Rheology Test and Finite Element Analysis: A Case Study of a Rockfill Dam in China

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Abstract. Rheology often occurs in the dam rockfill deformation. In this paper, we carried out a large-scale triaxial rheological test for the tuff rockfill materials of a concrete faced rockfill dam in China, and then obtained the parameters of the seven parameter rheology model. Finally, we analyzed the dam rheology using the three-dimensional finite element model. The results show that the dam settlement, horizontal displacement, face deflection and the displacement of the joints around the face slab are all obviously increased when considering the rheological behavior of the rockfill. We find that the calculated settlement of the dam body is in good agreement with the filed measured value when the dam is completed, and the maximum settlement during the impoundment period is within the normal range.

1. Introduction
Rheology is a basic deformation characteristic of rockfills [1]. The rheological mechanism of rockfill dam is relatively complicated, and it is not solved well so far. In recent years, some scholars have proposed a variety of rheological constitutive models of rockfills through indoor experiments and feedback analysis. Shen & Zhao [2] proposed an exponential three-parameter rheological model based on laboratory experiments and feedback analysis. Since then Guo et al. [3], Li et al. [4], and Wang et al. [5] intensively studied and revised the model. Recently, Cheng & Ding [6] proposed a 9-parameter model, which is based on several groups of large-scale rheological tests using the primary and secondary rockfill materials of the Shuibuya dam. Li et al. [7] proposed a power function model based on the rheological tests of the rockfill materials of the Jiudianxia dam. Wang et al. [8] introduced a solid hardness parameter reflecting particle strength in the isotropic compression equation, and derived a creep formula for deformation and proposed a visco elastic-plastic constitutive model for rockfill materials. Due to the practical physical meaning by fitting the rheological test curves and the simplicity for numerical analysis, the three-parameter (or its modified rheological model) is most widely used in real applications [9]. In this study, we perform a rheology test and finite element analysis of the rockfill of a dam in China. A large-scale triaxial rheological test using the high pressure triaxial creep apparatus is carried out on the tuff rockfill of a concrete face rockfill dam, to determine the three-parameter rheological model parameters. Three-dimensional finite element rheological calculations are also included and compared with the measured values.

The rest of the study is organized as follows. Section 2 introduces a brief background of the rockfill
Section 2 presents the project overview of Huangnan Reservoir, including its location, storage capacity, and main characteristics. The reservoir is located in Songyang County, Lishui City, Zhejiang Province, with a total storage capacity of 91.96 million cubic meters. The barrage is a concrete face rockfill dam with a crest elevation of 337.0m, a maximum dam height of 97.0m, a crest width of 10.0m, and a length of 267.0m. The upper and lower dam slopes are both 1:1.4. The downstream dam slope is equipped with three-level horse tracks at elevations of 270m, 292.0m, and 314.0m, with a width of 5.0m. From upstream to downstream, the rockfill zone of the dam is in the order of cushion zone, transition zone, main rockfill zone, and downstream rockfill zone. The rockfill material of the dam body is mainly breccia-bearing glass tuff, with a saturated compressive strength of 70-90MPa and a softening coefficient of 0.80.

Section 3 presents the triaxial rheological test of the rockfill materials. Figures 1 and 2 give the axial strain and volumetric strain curves of the main tuff rockfill materials under stepwise loading. Figure 3 shows the comparison between the single-step loading rheological test curve and the model fitting curve.

The results show that: (a) The deformation in the initial stage of each level of loading is relatively large, and the deformation is basically 80% to 90% after more than ten to dozens of hours later. As time goes by, the rheology of the rockfill body is generally gradually stabilized, and generally shows a decay curve that tends to stop; (b) As the confining pressure and stress level increase, the flow variable of the rockfill body increases correspondingly, and the time for the flow to stop will also increase; (c) The fitting curve of the rheological model and the results of the rheological test are generally in good agreement. However, due to the limitation of the sample size, the rheological rate obtained in the indoor rheological test is significantly greater than the actual rheological rate on site, leading to the larger rheological rate parameter value than its actual one. According to the similar engineering experience [5, 10] and the characteristics of tuff, the primary and secondary rockfill values are tentatively set as 0.007 and 0.006 respectively in our calculation. The rheological model parameters are list in Table 1.
Figure 3. Rheology test and model fitting curve (confining pressure: 0.8MPa)

