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An approach for deformation modulus mechanism of super-high arch dams

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Abstract. The reservoir basin bedrock produced significant impact on the long-term service safety of super-high arch dams. It was important for accurately identifying geomechanical parameters and its evolution process of reservoir basin bedrock. The deformation modulus mechanism research methods of reservoir basin bedrock deformation modulus for super-high arch dams was carried out by finite element numerical calculation of the reservoir basin bedrock deformation and in-situ monitoring data analysis. The deformation modulus inversion principle of reservoir basin bedrock in a wide range was studied. The convergence criteria for determining the calculation range of reservoir basin of super-high arch dams was put forward. The implementation method was proposed for different layers and zones of reservoir basin bedrock. A practical engineering of a super-high arch dam was taken as the example.

Keywords: wide basin bedrock; deformation modulus; finite element numerical calculation; inversion principle

1. Introduction

With the great development of hydropower in southwest China, a number of super-high arch dams more than 200 m high are constructed or under construction, such as Xiaowan (dam height 294.5 m), Laxiwa (dam height 250 m), Ertan (dam height 240 m), Goupitan (dam height 232.5 m), Jinping I (dam height 305 m), Xiluodu (dam height 285.5 m). Arch dam is statically indeterminate structure fixed in bedrock. Under the intense water pressure, reservoir basin bedrock will produce deformation, which led to additional stress and deformation of arch dams. A large amount of researches have been made on dam deformation factors near the dam area (Bayraktar *et al*. 2008, Lombardi *et al*. 2008, Mata *et al*. 2014, Sevim *et al*. 2018, Su *et al*. 2016). Observation results from the constructed dams show that reservoir basin bedrock deformation of high dam is objective existence. However, the deformation mechanism and its impact on arch dams operation behavior are lack of understanding. For high arch dams, tradition researches of engineering design, calculation and monitoring are restricted to field close to the dam area, and reservoir basin bedrock deformation far from the dam is often neglected, so big differences are often existed between numerical calculation results and in situ monitoring data of dam deformation. To guarantee engineering safety, it is of great significance to back analyze the geomechanical parameters and its evolution rule of reservoir basin bedrock, in which the geometry, geology and service environmental characteristics of super-large range of must be fully considered. Then, the reservoir basin bedrock deformation mechanism and its impact on the upper structure should be revealed.

In the 1980s, Wu and Gu firstly proposed reservoir basin deformation problem in Longyangxia gravity arch dam (dam height 178 m), and some exploratory studies about its impact on the dam working behavior are carried out (Benaissa *et al*. 2016, Wu 1990, Wang *et al*. 2003). With the development of science and engineering technology, reservoir basin deformation problem need to be studied more systematically and precisely. Currently, it is an effective method to research reservoir basin deformation based on the combination of in situ monitoring data and numerical simulation calculation. For high dams with lager reservoir, the influence scope of the reservoir basin bedrock deformation caused by reservoir water pressure is larger, so it is necessary to study the reasonable interception range of reservoir basin of finite element model and its sensitivity to reservoir basin deformation. Meanwhile, due to the large range of reservoir basin and in the complex geological conditions, it is necessary to reasonably determine the geomechanical parameters of reservoir basin bedrock for numerical simulation. At present, the field test is often used to determine the geomechanical parameters of rock mass near the dam area. However, geomechanical parameters of rock mass evolves with the long-term service of super-high arch dams, especially under the effect of seepage water, so some scholars proposed the inversion analysis method of mechanical parameters of rock mass near the dam area and dam body (Gu *et al*. 2006, Zhang *et al*. 2017, Yang *et al*. 2015), and analyzed the operation behavior of dams based

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on the inversion obtained parameters. However, the information of geomechanical parameters for a wide range of reservoir basin bedrock is very limited, and it is impossible to carry out detailed field tests. To solve these problems, based on the in situ reservoir basin monitoring data, inversion analysis of deformation modulus is firstly implemented for different layers and zones of reservoir basin bedrock, then its impact on the deformation of super-high arch dams is inversely analyzed.

In this paper, it is considered that the fractured mesh of the reservoir rock mass is very complicated, large-scale mountain fissures and seepage channels are difficult to be identified, and the seepage parameters and seepage boundary conditions are difficult to determine. At the same time, the seepage development process in the water inpouring process is difficult to determine. Therefore, the water pressure in the reservoir is calculated by the surface force method without considering seepage factors. Some research results (Zhang *et al*. 2005, Chen *et al*. 2002) show that the groundwater level of the Xiaowan dam site is shallow-buried, that is, most of the mountains before building the dam is saturated, only the superficial is in an unsaturated state, and the pressure added by the reservoir basin after water inpouring is mainly the water weight of the reservoir, so it should be appropriate to apply the reservoir water pressure in a surface force manner.

2. Basic principle and implementation method of deformation modulus inversion analysis of reservoir basin bedrock

2.1 Basic principle of inversion analysis of reservoir basin bedrock deformation modulus

In arch dam design phase, detailed geological exploration is usually done near the dam area, field and laboratory test are used to determine the geomechanical parameters of rock mass. When considering the reservoir basin deformation, it's unable to get detailed geomechanical parameters of a wide range of reservoir basin bedrock. Therefore, it is reasonable to divide the whole reservoir basin bedrock into different layers and zones according to geological conditions, then inversion analyses of bedrock deformation modulus are done for each zones based on the measured settlement data. The basic principle is as follows:

(1) Determine the influencing factors

The reservoir basin deformation is mainly caused by the water pressure, and its equilibrium equation is

$$[K]\{\delta\}=\{R_H\} \tag{1}$$

where $[K]$ is the global stiffness matrix of the reservoir basin; $\{\delta\}$ is the node displacement vector; $\{R_H\}$ is the water pressure equivalent node load vector.

$$\begin{aligned}[K]&=\sum_{n=1}^{M}\sum_{e_j}[C]_{e_j}^{\mathrm{T}}[K]_{e_j}[C]_{e_j}=\sum_{n=1}^{M}\sum_{e_j}[C]_{e_j}^{\mathrm{T}}E_n\iiint_{S_n}[B]^{\mathrm{T}}f(\mu_n)[B]dS[C]_{e_j}\\&=\sum_{n=1}^{M}E_n\sum_{e_j\in S_n}[C]_{e_j}^{\mathrm{T}}\iiint_{S_n}[B]^{\mathrm{T}}f(\mu_n)[B]dS[C]_{e_j}=\sum_{n=1}^{M}E_n[K_n]\end{aligned} \tag{2}$$

where $[C]_{ej}$ is the stiffness transformation matrix of element e_j; $[K]_{ej}$ is the stiffness matrix of element e_j; S_n is the nth computational domain of the reservoir basin, n=1,2,…,M; M is the number of domains; $[B]$ is the geometric characteristics matrix of the element and $f(\mu_n)$ is the influencing effect quantity of Poisson ratio.

