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ASEISMIC DESIGN OF ARCH DAMS

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ABSTRACT

The dynamic behaviour of a 292 m high arch dam, which is planned to be built in south-west part of China, has been thoroughly studied. Stochastic response of the dam to nonuniform multi-point seismic input excited by wave scattering at the dam canyon and spatial variation of ground motions was examined. high seismic stresses near the abutment of the arch dam are induced. Dynamic soil-structure interaction analysis of the dam using Green's function of semi-infinite half-space was performed. Seismic stresses in the central part of the dam are in general reduced due to vibration energy dissipated into the foundation rock medium. Dynamic rupture tests of the dam were conducted on seismic simulating shaking table with models having scale of 1:350. The acceleration that induces first tension crack at the dam body was predicted and the aseismic safety evaluation of the dam was made. Influences of the vertical construction joint on the damaging pattern of the dam were also studied. Concerning the dynamic fracture behaviour of concrete, according to the experimental results of about 200 specimens by wedge splitting test carried out at Dalian University of Technology, not only the influences of loading rate but also the influences of cyclic loading history should be considered in determining the dynamic strength of concrete under seismic loading. Based on the above investigation, aseismic design criteria of arch dam is suggested.

KEYWORDS

Aseismic design; arch dam; earthquake input; dam-foundation interaction; fracture mechanics properties; dynamic rupture model test; spatially varying ground motions; crack prediction.

INTRODUCTION

A 292 m high arch dam is planned to be built in south west part of China. The dam is located in seismic active area, where the design earthquake acceleration reaches 0. 308g, which corresponds to the probability of exceedance of $p=2\%$ for the lifetime of the dam—100 years. As it will be the highest arch dam in the world and we still lack experience of constructing such important dams in high seismic area, the safety evaluation of the dam against earthquake shocks is of great concern to the designers. Extensive investigations have been carried out in China to predict the performance of the dam during earthquakes. It is one of the most complex and challenging problems in structural dynamics. The research activities performed in Dalian University of Technology are briefly introduced in the following.

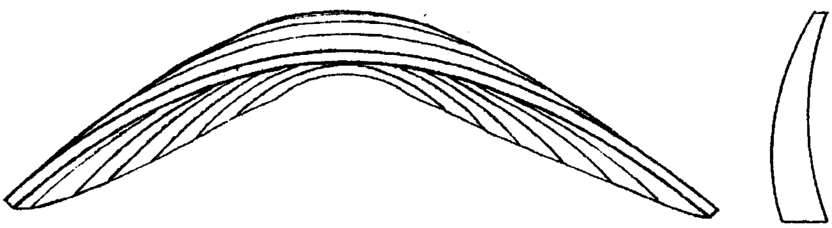


Fig. 1. Plane and cross section of the dam

EARTHQUAKE INPUT

In the current engineering design practice, seismic analysis of arch dams is based on the assumption of uniform input. Such an approach is inappropriate as the dam-foundation rock interface covers a distance which is comparable to the seismic wave length, spatial variation of ground motions along the dam boundary could be expected. Though actual earthquake records showing differential motion at dam canyon are very scarce, they do exist(Committee on Earthquake Engineering, 1990). Effect of nonuniform earthquake input on the dynamic response of the dam has been studied (Lin, 1996). Three factors that induce asynchronous earthquake excitation along the dam-foundation interface are taken into consideration. First, scattering and diffration of plane *SH* and *P*(or *SV*) waves caused by arbitrary canyon topography are determined by the solution of wave equations through a weighted residual and a one-cell cloning approach respectively. Second, in order to incorporate the effect of spatial as well as temporal variation of ground motion, a spacetime variation model is developed based on the observation data of SMART-1, the first operated closely spaced seismograph array in the world. And thrid, travelling waves effect, which induces phase differences from points to points is also included.