Table 1. Rheology model test parameters

| Material type        | $\alpha$ | $b$     | $c$     | $d$     | $m_1$ | $m_2$ | $m_3$ |
|----------------------|----------|---------|---------|---------|-------|-------|-------|
| Main rockfill        | 0.007    | 0.0012  | 0.0001  | 0.0019  | 0.46  | 0.81  | 0.69  |
| Secondary rockfill   | 0.006    | 0.0009  | 0.0002  | 0.0018  | 0.49  | 0.74  | 0.81  |

4. Three-dimensional rheological finite element analysis

4.1. Rheological constitutive model

Shen et al. [2] assumed that the deformation process line under the constant stress is a decay curve that gradually tends to stop, and they believe that the exponential decay curve can more accurately reflect the rheological characteristics of coarse-grained materials:

$$\varepsilon(t) = \varepsilon_i + \varepsilon_f (1 - e^{-\alpha t})$$  \hspace{1cm} (1)

where $\varepsilon_i$ is the initial rheology; $\varepsilon_f$ is the final flow variable when $t \rightarrow \infty$, including the final volume rheology $\varepsilon_{vf}$ and the final shear rheology $\varepsilon_{sf}$.

Volume rheological rate $\dot{\varepsilon}_v$ and shear rheological rate $\dot{\varepsilon}_s$ are expressed by the following two formulas:

$$\dot{\varepsilon}_v = \alpha \varepsilon_{vf} \frac{(1 - \varepsilon_{vf})}{\varepsilon_{sf}}$$  \hspace{1cm} (2)

$$\dot{\varepsilon}_s = \alpha \varepsilon_{sf} \frac{(1 - \varepsilon_{sf})}{\varepsilon_{sf}}$$  \hspace{1cm} (3)

where $\varepsilon_{vf}$ is the volumetric rheology accumulated during the $t$ period; $\varepsilon_{sf}$ is the shear rheology accumulated during the $t$ period.

According to the principle of increment, $\varepsilon_{vf}$, $\varepsilon_{sf}$ can be calculated by the following formula:

$$\varepsilon_{vf} = \sum \dot{\varepsilon}_v \Delta t$$  \hspace{1cm} (4)

$$\varepsilon_{sf} = \sum \dot{\varepsilon}_s \Delta t$$  \hspace{1cm} (5)

$\varepsilon_{vf}$ and $\varepsilon_{sf}$ can be expressed as:

$$\varepsilon_{vf} = b \left( \frac{\sigma_{vf}}{P_a} \right)^{m_v} + c \left( \frac{q}{P_a} \right)^{m_q}$$  \hspace{1cm} (6)
\[ \varepsilon_{sf} = d \left( \frac{S_l}{1-S_l} \right)^{m_1} \]  

where \( P_a \) is the atmospheric pressure; \( S_l \) is the stress level; \( q \) is the deviatoric stress; \( \alpha, b, c, d, m_1, m_2, m_3 \) are the 7 calculation parameters included in our rheological model.

4.2. Calculation model and its parameters

The three-dimensional model of the dam is shown in Figure 4. The total number of grid nodes in the finite element calculation is 11148, the total number of elements is 10450, the number of contact elements is 488, and the number of peripheral joints is 40.

![Figure 4. Three dimensional integral mesh of dam](image)

The constitutive model of the dam materials adopts the Duncan E-B model, and the parameters are obtained from large-scale static triaxial tests. The model parameters are shown in Table 2. The plinth and faceplate adopt a linear elastic model. A ‘Goodman’ contact surface unit is set between the panel and the cushion material to deal with the inconsistency of the displacement between the two. Between the panel and the panel and between the panel and the toe board, a thicknessless connection unit is used to simulate the interaction between the seams.