It can be known from Eq. (1)

$$\{\delta\}=[K]^{-1}\{R_H\} \tag{3}$$

Substitute the Eq. (2) into the Eq. (3).

$$\{\delta\}=(\sum_{n=1}^{M}E_n[K_n])^{-1}\{R_H\} \tag{4}$$

As shown in Eq. (4), under the action of $\{R_H\}$, $[K_n]$ is known for the given structure, so $\{\delta\}$ is mainly affected by E_n. Therefore,

$$\{\delta\}=F(E_1,E_2,\cdots,E_M,H) \tag{5}$$

For inversion analysis, the measured displacement and calculated displacement of in situ observation points are denoted as $\{\delta_i\}$ and $\{\bar{\delta}_i\}$, respectively.

(2) Inversion analysis of deformation modulus of reservoir basin bedrock at different layers and zones

It can be known from the above analysis that the reservoir basin deformation mainly depend on E_n and $\{R_H\}$ ($\{R_H\}$ is the function of water depth H). As the measured displacement values are known, the key point of the inversion analysis is to find the relationship between the measured displacement and the calculated displacement to make the calculated values approach to the measured values, this is a best fitting problem. So, the objective function is determined as the goal of minimizing the square sum of the difference between $\{\delta_i\}$ and $\{\bar{\delta}_i\}$

$$\begin{aligned}Q&=(\{\delta_i\}-\{\bar{\delta}_i\})^{\mathrm{T}}(\{\delta_i\}-\{\bar{\delta}_i\})\\&=(\{\delta_i\}-F(E_1,E_2,\cdots,E_M,H))^{\mathrm{T}}(\{\delta_i\}-F(E_1,E_2,\cdots,E_M,H))\end{aligned} \tag{6}$$

As δ_i and H are known, to minimizing the objective function of, the following formula can be established

$$\frac{\partial Q}{\partial E_n}=0\ (n=1,2,3,\cdots,M) \tag{7}$$

The inversion value E_n(n=1,2…,M) can be got by using the Eq. (7).

2.2 Inversion analysis process of deformation modulus of reservoir basin bedrock

To achieve the inversion analysis of reservoir basin bedrock deformation modulus, two problems should be solved: reasonable range interception of the reservoir basin finite element model and the determination of geomechanical parameters of bedrocks, which interact with each other. That would influence the convergence range of reservoir basin finite element model. While the intercepted range of reservoir basin would influence the computation result of bedrock deformation and affect the precision of inversion analysis. To solve this problem, the analysis error between the calculated basin bedrock deformation and the measured values should be controlled within a reasonable range, in which the numerical simulation is conducted according to the inversion analyzed parameters. The inversion analysis process, as shown in Fig. 1, is as follows.

Step 1: Collecting geological exploration, terrain, material experiment, technology design and construction design data.

Step 2: According to the geological conditions, dividing the intercepted reservoir basin bedrock into different layers and zones, determining the geomechanical parameters and building the reservoir basin finite element model preliminary.

Step 3: To conduct the sensitivity analysis of influencing factors of reservoir basin bedrock deformation, numerical simulations are conducted on several finite element models which are intercepted at different ranges, and the reservoir basin water pressure is modeled.

Step 4: According to the convergence criterion, the range of reservoir basin intercepted in finite element model is determined reasonably, which should ensure the boundary conditions have little influence on the bedrock deformation.

Step 5: Numerical simulation of reservoir basin bedrock deformation is conducted the finite element model determined in Step 4, and the water pressure corresponding to the monitoring date is applied;

Step 6: According to the least squares principle, inversion analyses of mechanical parameters of reservoir basin bedrock are conducted for each layers and zones;

Step 7: Using the inversion mechanical parameters to calculate the bedrock deformation corresponding to measured settlement data, and compare the calculated values and the measured values. If the differences are acceptable, it means that the inversion analysis is reasonable. Otherwise, the results are unreasonable, and the inversion analysis should be revised, namely it should be restarted in Step 2.