A stochastic approach is employed to calculate the seismic response of the dam considered. Based on the above investigations, the input power spectral density funciton of ground displacements at the dam canyon $[S_{xx}(\omega)]$ is determined. The diagonal and off-diagonal elements of the matrix are expressed in the following manner(Lin, 1996).

$$S_{ii}(\omega) = \beta_i(\omega)S_f(\omega)/\omega^4 \tag{1}$$

$$S_{ij}(\omega) = S_f(\omega)[\beta_i(\omega)\beta_j(\omega)]^{1/2}\rho(\omega,\Delta_{ij})exp[-\ i\omega\Delta_{ij}/c_a(\omega)]/\omega^4 \tag{2}$$

where $S_f(\omega)$ is the power spectral density function of the reference point; $\beta_i(\omega)$ is the coefficient of transmission of point i determined by solving wave equations; $\rho(\omega,\Delta_{ij})$ is the coherency function determined based on the space-time variation model developed; Δ is the distance between the two points considered and $c_a(\omega)$ is the apparent velocity of earthquake waves. Parameters of typical event E−45 of SMART-1 observation data are introduced into the space-time variation model. Numerical results of the 292 m high arch dam revealed that (Lin, 1996), in case of vertically incident *SH* waves exciting in the stream directioin, the nonuniform earthquake input tends to reduce the stresses in the central part of the dam to some extent. The arch stress levels generated may be only 60% of those that are due to uniform stream excitation. However, high stresses are developled at the upper part of the dam abutment due to pseudo-static deformation, the stress levels are comparable to those at the central part. Both the effect of wave scattering caused by canyon topography and the effect of temporal spatial variation of ground motion play important role in the stess distribution over the dam body. This findings provide some physical insight on the damage occurrence of cracking in both abutments of the Pacoima dam resulting from the Northridge Earthquake of January 17, 1994(Technical Report NCEER, 1994).

It is strongly suggested, that the spatial variation of ground motions along the dam-foundation interface should not be ignored for the aseismic design of arch dams, especially for high dams.

DAM-FOUNDATION INTERACTION

As the evaluation of dynamic impedance of infinite half-space along the dam boundary is very complicated, in the traditional design procedures the foundation rock is usually assumed to be massless and a portion of it is included in the finite element idealization of the system. However, the importance of dynmic soil-structure interaction effect on the seismic response of the dam is well recognized, and attempts of constructing mathematical models that properly account for this effect could be found in the literature (Chopra *et al.*, 1992; Dominguez *et al.*, 1992). In order to investigate the dam-foundation rock interation effect on the earthquake performance of the dam, dynamic Green's functions for the infinite half-space were derived (Lin *et al.*, 1994) and the dynamic impedance matrix of the rock along the dam boundary was calculated. The governing equations of the dam-foundation system by a substructure approach are formulated as

$$\begin{bmatrix} M_{ss} & \\ & M_{bb} \end{bmatrix}\begin{Bmatrix} \ddot{u}_s^t \\ \ddot{u}_b^t \end{Bmatrix} + \begin{bmatrix} C_{ss} & C_{sb} \\ C_{bs} & C_{bb} \end{bmatrix}\begin{Bmatrix} \dot{u}_s^t \\ \dot{u}_b^t \end{Bmatrix} + \begin{bmatrix} K_{ss} & K_{sb} \\ K_{bs} & K_{bb} + S_{bb} \end{bmatrix}\begin{Bmatrix} u_s^t \\ u_b^t \end{Bmatrix} = \begin{Bmatrix} 0 \\ S_{bb}u_g \end{Bmatrix} \tag{3}$$

where $[M]$、$[C]$、$[K]$ are the mass, damping and stiffness matrices of the dam respectively; $[S_{bb}]$ denotes the dynamic impedance of the unbounded foundation rock; $\{u^t\}$ denotes the total displacement of the dam, subscript b stands for the nodes in contact with the foundation and subscript s stands for the remaining nodes; $\{u_g\}$ denotes the free-field earthquake displacement along the canyon boundary.

