A hydro-mechanical coupling study with DDA numerical method to valley deformation mechanism of Xiluodu hydro-power station

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Abstract. A comprehensive investigation to the characteristics of valley deformation in Xiluodu project is briefly reviewed. Extensions for hydro-mechanical coupling simulation with DDA method for reservoir impoundment has been firstly derived. The DDA numerical model by considering interactional aspects of original geological cross section, geo-stress state, and the reservoir impoundment, etc., is then established. Simulations for the given numerical model with different initial geo-stress state after the water impoundment are performed, and the results are compared with that of typical valley deformation measurements, and at last, the deformation mechanism in causes of changing of effective stress in the particular geological condition is discussed.

Key words: Reservoir impoundment; Valley deformation; DDA method; hydro-mechanical coupling

1. Introduction

Reservoir impoundment will have a huge impact on the hydromechanics of water environment system in the dam site area. The huge impoundment in the reservoir is a favourable factor for the occurrence of water-rock interaction. After impoundment, the rock and soil contact with water in a large area makes the water infiltrate downward, and the rock and soil change in the dry and wet state, resulting in water-rock interaction, which is also the decisive factor for the change of geological environment in the reservoir area [1]. It can be seen that reservoir impoundment is an important inducing factor of geological disasters in the reservoir area. In addition to the traditional landslides in the reservoir area, the deformation of mountains on both sides caused by impoundment results in the contraction of valley, and it has become a major hidden danger endangering the structural safety and long-term operation stability of high dams. Since the completion of Xiluodu hydropower station, the maximum shrinkage deformation of its valley survey line has exceeded 90mm, and there is a trend of continuous deformation, which directly affects the Xiluodu arch dam structure and endangers the long-term operation safety of cascade hydropower stations.

After the impoundment of the dam, due to the infiltration of water, the reservoir water enters into the dam foundation and the slopes on both sides, causing the deformation of the dam foundation and the rock slopes, which results in degradation of dam foundation stability, stress state adjustment of the dam body or even the local cracking of the dam body, which poses a serious threat to the normal operation of the arch dam and the overall safety of the arch dam structure. The most typical cases are
Malpasset arch dam [2] and Vajont arch dam [3]. Scholars in related fields have conducted in-depth research and exploration on the valley deformation mechanism of arch dams [4-7]. The in-situ hydro-mechanical coupling test carried out in the dam site area of Xiluodu hydro-power project showed that changes in water pressure caused obvious shear deformation of the interlayer dislocation zone and tensile deformation and reduction in the triaxial compressive strength of the fractured rock mass [8-9].

In the process of research for numerical approach, continuous medium methods such as finite element method are widely used, but this method cannot well describe the large displacement and large deformation of complex fractured rock mass. Discontinuous deformation analysis method (DDA) has the advantage of simulating discontinuous deformation of rock mass, and many successful applications have been obtained in the field of practical engineering [10-17]. For DDA simulation in aspect of reservoir impoundment, few materials have been reported.

In this paper, on basis of investigation of geological conditions of stratum section and rock mass properties, the initial geo-stress measurement and valley deformation monitoring results, extensions for hydro-mechanical coupling simulation with DDA method for reservoir impoundment has been firstly derived. The DDA numerical model by considering interactional aspects of original geological cross section, supposed geo-stress state, and the reservoir impoundment, etc., is then established. After that, simulations for the given numerical model with different initial geo-stress state after the water impoundment is performed, and the results are compared with that of typical valley deformation measurements, and at last, the deformation mechanism in causes of changing of effective stress is discussed.

2. The valley deformation problems in Xiluodu project

The Xiluodu hydropower station is the third cascade hydropower station in the cascade development planning in the river reach of Panzhihua to Yibin of Jinsha River, the upstream part of Yangtze River. The normal reservoir operation level of the project is 600m. The project consists of double curvature concrete arch dam, water diversion and power generation structures on both banks, flood discharge and energy dissipation structures, etc. The maximum dam height is 278m (Figure 1).

2.1. Basic geological conditions

The terrain of the project area is generally characterized by high in the West and low in the East, high mountains and deep valleys in this area, and the elevation is more than 2000m-3000m. The mountain range where the dam is located is mainly in the direction of nearly south-north and north-east, which is controlled by the regional geological structure.

