Statistical Simplification and Discrete Element Analysis of Seepage Model for Complex Fracture Network of Dam Foundation Rock Mass

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Abstract. In this paper, a model of seepage in a fracture network is analyzed by taking the rock mass of the dam foundation of Datengxia Hydropower Station, the No. 1 Project of the Ministry of Water Resources, as an example. Complex discontinuity systems are present in the rock mass of the Datengxia Hydropower Station dam foundation, and faults, soft interlayers, and structural fracture systems intersect with one another. A multi-scale structural analytical scheme that combines the deterministic analysis of large-scale geological structures (i.e., faults and weak interlayers) with the statistical simulation of random discontinuities (i.e., structural fractures) is proposed in this paper to reduce the difficulty and uncertainty of the analysis of rock masses with complex structures. In particular, a chain analytical method from dominant group definition to statistical parameters (i.e., spacing and occurrence) is formed for the structural fracture system. In this way, the analysis of rock masses with complex structures is simplified to a regular and feasible scientific problem that could be solved by rock mass simulation. We then establish a seepage model of the rock mass in dam section 29# in UDEC by adopting the above structural simplification scheme. The quantitative analysis of seepage in complex-structured rock masses under normal water storage and dynamic conditions is then realized. Results show that the statistical simplification of the rock mass structure and discrete element simulation can efficiently solve the seepage analysis of complex rock masses. The negative influence of pore pressure caused by seepage on the rock mass, especially under dynamic conditions, should be emphasized for safety assurance in the stability analysis of dam foundations.
Keywords: Datengxia Hydropower Station; discrete fracture network; seepage; discrete element method

1. Introduction

In engineering projects involving rock slopes, tunnels, and dam foundations, discontinuities such as fractures and soft layers tend to propagate and coalesce under the influence of seepage, thereby resulting in rock mass deformation and geological disasters\(^1\). Hydropower is under vigorous development in China because of the special distribution of resource conditions. The rock masses of hydropower station dam foundations can easily form discontinuities, such as fractures and soft layers, on account of their unique geological structure and weathering effects. The stability of a dam could be reduced by the comprehensive effects of seepage and dynamic loading. Thus, the seepage analysis of rock masses with multi-scale discontinuities is an essential endeavor for engineering applications.

Henry Darcy, a French engineer, proposed Darcy’s law by conducting a large number of sand column seepage experiments in 1856. Since then, many researchers have conducted in-depth studies of the porous media seepage problem, established relatively complete porous medium theory, and sufficiently solved the seepage problem of homogeneous porous media. However, given the wide distribution of discontinuities in rock masses, researchers have gradually found that studying the seepage problem of rock masses using only seepage theory of porous media is not feasible. Consequently, scholars began to study new theories of fracture permeability to deal with the seepage problem of fractured rock masses in practical engineering\(^2\).

Previous research on seepage in fractured rock masses can be divided into two main aspects, namely, the mechanical characteristics of the permeability of single fractures and the fracture network. The research methods employed in these studies mainly include theoretical analysis, model experimentation, and numerical simulation. Single-fracture seepage is the main basis of the theoretical analysis of rock mass seepage\(^3\). In the 1940s, researchers of the former Soviet Union proposed a cubic law of groundwater movement in rock masses with a single fracture on the basis of laminar flow theory. However, the roughness of fractures leads to their non-compliance with laminar flow characteristics. This problem motivated other researchers to propose a number of correction methods with different forms\(^4-8\). Discontinuities are a controlling factor of the permeability characteristics of a rock mass because of the low permeability of rock materials. Several scholars have proposed a number of seepage models of fracture networks, including the equivalent continuum seepage model, the double-medium seepage model, and the discrete fracture network seepage model\(^9-11\). However, these models present a number of limitations. The equivalent continuous medium seepage model, for example, features simple calculations but does not show the effect of preferential flow. The double-medium seepage model considers water exchange between the rock and fractures and, thus, can represent real conditions; however, its applicability to the REV and water head determinations of fracture networks remains questionable. The discrete fracture network seepage model can well describe the heterogeneous anisotropy of seepage in the rock mass. Because continuous developments in rock engineering have clearly shown the limitations of continuity theory, the discrete fracture network seepage model has been increasingly used in various situations.