Calculated results of the dynamic foundation impedance $[S_{bb}]$ indicated that, in the frequency range of interesting (0—10 Hz), $[S_{bb}]$ varies very slightly with the change of exciting frequency (Fig. 2 depicts normalized real and imaginary part of it), it can be approximated by the following expression

$$[S_{bb}(\omega)] = [S_{\infty}] - \omega^2[M_{\infty}] + i\omega[C_{\infty}] \tag{4}$$

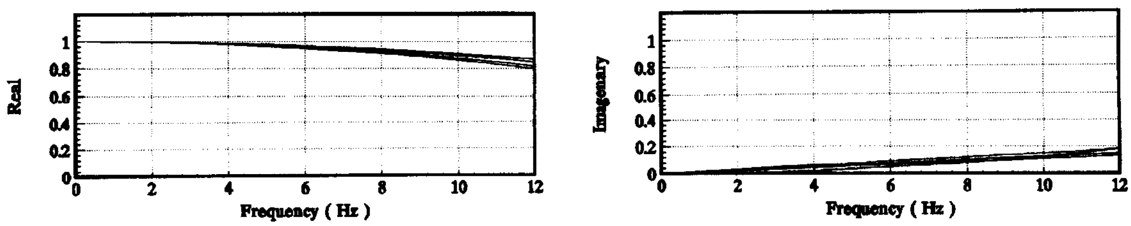


Fig. 2. Variation of real and imaginary part of $[S_{bb}]$ with exciting frequency.

that is, the real part of $[S_{bb}]$ can be fitted by a parabola and the imaginary part of $[S_{bb}]$ can be approximated by a straight line. $[S_{\infty}]$、$[M_{\infty}]$ and $[C_{\infty}]$ are all frequency independent. $[S_{\infty}]$ is related to the static stiffness of the foundation. For engineering design purpose, $[S_{\infty}]$、$[M_{\infty}]$ and $[C_{\infty}]$ can be determined by a static approach, we will discuss it in an another paper. Thus, the dam-foundation interaction analysis could be simplified to a great extent. Substituting (4) into (3), we get

$$\begin{bmatrix} M_{ss} & \\ & M_{bb} + M_{\infty} \end{bmatrix}\begin{Bmatrix} \ddot{u}_s^t \\ \ddot{u}_b^t \end{Bmatrix} + \begin{bmatrix} C_{ss} & C_{sb} \\ C_{bs} & C_{bb} + C_{\infty} \end{bmatrix}\begin{Bmatrix} \dot{u}_s^t \\ \dot{u}_b^t \end{Bmatrix} + \begin{bmatrix} K_{ss} & K_{sb} \\ K_{bs} & K_{bb} + S_{\infty} \end{bmatrix}\begin{Bmatrix} u_s^t \\ u_b^t \end{Bmatrix} = \begin{Bmatrix} 0 \\ S_{bb}u_g \end{Bmatrix} \tag{5}$$

Decomposing the total displacement into pseudo-static part $\{u^s\}$ and the dynamic part $\{u^d\}$

$$\{u^t\} = \{u^s\} + \{u^d\} = \begin{Bmatrix} u_s \\ u_b \end{Bmatrix} + \begin{Bmatrix} u_d \\ u_f \end{Bmatrix} \tag{6}$$

The pseudo-static solution gives

$$\{u_s\} = [R]\{u_b\}, \quad [R] = -[K_{ss}]^{-1}[K_{sb}] \tag{7}$$

$$\{u_b\} = [K_{bs}R + K_{bb} + S_{oo}]^{-1}[S_{bb}]\{u_g\} \tag{8}$$

Neglecting the small damping term, equations for determinging dynamic displacements become

$$\begin{bmatrix} M_{ss} & \\ & M_{bb} + M_{oo} \end{bmatrix}\begin{Bmatrix} \ddot{u}_d \\ \ddot{u}_f \end{Bmatrix} + \begin{bmatrix} C_{ss} & C_{sb} \\ C_{bs} & C_{bb} + C_{oo} \end{bmatrix}\begin{Bmatrix} \dot{u}_d \\ \dot{u}_f \end{Bmatrix} + \begin{bmatrix} K_{ss} & K_{sb} \\ K_{bs} & K_{bb} + S_{oo} \end{bmatrix}\begin{Bmatrix} u_d \\ u_f \end{Bmatrix} = \begin{Bmatrix} M_{ss}R \\ M_{bb} + M_{oo} \end{Bmatrix}\{\ddot{u}_b\} \tag{9}$$

