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SEISMIC MODEL RUPTURE TESTS AND SAFETY EVALUATION OF HIGH ARCH DAMS

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ABSTRACT

In this paper, a series of dynamic model rupture tests of an arch dam with 292 m in height, scaled 1/350, are performed to investigate the earthquake response and ultimate strength including the nonlinear effects of the contraction joints. Each dam model is mounted on the large shaking table excited by the harmonic wave until the final failure occurs and the model dam collapses into several pieces. The acceleration and stress duration are recorded and analysed. Experimental results show that the primary damage caused by earthquake is dynamic fracture at the weak zones of the dams, which depends on the joint amount, joint material behaviour, and, the openings at the up parts of the dam. The ground acceleration of the first tension crack appearing on the dam model is the most important parameter for converting the results to the prototype and basic index for assessing the dam safety evaluation.

KEYWORDS

Arch dam, Contraction joint, Seismic rupture model test, Dynamic fracture, First tension crack acceleration, Seismic safety evaluation.

INTRODUCTION

A number of 200-300 m high concrete dams have been built and will be built in the seismic active area in this decade to meet the developments of the hydraulic engineering and energy resources in China. The research of seismic safety evaluation of dams is much significant. Even though most of dams are aseismicly designed according to the Code (SDJ 10-78), the nonlinear effects of the contraction joints and cracks are not taken into account. Moreover, concrete dams are fracture sensitive structures and vulnerable to earthquake damage. It is cannot be overemphasized to develop the advanced analytical and experimental techniques of dam safety evaluation, especially for the high arch dams.

The most important problem of seismic safety evaluation is to reveal the critical failure response and mechanism of the high arch dams under the strong ground motions. Although some 3-D linear or nonlinear numerical models and sofewares have been developed so far, results show that the estimation of the cracking directions and positions are entirely distinct by using different computational model (W. P. Donlon et al., 1991). Thus, it is still not able to precisely estimate the critical state of the high arch dams under strong earthquakes by numerical analysis alone. However, the dynamic rupture model tests are reliable and visible to estimate the overload capacity and vulnerable positions of the high arch dams, which are necessary in design, in spite of some limits and uncertainties in this kinds of experiments (Gregory L Fenves et al., 1992, E. Bruhwiler et al., 1990).

A series of dynamic rupture model experiments of an arch dam with 292 m in height are performed to investigate the dynamic response, ultimate strength, and, final failure forms. The artificial concrete-like material is studied to construct the models. From the point of view that the seismic failure of a concrete dam is caused by dynamic fracture, the ground acceleration of the first tension crack appearing on the dam model is selected to be the parameter of converting the data from the model to the prototype. Consequently, the parameter is used to assess the seismic safety of the prototype. The overload capacity of the arch dam are than quantitatively obtained, in which the effects of the exciting waveforms, the contraction joints, the size scale, and other factors are also discussed. The experimental result show that the nonlinear response of an arch dam is largely related to the joints including its amount, construction, and, padding materials. It might be a new idea that the seismic response of the high arch dams could be controlled by the specific contraction joints.

DYNAMIC RUPTURE MODEL TESTS

Model parameters

The prototype of the double curved high arch dam is located in the south-west of China. The maximum height of the dam is 292 m. The dam site is in the earthquake active zone with the design intensity degree eight. The design acceleration reaches 0.308 g corresponding to 10% probability of exceedence in 500 years. The model scale in geometry is 1/350. It is considered as the rigid foundation to be mounted on the shaking table which size is 3.0 m x 3.0 m. The height of the dam model is 83 cm, the crest length 268.8 cm, crest thickness 3.43 cm, and, maximum thickness of crown 19.3 cm. Ten models with four different types are tested, which include: three monoblock models, two monoblock model with five openings, four contraction joint models, and, one contraction model with five openings. In each contraction model, there are four contraction joints to be simulated.

Model material

Model material is very important for the dynamic failure experiments of the high dams. In order for exciting the model with its fundamental frequency and rupturing under the nominal power of the shaking table, the Young's modulus and strength of the material should be as low as possible. On the other hand, the material should still remain the brittle behaviour like concrete and strong enough to construct the models solidly.