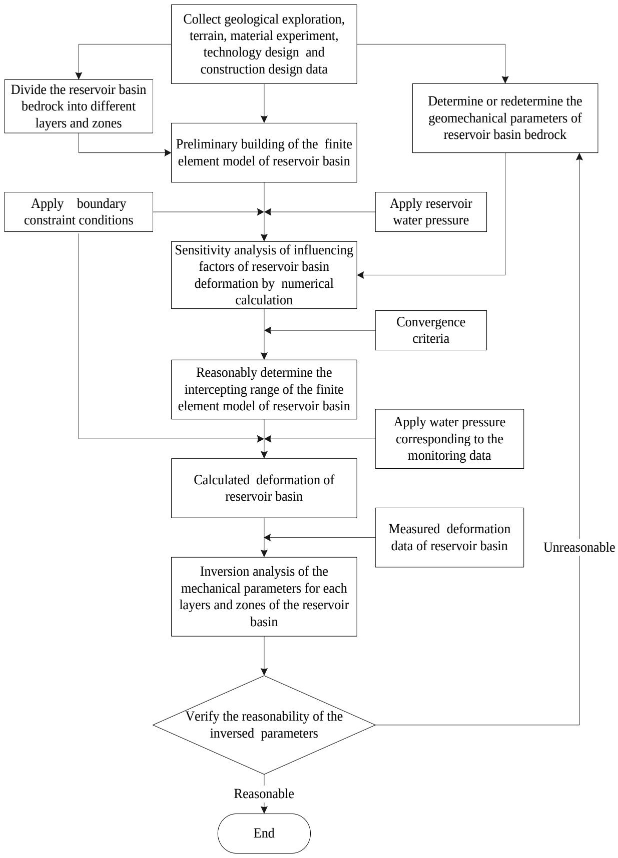


Fig. 1 Flowchart of inversion analysis for deformation modulus

3. Reasonable interception range of reservoir basin finite element model

3.1 Convergence criterion of the reservoir basin finite element model range

For the complexity and uncertainty of topographic and geological condition, the strain and stress of the reservoir basin are complex spatial problems and cannot to be obtained theoretically. While the finite element method can simulate the operation behavior of dam body and its foundation together, and the effect of reservoir bedrock deformation on super-high arch dam displacement can be easily analyzed under different reservoir basin types, such as the linear reservoir basin of Three Gorges dam, the inflected reservoir basin, the bifurcate reservoir basin of Xiao Wan arch dam, the sudden-enlarged reservoir basin of Long Yang Xia arch dam.

Thereby, reservoir basin finite element models of different types are firstly established, then analyzing the deformation rules of reservoir basin under different influencing factors. Here, some assumptions are made as follows: (1) the reservoir bedrock material is isotropic; (2) the bedrock permeability is ignored; (3) the bedrock is linear elastic and its creep property is neglected.

According to the aforementioned assumptions, the main factors affecting the finite element calculation accuracy are the element displacement mode, element shape and model range, in which the first two are the most important for accuracy, while the model range determines whether the calculation result can fully reflect the actual dam deformation or not. So, to study on the effect of interception range of finite element model on reservoir basin deformation, the better displacement mode and element shape should be guaranteed. Huang *et al*. (2013) theoretically investigated the reasonability of 6 typical constraint conditions of foundation interception boundaries of finite element model, based on the elastic theoretical analysis and the finite element calculation, some suggestions on model interception range were given (Chen *et al*. 2002, Yang *et al*. 2017, Chen *et al*. 2018), Lately, and an intelligent recognition method based on the neural network was put forward in his latish paper to determine the geometry size of uncertain dam foundation (Xiang *et al*. 2004, Huang *et al*. 2013).

The aforementioned researches are all aimed at concrete gravity dams which are not more than 200 m high. While, 300 m super-high arch dam are affected not only by the constraints of the upstream direction, the downstream direction and the foundation depth, but also those of both river bank.

For the complex reservoir type of the 300m-class super-high arch dam, the displacement of the reservoir basin is relatively large under the action of huge reservoir water pressure. When the percentage of the relative displacement difference is used as the control standard, the displacement difference between the two calculations is large, the resulting of the reservoir basin deformation is less accurate. At the same time, the finite element model of the complex reservoir type belongs to the three-dimensional model, which cannot be applied in the way of intercepting the range of the gravity dam finite element model. Besides, considering the "Technical Specification for Safety Monitoring of Concrete Dams" (SL601-2013), the medium error limit for horizontal displacement and vertical displacement in the monitoring of deformation of rock mass and high slope in the near dam area is specified as ±2.0 mm. Hence, the interception range of finite element model is determined by the following criterion

$$\left|\frac{\delta_{i+1}-\delta_i}{\delta_i}\right| \le 2\% \tag{8}$$

where δ_i and δ_{i+1} are calculated displacements of typical point for the ith and i+1th selected model range and boundary constraint condition, respectively.

3.2 Weight analysis for the influence of finite element model range on the reservoir basin deformation

Different reservoir basin types and model interception ranges have different influences on the reservoir basin deformation. Zhao *et al.* studied the model interception ranges of linear, inflected, bifurcate and sudden-enlarged reservoir basin, and the influence weights of upstream, downstream, depth and bank ranges of reservoir basin were determined by the improved entropy method (Qi *et al.* 2013). In order to determine the influence weights of reservoir basin deformation more reasonably, subjective-objective comprehensive weight determining method is introduced (Huang *et al.* 2008), in which the subjective methods are the Analytic Hierarchy Process (AHP) method and the Delphi method, while the objective method is the entropy evaluation method. The basic principle is as follows.

(1) Basic data processing

The properties and magnitude orders of evaluation indexes are different form each other, so, the original data need to be normalized. Presently, the general index types include efficiency type, cost type and fixed type, and the efficiency type is applied in settlement displacement data analysis.

Suppose the normalized matrix of settlement displacement data sample is as follows

$$B=\begin{bmatrix} b_{11} & b_{12} & \cdots & b_{1m} \\ b_{21} & b_{22} & \cdots & b_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ b_{n1} & b_{n2} & \cdots & b_{nm} \end{bmatrix}_{n\times m} \tag{9}$$

where b_{ij}($1\le i\le n$, $1\le j\le m$) is the i-th normalized settlement displacement data in the j-th index sequence, n is the number of settlement displacement calculated data changed by the model interception range, m is the number of evaluation indexes.

Each element of matrix B meets $0\le b_{ij}\le 1$, and each column at least has an element which equals 1. The element 1 is chosen from each column and constitute a new evaluation scheme, which could be considered as the optimal scheme and the evaluation value is m-dimensional all one-vector.