Taking into consideration the wave scattering effect at the dam canyon, $\{u_g\}$ is frequency dependent, and from eq. (8), $\{u_b\}$ is also frequency dependent. The problem may be treated in the following way. For an earthquake input specified in the time domain $\{u_{eq}(t)\}$, performing Fourier transform we get $\{\hat{u}_{eq}(\omega)\}$; solving wave scattering problem we obtain $\{\hat{u}_g(\omega)\}$; applying eq. (8) leads to $\{\hat{u}_b(\omega)\}$ and finally inverse Fourier transform gives $\{u_b(t)\}$. Thus, eq. (9) can be sovled in the time domain.

Fig. 3 to 5 show the envelope values of arch stresses of the dam with full reservoir due to artificial earthquake excitation, which matches the design response spectrum of China with maximum acceleration of 0. 308 g. It is clear that the dam-foundation interaction makes significant reduction in dam response arising from radiation damping, and wave scattering at the dam canyon alters stress distribtion over the dam body, high stresses are generated at two abutments of the dam. However, in case of cross-canyon seismic exciation, taking soil-structure interaction effect into consideration is not always on the safe side.

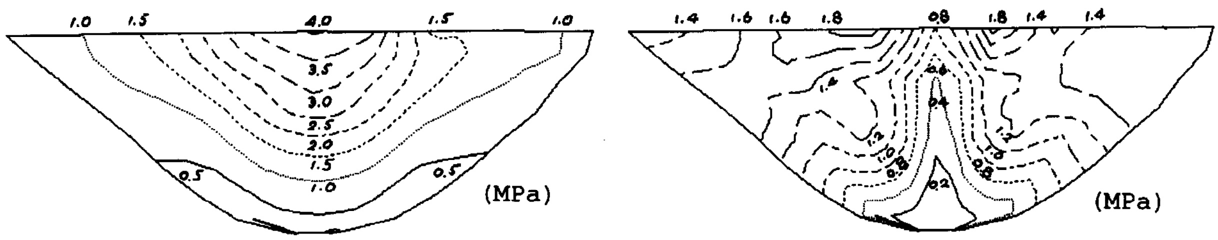


Fig. 3. Arch stress envelope for massless foundation, earthquake excites in stream and cross-stream direction

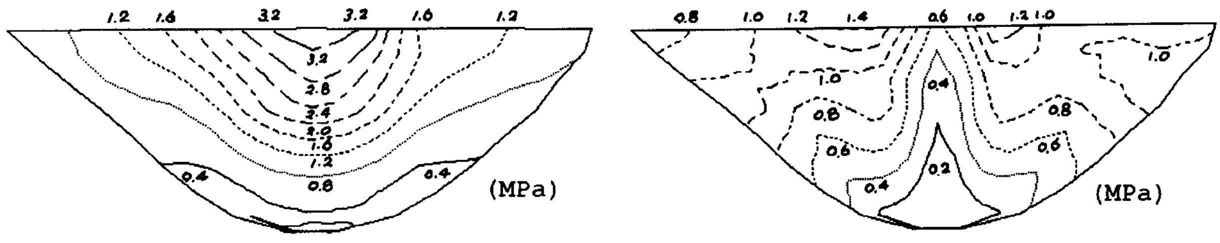


Fig. 4. Arch stress envelope, dam-foundation interaction included, uniform earthquake excitation in stream and cross-stream direction.

