Contact Analysis of Separation Between Concrete Slab and Cushion Layer in Tianshengqiao Concrete-Faced Rockfill Dam

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CONTACT ANALYSIS OF SEPARATION BETWEEN CONCRETE SLAB AND CUSHION LAYER IN TIANSHENGQIAO CONCRETE-FACED ROCKFILL DAM

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ABSTRACT

Tianshengqiao concrete-faced rockfill dam (CFRD), with a maximum height of 178m, is the highest dam of the same kind in China and the second highest in the world. During the construction of the dam, some problems special for high CFRDs occurred, such as deficient of cushion layer and separation of concrete slab from cushion layer. In this paper, a finite element analysis is made to understand the deformation of the cushion layer and the separation between the slab and the cushion. Direct constraints method and Coulomb friction law are used to simulate the contact behavior between the deformable concrete slab and the cushion layer. The methods are shown to be effective through a comparison of the numerical results with in-situ measurements. The mechanism of occurrence of the separation between the slab and the cushion is discussed. Valuable suggestions are made for further design and construction of high concrete-faced rockfill dams.

DESCRIPTION OF TSQ-I PROJECT

Tianshengqiao-I Hydroelectric Power Project (TSQ-I Project) is located on the Nanpan River in southwestern China. The dam controls a catchment area of 50,139km^2. The reservoir capacity is 10.26 billion m^3. This project is primarily for power generation and the power plant has a capacity of 1,200 MW in four units. Tianshengqiao dam is a concrete-faced rockfill dam, with a maximum height of 178m and a crest length of 1,140m. The dam body contains a rockfill volume of about 18 million m^3 and the area of the concrete face is 173,000m^2. It is known as the highest dam of this kind in China and the second highest in the world.

A general layout of TSQ-I Project is presented in Fig. 1. A surface chute spillway on the right bank allows a maximum discharge of 19,450m^3/s. The tunnel in the right bank is for emptying the reservoir during operation and is designed for the purpose of supplying a compensating discharge to the downstream TSQ-II plant during and after reservoir filling. Four power tunnels and a surface powerhouse are located in the left bank. The construction of TSQ-I Project began in June 1991 and power generation started in December 1998. The whole project finished by the end of 2000.

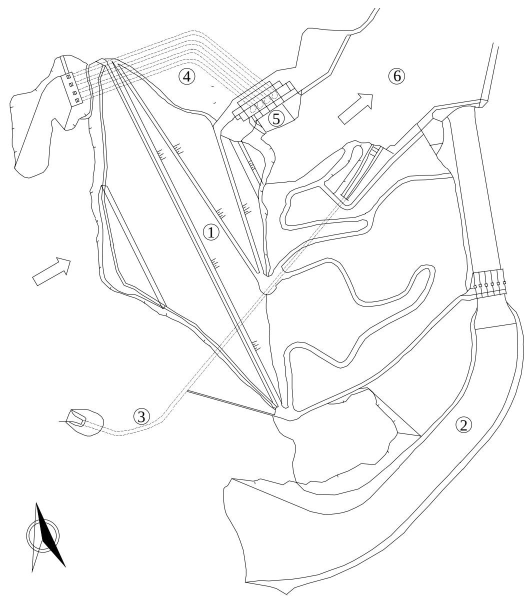
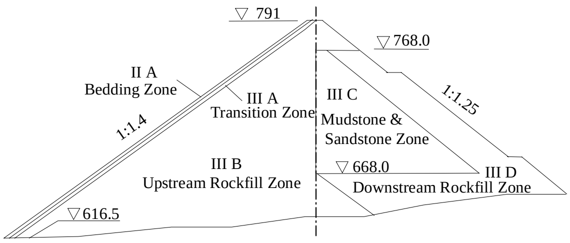