(2) Determining the comprehensive weight of the index

Comprehensive weight is a linear combination of subjective and objective weights. Dim $Q^*=\left(q_1^*,q_2^*,\cdots,q_m^*\right)^{\mathrm{T}}$ as the linear combination weight vector of the aforementioned subjective-objective weight vector Q^1, $Q^2,\ldots,Q^s$, which could be expressed as follows.

$$Q^*=\sum_{k=1}^{s}\beta_k Q^k \tag{10}$$

where β_k is the linear combination coefficient, which meets

$$\sum_{k=1}^{s}\beta_k=1,\ \ \beta_k\ge 0 \tag{11}$$

Dim $\beta=(\beta_1,\beta_2,\ldots\beta_s)^T$ as the combination coefficient vector. It could be verified that the determinate Q^* is the weight vector, which meets

$$\sum_{j=1}^{m}q_j^*=\sum_{j=1}^{m}\sum_{k=1}^{s}\beta_k q_j^k=1 \tag{12}$$

The comprehensive evaluation value of the ith model interception range under the combined weight vectors Q^* is supposed as p_i, thus

$$p_i=\sum_{j=1}^{m}q_j^* b_{ij}=\sum_{j=1}^{m}\sum_{k=1}^{s}\beta_k q_j^k b_{ij},\ \ i=1,2,\cdots,n \tag{13}$$

Therefore, the generalized distance between scheme p_i and ideal scheme is

$$l_i=\sum_{j=1}^{m}\sum_{k=1}^{s}\beta_k q_j^k\left(1-b_{ij}\right),\ \ i=1,2,\cdots,n \tag{14}$$

From the view point of mathematical statistics, the real weight coefficient of each evaluation index is a random variable in the practical systems. Thus, the real weight vector consisted by them is a random vector, and the weight vector Q^k could be considered as the kth sample value of the real weight vector. The linear combination coefficient β_k which meets Eq. (11) could be considered as the probability of real weight vector sample value Q^k. Therefore, the combination coefficient vector β has indeterminacy, and this indeterminacy could be expressed by Shannon entropy.

$$H=-\sum_{k=1}^{s}\beta_k\ln\beta_k \tag{15}$$

The aim of calculating the linear combination weight vector is to determine the proper combination coefficient vector β. On one hand, the sum of weighted generalized distance between real schemes and ideal scheme should be minimized, that is

$$\begin{aligned} &\min \quad \sum_{i=1}^{n} l_i = \sum_{i=1}^{n}\sum_{j=1}^{m}\sum_{k=1}^{s} \beta_k q_j^k \left(1-b_{ij}\right) \\ &s.t. \quad \sum_{k=1}^{s} \beta_k = 1, \beta_k \geq 0 \end{aligned} \tag{16}$$

On the other hand, the indeterminacy of combination coefficient vector should be eliminated. According to the Jaynes maximum entropy principle, to determinate comprehensive weight index, the Shannon entropy should be maximized.

$$\begin{aligned} &\max \quad H = -\sum_{k=1}^{s} \beta_k \ln \beta_k \\ &s.t. \quad \sum_{k=1}^{s} \beta_k = 1, \beta_k \geq 0 \end{aligned} \tag{17}$$

Thus, the calculation of liner combination weight vector is a problem of multi-objective optimization. Consequently, the following single object optimization (SP) is constructed

$$\begin{aligned} &\min \quad \mu\sum_{i=1}^{n} l_i = \sum_{i=1}^{n}\sum_{j=1}^{m}\sum_{k=1}^{s} \beta_k q_j^k \left(1-b_{ij}\right) + (1-\mu)\sum_{k=1}^{s} \beta_k \ln \beta_k \\ &s.t. \quad \sum_{k=1}^{s} \beta_k = 1, \beta_k \geq 0 \end{aligned} \tag{18}$$

where μ is a coefficient to balance the two objectives, which meets $0<\mu<1$. The suggested value could be determined in advance according to practical issues, and the suggested value is 0.8. The lagrange multiplier method is introduced for the calculation, and the result is

$$\beta = \left(\beta_1, \beta_2, \cdots, \beta_k\right) \tag{19}$$

where,

$$\beta_k = \frac{\exp\left\{-\left[1+\mu\sum_{i=1}^{n}\sum_{j=1}^{m} q_j^k \left(1-b_{ij}\right)/(1-\mu)\right]\right\}}{\sum_{k=1}^{s}\exp\left\{-\left[1+\mu\sum_{i=1}^{n}\sum_{j=1}^{m} q_j^k \left(1-b_{ij}\right)/(1-\mu)\right]\right\}}, k = 1, 2, \cdots, s$$

3.3 Sensitivity analysis for the influence of finite element model range on the reservoir basin deformation

To correspond with practical engineering, the bifurcate reservoir basin without fault is discussed to study the interception range and the influence weight of reservoir basin finite element model.

Supposing the boundary constraint condition has little influence on reservoir basin deformation, it can be seen from Fig. 2 that the deformation of bifurcate reservoir basin can be represented by the following formula

$$\delta = f\left(L, \alpha_1, \alpha_2, E, \mu, B/h, H\right) \tag{20}$$

where L is the distance between dam and river bifurcation; α_1 and α_2 are bifurcation angles of two branched rivers; E is the elastic modulus of reservoir basin bedrock; μ is the Poisson's ratio of reservoir basin bedrock; B/h is the aspect ratio of the river; H is the water depth ahead of dam.

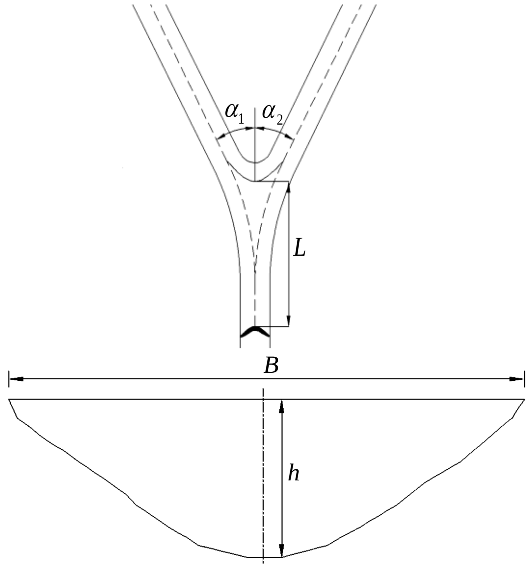
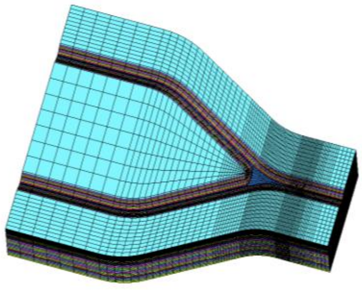


Fig. 2 Schematic diagram of bifurcation type reservoir basin

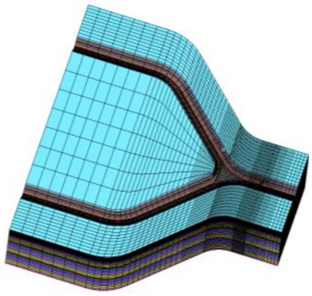
When L, E, μ, B/h and H are constant, δ is determined by bifurcation angles of α_1 and α_2. To study the influence of bifurcation angles on FEM model, interception range of reservoir basin α_1 and α_2 are set to be 30°, 45°and 60° respectively. FEM models of reservoir basin are shown in Figs. 3 and 4.