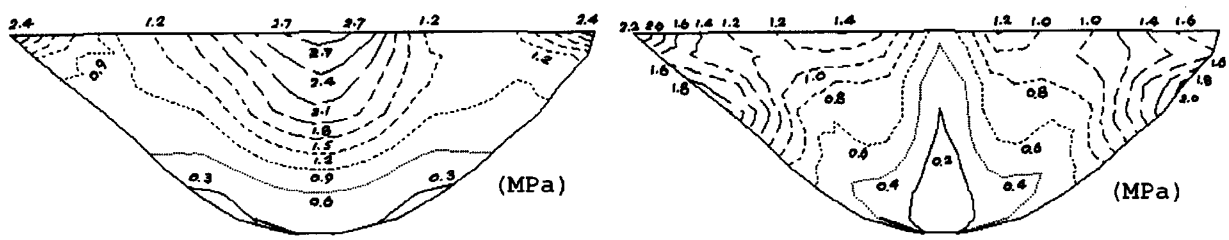


Fig. 5. Arch stress envelope, dam-foundation interaction included, nonuniform earthquake excitation in stream and cross stream direction

DYNAMIC MODEL RUPTURE TEST

Historical cases of concrete dam incidents during earthquakes, such as Koyna dam in India, Hsinfengkiang dam in China, Sefid Rud dam in Iran and Pacoima dam in USA indicated that, tension cracks are the significant overload responses of this type of dams. In spite of the fact, that during the last decade, our ability to analyse mathematical models of concrete dams subjected to earthquake ground motions has improved dramatically, sophisticated computer programs have been developed and used for numerical analysis of the linear as well as nonlinear seismic response of dams, these analyses have failed to predict the response of real dam structures particularly at their ultimate states. Large amount of variation from various models in the computed behaviour of the dam regarding predicted crack locations, orientations and extents (El-Aidi, 1988; Donlon *et al.*, 1991). The implication is that non-linear earthquake analysis of a concrete dam is highly uncertain. A combination method incorporating dynamic rupture experiments with analytical computation is proposed to give a quantitative safety assessment of concrete dams subjected to earthquake excitation (Lin *et al.*, 1993).

Dynamic rupture tests of ten 1/350 scaled dam models were carried out at our laboratory. Concrete-like mixes consisting of cement, barite sand, stone powder and water, were used to construct these models. As the formation and growth of cracks in a concrete dam may influence significanely the earthquake response of a dam, the earthquake ground acceleration which potentially induces the first tension crack at the weakest part of dam body is suggested as a basic index for the safety assessment of the dam. From the test results it can be predicted by the following expression (Lin *et al.*, 1993)

$$A_c = k_c \cdot a_c \cdot \frac{1}{\lambda} \cdot \frac{\beta_m}{\beta} \cdot \frac{\rho_m}{\rho} \cdot \frac{R_{tk}}{R_{tm}} \tag{10}$$

where A_c and a_c represent the earthquake ground acceleration that induces the first tension crack at the prototype and at the model respectively; λ denotes the geometric scale; ρ and ρ_m refer to the density of the prototype and model material respectively; β and β_m denote dynamic amplification factor of the dam and the model respectively; R_{tk} and R_{tm} represent the dynamic tensile strength of the dam and model material respectively; k_c is a correction factor taking into consideration the influences of earthquake wave form, higher modes, full reservoir and fracture mechanics properties of prototype and model materials etc. Test results are summarized in Table 1. Where R_{cm} is the compressive strength of model material. Assume that C30 class concrete will be used for the construction of the dam, according to the current design code for concrete structures in China, its standard tentile strength equals 2.0 MPa. The earthquake ground acceleration that will induce the first tension crack at the top part of the dam is estimated as 1.0 g. Compared with the design earthquake acceleration, the dam is regarded having higher resistance to withstand strong earthquake shock. From the point of view of crack formation, the weakest portion of the dam is the top central part of it, and the most critical state of the dam is not the case of full reservoir (water load generates compression stresses at that position), but the case when the water level is a little bite lower and crack formation is mainly controlled by the earthquake stresses.