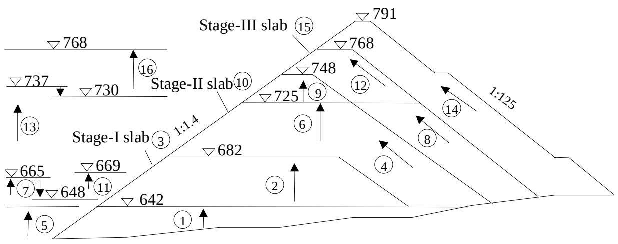
Fig. 1. General layout of TSQ-I Project

1. Concrete-faced rockfill dam 2. Spillway
3. Reservoir emptying tunnel 4. Power Tunnels
5. Power house 6. Nanpan River

Figure 2 a) shows a typical cross-section of Tianshengqiao CFRD. The upstream slope is 1 on 1.4 and downstream slope is 1 on 1.25, with two access berms 10m wide each. An economic dam zoning was achieved with materials of different qualities available from required excavations. The main parameters of the materials are listed in Table 1. The bedding zone IIA with a horizontal thickness 3.0m has a low permeability since it is expected to act as a semi-pervious layer during the diversion sequence before construction of concrete face. To prevent the fine particles of the bedding zone from entering the pores of the rockfill, a transition zone IIIA with a horizontal width 5.0m is provided between the bedding zone and the rockfill zone. The upstream rockfill zone IIIB forms the main part of the dam body, providing a support for hydrostatic loads transmitted from the bedding zone and transition zone. The downstream rockfill zone IIID consists of relatively lower quality materials since it takes smaller load pressure than the upstream rockfill zone IIIB. Weathered and fresh mudstone and sandstone available from the excavation of spillway are placed on the zone IIIC, which is above the water level in the downstream area.



a) Material Zoning



b) Construction Phases

Fig. 2. Material zoning and construction phases of TSQ-I dam

Table 1. Design Parameters of the Dam Materials

Mat. No.	Mat. Description	Max. Particle Size(cm)	Dry Unit Weight (KN/m^3)	Void Ratio (%)
IIA	processed limestone	8	22.0	19
IIIA	limestone	30	21.5	21
IIIB	limestone	80	21.2	22
IIIC	mudstone & sandstone	80	21.5	22
IIID	limestone	160	20.5	24

The upstream concrete face was divided into 69 slabs, with vertical joints spaced at 16.0m interval between the slabs. The thickness of the face slab is 0.3m at the top elevation of 787.3m to 0.9m at the bottom elevation of 616.5m, with a varying relationship t=0.3+0.0035H, where t is the thickness of the slab and H the vertical distance below the top elevation 787.3m. The reinforcement is placed in the center part of the slab with percentages 0.4% along the slope and 0.3% in the horizontal direction. The concrete material for the face slabs is classified as C25 in terms of strength and S12 in terms of seepage resistance.

The dam construction commenced in February 1996. The construction stages were established according to the requirements of river diversion and utilization of materials from the excavations. During the dam construction, five temporary sections were formed in the cross-section of the body, i.e. El.682m, El.725m, El.748m, El.768m and El.791m temporary sections as shown in Fig. 2 b). The upstream face slab was concreted in three stages, with top elevations at El.680m, El.746m and El.787.3m respectively. The overall dam body construction finished in March 1999 and the face slab completed at the end of May 1999. Reservoir filling started in December 1997 and in August 1999 the water level reached El.768m for the first time.

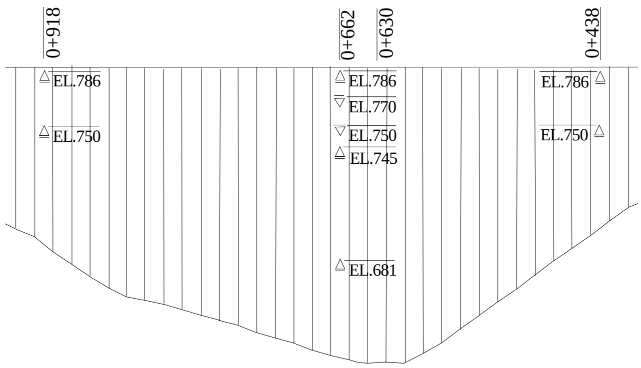


Fig. 3. Instruments layout for measurement of the separation of slabs from cushion layer

To monitor the performance of the dam, a safety monitoring system, including measurements of deformations and earth pressures within the dam, movement of the dam crest, deflections of the concrete face, movements of perimetric joints and vertical joints, stress and temperature in the concrete face slab, leakage through the dam body and foundation and dynamic behavior of the dam during earthquake, was installed. The instruments were arranged within three cross-sections, section 0+438m, section 0+630m and section 0+918m, respectively, as shown in Fig. 3. An additional system for measurement of the separation of slab from cushion layer was also installed and it was the first time to do so in a CFRD in China. Nine measuring points on section 0+438m, section 0+662m and section 0+918m respectively, as discribed in Fig. 3, were selected to observe the relative displacement between the face slab and the cushion layer.