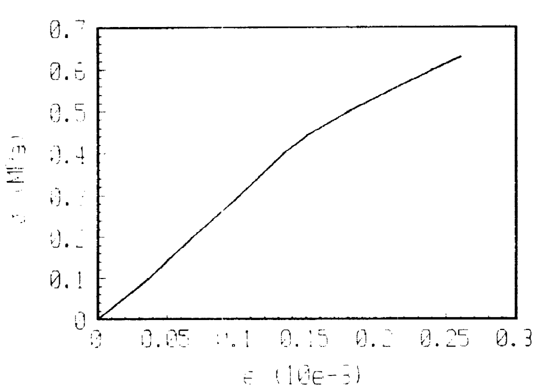


Fig. 1 P-δ relationship of model material

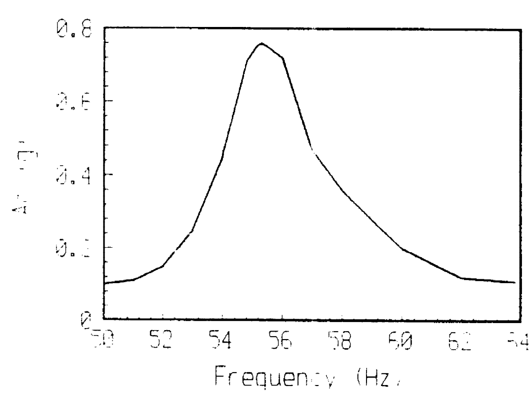


Fig. 2 Damping of a model dam

A special material consisting of cement, river sand, heavy quartz sand and water is used to construct the models. The elasticity and brittleness of the material is similar to concrete. Its density is also in agreement with concrete. The P-δ relation and damping of the model are shown in Fig. 1 and Fig. 2. The strength of the model is controlled by the age of material. Normally, the compressive strength is controlled at a range of 0.20-0.70 MPa, tensile strength 0.03-0.085 MPa, and, modulus of elasticity 500-1,000 MPa approximately.

Model construction

Since double curved arch dams are 3-D structures, the accuracy of geometry of the dam model is the key problem in the experiments, especially for the small scale models. The construction procedure is somewhat complicated. First, the semi-finished gypsum dam mode is carefully carved by using the geometric patterns of the arch at nine design elevations and beam at seventeen specifying sections on each stream. The finished gypsum dam mode is exactly the same as the tested model in geometry. Secondly, the finished gypsum dam mode is used as the positive mode to construct the negative concrete mode piece by piece. The mountains of the dam abutments are also built at the same time. Finally, The gypsum mode is cleaned up and the concrete-like material is cast into the negative concrete mode which is assembled layer by layer. The dam models to be tested are with high accuracy which the tolerance is less than ±1 mm in dimension.

The asphalt felts are used as padding inside the joints that keeps up continuity of the dam to a certain extent. The sketch of a joint model with openings is shown in Fig. 3.

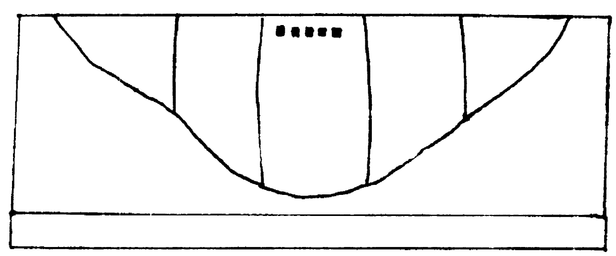


Fig 3 Sketch of an arch dam model (with joints and openings)

Procedure of seismic failure model test

Ten models are tested in this experimental series. The test procedure are divided into two steps. In the first step, the spring hammer method is employed to measure the first several frequencies and modes. In the second step, the model is excited by the shaking table until it collapses. Ten accelerometers on the dam model crest are used to record the response acceleration duration. Two video cameras are settled to inspect the cracks and failure of the models in the tests.

Because of the random discreteness of model material with the same behaviour of concrete, the experimental results would not be exactly the same in two tests even if all conditions would be the same. Thus, a large number of models should be performed if the random waves are used to excite the shaking table. Moreover, the results of the failure forms would be less of comparison since the different random wave could generate different response. An alternative method is to use the harmonic waves as the exciting waves, and, to select the fundamental frequency of the testing model as the exciting frequency. The reason why the harmonic wave could instead is that the main difference of the maximum response in elastic domain between harmonic input and random input is described by the dynamic amplification of the structure. That is, the maximum seismic response can derived from the harmonic excitation by modifying the amplification. In this manner, the random uncertainty is limited within the model material. Meanwhile, the repeatability of the model tests is much improved.