The initial boundary interception ranges of FEM model are set to be 21 km, 3 km, 3 km and 6 km in upstream direction, downstream direction, along both river banks and in depth direction, respectively. The dam is a hyperbolic arch dam of 300 meters. Assuming mechanical parameters just vary along elevation direction in the FEM model, geological stratification from the earth's surface to 600 m below the river centerline is shown in Fig. 5. For the deeper areas, elastic modulus increases linearly with a tendency of 5 GPa per 600 meters, while Poisson's ratio is set to be constant. The constraint conditions are complete constraints on the bottom intercepted boundary and normal constraints on other four intercepted boundaries. The load case is 295 meters of water depth before dam. A point on left bank slope 1 km away from dam site is selected as the typical point.

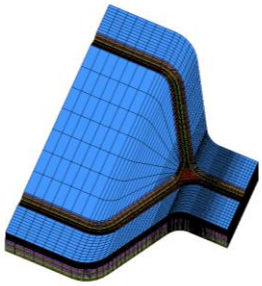
The calculation results can be seen from Fig. 6, and the following conclusions can be drawn. When only changing one kind of boundary interception range, settlement of typical slope point can always achieve convergence. According to the above convergence criterion, convergence ranges can be obtained for reservoir basin model for different bifurcation angles as shown in Table 1. To quantify the influence of boundary interception ranges on reservoir basin deformation, weight analysis is conducted with comprehensive objective-subjective weight method, and the results are shown in Table 2. From these results, it can be known that reservoir basin deformation is sensitive to foundation depth, both bank and upstream range, while the downstream range has little influence on the deformation. For the upstream range, once it grows beyond the river bifurcation, the increased range has little influence on reservoir deformation since it converges quickly.



(a) α_1, α_2=30°



(b) α_1, α_2=45°



(c) α_1, α_2=60°

Fig. 3 Reservoir basin FEM model of different bifurcation angles

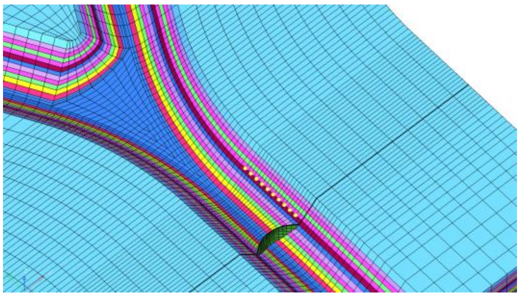


Fig. 4 Local details in FEM model of bifurcation type reservoir basin

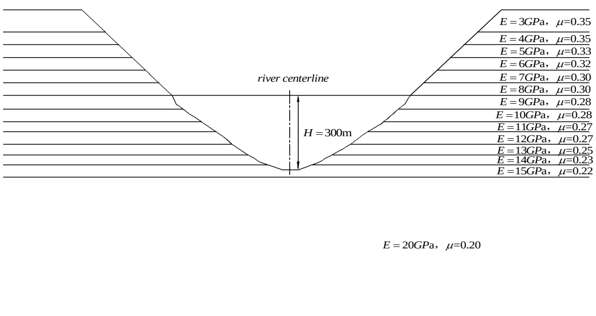


Fig. 5 Schematic diagram of geological stratification and mechanical parameters in reservoir basin model

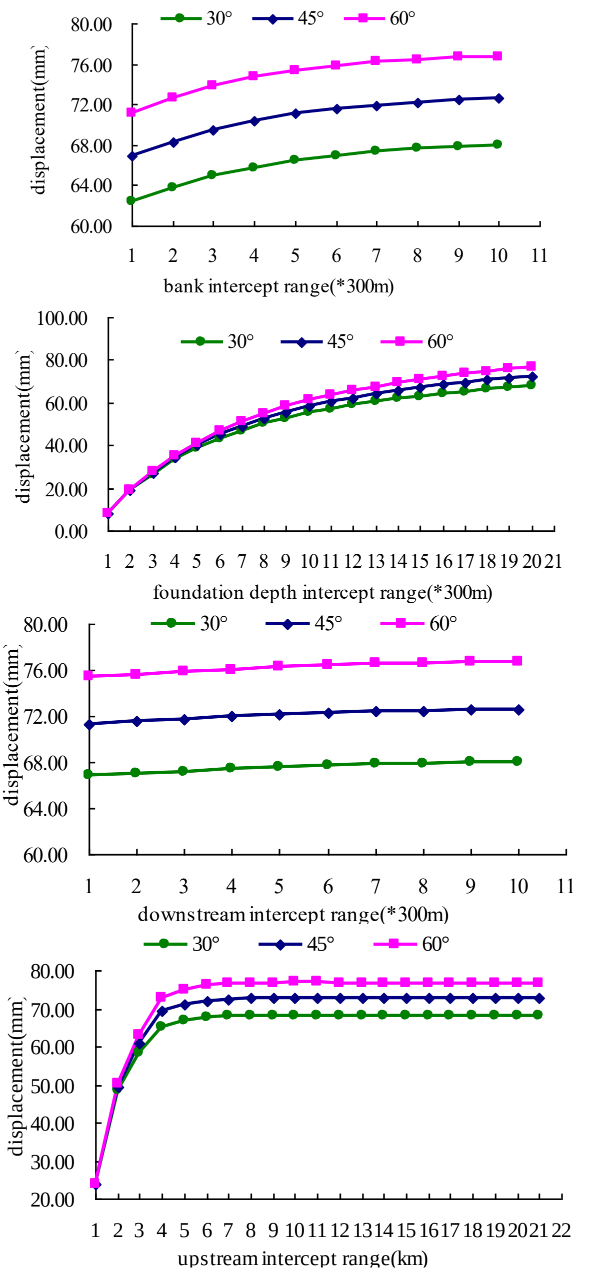


Fig. 6 Relationship between interception range of reservoir basin model and settlement of typical slope point for different bifurcation angles