Obtaining an analytical solution based on theoretical analysis is difficult on account of the complexity of fracture distributions in a rock mass. Moreover, hazardous field environments and the high cost of model experiments have promoted the gradual use of numerical simulations to replace these methods. Numerical methods can be divided into two categories: continuity-based methods and discontinuity-based methods. The former is suitable for simulating seepage in rock masses with a high fracture density and uniformity. Huang Runqiu\(^12\) et al., Cheng\(^13\) et al., Song Xiaochen\(^14\) et al. and Li Xinqiang\(^15\) et al. used the finite element method (or boundary element method) to conduct the seepage analysis of fractured rock masses and achieved remarkable results. Discontinuity methods present great advantages when dealing with non-uniform fractures with irregular shapes and prominent preferential flows. Zheng Chummei\(^16\) and Peng\(^17\) et al. conducted a simulation study of rock mass fracture seepage based on the discontinuous deformation analysis method and achieved good results. Jiao Yuyong\(^18\) et al. simulated the movement law of groundwater in a fracture network based on the discrete element method. Cappa\(^19\) et al. performed a hydromechanical
coupling analysis of fractured rock slopes based on the discrete element method. Wang Hui[20] et al. applied the discrete element method to analyze the anti-slip stability of gravity dams considering the coupling effect of seepage and deformation and derived a safety factor against sliding. Research results generally indicate that the discrete element method can well simulate the seepage problem of fracture networks in a rock mass. In previous studies of rock mass seepage, fractures were considered to be dense and uniformly distributed; thus, they were mainly simulated by the continuity method. If the number of fractures is small, these fractures are simulated singly and analyzed by the discontinuity method. However, studies on complex fractures with random distributions in the rock mass are scarce. Therefore, a reasonable and simplified method to analyze such fractures is urgently needed.

Complex discontinuity systems are present in the rock mass of the Datengxia Hydropower Station dam foundation. Here, faults, soft interlayers, and structural fracture systems intersect one another. A multi-scalar structural analytical scheme that combines the deterministic analysis of large-scale geological structures (i.e., faults and weak interlayers) with the statistical simulation of random discontinuities (i.e., structural fractures) is proposed in this paper to reduce the difficulty and uncertainty of the analysis of rock masses with complex structures. In particular, a chain analytical method from dominant group definition to statistical parameters (i.e., spacing and occurrence) is established for the structural fracture system. This work also establishes a seepage model of the rock mass in dam section 29# in UDEC by adopting the above structural simplification scheme. The seepage in rock masses with complex structures under normal water storage and dynamic conditions is finally simulated to provide data for further studies on dam foundation stability.

2. Study area

Datengxia Hydropower Station is located at the Qianjiang portion of the Zhujiang River basin in Guiping City, Guangxi Province, China (Figure 1). The hydropower station provides flood control, navigation, power generation, water supply, irrigation, and other water conservancy projects. The normal storage levels in the upper and lower reaches of the reservoir are 61.00 and 22.71 m, respectively, and the dam has a storage capacity of 2.813 billion m³. The main dam is a gravity dam located at the exit of Datengxia Canyon. The height and length of the dam are 80.01 and 1343.1 m, respectively. The reservoir area is divided into two sections with Lema as the boundary. The upper section of the reservoir belongs to the Dayao mountain area with an elevation of approximately 300–500 m, and the V-shaped river valley is deep. The lower section of the reservoir belongs to Guizhong Basin, which is hilly plain terrain with low in the middle and high in the periphery. The elevation of this section ranges from 60 m to 130 m, and the valley is U-shaped.
the ground elevation is 23–43 m. The rock masses in this area are characterized by the limestone and sandstone of Yujiangian (D1y) and Nakaolingian (D1n) (Figure 2). D1y includes three subformations, namely, D1y1-1, D1y1-2, and D1y1-3, while D1n includes three subformations, namely, D1n13-1, D1n13-2, and D1n13-3. The dip direction of the strata is 100°–110°, and the dip angle is 10°–15°. Discontinuities, such as weak interlayers, bedding planes, and faults, are well developed and show good persistence. The occurrence of weak interlayers and bedding planes is basically consistent with that of rock formations. After the completion of the project, the rock mass of the dam foundation could easily form integral failures along the bedding plane or a weak interlayer under high water pressure; thus, obvious seepage occurs. Fractures are well developed in the rock mass of section 29# below the sluice gate. Large faults pass through this rock mass and could affect its seepage conditions (Figure 3). We analyze the seepage of section 29# in this paper to determine the hidden dangers of dam instability caused by seepage.