Table. 1. Test results of model dams

Model No.	ρ_m (t/m^3)	R_{cm} (MPa)	R_{tm} (MPa)	a_c (g)	A_c (g)
C-2	2.51	0.537	0.0594	0.81	1.537
D-1	2.42	0.725	0.0844	0.66	1.004
C-4	2.78	0.367	0.0499	0.68	1.700
D-2	2.60	0.344	0.0446	0.70	1.832
C-5	2.65	0.418	0.0447	0.36	0.992
D-3	2.59	0.374	0.0471	0.42	1.074
D-4	2.60	0.386	0.0399	0.36	1.091
C-6	2.62	0.304	0.0360	0.32	1.083
D-5	2.62	0.439	0.0468	0.40	1.041
C-7	2.66	0.395	0.0421	0.34	1.000

Fig. 6 shows typical damage pattern of the model dam, in the figure the Arabic numerals indicate the time of crack formation successively. Since arch dams are typically coustructed as cantilever monoliths separated by vertical construction joints, 5 model dams, D-1 to D-5, were casted with four constuction joints filled with bituminous mat. During the vibration, upper part of the joints slipped and opened arch stresses released and crack was first formulated at one third height of the cantilevers.

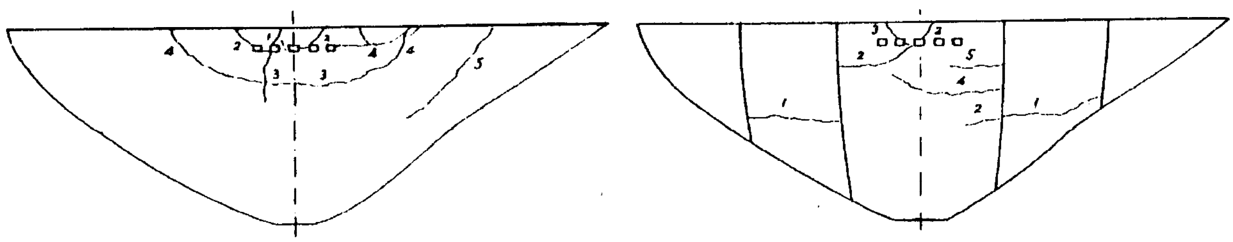
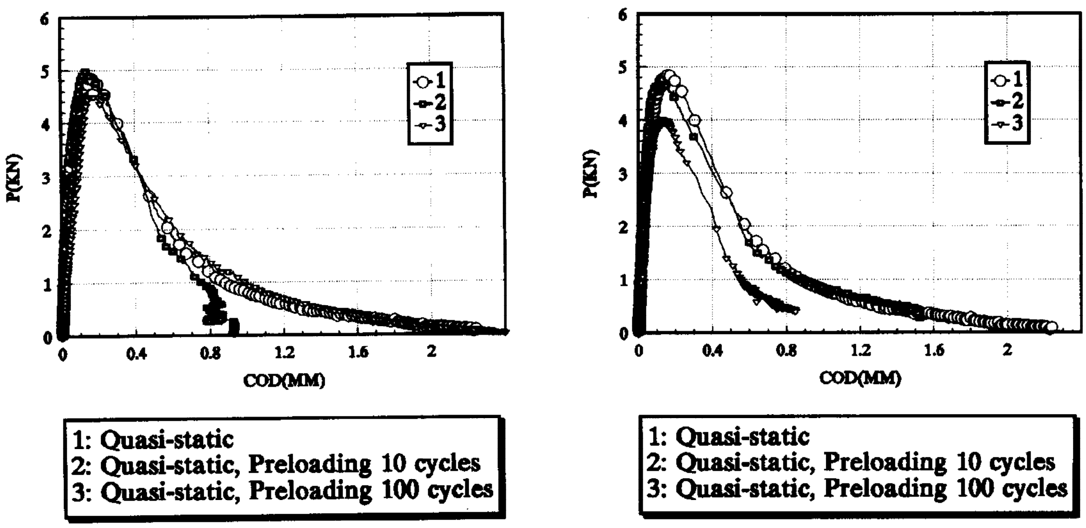


