Study on the reservoir dam slope stability considering the effect of seepage

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Abstract. Water conservancy dam plays a significant role in flood control, power generation, shipping, irrigation, aquaculture, tourism, urban water supply and so on. The stability of the dam is extremely important in the engineering design and research processes. Based on the basic principles of finite difference and strength reduction methods, the software of FLAC3D is adopted to analyze the stability of the dam, considering the seepage state, the reservoir water level height and the seepage coefficient of the dam body. The results show that with the increase of the reservoir water level, the seepage behavior of the dam body is more obvious, and the horizontal displacement of the dam increases, while the dam slip safety factor is reduced. With the increase of the seepage coefficient of the dam body, the seepage discharge at the dam foot increases linearly, and the stability of the dam body decreases obviously. The seepage of dam foundation and dam slope stability is evaluated in this research. It is found that the reservoir water level and the dam body permeability are the important factors affecting the dam slope stability, so it is necessary to enhance the anti-seepage measures during the dam design and construction.

1. Introduction

Earth-rock dam is a kind of water-retaining structure filled with local soil and stone materials, which are widely constructed and used in the world. The advantage of the earth-rock dam is the characteristics of low cost, convenient construction, and good aseismic performance, but also have problems such as leakage, landslides, and earthquake damage. Literature [1] summarised the dam-break accidents worldwide. Among them, the earth-rock dams account for about 70% of the total number of dam-breaks. According to statistics, it is found that floods overtopping, seepage failures, pipeline leakage and slope instability are the main reasons for the earth-rock dam accidents.

Aiming at the characteristics of earth-rock dams, the evaluation of dam deformation is very important. Liu (1983)²³ proposed that the calculation of earth-rock dams should focus on three issues: the effect of stress path, humidification deformation, and nonlinear constitutive models. Yin (2009)³ also pointed out in Huang Wenxi's lecture that stress and deformation analysis should be done for the earth-rock dam. The earth and rock dams have been built with a height of more than 200m or 300m. Non-linear stress-strain analysis method should be used in the project. The nonlinear elastic
constitutive models which are most used are Duncan Zhang E-B model and E-v modes. Yang et al. (2007) [4] used the Duncan-Chang E-B nonlinear elastic model to analyze the stress and deformation characteristics of the earth-rock dam diaphragm wall. It is found that the cross-section of the dam and the diafragm stiffness can obviously affect the deformation of the dam body.

In the stability analysis of the dam, the dam slope slip stability is important and necessary. Morteza et al. (2011) [5] introduced commonly used methods for the slope slip stability analysis, including limit equilibrium method, stress analysis method and stereographic projection method. These conventional methods can not consider the effect of internal water in the slope, so many modified formulas are proposed and studied. Stable seepage will be formed by the impounding in the earth-rock dam and foundation ground. Besides, the rapid fluctuation of the reservoir water level will have a serious impact on the dam. Using centrifuge tests and numerical simulations, Fattah (2017) [6] and Chen (2011) [7] analyzed the influence of the rising and rapidly falling water level in the reservoir on the dam slope stability. The water storage of the reservoir will reduce the anti-sliding resistance of the dam site, and the rapid drawdown will generate dynamic water pressure into the reservoir. In addition to the sliding stability of the dam body itself, the impact force caused by the landslide on the bank of the reservoir area also has a greater effect on the dam body [8].

The seepage effect on the slope stability of earth-rock dams is an important research topic related to earth-rock dam safety. Liu (2011) [9] and Zhang (2000) [10] summarized the seepage control theory of earth-rock dams and established relevant analysis models. However, the influence of groundwater seepage is seldom considered in the current slope stability analysis. Therefore, in this research, based on a real reservoir dam project, the impact of the reservoir water level height and the dam body permeability on the dam slope stability were studied.

2. **Analysis method and calculation model**

2.1. **Analysis method**
The finite-difference method is used to study the reservoir dam slope stability through FLAC3D (Fast Lagrangian Analysis of Continua) large commercial software. Considering the effect of dam seepage on slope stability, the dam slope slip safety factor is calculated through the strength reduction method. The basic principle of the strength reduction method is to reduce the shear strength of the soil until the slope is judged to reach the critical failure state. The factor of safety is defined as the ratio between the actual shear strength of the soil and the reduced strength of the soil.