FIELD OBSERVATIONS

During the construction of the dam some problems special for high CFRDs occurred, such as the deficient of the cushion layer and the separation of concrete slab from cushion layer (Bai, et al., 2000). During preparation of the slope face for the stage-II slab, it was measured that the constructed cushion layer was largely below the designed slope due to the settlement of the dam. The maximum deficient reached 43cm at the riverbed section. At the same time the top area of the stage-I slab was found to be separated from the cushion and the opening was 350m long, from slab number L14 to R8, maximally 15cm wide and 6.8m deep in the middle of the riverbed section. The opening gradually decreased when it came to the left bank and right bank sections. Similar situation occurred in the next construction stage. The maximum deficient of stage-III cushion reached 78.4cm although originally the cushion has been over constructed by 25cm. The separation of the stage-II slab from the cushion reached 720m long, from slab number L27 to R18, maximally 10cm wide and 4.7m deep. The stage-III slab was also separated from the cushion layer and the opening was 610m long, from slab number L25 to R11, maximally 15cm wide and 10m deep. Differently, the separation between stage-III slab and the dam body occurred in the riverbed and left bank sections while the maximum opening did not appear at the middle of the riverbed section but at a section in the left bank. Fig. 4 shows the distribution of the openings between the slabs and the dam body. Because of the separation of the slabs from the cushion layer, some concentrative cracks occurred on the face slabs near the bottom of the separation areas. Moreover, the width of the cracks increased with the dam deformation and therefore is harmful to the anti-seepage function of the face slabs. In addition, the deformation of the slabs in its geometrical shape, caused by the deficient of the cushion and the rockfill deformation, has worsen the mechanical status of the face slabs. In a word, the negative effects of the separation between the concrete face and the dam body and the deficient of the cushion are significant to the functional performance of the concrete face and further threatened the safety of the dam.

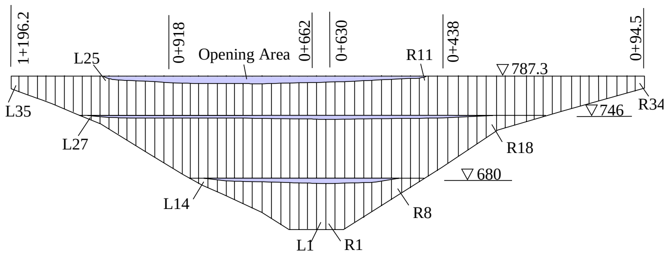


Fig. 4. Distribution of the openings between the slabs and the cushion layer

NUMERICAL METHOD

Contact Model

One of the difficulties in the finite element analysis of stresses and deformations of concrete-faced rockfill dam is the simulation of the contact behavior between concrete face and dam body, of which the deformation modulus are different greatly. The conventional method assumes the concrete slab and the dam body as two different material zones of one object and set interface elements between them to simulate their contact behavior. Many types of interface elements are currently used, such as Goodman interface element, thin-layer interface element and contact-friction interface element, to describe the physical properties of the interface especially the friction features in the tangential direction. The use of the interface element models has been limited to some extent, however, because of difficulties in representing displacement discontinuities especially when large-scale slip and separation occur as in the present case between the concrete face and the dam body.

In this paper, a new method is presented for numerical analysis of separation between concrete face and dam body in high CFRD. Direct constraints method and Coulomb friction law are proposed to simulate the contact behavior between the deformable concrete slab and cushion layer.

From the physical point of view, contact problem is a highly non-linear problem in boundary conditions. The analysis of contact behavior is complex because of the requirement to accurately track the motion of multiple geometric bodies, and the motion due to the interaction of these bodies after contact occurs. The numerical objective is to detect the motion of the bodies, apply a constraint to avoid penetration and apply appropriate boundary conditions to simulate the frictional behavior. Several procedures have been developed to treat these problems including the use of perturbed or augmented Lagrangian methods (Mottershead, 1993), penalty methods (Yagawa, et al., 1993) and direct constraints method (Chen, 2000). The Lagrange multiplier technique is the most elegant procedure to apply mathematical constraints to a system. Unfortunately, it leads to numerical difficulties with the computational procedure as their inclusion results in a nonpositive definite mathematical system. The lagrange multiplier technique has often been implemented in contact procedures using special interface element, which puts a restriction on the amount of relative motion that occur between bodies. The use of interface elements requires an apriori knowledge of where contact occurs. This is unachievable in many physical problems. The penalty method is an alternative procedure to numerically implement the contact constraints and it constrains the motion by applying a penalty to the amount of penetration that occurs. The choice of the penalty value can also have a detrimental effect on the numerical stability of the global solution procedure.

In the procedure of direct constraints method, the motion of the bodies is tracked, and when contact occurs, direct constraints are placed on the motion using boundary conditions both kinematic constraints on transformed degrees of freedom and nodal forces. This procedure can be very accurate if the program can predict when contact occurs. No special interface elements are required in this procedure and complex changing contact conditions can be simulated since no apriori knowledge of where contact occurs is necessary.