The permeability of rock mass and the type of water bearing medium in the dam site area are obviously different. Permain Xuanwei formation (P2x) clastic sedimentary rocks and Emeishan basalt P2β14、P2β13 and P2β11 top of the purplish red tuff, Silurian (S) shale and P2βn mudstone layer constitute the water blocking structure of the dam area. Interlayer dislocation zone structure and fracture structure are the main development characteristics of basalt structural planes in dam area. Groundwater is mainly distributed in basalt interlayer, interlayer dislocation zone and joint fissure of rock mass in the dam area. The fissure and solution fissure structure of limestone is the main
permeable structure in the dam area.

The distribution of in-situ stress field in the dam area is generally balanced, and it is in medium stress level. The results of in-situ stress measurement carried out in adits of the dam site show that the magnitude of in-situ stress increases with the increase of buried depth. The ratio of maximum horizontal principal stress to the minimum is 1.0-2.5, and mainly concentrated in 1.4-1.9.

The rock mass in the dam area of the project is composed of hard basaltic lava and basaltic breccia (agglomerate) lava. The occurrence of stratum is gentle, no fault is developed, and the engineering geological conditions are generally good. The structure of the basaltic rock mass is dominated by interlaminar and intraformational dislocation zones and matrix fractures in different scales. The material of the dislocation zone is mainly breccia and debris, with little argillaceous content; Some of the dislocated zones are filled with quartz epidote strips, which are compacted to form a smooth surface; Some weak intraformational dislocation zones are formed in the fracture dense zone or fractured rock block.

![Figure 1. The view of Xiluodu project from upstream](image)

2.2. The valley deformation characteristics

A total of 9 pairs of monitoring points is installed for the valley deformation monitoring of the project in two abutment banks of the dam, and the layout of monitoring points is shown in Figure 2. The convergence monitoring lines of VDL01-VDL07 installed earlier. The monitoring lines of VDL08 and VDL09 started for monitoring in 2014 and 2015 respectively, and relatively few monitoring data is obtained. The monitoring lasted for 7 years, and relatively complete valley deformation monitoring data were obtained. The data of each monitoring line and the variation curve of reservoir water level are shown in Figure 3.
The monitoring data of Xiluodu hydropower Station after impoundment shows that the deformation of dam and foundation rock mass has obvious characteristics performed as by the following: the reservoir basin settlement is relatively large after impoundment (the maximum
settlement is more than 20 mm); The maximum shrinkage deformation of the upper and lower reaches is more than 90 mm; When the reservoir water level drops, the rebound deformation of the arch dam to upstream is relatively large; However, when the water level rises, the deformation of the whole dam to downstream is relatively smaller than some other similar projects. During the whole impoundment process of Xiluodu arch dam, the valley convergence increases evenly and does not slow down due to the water level drop. The deformation rate has a good correlation with the impoundment process. In general, most of the valley deformation occurs during the period of stable water level, and the deformation shows the time dependent characteristics. According to the statistical results of valley contraction of different elevation survey lines, the valley contraction tends to increase with the increase of elevation.

According to the current research results, the research on the influence factors of Xiluodu valley deformation mainly focuses on the following issues:

a) Impact of reservoir basin water pressure: after the completion of the arch dam construction, before the impoundment, the dam and the foundation rock are in a relative equilibrium state, and after the impoundment, the equilibrium state is broken. b) Impact of seepage performance: after impoundment, the boundary condition of seepage field changes in the original equilibrium state, which leads to the change of seepage field in the foundation rock and dam body, and this change is reflected in the form of seepage stress coupling. c) Softening effect of rock and soil properties of bank slope: water storage may lead to softening of rock mass properties in a wide range of dam site area, especially for many rock flow rock layers, interlayer dislocation zones and weak intercalations in bedrock, whose properties may have very significant differences under different water pressure conditions. d) Temperature effect: the change of reservoir water level will change the temperature field in the original equilibrium state. Due to the thermal expansion and cold contraction of materials, the change of temperature field may also affect the valley deformation. There are many explanations for the excessive deformation of Xiluodu valley. Although some analysis methods can preliminarily explain the valley contraction deformation, a further deep study for the deformation mechanism is still needed, especially a comprehensive philosophy understanding associated with mutual effects of geological stratum, rock mass properties, geo-stress state and process of impoundment of the reservoir, etc., is rather a critical issue.

