Rheological investigations of tailings of kimberlite ore dressing and numerical simulation of its behaviour in PLAXIS

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Abstract. The article presents the results of analysis of rheology properties of sandy-clay tailings (wastes) of kimberlite ore dressing of the diamond deposit (Russia, Arkhangelsk region). The coefficient of secondary compression as main parameter of soil’s creep is defined by implementing standard one-dimensional consolidation test. The linear correlation between initial void ratio and coefficient of secondary compression of sandy-clay tailings were obtained. For numerical simulation of tailing’s behaviour subject to its rheology properties in Soft Soil Creep (SSC) model (time independent behaviour) of PLAXIS software was used. According to laboratory tests calibration of SSC model was implemented. It allows predicting dam’s safety and reliability for long-term outlook.

1. Introduction

Development of diamond deposits in the Arkhangelsk region requires to build special storage for industrial wastes, so-called tailing dumps. One of the main engineering structures of tailing dump is multi-tiered dam (Fig. 1). In the operation of the tailing dump a staged construction of dam and washing of tailings on upstream slope of the dam are implemented. Tailings, which are presented by sandy-clay soils with specific physical and mechanical properties, formed the foundation for the 2nd and following tiers of dam. Taking into consideration of the long-term operation and rate of responsibility of dam, specific properties of tailings and its time-to-time variability, the estimation of dam’s reliability subject to rheological properties of the foundation is an actual objective.

Figure 1. Cross-section of 3-tiered dam.
2. Laboratory testing

One of the rheological properties is a creep - the process of deformations in time under constant pressure. The main parameters of creep are compression index (\(C_c\)) and coefficient of secondary compression (\(C_\alpha\)). The first parameter characterizes the compressibility of the soil on phase of primary consolidation, the second - the deformability of the soil skeleton in time under constant pressure. Coefficient of secondary compression was determined by one-dimensional compression tests of fully saturated sandy-clay tailings and subject to two-side drainage in automated consolidation apparatus LoadTrac-II (GeoComp Corp, USA) (Fig. 2).

![Automated consolidation apparatus LoadTrac-II](image)

Figure 2. Automated consolidation apparatus LoadTrac-II

The sample had the following dimensions: diameter - 73 mm, height - 20.85 mm. We applied 300 kPa in tests, which corresponds to the representative stresses on sandy-clay tailings during the operation of the dam. To calculate the start time of the secondary compression we plotted the curve with axes: strain (\(\varepsilon\)) - time (t, min) in a logarithmic scale. On the intersection of two tangents to the part of the curve of the primary consolidation and secondary compression we determined the start point of the secondary consolidation (Fig. 3). Coefficient of secondary compression is defined as slope of straight line of strain (\(\varepsilon\))-logarithm of time (\(\lg t\)) curve (line 2, Fig. 3). Coefficient of secondary compression calculated on the test results of 12 samples of sandy-clay tailings with different initial void ratio. Initial void ratio varied between 0.72...0.91. This range includes all void ratios obtained from the results of laboratory tests of sandy-clay tailings during geotechnical monitoring [3].

![Strain-time curve of sandy-clay tailings](image)

Figure 3. Strain-time curve of sandy-clay tailings

Linear relationship between the initial void ratio \(e_0\) and \(C_\alpha\) under constant pressure (300 kPa) was determined:

\[
C_\alpha = 4.3937(1-0.9789e_0) \cdot 10^{-3}
\]  

(1)
Analysis of the consolidation of sandy-clay tailings showed that the primary consolidation is completed within 100-150 minutes after application of pressure. Due to the fact that the primary consolidation period significantly less secondary consolidation period (5000-6000 min), compression index can be defined as characteristic of primary consolidation under applied load.

To determine the compression index we applied pressure of 12.5, 25, 50, 100, 200, 300 kPa to the sample. Compression index \( C_c \) was determined for each value of the initial void ratio by plotting a straight line between initial void ration and applied pressure in the logarithm scale (Fig. 4). Relationship between compression index and initial void ration for industrial tailings is presented in Figure 5.

![Figure 4. Compression Index \( C_c \)](image)

![Figure 5. Linear relationship \( C_c \) and \( e_0 \)](image)

A linear relationship between the initial void ratio \( e_0 \) and \( C_c \) was defined:

\[
C_c = 0.0203 \cdot e_0 + 0.1105
\]  

(2)

### 3. Numerical Simulation

To estimate the reliability of the dam subject to the rheological properties tailings we used PLAXIS 2D software and numerical Soft Soil Creep model. The main parameters of the model are modified compression index \( \lambda^* \), modified swelling index \( \kappa^* \), modified creep index \( \mu^* \). The first two parameters are determined by plotting the logarithm of stress as a function of strain. The plot can be approximated by two straight lines. The slope of normal consolidation line gives the modified compression index \( \lambda^* \) and the slope of unloading (recompression) line gives us modified swelling index \( \kappa^* \). Modified creep index \( \mu^* \) are determined as slope of straight line in strain \( \varepsilon \) - logarithm of time \( \ln t \) curve.