3. Data and method
The mechanical strength of discontinuities is relatively weaker than that of intact rock masses; thus, developing an understanding of the distribution of discontinuities will be helpful in preventing and controlling geological disasters in the dam engineering area. In this research area, the large-scale discontinuities found in the rock mass of the dam foundation are mainly faults and weak interlayers and the random discontinuities are non-persistent fractures formed by tectonic movement. The data of these three types of discontinuities are systematically collected for analysis.

4. Data acquisition of faults
The dam section of the sluice contains eight faults with steep dip angles intersecting the dam axis at a relatively large angle. The largest fault, F216 (Figure 4), passes the sluice and runs through sections 29# and 30#. The upper wall of the fault runs through a number of rock formations, and its lithology is mainly gray–green siltstone, argillaceous siltstone, gray–black mudstone with purple–red siltstone, and argillaceous fine sandstone, which measures 50–100
cm thick. The lithology of the footwall is gray–black argillaceous siltstone and mudstone, which is a horizontal moving fault (anti-twist) with a fault throw of approximately 15–35 m. The fault occurrence is N70°W, SW <75°–85° with a maximum width of approximately 2–4 m. The composition of the fault is mainly gravel, fault breccia, and mylonite, and a slight discontinuous fault gouge with a width of 3–10 cm. The fault surface is rough and undulating with local abrasions.

**Figure 4. Field map of fault F216.**

### 4.1. Data acquisition of weak interlayers

The occurrence of weak interlayers developed in the field is basically consistent with that of rock formations. The weak interlayer shown in Figure 5 reflects the boundary between Dy1-2 and Dy1-1 downstream of section 29#. The weak interlayer is composed of mud clamps cuttings measuring 3–5 mm thick. The plane is flat and rough with visible abrasions, and its occurrence is N12°E, SE <12°. The thickness of 85% of the soft interlayers developed in the field is less than 3 mm. The upper and lower interfaces are smooth, and the extension length ranges from several meters to several tens of meters. The composition of the muddy zone is mostly mud clamps rock cuttings. The interval of the weak interlayers revealed by numerical imaging during drilling is generally 3–5 m, and the average interval of the weak interlayers revealed by the adit is 2–4 m.

**Figure 5. Weak interlayers of Dy1-2 downstream of section 29#.**

### 4.2. Data acquisition of random fractures

The fracture data (i.e., occurrence, trace length, spacing, roughness, filling, and weathering degree) in the exposures of Dy1-2 in section 29# are collected by the sampling window method. A total of 139 fractures were measured, and the 2D trace map of the fractures is shown in Figure 6. The dip angle of the fractures is mostly between 70°–90°. The average width of the fractures is 2 mm, and 24% of the fractures are closed. The fracture fillings are mainly yellow clay, rock cuttings, and gravel; some calcite could also be observed. The surface morphology of the fractures is mainly flat and smooth but sometimes wavy. The fracture walls are weakly weathered, and some show strong karst phenomena. The average trace length of the fractures is 2.17 m, and the maximum trace length is 6.8 m.