Table 1 Convergence range of reservoir basin FEM model for different bifurcation angles

Bifurcation angles	Range			
	Both bank (*300 m)	Foundation depth (*300 m)	Downstream (*300 m)	Upstream (km)
30°	6	15	1	6
45°	6	16	1	6
60°	6	17	1	6

4. Case study

Xiaowan hydropower station locates 1.5 km next to the intersection of the Lancang River and Heihui River, which

Table 2 Influence weight of FEM model interception range on reservoir basin deformation for different bifurcation angles

Bifurcation angles	Weight			
	Both bank	Foundation depth	Downstream	Upstream
30°	0.0892	0.6697	0.0423	0.1988
45°	0.0921	0.6617	0.0441	0.2021
60°	0.0943	0.6555	0.0455	0.2046

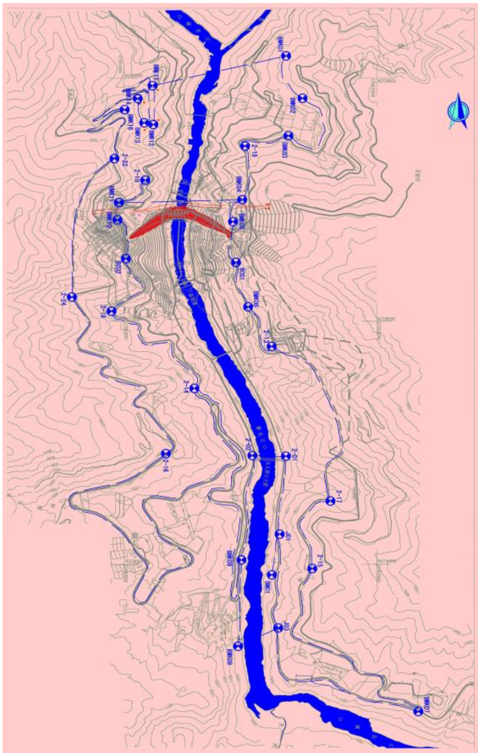
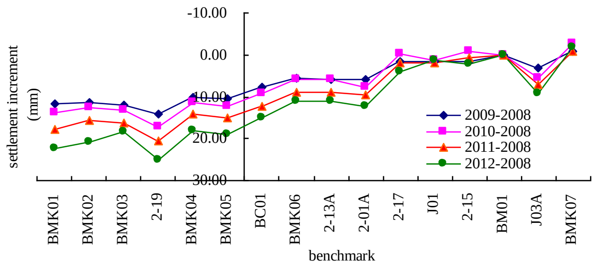
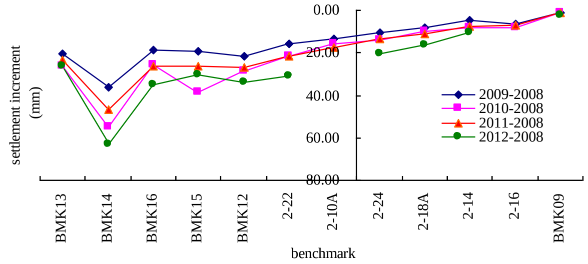


Fig. 7 Reservoir basin benchmark network



(a) Left bank



(b) Right bank

Fig. 8 Benchmark settlement increment on two banks of Xiaowan reservoir basin

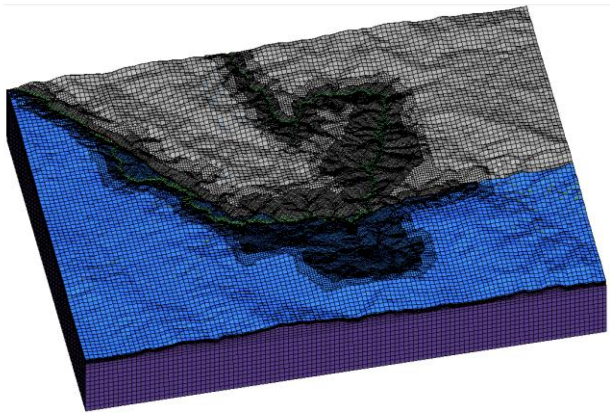


Fig. 9 FEM model of Xiaowan reservoir basin

Is at the junction of Nanjian County in Dali Prefecture and Fengqing County in Lincang City, in the west of Yunnan Province. The project is mainly consisting of concrete hyperbolic arch dam, water cushion pool with auxiliary weir behind the dam, spillway tunnel on the left bank, and underground diversion and power generation system on the right bank. The maximum dam height is 294.5 m, the bottom and crest elevation of crown cantilever are 950.5 m and 1245 m, respectively. After impounded to the normal water level of 1240 m, the reservoir will have a total capacity of 15 billion cube meters, making it a typical project with high dam and large storage, and a bifurcate reservoir basin appears.

(1) Deformation monitoring of reservoir basin

The monitoring scope of reservoir basin deformation ranges from 1 km in the upstream direction to 4 km in the downstream direction, with a total observation line of 33 km. The whole monitoring network has 33 benchmarks, in which 16 are arranged on the left bank, the other 17 are on the right bank. The layout of benchmark network is shown in Fig. 7. The reservoir basin monitoring was firstly conducted in 2008 and repeated once a year during 2009 and 2012, 5 times in all. The measured settlement distribution of benchmarks is shown in Fig. 8. Because of the impact of construction and water impoundment, the measured data of 24 benchmarks are chosen to do the inversion analysis based on the checking of data integrity and reliability.

(2) FEM model of reservoir basin

In the practical project, to consider the effect of faults, the scopes of FEM model are set to be 44km in the upstream direction, 21 km in the downstream direction, 40 km along the left bank, 50km along the right bank and 12 km in foundation depth. The model has 934740 elements and 958636 nodes, which is made up of 8-node hexahedral isoparametric elements mostly and 6-node pentahedral isoparametric elements for transition at detailed and boundary position of near-dam area, as shown in Figs. 9 and 10.