Fig. 6. Typical damage pattern of model dams

DYNAMIC STRENGTH OF CONCRETE

The current practice in the seismic safety evaluations of concrete dam is based on numerical results from linear dynamic response analyses. The tensile strength of concrete is the key property which determines the safety level of dams to withstand earthquake shocks, because the evaluations are in large part based on comparisons of computed levels of stress with acceptable strength of concrete. During an earthquake concrete is subjected to alternatively cylclic loadings. However, in the prior researches more attention were drawn on the effect of loading rate than that of loading history on the fracture mechanics properties of concrete.

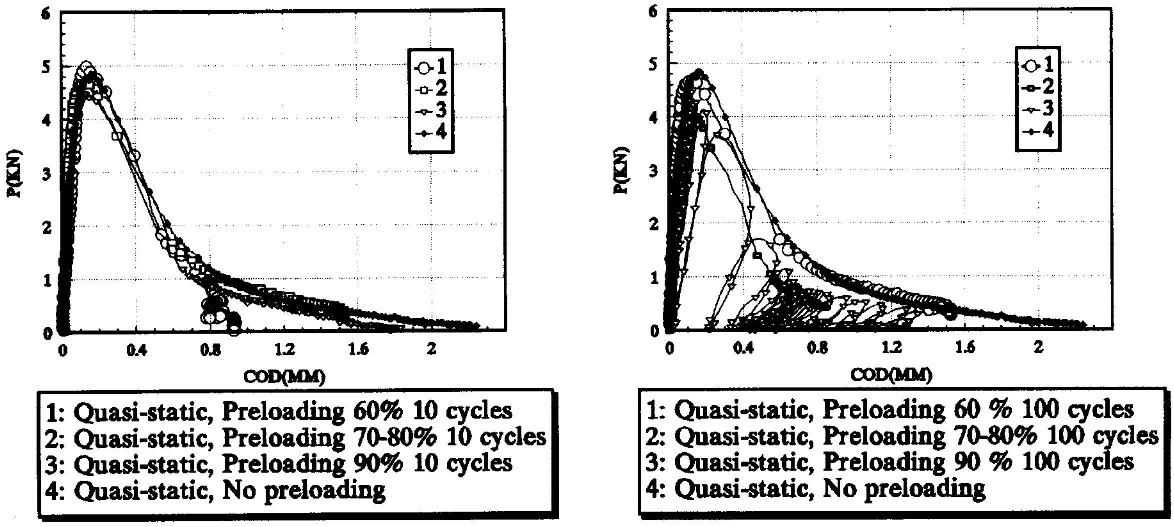


(a) 60% f_t preloading (b) 75% f_t preloading

Fig. 7. P-COD curve for different loading history

Dynamic wedge splitting tests of nearly 200 specimens were conducted in our laboratory. Some of the experimental results are summarized in the following figures. Fig. 7. (a) and 7(b) illustrate the averaged load-crack opening displacement diagram (P-COD) after 0,10 and 100 cycles of preloading with ampitudes of 60% f_t and 70%~80% f_t respectively, in which f_t is the maximum cracking strength.

Fig. 8 depicts P-COD curve after 10 cycles and 100 cycles of preloading with different amlitudes (% of f_t) respectively. Fig. 9 shows P-COD curve for different loading rate expressed as loading time from minimum strain to maximum strain, and Fig. 10 gives the comparison between cases with and without cyclic loading history (100 cycles of amplitude 75% f_t). From these results it can be concluded that: (1) 60% f_t is a threshold value, if the preloading amplitude is greater than this value, fracture energy, fracture toughness and tensile strength of concrete will be affected by the loading history, fracture energy and tensile strength tend to reduce, and crack forms rather suddenly. (2) Fracture energy, fracture toughness and tensile strength of concrete tend to increase with the raising of loading rate. But, they are different for cases with and without cyclic loading history. And, the higher the loading rate, the more unstable the load-displacement diagram. In brief, it is worth to emphasize, that not only the loading rate, but also the cyclic loading history should be considered in determining the dynamic fracture strength of concrete under seismic loading. In fact, the micro-crack zone in front of the crack tip could be repeatedly damaged by the cyclic loading history, which results in lowering the tensile strength.