**Figure 6. 2D trace map of fractures in section 29#.
The 2D trace map illustrates that the fractures are randomly distributed in the study area, but they present a certain rule of grouping due to the effect of the geological structure. Therefore, the probabilistic statistical dominance grouping method based on the lower-hemisphere Schmidt equal-area polar plot is used to conduct fracture grouping. The fractures can be divided into two groups (Table 1), and the pole rose diagram of each fracture group is shown in Figure 7. Table 1 and Figure 7 illustrate the steep dip angle of both groups of fractures. Fractures in first group are oriented nearly parallel to the profile direction (143°), and fractures in the second group are oriented nearly vertical to the profile direction. The second group contains a large number of fractures that could easily form the breaking or shear-opening plane of the rock mass of the dam foundation. Therefore, fractures in the second group more dangerous than those in the first group and play an important role in the stability of the dam foundation.

| Fracture group | Fracture number | Average dip direction (°) | Average dip angle (°) |
|----------------|----------------|---------------------------|-----------------------|
| 1              | 60             | 327                       | 80                    |
| 2              | 79             | 253                       | 82                    |

Fracture spacing is an important parameter in the analysis of rock mass stability via numerical simulation; this property controls the location or range of the breaking or shear-opening plane. In this section, several survey lines are arranged to measure the frequency fracture (i.e., the number of fractures intersecting the survey line per unit length) and the fracture spacing is obtained. Because the stability of the dam foundation is mainly controlled by fractures near the vertical direction of the profile, the profile direction is chosen as the line direction. Fractures within 30° relative to the vertical direction of the profile are selected. The intersection of fractures and survey lines is shown in Figure 8. The fracture frequency is determined as 0.48, and the average fracture spacing is calculated as 2.07 m, which could be approximated as 2 m. The subsequent modeling steps, which fully consider the fracture spacing, are described in Section 2.4.
4.3. Fluid–solid interaction analysis

4.3.1 UDEC seepage theory

Fractures in the rock mass are the main channels of fluid seepage and provide locations for fluid storage and migration. The seepage force produced by fluid flow acts on the surrounding rock mass and affects the distribution of stress fields in the rock mass. Changes in the distribution of stress fields often cause changes in fracture distributions, which directly control the permeability of fractures. The change in fracture permeability, in turn, restricts the seepage field of the rock mass. The above interaction is called seepage–stress coupling. In this study, the steady-state flow module of the discrete element program UDEC is used to simulate the seepage of water in the fractured rock mass. UDEC presents distinct advantages in this regard because it can simulate fractures and seepage simultaneously. In the flow process, the permeability of fractures depends on the mechanical deformation of the block, and the fluid pressure in the fracture affects the mechanical deformation of the block. Therefore, this is an analysis of fluid–solid coupling.

UDEC describes seepage through fields. When the fluid boundary condition is applied, the pore pressure differs in each region. Water flows in the fracture because of the water pressure difference, and the cubic law of parallel plate fractures is used to calculate the flow of each point. Then, the pore pressure of the model is updated according to the flow condition of the fluid and fracture width in the fracture network. A new pore pressure and other forces are added to the iterative calculation of the discrete element block element, and then new stress and displacement distributions are obtained until the model is balanced. The calculation principle is shown in Figure 9.

\[
\Delta p = \frac{k}{V} (\Sigma Q \cdot \Delta t - \Delta V)
\]

where \(\Delta V\) is the change in volume, \(V\) is the average of the old and new volumes, \(k_w\) is the volume modulus of the fluid, and

(a) Generation of pore pressure
4.3.2 Model construction

Fault F216 passes below section 29# (Figure 10) and affects the seepage state of the rock mass. The numerical simulation model of section 29# is established by using UDEC software.