2.2. **Numerical model**
Taking a real reservoir dam as an example, the numerical model is established as shown in Figure 1. The reservoir water level, h, is set to 5m, 12m, 14m, 15m, 16m and 17m, respectively. The silty clay layer of the dam foundation is thought to be a permeable layer. There are 2602 elements and 3327 nodes totally in this model. The boundary condition is set as fixed in the bottom nodes, while the left and right sides nodes are fixed in the horizontal direction and free in the vertical direction. The bottom of the reservoir, the slopes on both sides of the dam body and the surface of the dam site are set as drainage boundaries.
The reservoir dam and foundation ground material parameters are shown in table 1.

| Material  | Elastic Modulus $E$ (MPa) | Poisson ratio $\mu$ | Density $\rho$ (kg/m$^3$) | Cohesion $c$ (KPa) | Friction angle $\phi$ (°) | Permeability coefficient $K$ (cm/s) | Porosity $n$ |
|-----------|---------------------------|---------------------|---------------------------|-------------------|--------------------------|-----------------------------------|-------------|
| 1 Loam   | 23                        | 0.25                | 1983                      | 32                | 21.9                     | $7.05 \times 10^{-5}$            | 0.42        |
| 2 Silty clay | 32                        | 0.3                 | 1850                      | 24                | 22                       | $2.45 \times 10^{-4}$            | 0.5         |
| 3 Bed rock | 60000                     | 0.3                 | 2700                      | 30                | 40                       | ——                               | ——          |

3. Result analysis

3.1. Seepage behavior of reservoir dam

The seepage behavior of the reservoir dam was simulated when the reservoir water level was set as 5m, 10m, 12m, 14m, 15m, 16m and 17m, respectively. The distribution of pore water pressure inside the earth-rock dam is shown in Figure 2. It is shown that the saturation line is higher when the water level is higher, the seepage effect of underground water is more obvious.

![Pore-water pressure contours at different water storage levels](image)

Figure 2. Pore-water pressure contours at different water storage levels

Figure 3 shows the seepage flow at the foot of the earth-rock dam. With the increase of the water storage level, the seepage flow increases approximately linearly. With the increase of the permeability coefficient of the dam, the seepage discharge increases. It can be observed that the reservoir water level and the permeability of the dam body have a greater impact on the seepage flow of the dam foot.

3.2. The deformation behavior of the reservoir dam

Figure 4 shows the horizontal displacement curves of the monitoring points on the central axis of the dam body at different water storage levels. It can be found that the displacement of the earth-rock dam increases firstly and then decreases from the top to the bottom. As the water storage level increases,
the horizontal displacement keeps increasing. When the reservoir water level is 17m, the maximum displacement value in the dam is 0.01064m.

When the water storage level $h=17m$, the horizontal deformation contours of the entire earth-rock dam is shown in Figure 5. With the constant growth of the storage level height, the hydro pressure on the upstream face of the earth-rock dam increases, causing the horizontal displacement of the earth-rock dam towards the outside of the reservoir, and the maximum displacement is at the position of the upstream face.

![Figure 3. The seepage flow at the foot of earth-rock dams](image1)

![Figure 4. Horizontal deformation of the central axis of the dam](image2)

3.3. The slip stability of the reservoir dam

The strength reduction method is used to study the earth-rock dam slope stability, and the impact of the reservoir water level and the permeability of the dam body is comprehensively compared. Figure 6 shows the change of slope safety factor considering the change of water storage level and dam permeability. It can be observed that with the increase of the water storage level, the stability safety factor of the dam body obviously decreases, and as the permeability of the dam body increases, the stability safety factor of the dam body also decreases to some extent. It shows that the storage level of the reservoir and the permeability of the dam are important factors affecting the reservoir dam slope stability.

Taking case of $h=16m$ as an example, the distribution of maximum shear strain increment is shown in Figure 7. It is easily shows the position of the most dangerous sliding surface, which is roughly an arc-shaped sliding surface. And the most dangerous sliding surface is located at the back side of the dame connecting the dam crest and the dam foot,
4. Conclusion

Through FLAC3D finite difference software, the fluid-solid coupling and strength reduction method is used to analyze the seepage of the reservoir earth-rock dam and the dam slope stability. The following conclusions can be summarized:

1. With the increase of the reservoir water level, the horizontal displacement of the earth-rock dam increased significantly. The displacement line of the center axial of the dam shows that the maximum displacement occurs inside the dam body.

2. It shows that the seepage flow increases approximately linearly with the increase of the water storage level. As the permeability coefficient of the dam increases, the seepage flow increases significantly.

3. The strength reduction method is used to analyze the earth-rock dam slope stability. With the increase of the reservoir water level and the permeability of the dam body, the safety factor of the dam body decreased significantly, indicating that the reservoir water level and dam body permeability are important factors affecting the reservoir dam slope slide hazard.

Acknowledgments

The authors are grateful for the technical and financial support Provided by the National Natural Science Foundation of China (grant number 51708251), the China Postdoctoral Science Foundation (grant number 2019M652304), the Key Technology Research and Development Program of Shandong Provincial (grant number 2019GSF111031) and the Natural Science Foundation of Shandong Province (grant number ZR2017BEE074).
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