3. Basic principle of DDA and water rock coupling simulation method

3.1 Basic principle of DDA

The Discontinuous Deformation Analysis (DDA) method, proposed by Shi (1985, 1988), is viewed as a new computation method for studying the movements and deformations of blocky system. In order to obtain the real solution of stresses and the corresponding deformations, the three items including open-close iteration, equilibrium of force system, and convergence of dynamic solution based on the inertia force must be satisfied.

1) Displacement and deformation of block

Displacement and deformation of the block can be determined by the six parameters:

\[
[D_i] = \begin{bmatrix} U_0 & V_0 & r_0 & \varepsilon_x & \varepsilon_y & \gamma_{xy} \end{bmatrix}^T
\]

where \((U_0, V_0)\) is the rigid body displacement at the point \((x_0, y_0)\), \(r_0\) is the rotation angle with
respect to the centroid of block, \((\varepsilon_x, \varepsilon_y, \varepsilon_z)\) are the strain components.

Displacement at arbitrary point \((x, y)\) in the block can be represented as

\[
\begin{pmatrix}
U \\
V
\end{pmatrix} = \left[T_i\right]\left[D_i\right]
\]

(2)

\[
\left[T_i\right] = \begin{bmatrix}
1 & 0 & -(y-y_0) & (x-x_0) & 0 & (y-y_0)/2 \\
0 & 1 & (x-x_0) & 0 & -(y-y_0) & (x-x_0)/2
\end{bmatrix}
\]

(3)

2) Contact types and convergence criterion

There are 3 contact types in DDA including vertex-to-edge contact, vertex-to-vertex contact and edge-to-edge contact.

The two conditions including no penetration and no tensile force must be satisfied during the DDA calculation to make open-close iteration converge, which needs to fix and remove the artificial springs repeatedly. Stiffness of spring is suggested to take the value of (1-1000) \(E\), where \(E\) is elastic modulus.

3) Solutions of equilibrium equations and iterations

Block system is constituted by the blocks and constraints are formed by contacts between them. Assume there are \(n\) blocks, the global equations can be expressed as follows:

\[
\begin{bmatrix}
K_{11} & K_{12} & \cdots & K_{1n} \\
K_{21} & K_{22} & \cdots & K_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
K_{n1} & K_{n2} & \cdots & K_{nn}
\end{bmatrix} \begin{bmatrix}
D_1 \\
D_2 \\
\vdots \\
D_n
\end{bmatrix} = \begin{bmatrix}
F_1 \\
F_2 \\
\vdots \\
F_n
\end{bmatrix}
\]

(4)

Where \([K]\) is a submatrix with the size of 6×6, \([D]\) is the deformation components and \([F]\) is the load vector and they are both 6×1.

According to the minimum potential energy principle, \([K]\) and \([F]\) can be calculated as follows:

\[
\frac{\partial^2 \Pi}{\partial d_r \partial d_s} \quad r, s = 1, 2, 3, \cdots, 6
\]

(5)

\[
\left. -\frac{\partial \Pi}{\partial d_r} \right|_{[d]=0} \quad r = 1, 2, 3, \cdots, 6
\]

(6)

Where \(\Pi\) is the total potential energy.

Deformation and the displacement of block can be calculated by Equation (2), then fix and remove the artificial springs at the contact points to modify the global equations until the criterion of no penetration and no tension is satisfied. After then, the stress and deformation of block system can be further calculated at the given force and displacement boundary conditions.

3.2 Water rock coupling simulation method

In the simulation of valley contraction deformation of reservoir basin during impoundment period, the finite element method is difficult to simulate the large deformation of rock mass with a large number of internal structures in solving the contact problem, so the simulation effect of valley contraction is often not consistent with the monitoring value, and even the deformation direction is different. DDA
method uses the displacement as the unknown quantity and solves the equilibrium equation in the same way as the structural matrix analysis in the finite element method. According to many research results [16-17], DDA has unique advantages in simulating discontinuous deformation fields such as opening and sliding of rock mass along structural plane and large deformation and large displacement of rock mass.

