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Study on real working performance and overload safety factor of high arch dam

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Considering the fact that high arch dams have problems such as complicated stress, high cost, and hazards after being damaged, this paper intends to study the effects of load, material strength, and safety analysis method on dam safety and working performance of arch dams. In this article, the effects of temperature, self weight exaction way and water loading on structure response are first discussed, and a more reasonable way of considering is then put forward. By taking into consideration the mechanical property of materials and comparing the effects of different yield criteria on overloading safety of high arch dams, this paper concludes that brittle characteristics of concrete should be fully considered when conducting safety assessment for high arch dams to avoid overestimating the bearing capacity of the dams. By comparing several typical projects, this paper works out a safety assessment system of multiple safety and relevant engineering analogical analysis methods, which is closer to the actual situation, and thus is able to assess the response of high arch dam structure in a more comprehensive way, elicit the safety coefficients in different situations, and provide a new way of considering the safety assessment of high arch dams.

high arch dam, real working performance, safety, load, strength, safety assessment method

1 Introduction

The real working performance and safety assessment of high arch dam is a core subject in the field of hydraulic structure. Many experts have made great efforts, and obtained fruitful results. There are three aspects related to the real working performance and safety assessment of high arch dams, i.e. load of foundation-dam system[1], strength of rock and concrete[2], and methods of safety assessment[3,4]. These three aspects should be considered together.

The load of foundation-dam system is the sum of loads acted on the whole structures, includ-

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ing self weight, water pressure, temperature, seepage, etc., and the response of dam is related to the loading process of all these loads. All loads have been considered in current safety assessment and design of high arch dam. However, due to the limit of analysis methods, theses loads have been usually simplified into the following manners: (i) Temperature loads of arch dam have been separated subjectively into two parts: the temperature loads of construction period and of operation period which are not overlapped. The temperature boundary conditions calculated by the temperature load in operation period is different from the one in practical situation; (ii) the impact of operation process is not considered in calculating self weight; (iii) there are no unified methods on consideration of reservoir basin water pressure, and no sufficient attention is paid to the consideration of the influence of by-stage impoundment; (iv) seepage analyses are more often conducted separately, with safety assessment of high arch dam considered in accordance with the simplified uplift pressure formula, or even not considered at all.

The strength of materials in foundation and dam is the critical factor influencing the bearing capacity of the system. For foundation, the bearing capacity is influenced mainly by the strength of discontinuity. At present, the strength of discontinuity is often estimated by tests and experience. However, different strength values of the same discontinuity may be given by different ways of test and experts. Hence, these parameters are of great uncertainty. There are also some confusions in the consideration of concrete strength[5], including (i) the influence of shape, size and gradation of specimen. Experimental studies show that great difference of tensile strength exits between large specimens and small specimens, though the compressive strength is about same. According to many experiment data, the tensile strength ratio of small specimen to fully-grade specimen is mostly between 0.6 and 0.7, for some concrete laies between 0.5 and 0.6. The disparity of strength should be taken into account in safety assessment; (ii) the strength of concrete can be affected by loading rate. Commonly, the strength will increase with loading rate increasing, and the ratio of strength of concrete under loading rate of 2 MPa/s to that under loading rate of 0.02 MPa/s is 1.26[6]. In fact, the real loading rate is far slower than that in indoor test; (iii) the strength of concrete can be greatly affected by age and loading duration time. If the same concrete sample is loaded by general rate with bearing loading of P, it will be destroyed when the load is $0.9P$ for load duration of an hour, $0.77P$ for one year, and $0.7P$ for about 30 a. Most of strength tests are conducted on concrete of an age of 90—180 d to evaluate the safety of high arch dams, the subsequent strength increment are taken as safety reserve. The effect of loading rate and loading time on strength is studied inadequately. In order to cognize the real performance and long term safety of dams, more attention should be paid to the long-term strength and durability of concrete.

Analysis method is a key factors in the safety assessment. In the current dam safety analysis, there are a variety of methods[7,8], including experimental methods[9,10], empirical methods[11], numerical methods[12−15] and so on. Experimental methods can be used to obtain the process of damage on dam body and overload factors under set conditions, but it is difficult to replicate due to the great cost and time, and unsolved problems still exist in similarity of experimental model to the real structure and simulations under different loads. Empirical method refers to some given design criteria and experience factors based on the safe operation of the dam, such as stress control standards and slenderness coefficient of arch dams. This method can be applied to evaluating the relative safety of arch dams, but is hard to reflect the specific working performance of dams, and is thus a rough method of safety assessment. Based on different theories of mechanics, the method of numerical analysis reasonably simplifies the structure and simulates in a more detailed way to work out the distribution of stress and deformation. Among different numerical methods, nonlinear finite element method is commonly used.