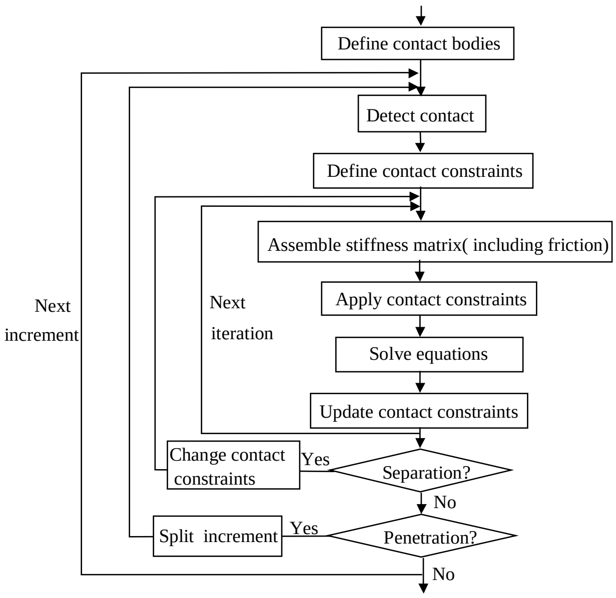


Fig. 5. Flowchart of the procedure of direct constraints method

Figure 5 shows a flowchart of the procedure of direct constraints method. It includes definition of contact bodies, detection of contact, implementation of constraints, friction modeling, changing contact constraints, checking the constraints and judgement of separation and penetration.

During the incremental procedure, each potential contact node is first checked to see whether it is near a contact segment. Because there can be a large number of nodes and segments, efficient algorithms have been developed to expedite this process. A bounding box algorithm is used so that it can be quickly determined whether a node is near a segment. If the node falls within the bounding box, more sophisticated techniques are used to determine the exact status of the node. During the contact process, it is unlikely that a node exactly contacts the surface. For this reason, a contact tolerance is associated with each surface. If a node is within the contact tolerance, it is considered to be in contact with the segment. During an increment, if a node penetrates into a surface, either the increment is divided into subincrements or the increment is reduced in size.

When a node of a deformable body contacts a deformable body, a multipoint constraint is automatically imposed. Recalling that the exterior edges of the other deformable bodies are known, a constraint expression is formed. For two-dimensional analysis, the number of retained nodes is three - two from the edge and the contacting node itself (Fig. 6). In the local coordinate system, the constraint equation can be represented as,

$$\Delta\overline{V}_A = 0.5(1-\xi_A)\Delta\overline{V}_B + 0.5(1+\xi_A)\Delta\overline{V}_C \qquad (1)$$

where, $\overline{V}$ is the normal displacement of contacted segment BC in the local coordinate system, ξ is the natural coordinate of contacted segment BC.

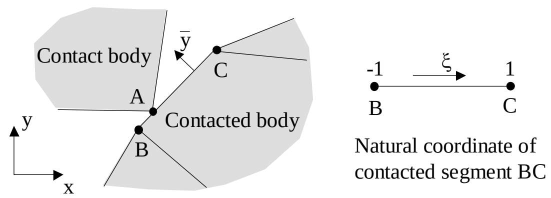


Fig. 6. Contact between 2-D deformable bodies

Friction is another complex physical phenomena in contact analysis. The friction features between concrete face and rockfill material are related to the roughness of the concrete slab, composition and mechanical properties of the rockfill material. In this paper, Coulomb Friction model, the most popular friction model, is used to simulate the friction characteristic between the concrete face and the rockfill material.

$$f_t \le \mu \cdot f_n \cdot t \qquad (2)$$

where, f_t is the tangential friction force, f_n is the normal force at the contact nodes, μ is the friction coefficient and t is the tangential vector in the direction of the relative velocity.

The constraint equation is such that the contacting node should be able to slide on the contacted segment, subject to the current friction conditions. This leads to a nonhomogeneous, nonlinear constraint equation. During the iteration procedure, a node can slide from one segment to another, changing the retained nodes associated with the constraint. A recalculation of the bandwidth must be made and the bandwidth optimization is also conducted.

After a node comes into contact with a surface, it is possible for it to separate in a subsequent iteration or increment. When contact occurs, a reaction force associated with the node in contact balances the internal stress of the elements adjacent to this node. When separation occurs, this reaction force behaves as a residual force. This requires that the internal stresses in the deformable body be redistributed. Depending on the magnitude of the force, this might require several iterations.