In order to solve the problem of DDA program simulating water rock coupling on fractured rock mass, a submatrix considering water pressure on block surface is added based on the principle of minimum potential energy. Assuming that the water pressure load is linearly distributed, block $i$ is below the waterline (Figure 4.), and the water head values at both ends of the edge $p-p+1$ are $h_p$, $h_{p+1}$, the vertical and horizontal components of the water pressure at the edge $p(p+1)$ are expressed as follows:

$$
\begin{align*}
    f_{xp} &= -F_p \sin \alpha, f_{yp} = F_p \cos \alpha \\
    f_{xp+1} &= -F_{p+1} \sin \alpha, f_{yp+1} = F_{p+1} \cos \alpha
\end{align*}
$$

(7)

**Figure 4.** Water pressure of block $i$

The work done on block $i$ is

$$
\Pi_i = -\int_0^{L_x} (f_{ix}u_x + f_{iy}v_y) dL = -\left\{ \begin{array}{c} \\
\{D_i \}^T T_i \{x_p, y_p\} [E] \\
\{D_i \}^T T_i \{x_{p+1}, y_{p+1}\} [G]
\end{array} \right\}
$$

(8)
$$[E] = \begin{pmatrix} \frac{-L}{3} \sin \alpha & \frac{-L}{6} \sin \alpha \\ \frac{L}{3} \cos \alpha & \frac{L}{6} \cos \alpha \end{pmatrix} \begin{bmatrix} F_p \\ F_{p+1} \end{bmatrix}$$

$$[G] = \begin{pmatrix} \frac{-L}{6} \sin \alpha & \frac{-L}{3} \sin \alpha \\ \frac{L}{6} \cos \alpha & \frac{L}{3} \cos \alpha \end{pmatrix} \begin{bmatrix} F_p \\ F_{p+1} \end{bmatrix}$$

$L$ is the length of edge $p$-$p+1$. The node load of block $i$ caused by distributed water pressure is as follows:

$$-\frac{\partial \Pi_i(0)}{\partial d_n} = T^T_i(x_p, y_p)[E] + T^T_i(x_{p+1}, y_{p+1})[G] = [F_i]^L$$

4. The valley deformation numerical simulation by DDA

4.1. Constitution of numerical model

According to the actual landform and strata distribution on both sides of the valley (Figure 5), combined with the characteristics of DDA method, the calculation model established is shown in Figure 6. There are 1219 blocks and 10154 vertices in the model. The vertical calculation elevation is 100-860m and the total length in horizontal direction is 1067m. The typical interlayer dislocation zone in the rock mass on both sides of the river valley is fully considered.

Figure 5. Typical cross section of Xiluodu
According to the geological data of Xiluodu, the rock strata of the calculation model are divided into 22 kinds and the joint structural planes are 37 kinds, as shown in Figure 7 and Figure 8.

The mechanical parameters of rock mass for different rock quality grades are shown in Table 1. The mechanical parameters of large structural plane are shown in Table 2, where the mechanical parameters of artificial joints in rock stratum are slightly larger than those of structure faces.
Table 1. Mechanical parameters of rock mass for different rock quality grades

| Rock grade | Elastic modulus E/GPa | Tensile strength f/MPa | Cohesion c/MPa |
|------------|-----------------------|------------------------|---------------|
| I          | 40                    | 1.64                   | 4.0           |
| II         | 20                    | 1.35                   | 4.1           |
| III        | 10                    | 1.22                   | 3.9           |
| IV         | 6                     | 1.02                   | 2.5           |
| V          | 2                     | 0.35                   | 0.24          |

Table 2. Engineering classification and mechanical parameters of structural plane in dam area

| Major categories | Subclass | Weathering degree | Tensile strength $f'$/MPa | Cohesion $c'$/MPa |
|------------------|----------|-------------------|---------------------------|------------------|
| Rigid structural plane | A       | slightly to unweathered weakly weathered | 0.98 | 0.50 |
|                   | B_1      | weakly~slightly weathered | 0.75 | 0.22 |
| weak structural plane | B_2      | weakly weathered | 0.55 | 0.20 |
|                   | B_3      | strongly weathered | 0.51 | 0.20 |
|                   | C_1      | weakly weathered | 0.44 | 0.10 |
|                   | C_2      | strongly weathered | 0.43 | 0.08 |