Strength criterion in nonlinear analysis has considerable influence on the results. Generally, rock discontinuity is analyzed with Mohr-Coulomb criteria, while intact rock and concrete with Drucker-Prager criteria[16,17]. It may be appropriate to analyze rock foundation with Mohr-coulumb criteria and Drucker-prager criteria. But the application of Drucker-prager criteria to concrete will exaggerate the bearing capacity of dam. The ideal elastic-plastic model is frequently used in nonlinear calculation[18]. This model is suitable for simulating the flow failure of medal and plastic materials, but it also exaggerates the bearing capacity of brittle materials including concrete and rock.

Simplification and uncertain factor exist regarding to load, material parameters and methods in safety assessment of high arch dam. These uncertainty might be covered by greater empirical safety factors in the assessment of medium and low arch dams. But for high dams, especially for the super-high arch dams, some problems and uncertain exceed our experiments and knowledge, and cannot be simply covered by the same safety factor with common arch dam.

In this paper, some factors that influence the safety of arch dam will be discussed. Three perspectives, including the load, strength of concrete and analysis methods, relating to the real working performance of arch dam are studied.

2 Real load of high arch dam

2.1 Temperature

Arch dam is hyperstatic 3D shell structure with rim restricted by bedrock, temperature load accounts for a large proportion of the total load, and both temperature rise and drop can cause tension-compression stress in different parts. It is important to evaluate the effect of temperature load on the safety of high arch dam.

2.1.1 Effect of residual thermal stress in construction period. Only the temperature load after sealing is considered in the current standard, while the residual thermal stress produced in the construction process is not considered. In fact, the residual stress produced in the construction process does not disappear but goes to the operation period and should be superimposed with stresses in operation period[19], and it is one of the reasons that cause cracks in dam body during the operation. Figure 1 shows the distribution of vertical stress above 1 m of the base surface of one monolith caused by temperature load in construction period before sealing. The tensile stress on upstream and downstream surface is about 0.3—0.6 MPa. Stress inside is compressive stress. Figure 2 shows the contour of stress along river flow direction in middle section of some monolith when the arch is sealed, and the maximum residual stress along river flow direction is 1 MPa in base restrained area. The residual stresses will be brought into operation period as initial stresses.

2.1.2 Uncertainty of temperature boundary conditions in operation period. Calculation of temperature load in operation period starts from sealing temperature, and with annual mean temperature and annual temperature change taken into consideration, the increase and decrease values of temperature field of arch dam are calculated and equated into average temperature difference, linear temperature difference and nonlinear temperature difference. Only the average temperature and linear temperature difference are considered in the current arch dam specifications.

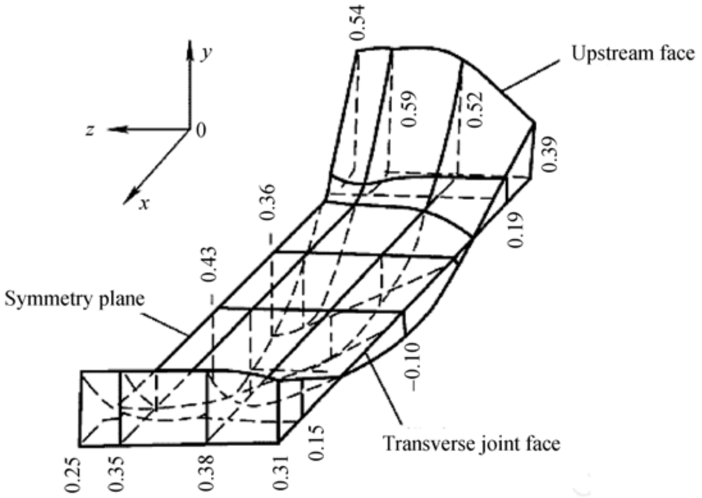

Figure 1 Vertical stress (MPa) caused by temperature change in construction period before sealing.

