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RESPONSE OF A CONCRETE ARCH DAM IN THE 1994 NORTHRIDGE, CALIFORNIA EARTHQUAKE

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ABSTRACT

The response of Pacoima dam, a 365 ft high arch dam located near Los Angeles, California, to the 1994 Northridge earthquake is studied using the accelerograms recorded in the canyon and on the dam body. The nonlinear effects due to opening of the contraction joints, lift joints and the dam–foundation interface are represented in the model. The effects from the spatial variation of the free–field motion in the canyon are also included. Although a simple assumption is made concerning the spatial distribution of free–field motion, because of lack of recorded data, the computed response is in reasonable agreement with the accelerations recorded on the dam body. The concrete stresses in the model are substantially different from those which are typically computed from an analysis assuming a monolithic dam and uniform free–field canyon motion. The opening of the joints reduces the arch and cantilever stresses, whereas the non–uniform motion of the canyon significantly increases these stresses. The pseudo–static response to the non–uniform input motion is the major cause of large concrete stresses, particularly near the abutments.

KEYWORDS

Dam; arch dam; concrete; joints; finite element; nonlinear analysis; non–uniform ground motion.

INTRODUCTION

Concrete arch dams are constructed as cantilever monoliths separated by contraction joints. The joints cannot transfer substantial tensile arch stresses, so they may open and close as the dam vibrates in response to earthquake ground motion. The opening of contraction joints and the transfer of loads from arch action to cantilever action may result in the opening of lift joints or horizontal cracking of the concrete. For seismic safety evaluation, however, an arch dam is often analyzed as a linear monolithic structure and resort is made to *ad hoc* interpretation of the tensile arch and cantilever stresses predicted by a linear analysis.

The earthquake response of an arch dam is further complicated by dam–water and dam–foundation interaction effects, which are included in an analysis using procedures of varying accuracy. Generally, the free–field motion along the dam–foundation interface is assumed to be uniform. The spatial variation of the free–field motion is disregarded due to lack of data on the actual free–field motion of canyons. A theoretical study of plane wave cases was performed by Nowak and Hall (1990).

Analytical as well as experimental studies on the effects of contraction joint opening have been conducted in recent years. However, there has been no evidence of contraction joint opening in a dam during an earthquake until January 1994 when Pacoima dam was subjected to the Northridge earthquake. The vertical contraction joints in the dam opened during the earthquake, as evidenced by their subsequent clean appearance. After the earthquake, they closed under static loads, except for the left-most joint which had a permanent opening of up to two inches because the thrust block slid downstream. Minor cracking of concrete and block offsets in horizontal and vertical directions also occurred in parts of the dam body.

The response of Pacoima dam in the Northridge earthquake was recorded by a network of California Division of Mines and Geology (CDMG) accelerometers (CSMIP, 1994). The peak accelerations of 1.6 g and 1.2 g, at the left abutment in the horizontal and vertical directions, respectively, are among the largest ever measured during an earthquake. The strong motion accelerograms provide a unique opportunity to examine the contraction joint behavior in an arch dam subjected to a large earthquake. In addition, the limited processed records from the canyon can be used to study the effects of spatial variation of the input motion on the dam response. This paper presents the results of earthquake analyses of Pacoima dam to investigate the effects of opening of the vertical and horizontal joints and the spatial variation of the input motion.

RESPONSE OF PACOIMA DAM TO NORTHRIDGE EARTHQUAKE

Pacoima dam, with a 365 ft height and 589 ft crest length, is a flood control arch dam located 4.5 miles northeast of San Fernando, California. The thickness of the crown section varies from 10.4 ft at the crest to 99 ft at the base (Fig. 1). Uniformly spaced contraction joints with 12 in. deep beveled keys divide the dam into eleven cantilevers. The left abutment is supported by a concrete thrust block through a 60 ft tall joint. The dam was subjected to severe shaking by the M_S=6.8 magnitude 1994 Northridge earthquake, with the epicenter 11 miles from the dam. The reservoir level was 233 ft above the base (about two-thirds full).

Over-stressing of the dam occurred during the earthquake, as indicated by cracks and permanent movements of the concrete blocks. Most of the damage, however, can be attributed to the movement of the thrust block due to a failure in the supporting foundation rock. The contraction joint between the dam and the thrust block opened and remained open after the earthquake: about 2 in. at the crest and 1/4 in. at the bottom. Some permanent differential movement in the vertical direction also occurred at the joint, with the thrust block lower with respect to the dam. A large diagonal crack occurred in the thrust block near the bottom of the thrust block joint. The dam body suffered less damage. A fine diagonal crack opened near the base of the thrust block. A permanent horizontal offset of 3/8 in. to 1/2 in. occurred along the horizontal joint at 48 ft below the crest, with the top block shifting downstream relative to the bottom block. Permanent vertical offsets occurred along most of the joints, with the right block remaining lower relative to the left block. Opening of the contraction joints during the earthquake was indicated by their clean appearance after the earthquake.