In the experimental series, all model tests are considered to be reservoir empty. The survey of real dams and dynamic model tests have shown that the up area of the arch dam is the weak zone. In general, cracks are firstly found at this part during earthquake. But, seismic stress in this area is scarcely affected by reservoir water. Furthermore, it will be very arduous to inspect and measure the cracks when the model is swamped in water. Therefore, using a modification factor to compensate the influence of reservoir water is reasonable and necessary.

CONVERTING FACTORS OF FIRST TENSION CRACK ACCELERATION

At the critical moment of concrete cracking, the arch dam is substantially working in the elastic domain. The model simulation law is still suitable for converting the data from model to prototype (Gao Lin et al., 1993). The scales of frequency, acceleration and stress between prototypes and models are as follows:

$$f_\lambda = \frac{1}{\lambda}\sqrt{\frac{E}{E_m}\frac{\rho_m}{\rho}} \tag{1}$$

$$\alpha_\lambda = \frac{1}{\lambda}\frac{E}{E_m}\frac{\rho_m}{\rho} \tag{2}$$

$$\sigma_\lambda = \frac{E}{E_m} \tag{3}$$

in which, f_λ, α_λ, σ_λ are the scales of frequency, acceleration and stress, respectively. λ is the geometric scale. E and ρ represent the modulus of elasticity and density of mass. The subscription "*m*" expresses the physical constant of models.

The acceleration scale due to the difference of the input wave and material damping is further expressed as:

$$\sigma_\lambda = \frac{\beta}{\beta_m}\frac{A_c}{a_c} \tag{4}$$

Where, β and β_m are the amplification factors of the prototype and the model, respectively. A_c and a_c represent earthquake acceleration acting on the dam foundation of prototype and model, respectively.
Substituting Eq. (1), Eq. (2) and Eq. (4) into Eq. (3), The relationship between stress scale and input acceleration scale is written as:

$$\sigma_\lambda = \lambda\frac{\beta}{\beta_m}\frac{A_c}{a_c}\frac{\rho}{\rho_m} \tag{5}$$

The dynamic fracture is assumed to be controlled by the dynamic tensile strength. From the point of view, the converting factor of the first tension crack acceleration is:

$$A_c = a_c\frac{1}{\lambda}\frac{\beta_m}{\beta}\frac{\rho_m}{\rho}\frac{R_{tp}}{R_{tm}} \tag{6}$$

where A_c and a_c represent the first tension crack acceleration of the prototype and the model, respectively. R_{tp} and R_{tm} are dynamic tensile strength of the prototype and the model, respectively.

It should be mentioned that the first tension crack acceleration derived from Eq. (6) is in the ideal conditions. The seismic environment of the prototype is dissimilar to the conditions of the testing model. Thus, a series of coefficients should be introduced into Eq. (6) to represent the influences of the real conditions. These coefficients include reservoir full, high vibration modes, vertical earthquake component, material behaviour and so on. After these factors involved, the first tension crack acceleration of the prototype is expressed as:

$$A_{cc} = C_r C_h C_v K_w K_h K_s K_m A_c \tag{7}$$

in which, C_r, C_h and C_v represent the modification factors dealt with the input wave. The subscript "r", "h" and "v" express the load rate, history and vertical component, respectively. K_w, K_h, K_s and K_m represent modification factors of reservoir water, high vibration modes, scale effect, and, material behaviours. Since dam-water-foundation interaction is a specific research problem, its effect is not includes in Eq. (7).

EXPERIMENTAL RESULTS AND ANALYSIS

Overload capacity and final failure forms

The test results of ten models are listed in Table 1. In the test series, five monoblock models and five joint models are performed. The series number "C" and "D" represent the monoblock models and the joint models, respectively. R_{cm} and R_{tm} are the compressive strength and tensile strength of the model material, respectively.