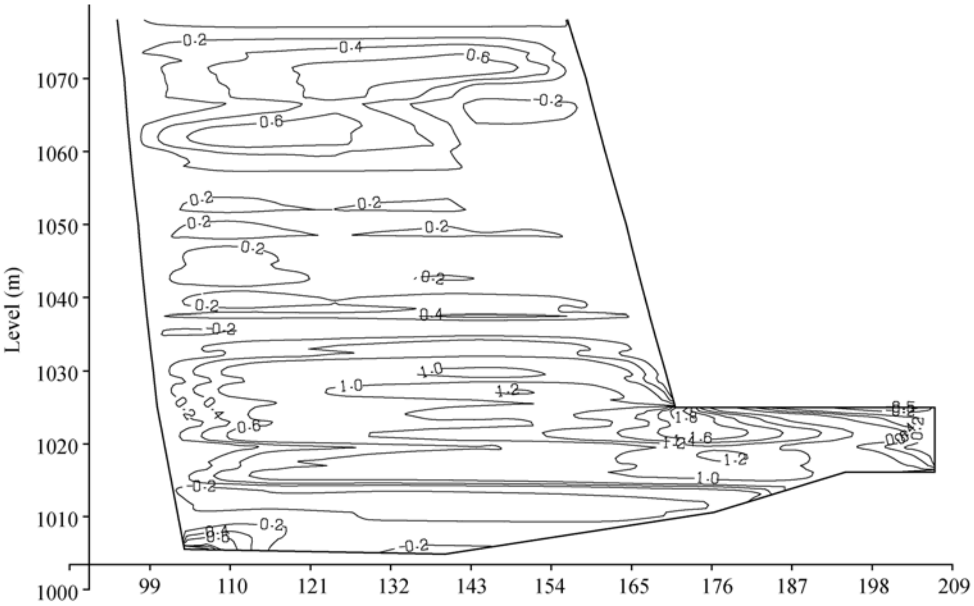

Figure 2 Stress (MPa) along river flow direction of an arch dam.

Actually, annual average temperature and temperature change of arch dam are affected by various factors such as reservoir water temperature, air temperature and radiant heat, of which the most uncertain factor is reservoir water temperature. Generally, the reservoir water temperature of arch dam is calculated by the finite element method considering the main factors such as the shape of reservoir, hydrological and meteorological conditions and reservoir operation conditions, all of which might affect the distribution of reservoir water temperature. But the observed data indicate that actual reservoir water temperature distribution has significant difference from the predicted one, especially the temperature at the bottom of reservoir. With regard to a high arch dam, the measurement and calculation results of water temperature distribution in a reservoir are shown in Figure 3, with a preferable agreement in the upper part, and a large gap of differences on the bottom.

Such differences have a direct impact on the calculation accuracy of dam loading and thereby on the evaluation of working performance and safety assessment of dam. Some experts propose an enveloping method in the design period. In this method, the probable maximum and minimum reservoir temperature would be predicated according to the existing conditions, and then appropriate sealing temperature is adopted to ensure that the dam body stress meets the requirement when the reservoir water temperature is the highest or the lowest.

In light of the feedback data on the temperature of Ertan Reservoir, according to hydrology, meteorology and reservoir conditions of Jinping-1, the maximum, minimum and median water temperatures of Jinping-1 reservoir are predicted as is shown in Figure 4, and the difference between the maximum and minimum water temperature at bottom of reservoir is about 3—5℃. The stress can be changed by about 0.05—0.1 MPa due to the 1℃ sealing temperature change according to the results. It is obvious that the stress induced by temperature difference of reservoir shown in Figures 3 and 4 should not be ignored.