The accelerations of the dam and the canyon were recorded by a network of CDMG strong motion accelerometers. The locations of the accelerometers on the dam are shown in Fig. 1. CDMG could not digitize and process all the records because large acceleration peaks, which exceeded the range of instruments, were intertwined on the film. Processed records are available for two locations in the canyon, one at the downstream and the other 50 ft above the left abutment, and channels 8 to 11 on the dam.

The peak accelerations recorded in the canyon were 0.43 g and 1.58 g for the downstream and the upper left abutment (ULA) instruments, respectively, indicating the amplification of ground motion by the canyon topography. The stream component of these motions are shown in Fig. 2. with the radial acceleration recorded at base. Channel 8 recorded the radial acceleration, with a peak of 1.31 g, at the left quarter point at 80% height of the dam. Figure 3 shows the radial accelerations of the dam at three different elevations, the base, 80% height and the crest. The partially digitized but unprocessed acceleration records from the crest of crown section are plotted in Fig. 4.

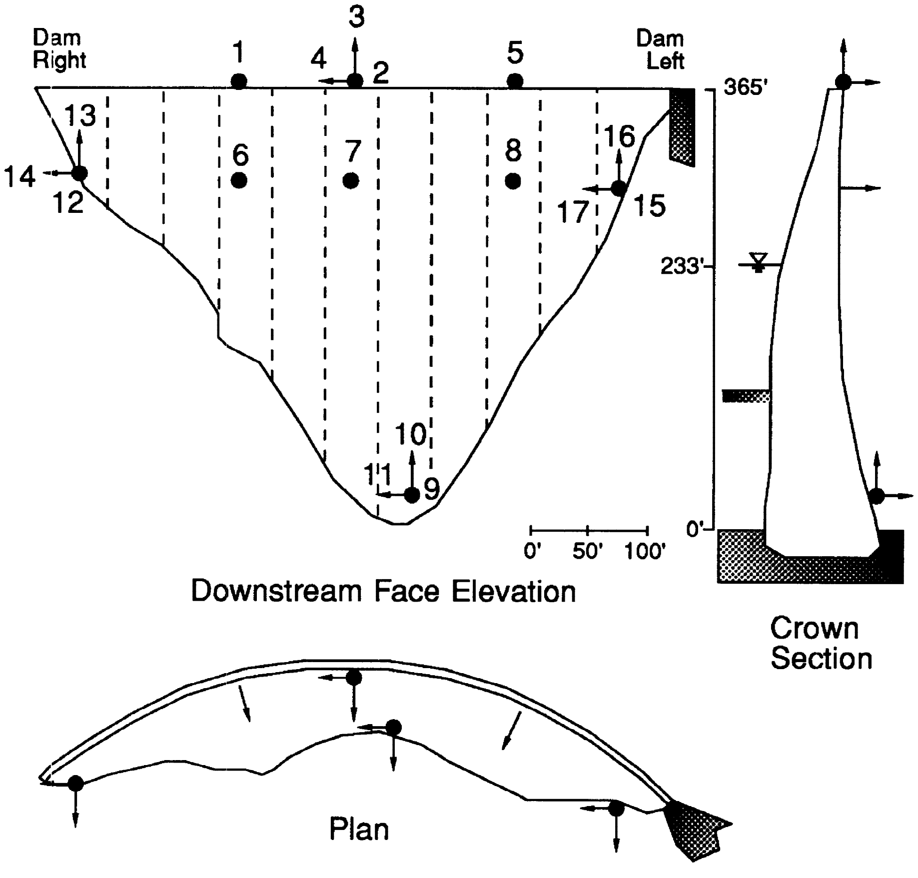


Fig. 1 Pacoima dam showing channels of accelerometers.

FINITE ELEMENT MODEL, INPUT, AND ANALYSIS

The finite element computer program ADAP–88, developed at the University of California, Berkeley, (Fenves, Mojtahedi *et al.*, 1989; Fenves, Mojtahedi *et al., 1992*) was used for the earthquake analysis of Pacoima dam. The program has been verified by a shaking table test of a 1:300 scale model of an arch dam (Chen and Li, 1994). Standard 3–D solid elements are used to model the concrete arch and the foundation rock. Nonlinear joint elements simulate opening–closing of the contraction joints, lift joints, and the dam–foundation interface. Spatially non–uniform seismic input, can be specified through displacement histories at the dam–foundation interface (Mojtahedi and Tseng, 1994).