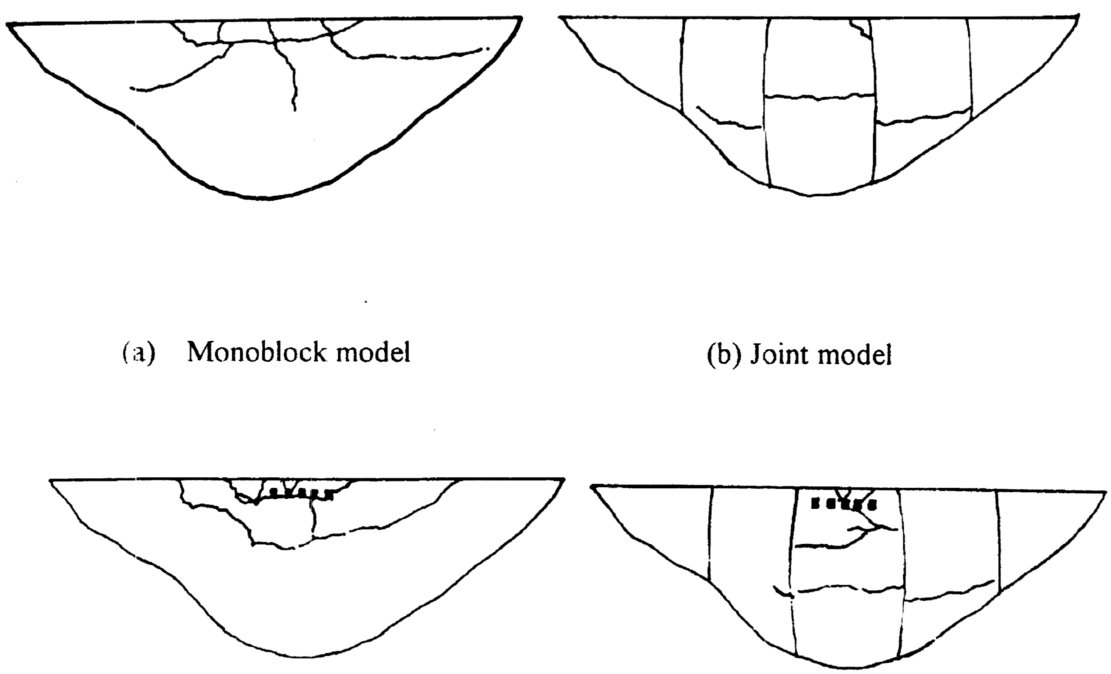
Table 1. Results of dynamic rupture model test series

No.	Dam type	ρ (t/m^3)	R_{cm} (MPa)	R_{tm} (MPa)	a_c (g)	A_{cc} (g)
C-1	monoblock	2.51	0.537	0.0594	0.81	1.537
C-2	monoblock	2.78	0.267	0.0499	0.66	1.004
C-3	monoblock	2.65	0.718	0.0447	0.36	0.992
C-4	monoblock, 5 openings	2.62	0.404	0.0360	0.32	1.083
C-5	monoblock, 5 openings	2.66	0.395	0.0421	0.34	1.000
D-1	4 joints	2.42	0.725	0.0844	0.66	1.004
D-2	4 joints	2.60	0.244	0.0446	0.70	1.832
D-3	4 joints	2.59	0.674	0.0471	0.42	1.074
D-4	4 joints, 5 openings	2.60	0.486	0.0399	0.36	1.091
D-5	4 joints, 5 openings	2.62	0.439	0.0468	0.40	1.041

The dam concrete is assumed to be C30 with tensile strength 2.0 MPa. The first tension acceleration of the prototype which is converted from the model tests is 1.0g approximately. Since the design acceleration is 0.308 g, the overload capacity of the prototype is much higher. In addition, it seems that the first tension crack acceleration is not obviously affected by the contraction joints and openings. But, the failure duration and final damage forms of the joint models are indeed different which are shown in Fig. 4.

The experimental results indicate the prototype is safety under the design conditions. However, it should also be pointed that the tests are performed in the ideal conditions. In fact, the construction faults and microcracks in the real dam concrete will affect the overload capacity. Certainly, the overload capacity of the high arch dam is lower than the experimental value. The method of combining the experimental and numerical results to determine the overload capacity, in which more complicated conditions are considered, is suggested. Owing to the limit of pages, the numerical and dynamic fracture analysis are not discussed in this paper.