In this paper the dam body, stage-I slab, stage-II slab and stage-III slab were considered as four deformable contact bodies. The contact tolerance between the concrete face and the dam body took as 1mm and friction coefficient 0.3. A glue model was applied between face slabs, in which a very large separation force and no relative tangential motion were specified.

The detailed calculation procedure for the separation between the face slab and the dam body is as follows: first, according to the actual construction sequence, construction of El.682m temporary dam section is simulated. The calculated displacements in the dam body are eliminated in order to make stage-I concrete slab strictly contact with the upstream slope of El.682m temporary section, while the calculated stresses in the dam body are remained. Then by activating the elements of stage-I slab and continuing the simulation of the dam construction, the final values of the separation between stage-I face slab and the dam body and the deficient of the upstream slope for stage-II face slab are acquired when the construction of the dam body of El.748m temporary section finished (after the construction phase ⑨ in Fig. 2 and before the construction of stage-II slab). Similarly, by eliminating the calculated displacement of the dam body and continuing the simulation of the dam construction according to the actual constructive sequence, the final values of the separation between stage-II face slab and the dam body and the deficient of the upstream slope for stage-III face slab can be gained when the construction of the whole dam body was completed.

Constitutive Model for Concrete Face and Rockfill

The concrete face was modeled as linear elastic material, with elastic modulus 3×10^4MPa, Poisson's ratio 0.2. Duncan and Chang's E-B constitutive model (Duncan, et al., 1980) was applied to rockfill materials. In Duncan and Chang's E-B model for soil, it is defined that the stress-strain relation of soil can be represented as the following hyperbola equation,

$$\sigma_1 - \sigma_3 = \varepsilon_1 /(a + b\varepsilon_1) \tag{3}$$

where, $(\sigma_1 - \sigma_3)$ is deviatoric stress, ε_1 is strain in axial direction corresponding to $(\sigma_1 - \sigma_3)$, a and b are two parameters determined by soil properties.

A function about the initial deformation modulus E_i of soil was proposed as,

$$E_i = k \cdot P_a (\sigma_3 / P_a)^n \tag{4}$$

where, P_a is the standard air pressure, k and n are two parameters which can be acquired form laboratory tests.

The tangent deformation modulus E_t can be obtained from the differential of equation (3) to ε_1 while Mohr-Coulomb law is used,

$$E_t = [1 - R_f (1 - \sin\phi)(\sigma_1 - \sigma_3)/(2c \cdot \cos\phi + 2\sigma_3 \sin\phi)]^2 E_i \tag{5}$$

where, c is cohesion intercept, ϕ is the angle of internal friction, R_f is a correlation factor called "failure ratio".

For coarse particle soil, the cohesion intercept c is generally taken as zero and the angle of internal friction ϕ is acquired by the following expression,

$$\phi = \phi' - \Delta\phi \log(\sigma_3 / P_a) \tag{6}$$

where, ϕ' is the friction angle of coarse particle soil while σ_3 is the standard air pressure.

The bulk modulus of soil was proposed in the following form,

$$B_t = k_b P_a (\sigma_3 / P_a)^m \tag{7}$$

where, k_b and m are two parameters which can be acquired from laboratory tests.

Two main characteristics of soil behavior, non-linearity and stress dependency, are accounted for in Duncan and Chang's E-B model because the deformation modulus E_t and bulk modulus B_t of soil change with the stress state.

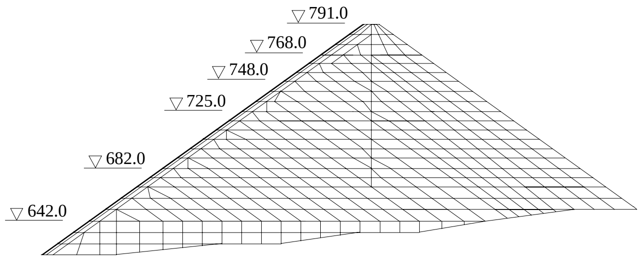


Fig. 7. 2-D finite element mesh

Computational Section and Parameters

A two-dimensional finite element analysis was conducted to study the separation of the concrete slab from the cushion and the deficient of the cushion layer in TSQ-I dam. The maximum cross-section in station 0+630m, which is located in the middle of the riverbed and is also the major section monitored, was chosen as the computational section. Fig. 7 shows the finite element mesh used in the FEM analysis, with a total of 402 dam elements and 46 concrete face elements. Since the dam is located in a wide valley (crest length/dam height equals 6.4), three-dimensional effect at the maximum cross-section is negligible. Thus two dimensional plane strain conditions were assumed.