(a) Boundary constraint condition: complete constraints on the bottom boundary, normal constraints on the other four boundaries.

(b) Loads for calculation: as the monitoring work of

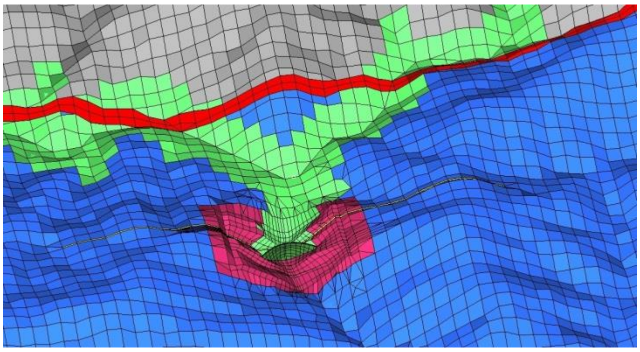


Fig. 10 Local details of the bifurcate reservoir basin of Xiaowan arch dam

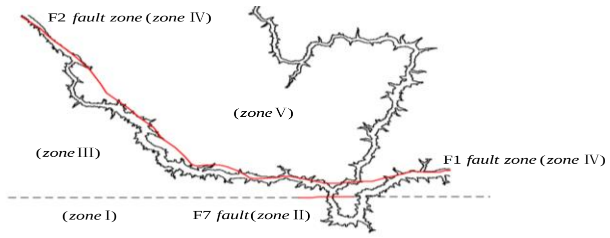


Fig. 11 Generalized geological zones along the horizontal direction of Xiaowan reservoir basin

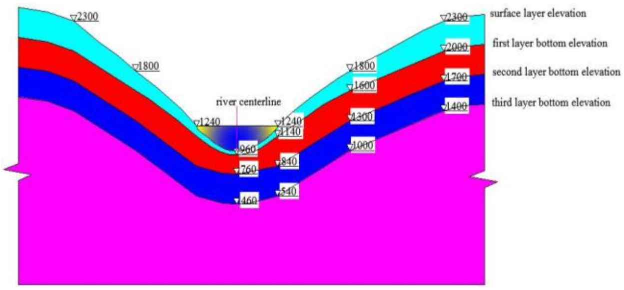


Fig. 12 Generalized graph of layers along vertical direction in zones I, II, III, V

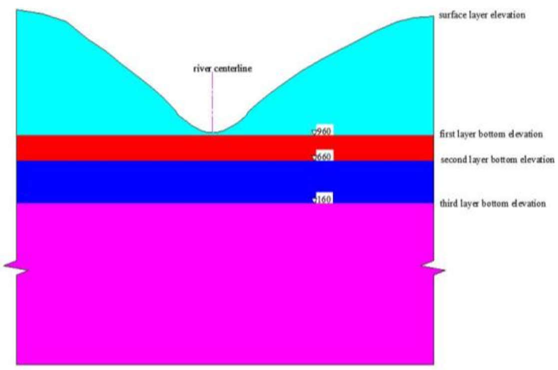


Fig. 13 Generalized graph of layers along the vertical direction in zone IV

each time lasts a period of time, so the calculated water levels are set to be the average water levels of 5 monitoring period, which are 1000.42 m (2008), 1166.04 m (2009), 1207.9 m (2010), 1213.42 m (2011) and 1235.39 m (2012). Water pressure is applied to the upstream element surface of reservoir basin FEM model, thus the corresponding displacement field is calculated.

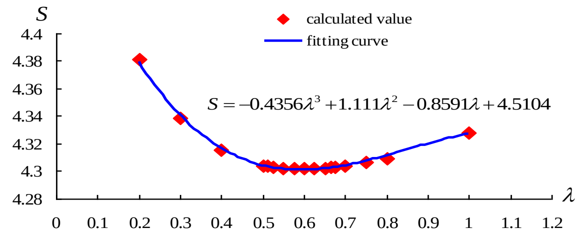


Fig. 14 Relationship curve between λ and S

Table 3 Geomechanical parameters of reservoir basin bedrock

Zone		Parameter			
		Deformation modulus interval (GPa)	Poisson's ratio	Density (kg/m^3)	Inversed deformation modulus (GPa)
I, III	Layer1	0.6 ~ 5.0	0.25	2300	3.209
	Layer2	5.0 ~ 20	0.23	2500	13.895
	Layer3	20 ~ 50	0.2	2700	37.79
	Layer4	50	0.2	2700	50
V	Layer1	0.4 ~ 3.0	0.28	2100	1.942
	Layer2	3.0 ~ 12	0.25	2300	8.337
	Layer3	12 ~ 30	0.23	2500	22.674
	Layer4	30	0.23	2500	30
II(F7)	Layer1	0.3 ~ 1.0	0.3	2000	0.715
	Layer2	1.0 ~ 2.0	0.28	2200	1.593
	Layer3	2.0 ~ 5.0	0.25	2300	3.779
	Layer4	5	0.25	2300	5
IV (F1-F2)	Layer1	0.3	0.3	2000	0.3
	Layer2	0.3 ~ 1.0	0.28	2100	0.715
	Layer3	1.0 ~ 3.0	0.28	2200	2.186
	Layer4	3	0.28	2200	3

Geological conditions of Xiaowan reservoir basin could be generalized as 5 zones along the horizontal direction, which are separated by F7 fault and F1-F2 fault zone. The downstream area of the F7 fault is zone I, F7 fault is zone II, the area between F7 fault and F1-F2 fault is zone III, F1-F2 fault is zone IV and the upstream area of F1-F2 fault is zone V, as shown in Fig. 11. Each zone could be generalized as 4 layers along the vertical direction based on the difference of bedrocks, as shown in Figs. 12 and 13.