The cracks are always appearing at the up area first which are the weak zones of the arch dams. More attention should be paid to the corners of the openings because of the stress concentration there. Once dynamic fracture occurs at the corners, the cracks expand rapidly and cause serious failure. The experiments is also indicate that the first tension crack appearing positions and final failure form are entirely different between the monoblock arch dams and joint arch dams. The failure forms of the joint models are more regular than that of monoblock models. The cracks on the joint models are usually horizontal in the middle of beam sections It means that the arch tensile stresses are significantly released when joints open. In such instance, the cantilever stresses increase. Thus, the positions of the high stress are changed which cause the different failure forms from the monoblock models.



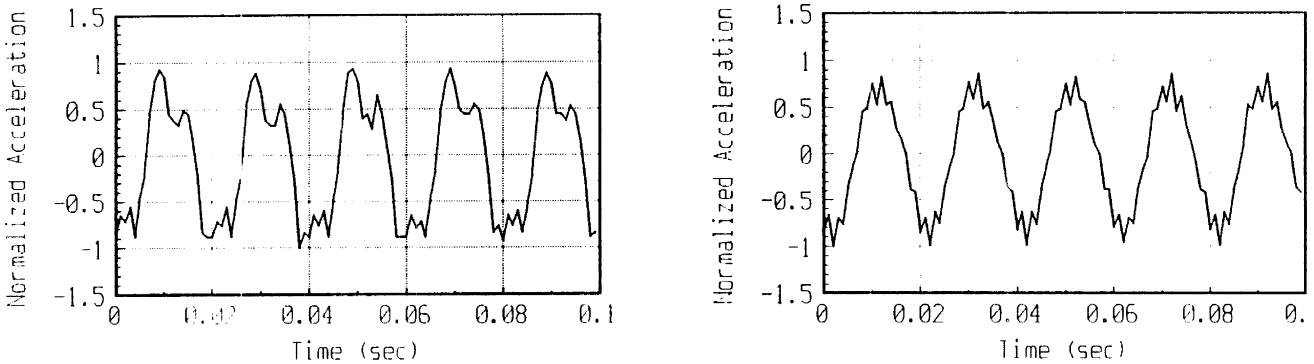
(a) Monoblock model (b) Joint model

(c) Monoblock model with openings (d) Joint model with openings

Fig. 4 Final failure forms of arch dam models

Effects of contraction joints

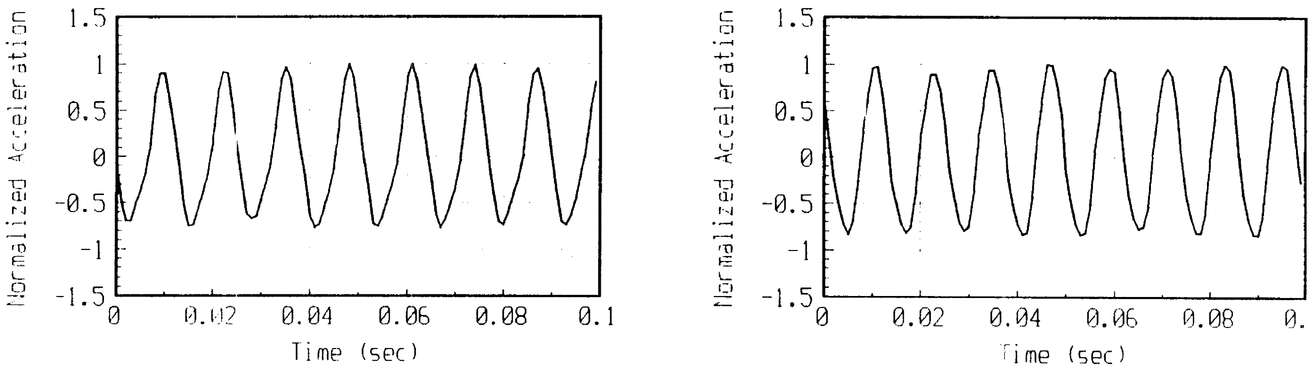
The response acceleration duration at ten measuring points of the crest are recorded. Fig. 5, Fig. 6 and Fig. 7 give the normalised values of the middle point of three models, respectively. In which, Fig. 5 is the record of a joint model. Fig. 6 is for monoblock model, and, Fig. 7 is for a joint model with openings. In these figures, series (a) represents the model excited under the small acceleration around 0.2 g and series (b) is the response at the first tension acceleration appearing instant. The fundamental frequencies of the models are adopted to excite the shaking table.