As an alternative parameters PLAXIS uses the compression index \( C_c \), recompression index \( C_r \), the index of secondary compression \( C_{\alpha'} \). Index \( C_{\alpha'} \) is determined as slope of straight line of initial void ratio \( e_0 \) and the logarithm of time \( \ln t \) curve and can be calculated by multiplying the coefficient of secondary compression \( C_{\alpha} \) by \( (1+e_0) \). Alternative parameters associated with the basic characteristics of creep model by the following expressions (3) - (5) [2]:

\[
\lambda^* = \frac{C_c}{2.3(1+e)}
\]  

(3)

\[
\kappa^* = \frac{2}{2.3} \cdot \frac{C_r}{(1+e)}
\]  

(4)

\[
\mu^* = \frac{C'_{\alpha}}{2.3(1+e)}
\]  

(5)
The mean of initial void ratio of sandy-clay tailings was equal 0.86 according to results of geotechnical monitoring. Indexes $C_c$ and $C_a$ related to defined initial void ration are shown in Table 1.

In the virtual laboratory PLAXIS were modeled odometer tests taken into consideration indexes from Table 1. The results are shown in Figure 6a. The simulated and observed compression curves are differed. To model the behavior of sandy-clay tailings properly it is necessary to calibrate the parameters of the numerical model of Soft Soil Creep according to laboratory tests. Calibration of the parameters is made in a virtual laboratory of PLAXIS software for the following parameters: $\lambda^*$, $\mu^*$, $c$ - cohesion and $\varphi$ - friction angle. Observed and simulated results have a good agreement (Fig. 6b).

Table 1. $C_c$ and $C_a$ indexes ($e_0=0.86$)

|        | $C_c$  | $C_a \times 10^3$ |
|--------|--------|--------------------|
| Mean   | 0.128  | 0.695              |
| Min    | 0.111  | 0.586              |
| Max    | 0.149  | 0.830              |

Figure 6. Calibration of Soft Soil Creep Model:
1- observed; 2 – simulated
a – before calibration; b – after calibration

To estimate the stress-strain state of the dam and determine its stability we modeled dam’s behavior in the PLAXIS 2D (Fig. 7). Hardening soil model was applied for simulating foundation’s and dam body’s soils. Soft Soil Creep model was used for simulating rheological behavior of tailings.

Figure 7. FE model of dam

Staged construction method was applied and we simulated the following stages:
1. Building of 1-st tier of dam and washing of tailing on upstream slope;
2. Building of 2-st tier of dam and washing of tailing on upstream slope and etc;
3. Evaluation of reliability of the dam at 1 year and 15 years of operation after the completion of third tier of dam.
Safety factors were 1,369 and 1,373 in 1 year and 15 years respectively. Various parameters of the numerical model have a different influence on the safety factor. Assessment of the influence of parameters is key objective in terms of planning and carrying out additional researches of soils and sandy-clay tailings.

We performed parameter mapping of Soft Soil Creep model on rate of influence in the short-term and long-term outlook in PLAXIS software. Distribution of the rate of influence \( \lambda^*, \mu^* \) on the safety factor is shown in Figure 8. For further analysis 4 parameters were selected: \( \lambda^* \)- for tailings of 2 and 3 tiers; \( \mu^* \)- for tailings of 1 and 2 tiers which had the maximum rate of influence.

So we calculated the maximum and minimum safety factor with specified variation of the rheological properties of sandy-clay tailings. Maximum safety factor was 1,375 after 15 years, the minimum - 1,348.

**Figure 8.** Rate of influence \( \lambda^*, \mu^* \) on safety factor

### 4. Conclusion

Calibration of characteristics Soft Soil Creep model in PLAXIS must be performed taking in consideration the results of laboratory tests. The initial parameters of the numerical model have been changed: \( C_c \) decreased by 24.5%, \( C_{\alpha} \) increased by 31.5%.

Modeling of building and operation of dams subject to variation of the rheological characteristics of the soils and tailings, obtained by laboratory testing is appropriate. It provides us to get qualitative and quantitative assessment of the safety factors over time, as well as to establish the limits of their variation depending on the initial rheological properties of soils.

Such approach will allow to evaluate the influence of various factors independently (e.g., strength parameters and filtration characteristics) on the reliability of dams.

### References

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