Input Motion

Two types of earthquake analysis were performed which differed in the specification of the free–field motion at the dam–foundation interface. The first type used a uniform free–field motion, whereas non–uniform free–field motion was considered in the second type. The free–field motions for both cases were derived from the motions recorded in the canyon during the Northridge earthquake. For determining the non–uniform free–field motion, it was not possible to separate dam–foundation interaction effects from the spatial variation of the canyon motion. Hence, those dam–foundation effects were neglected and the recorded motion at the interface was assumed to be the free–field motion.

Due to the profound difficulties in determining the motion of canyon and also lack of sufficient acceleration records form the earthquake, a simple approach was adopted for specification of the non–uniform free–field motion. The same motion was specified for the right and the left abutments. The ULA and the dam base records were specified for the crest and the base of the dam, respectively. The motion at intermediate elevations was computed by linear interpolation from these records. The acceleration histories corresponding to the assumed input motion variation are shown in Fig. 5 for different elevations of the model.

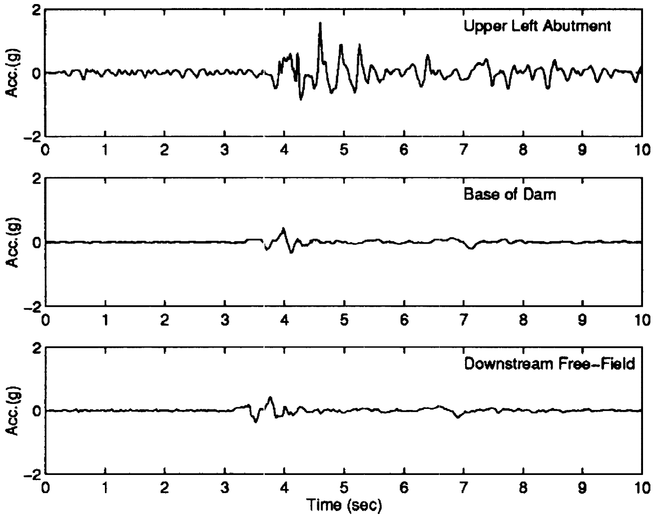


Fig. 2 Recorded acceleration histories for the canyon.

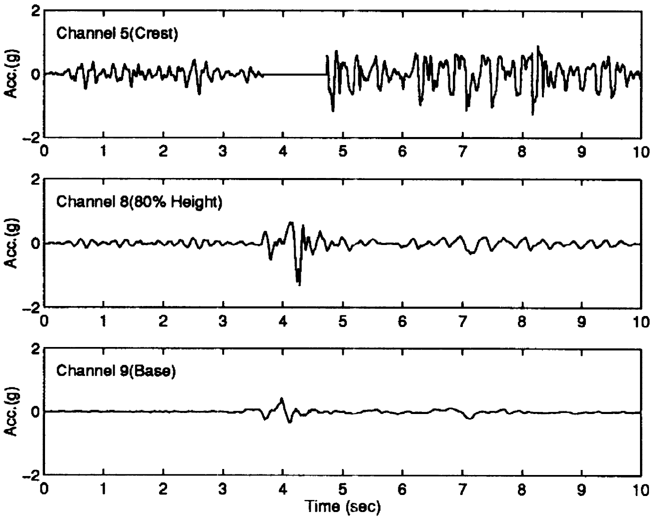


Fig. 3 Recorded radial acceleration history of dam. Zero acceleration is given for gaps in digitization of Channel 5.

Model

A total of 588 eight–node 3–D elements model the dam body. Three joint elements and 3–D solid elements were used through the thickness. Slippage of the joints was not allowed in the model. This assumption is valid for the keyed contraction joints, but may not be true for the horizontal joints, as discussed later. Zero tensile strength was assumed for the joints.

The number of contraction joints and lift joints in the dam model was selected from trial analyses. Of the twelve vertical joints in the dam, only five were included in the model. In addition, five horizontal joints, at 50, 97, 135, 202, and 282 ft above the base, were included to represent lift joints. Each horizontal joint spans an entire horizontal section between the right and left abutments. The material properties used for concrete were obtained from a previous study of the dam: modulus of elasticity = 2400 ksi, Poisson's ratio=0.20, based on testing of core samples of concrete.

A foundation rock region with a depth approximately equal to the height of the dam was included in the model to account for dam–foundation interaction effects. Although the foundation rock geometry and material properties are complicated, a prismatic shape was assumed for the canyon using a coarse mesh of the foundation rock region with 220 3–D solid elements. The material properties for the foundation rock were obtained from the previous studies: modulus of elasticity=2000 ksi, Poisson's ratio=0.20. To suppress the propagation of seismic waves, the foundation rock was assumed to be massless. For analysis with uniform free–field motion, the acceleration was specified at the rigid base of the foundation model. For analyses with non–uniform free–field motion, the displacement was specified at the nodes on the dam–foundation interface.