| Material type        | \( \gamma_d \) [g cm\(^{-1}\)] | \( \varphi_0 \) [°] | \( \Delta \varphi \) [°] | \( R_f \) | \( K \) | \( n \) | \( K_b \) | \( m \) |
|----------------------|---------------------------------|---------------------|-----------------------|--------|-------|-------|--------|-------|
| Cushion material     | 2.21                            | 58.7                | 11.4                  | 0.79   | 1198  | 0.46  | 810.5  | 0.21  |
| Transition material  | 2.12                            | 56.4                | 9.5                   | 0.74   | 1146  | 0.44  | 813.3  | 0.20  |
| Main rockfill        | 2.07                            | 56.9                | 10.8                  | 0.71   | 1184  | 0.26  | 665.4  | 0.19  |
| Secondary rockfill   | 2.00                            | 60.1                | 13.4                  | 0.64   | 956   | 0.30  | 689.4  | 0.22  |

4.3. Calculation results

The Huangnan Reservoir began to be filled on November 8, 2018, and was completely filled to an elevation of 332m on November 30, 2019. The panel pouring began on March 22, 2020, and the panel layers according to the level. After the dam body was completely filled, the panels were laid at one time. After the construction was completed, the water was stored in stages until the normal water level was loaded in 38 stages.

| Table 3. Results of dam displacement and stress |
|-----------------------------------------------|
| Project                        | Completion period | Storage period |
|                                | Regardless of rheology | Consider rheology | Regardless of rheology | Consider rheology |
| Dam displacement /cm settlement | 23.52             | 39.93            | 32.35             | 52.10            |
Table 3 shows the calculation results of dam displacement and stress considering rheology during the completion period and storage period. The settlement contour of the rockfill body during the completion period considering the rheology is shown in Figure 5. The contours of rockfill settlement during the storage period are shown in Figure 6. The contours of panel stress are shown in Figures 7 and 8.

The result shows that: (a) the calculated maximum settlement inside the dam upon completion is 39.93 cm (near the 303.0 m dam axis), which is slightly larger than the field measured maximum settlement of 34.0 cm (near the 293.0 m dam axis). If the calculated settlement result near the elevation of 293 m is considered, the calculated value is basically equivalent to the observed value; (b) except that the stress of the rockfill body is reduced when the rheology is considered, the settlement of the dam body, the horizontal displacement, and the deflection of the slab are significantly increased compared with the case when the rheology is not considered; (c) when considering the rheology, the maximum settlement of the dam body during the impoundment period is 52.1 cm, which is about 0.54% of the dam height. Compared with similar projects, the settlement is within the normal range.

| Dam stress /MPa        | Downstream | 7.25 | 11.20 | 11.17 | 18.13 |
|------------------------|------------|------|-------|-------|-------|
| Major principal stress | 1.42       | 1.21 | 1.56  | 1.48  |
| Small principal stress | 0.63       | 0.60 | 0.66  | 0.62  |
| Stress level           | 0.46       | 0.34 | 0.34  | 0.22  |

| Panel deformation /cm  | Deflection | 7.58 | 10.37 | 15.0  | 24.2  |
|------------------------|------------|------|-------|-------|-------|
| Downhill compressive   | 1.12       | 1.98 | 3.02  | 3.89  |
| stress                 | 0.03       | 0.1  | 0.20  | 0.45  |
| Downhill tensile stress| 0.01       | 0.02 | 0.30  | 0.33  |
| Axial compressive stress| 0.01    | 0.02 | 0.30  | 0.33  |
| Axial tensile stress   | 0.04       | 0.06 | 0.20  | 0.23  |

Figure 5. Contour map of dam vertical displacement during completion (cm)
Figure 6. Contour map of dam vertical displacement during storage period (cm)
Figure 7. Stress contour map along slope of slab during water storage period (MPa)
5. Conclusions
When the test confining pressure and the stress level increase, the rheology of the rockfill body will increase correspondingly, and the time when the rheology tends to stop will also gradually increase. The fitted rheological rate using the indoor rheological test is far larger than the actual on-site rheological one, leading to the model parameters, which reflect the rheological rate, are mostly larger than the actual situation. As such, we point out that the rheological calculation should be adjusted according to the actual project.

Considering the rheology of the rockfill body, the dam settlement, horizontal displacement, and deflection of the slab have all increased significantly. When the dam is completed, the calculated settlement of the dam body is in good agreement with the field measured value, and the maximum settlement during the impoundment period is within the normal range.

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