Table 2. Computational Parameters

	Mat. No.	Density kg/m^3	ϕ' [°]	$\Delta\phi$ [°]	k	n	R_f	k_b	m
1	IIA	2200	50.6	7.0	1050	0.35	0.71	480	0.24
	IIIA	2100	52.5	8.0	970	0.36	0.76	440	0.19
	IIIB	2100	54.0	13.0	940	0.35	0.85	340	0.18
	IIID	2050	54.0	13.5	720	0.30	0.80	800	-0.18
	IIIC	2150	48.0	10.0	500	0.25	0.73	250	0.00
2	IIA	2200	50.6	7.0	1000	0.35	0.71	450	0.24
	IIIA	2100	52.5	8.0	900	0.36	0.76	400	0.19
	IIIB	2100	51.0	13.0	564	0.35	0.85	204	0.18
	IIID	2050	51.0	13.5	432	0.30	0.80	300	-0.18
	IIIC	2150	45.0	10.0	250	0.25	0.73	125	0.00

where, 1 - Parameters from Laboratory Tests;
2 - Parameters from Back-Analysis.

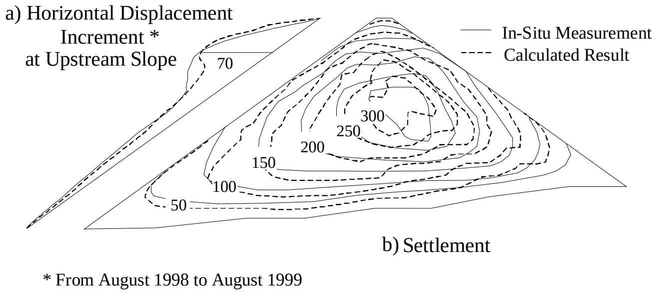


Fig. 8. Deformation measured in-situ and calculated from back-analysis (Unit: centimeter)

Table 2 gives the computational parameters of the rockfill materials. Because the calculated deformation of the dam body using the model parameters from laboratory tests is much smaller than the actual measurements (Zhao, et. al., 2002), a back-analysis was made based on the in-situ measurements. Fig. 8 shows a comparison between calculated results from back-analysis and in-situ measurements of the dam deformation (in August 1999). A good agreement is observed in terms of settlement values and horizontal displacement increment at the upstream slope.

NUMERICAL RESULTS AND DISCUSSIONS

The calculated results of the separation between face slab and cushion layer with parameters from laboratory tests and back analysis are presented in Fig. 9 and Fig. 10, respectively. From the figures, it can be observed that the top of stage-I and stage-II face slabs are both separated from cushion layer, and the deficient of the upstream slopes for stage-II and stage-III concrete slabs also occurred.

Table 3 is a comparison of the calculated and measured results. From Table 3, it can be seen that the calculated openings and deficient with the parameters from laboratory tests are lower than that observed in-situ, except for the opening between stage-II slab and cushion. This situation is similar to the calculated deformation of the dam body with the parameters from laboratory tests and in-situ measurements.

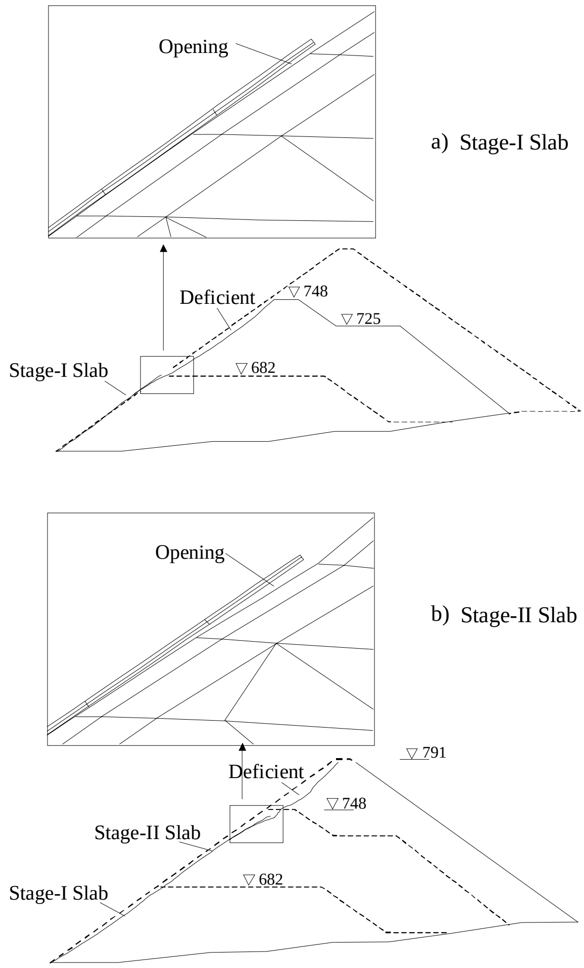
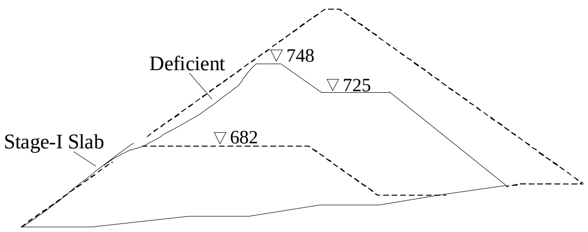