4.2. Analysis of initial stress field

Based on the newly developed DDA program considering water-rock interaction, the vertical stress of the mountain before and after impoundment is calculated, as shown in Figure 9. Before impoundment the vertical stress of the mountain increases with the buried depth, the stress distribution does not change significantly after impoundment, but the stress value decreases significantly. This is because the reservoir water enters into the fracture structural planes after impoundment, and the completely submerged rock mass is subjected to upward buoyancy force, which reduces the vertical stress produced by the self-weight of the element and the effective stress of the element.
In the process of tectonic movement, the initial stress field dominated by horizontal tectonic stress was formed in the dam site area. Before and after the occurrence of downcutting and denudation in Jinsha River, the change of crustal stress in this area occurs. After the Jinshajiang River is cut down, the initial stress equilibrium state in the rock strata is broken, resulting in the release of stress, and the mountains on the both sides of the river deform towards the free direction of the valley. When the stress potential energy is released and the valley undercutting reaches a new stability, the mountain deformation will not develop. Therefore, in addition to the vertical stress, there is a certain magnitude of tectonic stress near the horizontal direction in the valley slope. The in-situ stress measurements have been carried out in Xiluodu dam area. Up to now, 18 groups of in-situ stress measurements have been carried out by borehole radial relief method; 10 groups of three dimensional in-situ stress measurements were conducted by hydraulic fracturing method; There were 12 groups of two dimensional stress measurement by hydraulic fracturing method. According to the measurement results, the ratio of horizontal stress to vertical stress (lateral pressure coefficient) is between 1.5 and 2.0.

In order to investigate the influence of horizontal tectonic stress field on valley deformation, the lateral pressure coefficient ($k_h$) of 0.5~2.0 is selected for numerical simulation to analyze the influence of tectonic stress under different lateral pressure coefficients on valley deformation. After the mechanical balance reached, the horizontal stress field is shown in Figure 10. It can be seen from the figure that the horizontal stress of rock mass increases with the increase of lateral pressure coefficient.
4.3. Analysis of valley deformation considering high water pressure

After impoundment, a new seepage field is formed in the rock mass on both sides. The water flows in the fracture network and acts on the contact surface between rock blocks in the form of interface force, resulting in the increase of uplift pressure and the decrease of effective stress. In addition, after impoundment, water infiltrates into the rock along the interlaminar and intraformational dislocation zones and fissures, and the mechanical strength of the rock mass originally in the waterless state was changes after immersion.

The valley deformation simulation considering only horizontal tectonic stress with different lateral coefficients before and after impoundment have been carried out, and the relevant results are shown in Figure 11-14. The increment of the displacement calculated before and after impoundment means the real valley deformation compared to the actual deformation monitoring results. In these figures the component of displacement along horizontal direction are shown, and the total displacement with $k_h=2.0$ is shown in Figure 15. For calculation in cases of impoundment, the deformation modulus in water submerged area has a relevant reduction to some extent. Here, the reduction ratio is 0.8.
a. Before impoundment  

b. After impoundment

**Figure 11.** X-direction displacement of $k_h = 0.5$ (Unit: m)

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a. Before impoundment  

b. After impoundment

**Figure 12.** X-direction displacement of $k_h = 1.0$ (Unit: m)

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a. Before impoundment  

b. After impoundment

**Figure 13.** X-direction displacement of $k_h = 1.5$ (Unit: m)
It is shown that the valley deformation caused only by considering the horizontal tectonic stress is mainly concentrated in the unloading zone on the surface of the valley, and there is no overall displacement deformation in the deep part of the mountain. The displacement of the rock mass in the unloading zone is the most obvious, and the displacement of the rock mass in the middle is relatively uniform, and the displacement gradually decreases with the increase of burial depth. It is also shown that the lateral coefficients with different values have quite different characteristics in magnitude of valley deformation, and it is proven that the geo-stress state in both side of the river may perform a very critical role for the valley deformation phenomenon after reservoir impoundment.