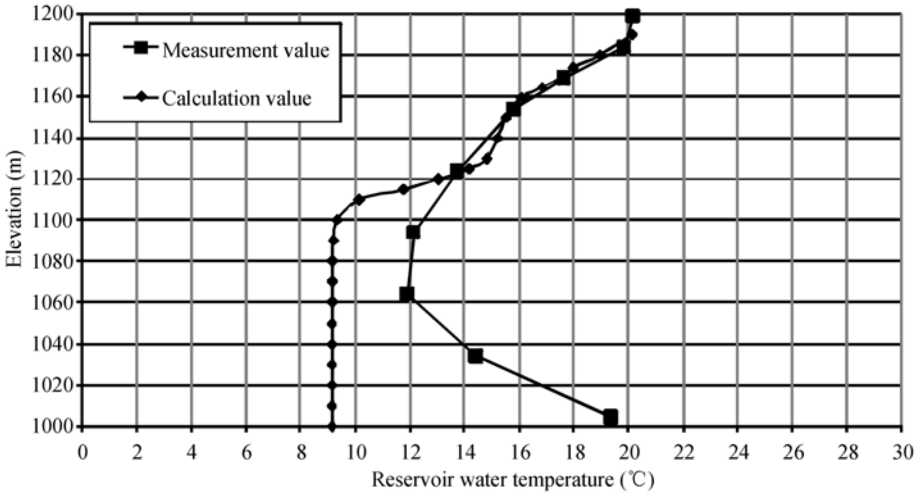

Figure 3 Measurement and calculation results of reservoir water temperature for high arch dam.

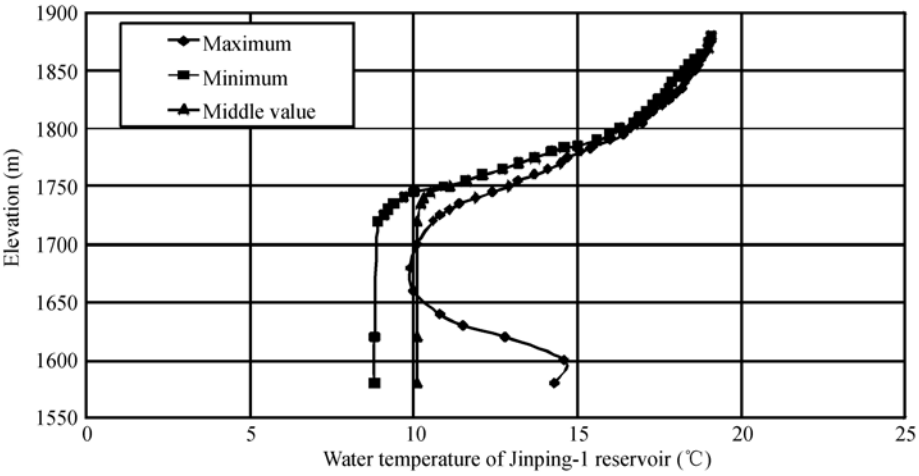

Figure 4 Predicted maximum, minimum and median water temperature of Jinping-1 reservoir.

2.1.3 The impact of nonlinear temperature difference in operating period. Stress of dam is affected greatly by nonlinear temperature difference in operation period. As an example, Figure 5 illustrates linear temperature difference in contrast with nonlinear temperature difference of Laxiwa Arch Dam crown cantilever, as well as stress distribution along river direction under the above temperature loads. The figure shows that a difference of 8—10℃ exists between linear temperature and nonlinear temperature on the dam surface. The stress value of dam surface can increase by 1.7 MPa when nonlinear temperature is considered. A super-high arch dam in southwestern China has been built under strict quality and temperature control. Rare cracks have been found in the dam after construction. But a few years later, many cracks in the dam appeared constantly. It is proved that these cracks are directly related to nonlinear temperature difference[10].