Fig. 9. Calculated deformation of the slab and upstream slope with laboratory parameters

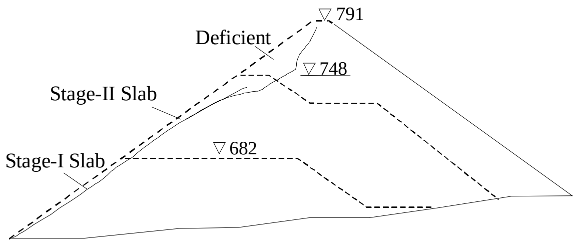
(The deformation is scaled up by 20 times in the global section and 5 times in the detailed gragh.)

Both of them indicate that the rockfill materials used in the dam construction have a greater deformability than the materials for laboratory tests. It also can be seen that there is a good agreement of the calculated results with parameters from back analysis and in-situ measurements, except for the separation between the stage-II slab and the cushion layer.

Some engineers and scholars considered that the separation between the concrete face and the cushion layer in TSQ-I dam is mainly induced by the creep deformation of the dam body. From the calculation procedure with parameters from



a) Stage-I Slab



b) Stage-II Slab

Fig. 10. Calculated deformation of the slab and upstream slope with parameters from back-analysis

（The deformation is scaled up by 20 times.）

Table 3. Calculated and Measured Results of the Openings and Deficient (Unit: meter)

Opening and Deficient		1	2	3	4
Stage-I Slab	Opening Width	0.15	0.07	0.13	0.12
	Opening Depth	7.2	7.0	8.0	7.5
	Max. Deficient	0.43	0.26	0.45	0.50
Stage-II Slab	Opening Width	0.10	0.20	0.40	0.25
	Opening Depth	5.0	12.0	14.0	13.0
	Max. Deficient	1.03⑤	0.52	1.00	0.93

where,
1- In-situ Measurements;
2 - Calculated Results with Parameters from Laboratory Tests;
3 - Calculated Results with Parameters from Back-Analysis;
4 - Calculated Results when Constructed Layer by Layer;
5 - 0.78m (the measured deficient) + 0.25m (over constructed layer).

laboratory tests, since the creep behavior of the rockfill materials was not considered in the calculation, it can be seen clearly that the openings and deficient are caused directly by the gravity loads of the newly compacted rockfill layers. Take the stage-I face slab for an example. When continuing to construct the dam body after stage-I face slab was concreted, the previous compacted rockfill layers at El.682m temporary section, which support the stage-I slab, will produce additional vertical and horizontal deformation under the gravity loads of the newly added layers. While the concrete slab cannot deform harmoniously with the cushion layer due to its high stiffness, the separation between stage-I slab and the dam body must take place. The occurrence of the cushion layer deficient can also be explained that the gravity loads of the newly compacted layers induce a large vertical displacement to the previous constructed layers. From the analysis, it can be concluded that in high CFRD, the separation between the face slab and the dam body and the deficient of the cushion layers are inevitable when the face slab is concreted in stages due to the requirement of river diversion. In order to reduce the opening, the top of staged concrete face slab should be lower than the top of the temporary dam section for supporting it. The creep deformation of the dam body is not the essential factor leading to the separation of face slab from cushion layer and the deficient of cushion layer.

It is important to note that creep deformation of dam body is remarkable in high CFRD. In the back-analysis, the creep deformation is included in the whole measured deformation. So the influence of rockfill creep behavior on the openings of stage-I and stage-II slabs and the deficient of the upstream slope for stage-II and stage-III slabs was involved in the calculation results with the parameters from back-analysis. However, because the rockfill creep characteristic was not modeled in this study, the separation between stage-III slab and the dam body could not be obtained from this calculation.