When the lateral pressure coefficient is 2.0, the displacement calculation curves are compared with that of the actual monitoring results (Figure 16-18). It is shown that the DDA simulation results at different elevations are totally consistent with the actual monitoring results. The simulated valley deformation curve shows that the DDA method based on water rock coupling can better reflect the characteristics of valley deformation.
Figure 16. Valley deformation of 749m elevation

Figure 17. Valley deformation of 722m elevation

Figure 18. Valley deformation of 610m elevation

5. Conclusion
On basis of investigation of geological conditions of stratum section and rock mass properties, the initial geo-stress measurement and valley deformation monitoring results, the characteristics of valley deformation in Xiluodu hydro-power project are briefly reviewed. Extensions for hydro-mechanical coupling simulation with DDA method for reservoir impoundment has been firstly derived. In order to reveal the valley deformation mechanism after reservoir impoundment, the newly developed DDA method is used to analyse the mutual effects of essential factors, such as original geological cross
section, geo-stress state, and the reservoir impoundment, etc., to valley deformation characteristics. The results show that when the ratio of lateral geo-stress component is equal to or around 2.0, the displacement calculation results are totally consistent with the actual monitoring results. The calculation results reveal that the geo-stress state in both sides of the river and the particular terrain condition and rock mass structure may perform a critical role for the valley deformation phenomenon after reservoir impoundment. In addition, the developed DDA method shows a potential application in dealing with mutual effects of rock mass structure, geo-stress state and water rock coupling, etc. in discontinuous rock mass simulations.

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References
[1] Wang S J, Ma F S and Du Y L. 1996 On the rock-water interaction in reservoir areas and its geoenvironmental effect. Journal of Engineering Geology, 4(3): 1-9.
[2] Jaeger C 1963 The malpasset report. Water Power, 15(2): 55–6.
[3] Müller L 1964 The rock slide in the Vajont Valley. Rock Mechanics and Engineering Geology, 2(3): 148–212.
[4] Yang J, Hu D X and Guan W H. 2005, Analysis of high slope rock deformation and safety performance for left bank of lijiaxia arch dam. Chinese Journal of Rock Mechanics and Engineering, 24(19): 3551–60.
[5] He Z, Liu Y R and Yang Q. 2018, Mechanism of valley deformation of Xiluodu arch dam and back analysis and long-term stability analysis. Chinese Journal of Rock Mechanics and Engineering, 37(S2): 401-409.
[6] Deng H F and Li J L. 2014, Research on the influence mechanism of water level fluctuation on the bank landslide deformation and stability. Journal of Hydraulic Engineering, 2014(S2): 45-51.
[7] Liu C H, Chen C X and Feng X T. 2005, Study on mechanism of slope instability due to reservoir water level rise. Rock and Soil Mechanics, 26(5): 769-773.
[8] Wu A Q, Fan L, Fu X, et al. 2021, Design and application of hydro-mechanical coupling test system for simulating rock masses in high dam reservoir operations. International Journal of Rock Mechanics and Mining Sciences 140.
[9] Wu A Q, Fan L, Zhong Z W, et al. 2020, Development of an in situ hydro-mechanical coupling true triaxial test system for fractured rock mass and its application. Chinese Journal of Rock Mechanics and Engineering, 39(11): 2161-2170.
[10] Shi G H, and Goodman R E 1985, Two dimensional discontinuous deformation analysis. International Journal for Numerical and Analytical Methods in Geomechanics 9:541-556.
[11] Shi G H, 1988 Discontinuous Deformation Analysis: A New Numerical Model for the Statics and Dynamics of Block System [Ph. D. Thesis] [D]. Berkeley: Department of Civil
Engineering, University of California.

[12] Wu A Q, Ding X L, Lu B, et al. 2008, Validation for rock block stability and its application to Rock slope stability evaluation using dda method. Chinese Journal of Rock Mechanics and Engineering, 27(04): 664-672.

[13] She W D, Wang Y, Zhou L F, et al. 2019, Improvement and application of recognition method of seepage network in fractured rock mass in DDA. Water Resources and Power, 37(03): 117-120.

[14] Lu B, et al. 2013, Mixed higher-order Discontinuous Deformation Analysis. 11th international conference on Analysis of Discontinuous Deformation (Fukuoka, Japan),243-248.

[15] Shen Z Z and Ohnishi Y. 2004, Stability analysis method for reservoir rock slope based on discontinuous deformation analysis. Journal of Hydraulic Engineering, (03) :117-122+128.

[16] Wu A Q, Ding X L, Li H Z, et al. 2006, Numerical simulation of startup and whole failure process of Qianjiangping landslide using discontinuous Deformation analysis method. Chinese Journal of Rock Mechanics and Engineering, (07): 1297-1303.

[17] Xu D D, Wu A Q, Yang Y T, et al. 2020, A new contact potential based three-dimensional discontinuous deformation analysis method. International Journal of Rock Mechanics and Mining Sciences 127.