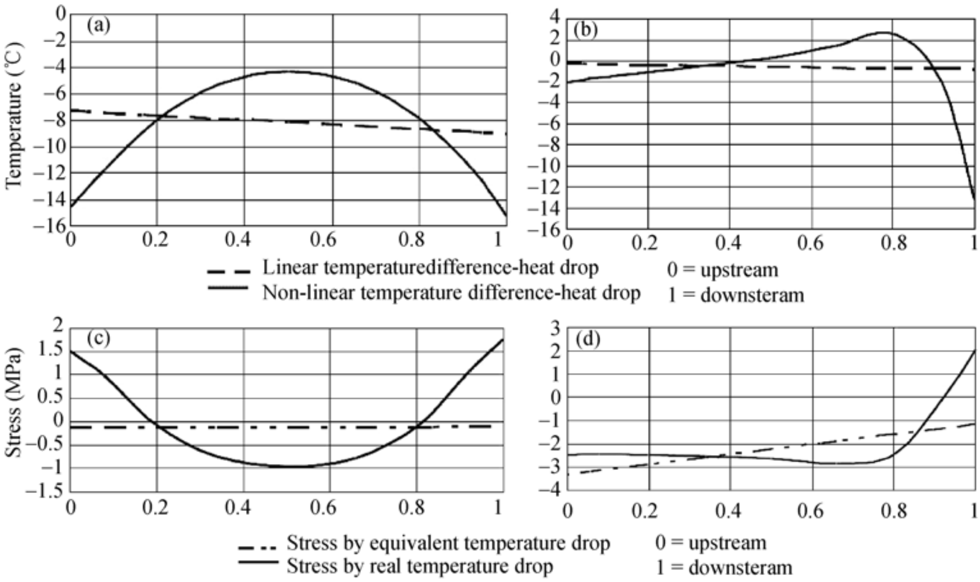

Figure 5 Comparison between linear and nonlinear temperature difference influenced stress. (a) Comparison of temperature drop at the bottom height of crown cantilever; (b) comparison of temperature drop on the top height of crown cantilever; (c) comparison of cantilever stress at the bottom height of crown cantilever; (d) comparison of cantilever stress on the top height of crown cantilever.

2.2 Self weight

Arch dam is constructed with monoliths, and then an arch is completed by grouting. The monolith sustains all of the self weight before sealing. Once an arch dam is formed after sealing, self weight is placed on both the beams and arches. Stress distribution of super-high arch dam would be significantly affected by calculating mode because of huge self weight[20].

There are two calculation modes for self weight: One by an integral and the other by stages. The latter can be divided further into two ways: One is integral arch layer without considering the grouting process, and the other takes the arch layer into blocks and the grouting process is considered. Suppose the whole dam is divided into n layers in the first way:

$$H_i = \Delta H_1 + \Delta H_2 + \Delta H_3 + \cdots + \Delta H_i, \quad i = 1, \cdots, n. \tag{1}$$

The calculation is performed layer by layer from the bottom, and self weight of each layer is shared by the whole integrated part of dam. The process is shown in Figure 6.

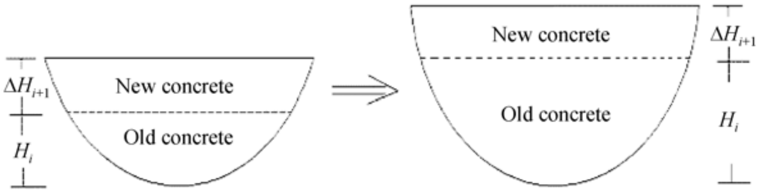

Figure 6 Self weight consideration by arch layers.

The dam is divided into *n* layers in the second way just like first one, but further divided into blocks. The beams sustain self weight singly above the sealing height. The increased load is shared by beams and arches in the integrated part formed under the grouting height, as is shown in Figure 7.

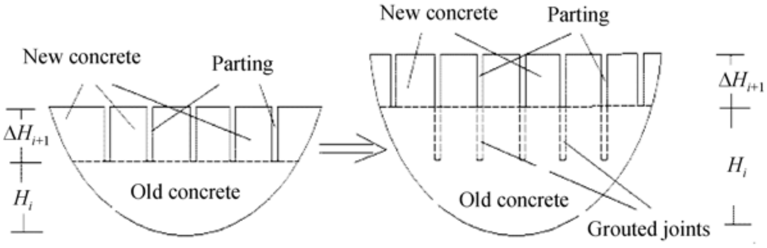

Figure 7 Self weight consideration by arch layers and blocks.

We take the Xiluodu Arch Dam as an example to study the influence of self weight consideration on the stress distribution. The dam is divided into different numbers of layers, such as 1, 2, 4, 8, 15, 28 separately. The results obtained by two ways are shown in Table 1.

Table 1 Heel stress of Xiluodu Arch Dam (MPa)

Number of layers	Layer by layer	Layer and block
1	−11.74	−16.65
2	−12.87	−15.27
4	−13.57	−14.69
8	−13.97	−14.60
15	−14.16	−14.33
28	−14.26	−14.27

When the dam is considered as an integral one and the self weight is set by one step, the whole dam weight is passed down to beams and arches, more self weight is passed to abutment of the dam, thus the heel stress of crown cantilever is the minimum, and the load sustained by the base surface is the least. When the dam is modeled by the multi-layer way, self weight is transfered by beams in larger proportion compared with the one-step way. Obviously, the multi-layer way enhances the beam effect. The heel stress of crown cantilever and the load placed on the base surface will become larger with the number of layer increasing. When an arch is divided into blocks and all the self weight is set to monolith, heel stress is the largest because each cantilever sustains all the self weight independently. Heel stress will decrease with the number of layer increasing, but the rate decreases gradually and tends to a steady value.