(a) Small acceleration exciting

(b) First tension crack appearing

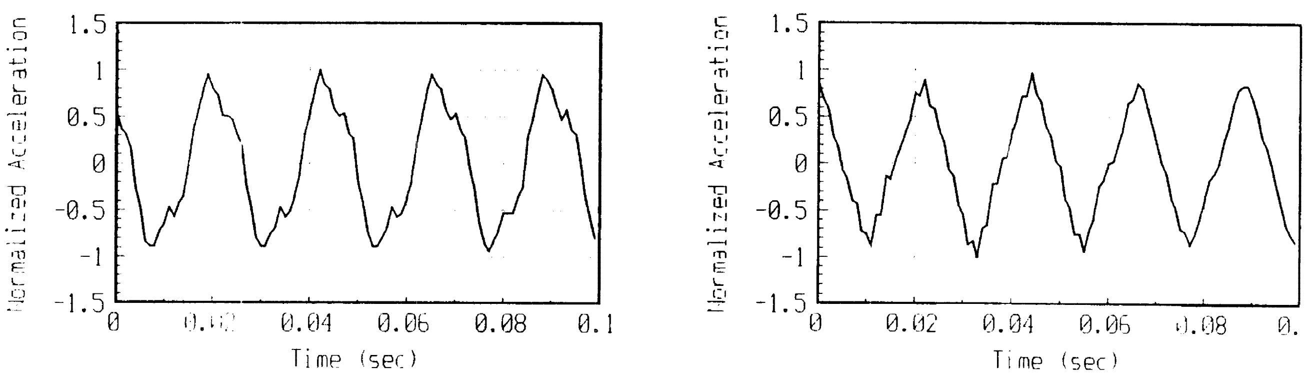
Fig. 5 Response acceleration duration of a joint model



(a) Small acceleration exciting

(b) First tension crack appearing

Fig. 6 Response acceleration duration of a monoblock model



(a) Small acceleration exciting

(b) First tension crack appearing

Fig. 7 Response acceleration duration of a joint model with openings

From Fig. 6, it is clear that the response of monoblock model is substantially linear before the model cracks. This phenomena also verify that the model material is prefect to perform the ultimate strength experiments of the high concrete dams. The nonlinear responses are undoubtedly shown in Fig. 5 and Fig. 7. It means that the nonlinear response of an arch dam has a bearing on the contraction joints. The interactions of the joint edges change the dynamic responses significantly. In this experimental series, it is found that the response of the arch dams is correlated with the construction of the contraction joints. If the padding inside the joints are relatively tight, the nonlinearity is small. Otherwise, the nonlinearity is much stronger. That is the reason why the nonlinearity is much apparent in Fig. 5 than in Fig. 7 even both are joint models. From this point of view, the joints can be used to control the responses of high arch dams in order to reduce the damage. Although passive and active control of vibration for dams are all very complicated and difficult, it will be becoming attractive and important technology because the Hanshin-Awaji earthquake has given us so many lessons of the disaster.

CONCLUSIONS

The experimental series indicate that the seismic model rupture tests of the high arch dams are not only for surveying the final failure forms qualitatively but also for determining the seismic safety quantitatively. The first tension crack acceleration is the key parameter for converting the data from model to prototype. Since the factors included in Eq. (7) are mostly from the field investigation and involved in some engineering experience, it is actual and reliable for the real high dams.

The results show that the researched high arch dam is safety under the design earthquake. The overload capacity is high enough. However, the model tests are performed in the ideal conditions which the microcracks and faults inside the concrete are not taken into account. Thus, the actual overload capacity will be lower. It depends on concrete quality, joint construction, dam foundation, and, other conditions. The method of combing the experimental and numerical analysis is suggest to evaluate dam safety completely.

The tension cracks are usually appeared at the up area of the high arch dams. For monoblock arch dam, the weak zone is roughly located at the up 1/3 area of the dam elevation. For joint arch dams, it is comparatively lower. The corners of openings are sensitive and vulnerable. Therefore, the special concrete such as the high strength concrete or fiber concrete is suggested to be used at the weak zones.

The joints cause the nonlinear responses. The nonlinearity depends on the construction, padding material, as well as amount of joints. Thus, it seems that using the contraction joints to control the responses and seismic damages of arch dams will be reasonable and potential even though the complicated research is just at the start.

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