K2}$ has a greater impact on the short-term creep settlement value. When $\eta_{K2}$ is the maximum and minimum values, the creep difference reaches 0.003 at 4320 min.
It can be seen from the previous section that the linear fitting coefficients of $n_k1$ and $n_k2$ in double logarithmic coordinates are not high, and the values of $n_k1$ and $n_k2$ are averaged for calculation. The picture shows the comparison between the final fitting curve and the experimental data.

6. Conclusion
In this paper, through indoor creep tests on sandy soils with different fine content and different type’s soils, the creep characteristics and changing pattern are analyzed. The main conclusions are as follows:

1) Different types of fine particles have different influence on the creep settlement of sandy soil, especially the settlement of creep stable stage. For sand with silt and clay, the influence of fine content on the stable creep value is linear, and the influence of content of clay is far bigger than the influence of content of silt.

2) The parameters of the five-element generalized Kelvin model are obtained by fitting, and the calculation formulas of the parameters of the five-element generalized Kelvin model are obtained through parameter analysis. The comparison results prove that the calculation results of the parameters are in good agreement with the test results.

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