The results show that heel stress got by two ways will be close when the number of layer is big enough. Therefore, a preliminary conclusion can be drawn that the impact of transverse joints on self weight can be neglected when the number of self weight loading stages is big enough.

2.3 Water load

2.3.1 Effect of water pressure on dam basin. Water pressure is the main load of arch dam. Water acts on the surface of a dam directly, while bedrock is affected by seepage pressure. There are three modes to simulate basin pressure, that is, the mode without considering bedrock pressure, the mode considering full water load by surface force, and the one considering as seepage force. The stress result is different when different modes are used. The Xiluodu Arch Dam is taken for an example, and three-dimensional finite element analysis is made in three modes, namely: (i) Only water pressure on dam surface is considered, and reservoir water pressure is ignored; (ii) both water pressures on dam surface and bedrock are considered; (iii) water pressures on dam surface and bedrock seepage pressure are considered. The result is shown in Table 2.

Table 2 Effect of reservoir water pressure on stress of Xiluodu Arch Dam (MPa)

Position	Upstream crown cantilever				Upstream of base surface	
	Maximum tensile stress	Maximum tensile vertical stress	Range of tensile stress (m)	Range of vertical tensile stress (m)	Maximum tensile stress	Maximum vertical stress
Water pressure on dam surface	10.01	8.70	37.2	32.2	12.82	10.43
Water pressure on dam surface +bedrock	12.09	11.08	59.5	29.8	15.94	12.49
Water pressure at dam surface +seepage of foundation	11.53	10.04	59.5	32.2	14.52	11.70

From the result, we can find that the maximum tensile stress and vertical tensile stress increase by 10%—20% with consideration of basin water pressure; an increase can also be seen in the tensile stress range at foundation plane. For basin water pressure, the tensile stress and vertical stress calculated by imposing pressure on reservoir basin are greater than that by seepage force, but it does not exceed 10%. So it underestimates the water load if only water pressure on dam surface is considered, and overestimates the water load with method of surface force. When conditions are allowed, the water pressure on reservoir basin should be considered as seepage force in bedrock.

2.3.2 Effect of impoundment. In fact, reservoir water is impounded by stages and water level increases gradually. The one-time overall water loading was mainly adopted in the common calculation; the result of this method is different from that of actual impoundment. In order to compare the effect of different ways of water loading on dam stress, the Xiluodu Arch Dam is taken as an example, and a total of 4 cases are calculated, i.e., impoundment by stages 1, 2, 4, 7; only water pressure is taken into consideration in each case. From Table 3, it can be seen that with step increase of sealing by layers and impoundment, the vertical tensile stress increases gradually. During the period of sealing and impounding by stages, the lower part of water pressure is supported by lower part of the dam, and the water pressure increment caused by the water level increase is borne by upper and lower parts of the dam. But, if the whole water pressure acts upon the dam face step by step, all the water load is supported by the integrated dam. Therefore, stress at dam heel of sealing and impoundment by stages is larger than that of one-time impoundment after the dam being completed and arch being sealed. Meanwhile, the tensile stress at dam heel increases with the increase of steps of sealing and impoundment by stages.

Table 3 The effect of water impounding on the dam stress (MPa)

Steps of sealing and impounding	Vertical stress at dam heel	Maximum principal stress of dam
1	15.53	21.5
2	15.97	21.8
4	16.91	22.6
7	18.35	23.9

From the specific data, we can find that the tensile stress of dam heel of impounding by stages is 20% stronger than that of one-time impounding. The dam stress tends to steady under more stages of impounding. Therefore, in safety analysis of high arch dams, the effect of water impounding by stages should be taken into consideration.

3 Nonlinear finite element method and yield criteria

Ideal elastic-plastic model is commonly used in the calculation of arch dam nonlinear problems, i.e. strength of material remains a certain value after the yield, as is shown in Figure 8(a). But as a kind of brittle material, the strength of rock and concrete will decrease by a certain degree once yielded, or even disappear. For example, tensile strength of concrete should be zero after it was damaged by tension stress, and cohesion and friction coefficients will also decrease. Obviously, the safety factor obtained from ideal elastic-plastic model overestimates the bearing capacity, in order to avoid this problem, brittle fracture model can be used here to consider strength softening of yielded materials, as is shown in Figure 8.