In order to study the effects of construction stages on the openings, another calculation was performed, in which the concrete face was still concreted in three stages while the whole dam body was constructed layer by layer in the entire cross- section. That is to say that during the construction there was no elevation difference in the entire cross-section. In this calculation, the finite element mesh shown in Fig. 7 and the parameters obtained from the back-analysis given in Table 2 were used, the process of reservoir filling was ignored. The calculation result is also summarized in Table 3. It can be seen clearly that the openings of stage-I and stage-II slabs from the dam body are smaller than the calculation results in actual construction stages, especially the opening of stage-II slab from the dam body (if reservoir filling is considered, the difference will be larger). Thus it can be concluded that optimization design of the temporary dam sections to lessen the construction elevation difference between the blocks in different construction stages can reduce the openings to some extent. It can also be seen that not much improvement is achieved for the deficient of cushion from using the new construction stages.

Furthermore, the evolution of the separation between stage-II slab and the cushion was traced. Fig.11 and Table 4 respectively give the phases of the dam construction after concreted the stage-II slab and the corresponding results of the calculation. From this result, one can know that the opening at the top of stage-II slab already reached 31cm wide when the construction of the dam body of El.768m temporary section finished. It is shown that the gravity loads of the rockfill layers adjacent to the top of the face slab are the primary factor of the separation. With the reservoir impounding, the face slab was gradually pressed to the cushion layer and the opening only existed above the water level. As a result, when the upstream water level reached El.737m, the width of the opening at top of the stage-II slab decreased by 5cm and the depth of the opening decreased drastically. By construction of the downstream block behind the El.768m temporary section, from the dam foundation to EL.733m (construction phase ③ in Fig. 11), the 80m high rockfill's gravity loads induced the opening to widen only by 6cm. And this illustrates that the construction of the downstream block, which is far from the face slab has relative smaller influence on the opening. In the following construction phases, the width of the opening increased by 8cm caused by the gravity loads of the 58m high rockfill block (construction phase ④ and ⑤ in Fig. 11). This indicates that the gravity loads of rockfill layers adjacent to and above the top of stage-II face slab have relatively great influence on the opening. From table 4, it can also be seen that the deficient of the cushion layer increased with the dam construction by the gravity loads of the newly added rockfill layers.

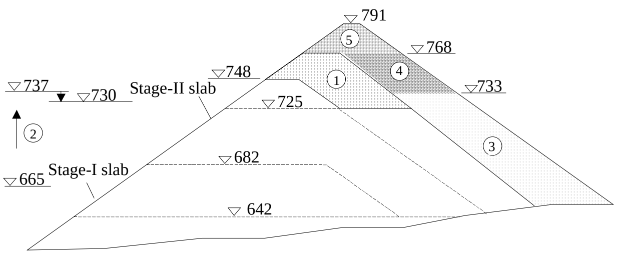


Fig. 11 Construction phase after concreted of stage-II slab

Table 4. Evolution of the Opening between Stage-II Slab and the Cushion Layer (Unit: meter)

Construction Phase	Opening Width	Opening Depth	Max. Deficient
1	0.31	13.0	0.62
2	0.26	7.5	0.69
3	0.32	13.5	0.76
4	0.36	13.5	0.84
5	0.40	14.0	1.00

CONCLUSIONS

In this paper, a new method for numerical analysis of separation between concrete slab and cushion layer in high CFRD was proposed, in which direct constraints algorithm and Coulomb friction law were used to simulate the contact behavior between concrete face and dam body. The effectiveness of the method was confirmed by applying it to the TSQ-I CFRD.

The results of the study indicated that the separation between face slab and dam body and the deficient of cushion layer are inevitable in high CFRD when the face slab is concreted in stages due to the requirement of river diversion. The primary reason for the separation was found to be that the previous constructed rockfill blocks, which support the face slab, produce additional vertical and horizontal deformation under the gravity loads of the later compacted rockfill blocks but the concrete slab cannot deform harmoniously with the cushion layer due to its high stiffness. The deficient of cushion is also caused by the large vertical deformation of the previous constructed rockfill blocks under the gravity loads of the later compacted rockfill blocks. Although creep deformation of the dam body can increase the separation and the deficient, it is not the essential factor.

To reduce the separation between the concrete face and the dam body and the deficient of the cushion layer, it is suggested that: 1) the top of staged concrete face slab be lower than the top of the temporary dam section supporting it; 2) the temporary cross-sections of the dam be optimized in order to reduce the elevation difference between the blocks in different construction stages.

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