(3) inversion analysis results

Based on the measured data of benchmarks around Xiaowan reservoir basin, the objective function is conducted by the mean square error of the measured and the calculated displacement of benchmark as follows

$$S = \frac{1}{K}\sum_{j=1}^{K}\sqrt{\frac{1}{N}\sum_{i=1}^{N}(\delta_{ic} - \delta_{im})^2} \tag{21}$$

where δ_{ic} are the calculated settlement of nodes corresponding to benchmark points; δ_{im} are the measured settlement of benchmark points, N is the number of benchmarks; K is the measured times. When the value of S

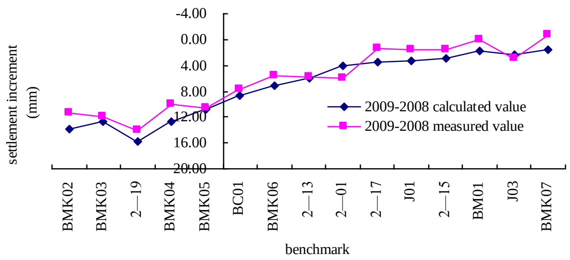


Fig. 15 Calculated and measured settlement increment of benchmarks on left bank between the year 2008 and 2009

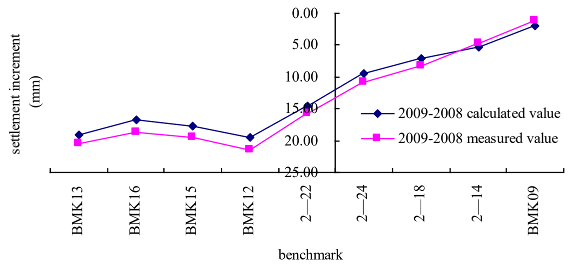


Fig. 16 Calculated and measured settlement increment of benchmarks on right bank between the year 2008 and 2009

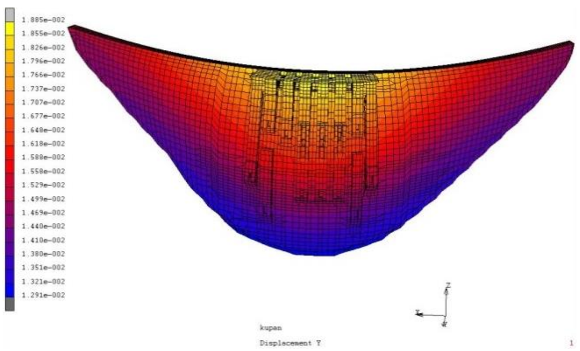


Fig. 17 Displacement of Xiaowan dam along the river at 1240 m water level

reaches minimum, the corresponding parameters of the FEM model represents the true material parameters of the reservoir basin bedrock.

When doing the inversion analysis, various combinations of material parameters should be set before the FEM calculation. Each group of material parameters is determined with the following formula

$$E=(1-\lambda)E_l+\lambda E_u \tag{22}$$

where E_u and E_l are the upper and lower limits of proposed parameter interval; λ is the distribution coefficient. When λ is set to be 0, 0.5 and 1, the parameters denote the lower limits, middle value and upper limits of proposed interval, respectively.

The mechanical parameter intervals of each layers and zones are listed in Table 3. Based on the initial parameters and the measured data of settlement in 2008-2012, mechanical parameters of reservoir basin bedrock are inverted by the optimizing method. After optimizing calculation, the relationship between λ and S is shown in Fig. 14, and the function formula is fitted with a cubic polynomial. The objective function reaches the minimum when λ=0.593, so the corresponding mechanical parameters are obtained as shown in Table 3.

(4) Rationality verification of the inversion results

Rationality of the FEM model interception range of reservoir basin and the inversed deformation modulus of bedrocks need to be verified. With the inversed deformation modulus, deformation is calculated under different water levels that corresponding to the measured settlement data. Comparison of the calculated and the measured deformation shows that the error is within a reasonable range, so the interception range and the inversed deformation modulus are rational. The calculated and measured settlement increment of benchmarks between the year 2008 and 2009 are shown in Figs. 15 and 16.

The final objective of all these analyses is the dam safety not the basin or other parts. Therefore, the influence extent of the water factor to the dam was included According to the inversion results of the parameters, the influence of the deformation of the Xiaowan reservoir basin on the working behavior of the dam is calculated and analyzed. The general focus of the project is on the radial displacement of the arch crown beam of the arch dam. Therefore, under the normal water storage level (1240 m water level), the displacement of the dam along the river direction caused by the deformation of the reservoir basin is shown in the Fig. 17. Under the deformation of the reservoir basin, the Xiaowan dam body is toppling upstream for deformation, and the riverbed dam section has a large displacement to the upstream. The calculation results show that the top of the arch crown dam is displaced upwards to 18.46 mm. Only the calculation results are given here. Since it is not the focus of this analysis, the calculation results are not included in this study.

5. Conclusions

Based on the finite element numerical calculation and the in-situ monitoring data, to better evaluate the working behavior and safety situation of super high arch dams, it is of great significance to back analyze the mechanics parameters and its evolution rule of reservoir basin bedrock. Aiming at the inversion analysis of deformation modulus of reservoir basin bedrock, by fully considering the characteristics of topographic and geologic condition of reservoir basin, the key problems such as the implementation method of the inversion analysis for a wide range reservoir basin of super-high arch dams and how to improve the inversion accuracy are studied in this paper.

(1) In order to simulate the bedrock deformation of reservoir basin more accurately, the convergence criteria of reasonable intercepting range for FEM model is proposed. The sensitivity analysis of the influence of interception range on reservoir basin bedrock deformation is performed respectively from the aspects of upstream range, downstream range, two banks range, and depth of foundation. To quantify the influence of interception ranges on reservoir basin deformation, weight analysis is conducted by the comprehensive objective-subjective weight method. The analysis shows that the reservoir basin

deformation is sensitive to foundation depth, both bank range and upstream range, while downstream range have little influence.

(2) In view of the wide range of reservoir basin, the inversion analysis of deformation modulus is conducted for different layers and zones of the reservoir basin bedrock, so the influence of the reservoir basin bedrock deformation on super-high arch dams can be analyzed. Meanwhile, the reasonable reservoir basin deformation field can be taken as the initial boundary conditions when analyzing the working behavior of super-high arch dams by the FEM models of small ranges.

Acknowledgments

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