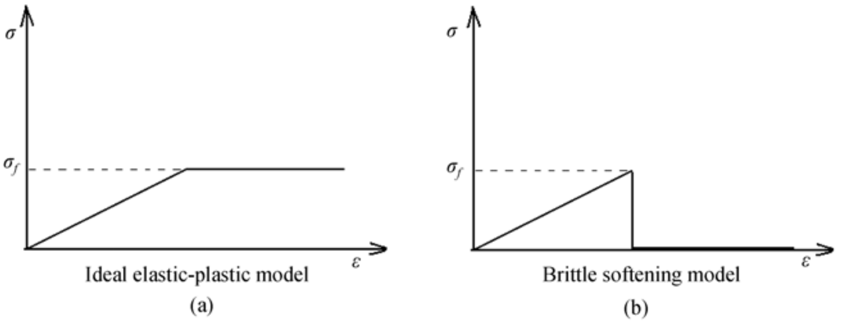

Figure 8 Different constitutive models.

Here Kolnbrein Arch Dam is taken as an example and the effect of different extended criteria on arch dam safety is investigated. Material parameters are shown in Table 4. Four criteria are used: (i) Ideal elastic-plastic model with tension and shear failure; (ii) tension softening model; (iii) tension and cohesion softening model; (iv) ideal elastic-plastic model with tension, compression and shear failure. The overloading factor is defined as the times of normal water load. The overloading factor-displacement along river direction is shown in Figure 9. The figure shows that, when only tensile softening is considered, dam deformation increases and bearing capacity decreases slightly as compared with the value obtained from the result without considering softening; when both types of softening are considered, bearing capacity will decrease about 13% compared with the result without considering softening. The bearing capacity is the least when tension, compression and shear failure are all considered. Thus, the bearing capacity of arch dam calculated with ideal elastic-plastic model is exaggerated if compression failure and softening are

Table 4 Materials parameters of rock and concrete

Material	Density (kg/m^3)	E (GPa)	υ	c' (MPa)	f'	f_t (MPa)	f_c (MPa)
Rock	2450	7—30	0.30	0.2—3.0	0.8—1.3	0	40
Concrete	2370	26.0	0.20	4.0	1.3	3	30

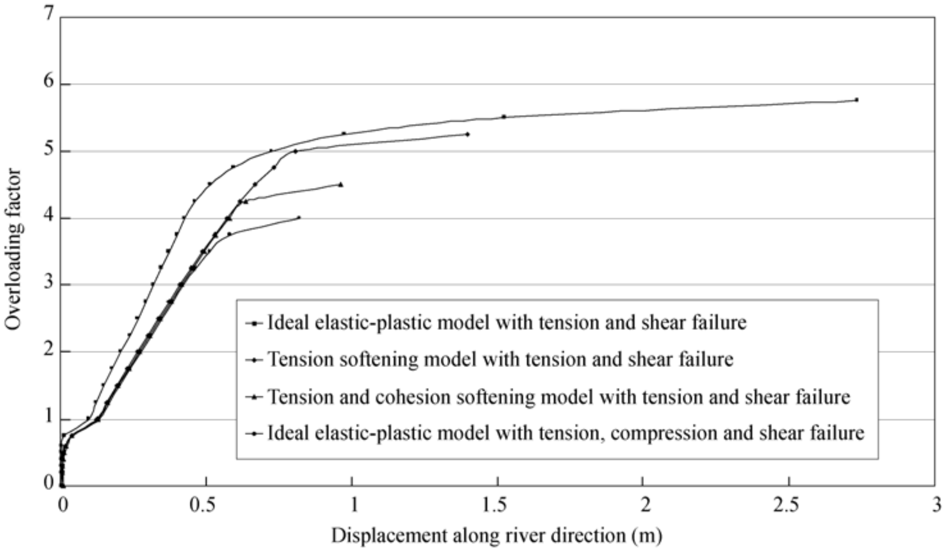

Figure 9 Overloading factor-displacement along river direction of dam crest under different models.

not considered.