The scope of the model should be large enough to consider the boundary effects and percolation paths of the numerical models. The height of the sluice is 42 m. In this simulation, the upstream length of section 29# extends to five times the height of the sluice (i.e., 210 m), the simulated downstream length of the section extends to three times the height of the sluice (i.e., 126 m), and the buried depth of the rock mass of the dam foundation is 122 m. According to Section 2.3, the average spacing of surface fractures near the sluice is approximately 2 m; thus, 2 m is taken as the spacing of near-surface fractures. The field fractures are oriented nearly vertical to the bedding plane and inclined toward the upstream
direction with an average dip angle of 79°. The dip angle of the bedding plane is approximately 11° and inclined toward the downstream direction. The fractures of the deep rock masses have a negligible influence on the seepage of the dam foundation. Therefore, the spacing of the deep fractures is taken to be five times the near-surface fracture spacing (i.e., 10 m) to improve the calculation efficiency. The occurrence of deep fractures should be consistent with that of near-surface fractures. Field observations demonstrate that fractures do not run through the soft layer and stratigraphic boundary. Therefore, fractures are regarded as staggered structures in the model. The fault is divided by random fractures to fully consider the fragmentized situation of the fault and ensure the fluid–solid coupling analysis in the following. The final numerical model is shown in Figure 11.

![Figure 11. Numerical model of section 29#](image)

4.3.3 Parameter selection

The Mohr–Coulomb failure criterion is adopted for the rock mass of the dam foundation. The required physical and mechanical parameters and their values are shown in Table 2. Specifically, the Poisson ratio and elastic modulus are obtained by a uniaxial compression test, the cohesion and internal friction coefficient are obtained by a triaxial compression test, and the tensile strength is obtained by the Brazilian test.

The Coulomb sliding model (total elastic–plastic model) is used for discontinuities. Water seeps through fractures, and the hydraulic parameters needed for the analysis of seepage are the permeability coefficient of joint \( k \) \((k = 1/12 \mu, \mu \) is the dynamic viscosity of water), initial fracture width \( a_0 \), and remaining fracture width \( a_{res} \). The friction angle and cohesion of discontinuities are obtained by a series of direct shear tests. The required parameters of discontinuities are shown in Table 3.

| Stratum  | Internal friction coefficient | Cohesion (MPa) | Density (g/cm³) | Tensile strength (MPa) | Elastic modulus (GPa) | Poisson ratio |
|----------|------------------------------|----------------|-----------------|------------------------|----------------------|--------------|
| D1y1-3   | 0.60                         | 0.76           | 2.82            | 1.58                   | 8                    | 0.28         |
| D1y1-2   | 0.62                         | 0.78           | 2.82            | 1.58                   | 12                   | 0.26         |
| D1y1-1   | 0.60                         | 0.75           | 2.79            | 4.26                   | 8                    | 0.28         |
| D1n13-3  | 0.58                         | 0.72           | 2.75            | 6.1                    | 4                    | 0.32         |
| D1n13-2  | 0.64                         | 1.02           | 2.77            | 7.0                    | 8                    | 0.28         |
| D1n13-1  | 0.71                         | 1.13           | 2.73            | 5.0                    | 12                   | 0.26         |
D$_1$n$_{12}$  0.75  1.19  2.69  6.5  8  0.26
Curtain  1.42  3.18  2.4  1.54  25.5  0.2

Table 3. Parameters of discontinuities

| Type of discontinuities | $K_a$ (Pa/m) | $K_s$ (Pa/m) | $\phi_j$ (°) | $c_j$ (Pa) | $k_j$ (Pa·s$^{-1}$) | $\alpha_0$ (m) | $\alpha_{res}$ (m) |
|-------------------------|--------------|--------------|--------------|------------|---------------------|--------------|-----------------|
| Fractures               | 4.2×10$^{11}$ | 4.2×10$^{10}$ | 26.5         | 0          | 83.3                | 2×10$^{-3}$  | 1×10$^{-3}$     |
| Weak interlayers        | 4.0×10$^{11}$ | 4.0×10$^{10}$ | 16.7         | 3.0×10$^4$ | 83.3                | 3×10$^{-3}$  | 1.5×10$^{-3}$   |
| Fault boundaries        | 1×10$^{11}$   | 1×10$^{10}$   | 0            | 0          | -                   | -            | -               |

4.3.4 Boundary conditions

Displacement-constrained boundary conditions are applied in this paper. The vertical direction at the bottom of the model and the horizontal direction at the left and right boundaries are fixed. Under the condition of a normal water level (i.e., upstream and downstream water levels of 61.00 and 22.71 m, respectively), a hydrostatic pressure is applied to the upstream and downstream surfaces of the sluice chamber. A corresponding water head is applied to the upstream and downstream bedrock surfaces to simulate water seepage along discontinuities.