(a) 10 cycles preloading (b) 100 cycles preloading

Fig. 8 P-COD curve for different amplitude of preloading.

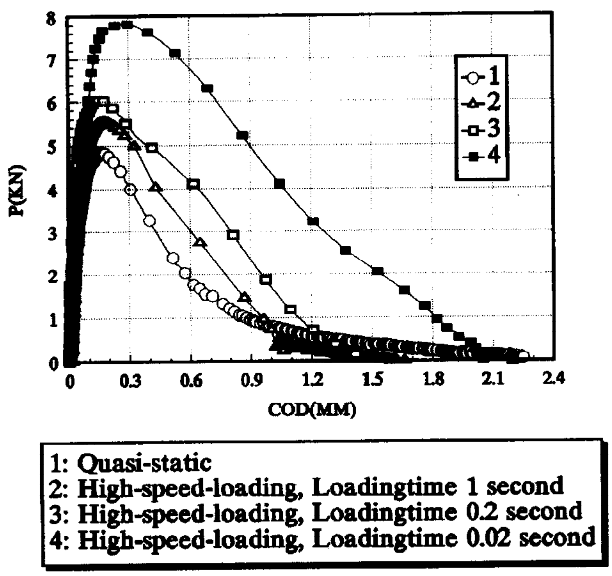


Fig. 9 P-COD curve for different loading rate

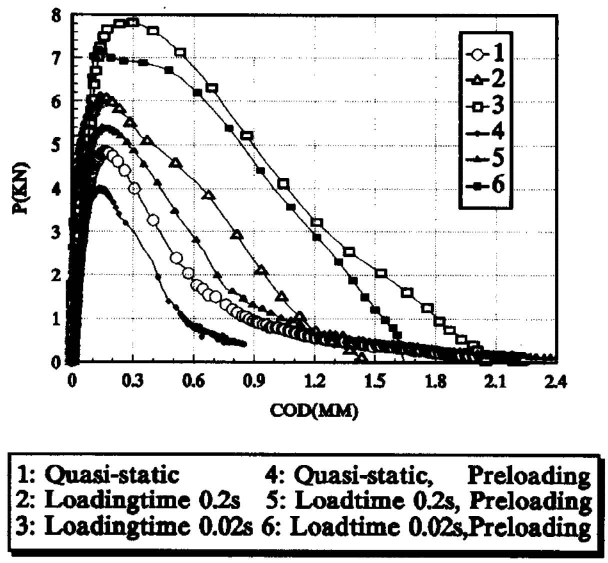


Fig. 10. Comparison between cases with and without cyclic loading history

CONCLUDING REMARKS

Based on the above investigation, for the safety and economic design of arch dams to resist earthquake shocks, it is suggested to update the design criteria of arch dams to take into consideration the following aspects: (1) Nonuniform earthquake input is more resonable than uniform input. Particular attention should be paid to the abutment part of the dam, where high stresses may be induced. (2) Dam-foundation interaction effect makes the earthquake stresses in the central part of the dam significantly reduced due to vibration energy dissipated into infinite half-space. However, in case of cross-stream excitation, including such effect is not always on the safe side. And wave scattering at the dam canyon leads to stress concentrations near the abutment of the dam. (3) To specify the dynamic strength of concrete subjected to seismic loading, not only the influences of loading rate, but also the influences of cyclic loading history should be taken into account. (4) Dynamic model rapture test with concrete-like material is useful for crack formation prediction. (5) Further study of the effect of vertical construction joint on the seismic response of arch dams is recommended.

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