4 Analogical analysis

Engineering Analogy is one of the methods to conduct safety analysis of high arch dam[21]. By the same method, analyzing the stress, deformation and safety factor of some dams in operation with similar condition, we can get a overall safety estimate for dam under design or construction. Table 5 lists the main characteristic of 6 arch dams. Here five arch dams in operation are chosen to do the analogical analysis with Xiaowan Arch Dam. Using the method of nonlinear FEM, the bearing capacity of 6 arch dams and damage process are simulated with a similar model. During the simulation, main loads, construction process, and impounding process are considered. After normal water level is reached, overloading by increasing density of water begins. Table 6 shows the calculation results. According to the definition given by Jin et al.[7], four safety factors (k_1—k_4) are given in the table, while k_1 is the overloading value of the crack depth from the dam heel to anti-seepage curtain, k_2 is that of the notable inflexion of the curve of overloading value-plastic yield volume of the dam, k_3 is that of the notable inflexion of the curve of overloading value-crest deformation, and k_4 is overloading value when calculation is not convergent[6].

Table 6 shows that, when the water is impounded at 0.7—0.8 times of the normal water head, the failure zone penetrate the anti-seepage curtain for Kolnbrein, Sayano-Shushenskaya and Shimen dams. In the practical operation, there has been serious leakage in the impounding period of those dams. When Xiaowan Arch Dam reaches normal water level, yield zone at dam heel can spread to the vicinity of the curtain, which calls for more attention. Yield zone of other two arch dams and reinforced Kolnbrein dam has not reach the curtain when the dams reach their normal

Table 5 Main characteristic of the 6 dams

Project's name	Dam height (m)	Crest length (m)	Maximum width (m)	Arch length-height ratio	Thickness-height ratio	Water thrust (10^4 t)
Xiaowan	294.5	892	73.12	3.029	0.248	1900
Sayano	245	1066	110.75	4.35	0.452	1530
Kolnbrein	200	626	37	3.13	0.185	876
Lijiaxia	155	414	45	3.04	0.29	242
Tengzigou	124	339.475	20.01	2.73	0.161	131
Shimen	88.6	254	27.3	2.867	0.308	55.6

Table 6 Overload safety factors of 6 arch dams under different failure conditions

Project's name	Friction coefficient	Cohesion (MPa)	K_1	K_2	K_3	K_4
Xiaowan	1.4	1.6	1.0	1.75	4.0	6.25
Lijiaxia	1.0	2.5	1.2	2.2	6.5	7.5
Tengzigou	1.1	3.0	1.1	2.5	7.5	8.5
Shimen	1.2	1.2	0.7	1.5	4.5	5.0
Sayano-Shushenskaya	1.4－1.7	1.8－2.4	0.8	1.25	3.5	3.75
	1.3	4.0	0.75	2.25	4.5	6.0
Kolnbrein (before reinforced)	1.5	2.0	0.75	1.5	2.75	3.5
	1.4	1.6	0.7	1.25	2.25	2.75
Kolnbrein (after reinforced)	1.3	4.0	1.25	3	5.0	6.25

water level. All those 6 dams have big overloading capacity. Overload safety factor is in general more than 3.0 when large yield zone and large distortion of deformation curve occur. Table 6 approximately shows that among those strength variables cohesion has larger effect on dam's carrying capacity, the two factors almost in a linear relation. If cohesion c falls from 4.0 to 1.6, the bearing capacity of dam will reduce subsequently to 1/2.

5 Conclusion

As to the arch dam structure, the most important thing is to ensure safe operation under normal condition. Thus, when conducting safety analysis for the arch dam, we should not only study the ultimate bearing capacity, but also need to understand the real working performance under normal operation condition, and the three aspects of load, resistance and analysis method should be paid attention to.

In addition to the load and calculation method defined by criterion, the residual stress from construction period and the stress caused by nonlinear temperature difference should be considered in calculation of the real load of arch dam. The impact of dam construction and sealing process should be considered in calculation of self weight. As for water pressure load, the effect of both by-stage impoundment and seepage pressure should be taken into consideration.

To calculate the real bearing capacity of arch dam, first we need to know the real strength of materials. The sample size effect, gradation of specimen, and load duration effect upon strength should be taken into consideration. Yield criterion should reflect materials strength change correctly. As to concrete, its brittle fracture characteristics needs to be considered, and models reflecting its real characteristics should be adopted if possible.

Nonlinear finite element method is the main method used to analyze real working performance of arch dam and to calculate bearing capacity. When analyzing with nonlinear finite element method, failure models will have certain influence on the result. Among those models, ideal elastic-plastic model overestimates bearing capacity of arch dam. Therefore, the softening effect of material strength after yield should be considered. At the same time, in order to ensure the accuracy of safety evaluation, it is feasible to use engineering analogy method in the study.

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