5. Results and discussion

First, the seepage of the rock mass in section 29# with and without a curtain is studied, after which the seepage in the dam section is analyzed to verify the waterproofing effect of the curtain. The seepage in the rock mass of the dam foundation with and without a curtain is obtained by numerical calculation, as shown in Figures 12 and 13. The red lines in these figures represent the water in the fractures, and the arrows show the direction of water flow. The figures reveal that seepage mainly occurs in the fractures, weak interlayers, and faults below the sluice. Comparison of the two figures confirms that, when the curtain is installed, the amount of seepage in discontinuities is significantly reduced. This finding reflects the obvious effect of the curtain.

Figure 12. Seepage in section 29# with a curtain.
Figure 13. Seepage in section 29# without a curtain.

Figure 14 compares the pore pressures at nine monitoring points A–H with and without a curtain. The pore pressure without the curtain is significantly larger than that with the curtain. In addition, the pore water pressures at points F, G, and H are significantly greater than those at other points. These three monitoring points are located near the fault. Thus, we can assume that the pore pressure will apply a considerable load on the fault when groundwater passes through the fractures in this fault. Excessive seepage pressure within the fault could increase the internal stress and eventually affect the overall stability of the rock mass of the dam foundation.

Figure 14. Comparison of pore pressures at each point of section 29#.

The stability of the dam section is greatly reduced under the action of water seepage. When a strong earthquake occurs, the amplitude of the pore pressure increases relative to the original pore pressure in the seepage pipeline, which could lead to a dynamic change in pore pressure. Changes in seepage and seepage path could accelerate the instability failure of the dam section. Therefore, dynamic analysis is carried out in this work to study the effect of dynamic loading on the seepage of the dam foundation under an earthquake.

According to the seismic safety evaluation report of Datengxia Hydropower Station, the peak acceleration of ground motion with a 2% probability of being exceeded within 100 years is 0.135 g and the characteristic period is 0.45 s. These two parameters are inputted into UDEC to simulate seismic waves and then applied to the simulated dam section. Section 29# is selected as the seepage dynamic analysis model in this paper. A dynamic load is applied to the section under the normal water level to simulate the seepage field and analyze changes in pore pressure. The monitoring results are shown in Figure 15; here, the dynamic load increases the pore pressure of each monitoring point by approximately 40%. Therefore, the pore pressure and seepage velocity could increase under the dynamic action and lead to the accelerated destruction of the dam foundation. Thus, an earthquake with a ground motion with a 2% probability of being exceeded within 100 years could be concluded to lead to a large increase in pore water pressure and accelerated seepage velocity.
6. Conclusion

This paper takes section 29# of the sluice of Datengxia Hydropower Station in Guangxi as the research object. The seepage of the rock mass of the dam foundation is simulated and analyzed using UDEC. The major findings could be summarized as follows.

(1) The proposed chain analytical method from dominant group definition to statistical parameters (i.e., spacing, occurrence) can simplify the analytical steps of the simulation of rock masses with complex structures. Thus, the feasibility of accurate simulations of rock masses with random and complex fracture systems is greatly increased.

(2) A numerical model of section 29# is conveniently established according to the proposed simplification scheme in UDEC. The pore pressure along the discontinuities of the bottom of the dam foundation under normal water storage conditions is obtained on the basis of the fluid–solid coupling analysis of the numerical method, which reduces the uncertainty of its distribution and provides a certain reference and guiding significance for the following engineering construction.

(3) The seepage of section 29# under dynamic loading is analyzed using UDEC with dynamic loading parameters. Results show that the pore pressure in the dam foundation increases by approximately 40% when a dynamic load is applied to it. This effect greatly weakens the effective dead weight of the bedrock and reduces the anti-sliding stability and anti-overturning stability of the dam. Therefore, this unfavorable factor should be fully considered when constructing hydropower stations near seismic zones.

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