The first natural frequency computed for the dam using these properties, with the 233 ft reservoir level, was 4.3 Hz with an essentially anti–symmetric mode shape. To confirm the selected properties, the transmissibility function was computed for the radial motions recorded at the base and channel 8. The fundamental frequency of the dam from the peaks of transmissibility function was 4.0 Hz which, considering the limited processed data, is in reasonable agreement with the model frequency.

Rayleigh damping was assumed for the dam–foundation system with parameters selected to produce 10% damping at 5 Hz and 20 Hz. The assumed damping is relatively high, but is justified considering that radiation damping in the massless foundation is not explicitly included in the model.

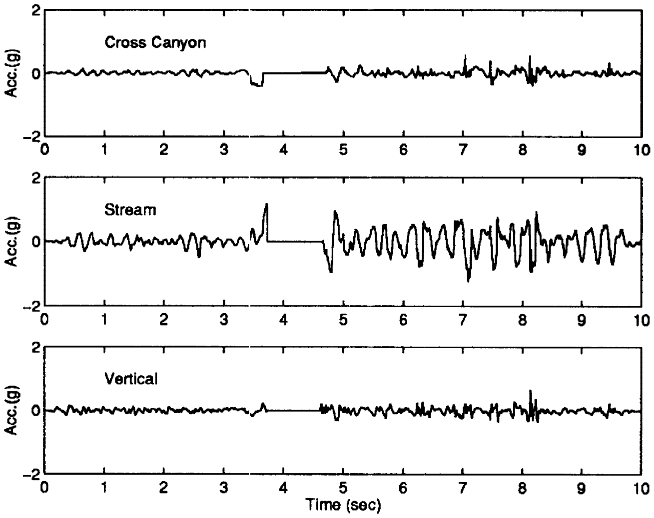


Fig. 4 Unprocessed acceleration histories at crest (channels 2–4). Zero acceleration given for gaps in digitizing.

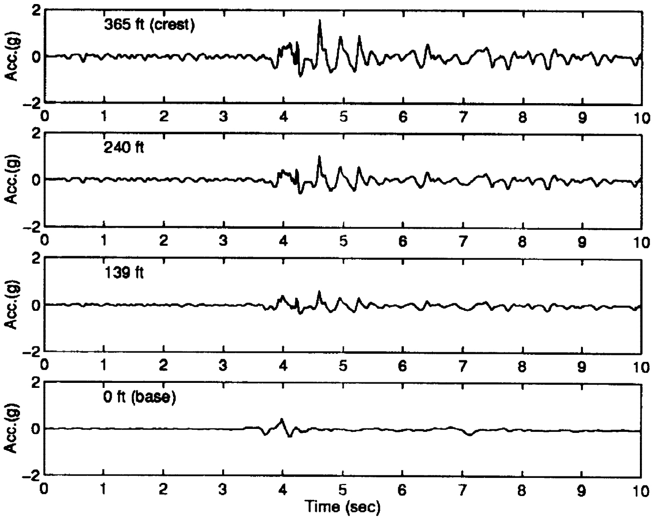


Fig. 5 Assumed non–uniform acceleration histories at the dam–canyon interface in stream direction.

The solution procedure in ADAP–88 is based on a time integration of the nonlinear equations of motion. The hydrodynamic pressures acting on the dam is represented by an added mass matrix neglecting compressibility of water (Kuo, 1982). For computing the added mass, the reservoir is assumed to be bounded by a cylindrical surface obtained by translating the dam–reservoir interface in the upstream direction.

To account for effects of static stresses on opening of the joints, the seismic analysis was preceded by the static analyses for hydrostatic and gravity loads. The vertical joint elements were omitted in the gravity load analysis to account for the independent behavior of the cantilever monoliths. The hydrostatic load was applied to the entire model, including all of the joint elements.

SEISMIC RESPONSE OF PACOIMA DAM

Amplification Effects of Canyon Topography

The amplification of seismic waves in the canyon was indicated by variation in the acceleration amplitudes recorded at the downstream, base, and upper left abutment (Fig. 2). To assess the effects of the ground motion input on the response of the dam, two cases were analyzed with all joints closed. Following previous studies of the dam (Dowling and Hall, 1989), two–thirds of the ULA motion was considered as the average motion of the canyon and was specified as uniform input motion for the first case. The previously described non–uniform free–field motion was used for the second case.

The recorded and computed accelerations for channel 8 are shown in Fig. 6. The accelerations computed for the two closed joint cases differ in amplitude and phase. The case with non–uniform input agrees better with the recorded acceleration than does the uniform input case. However, the response computed for both cases contain a large amplitude cycle which is not present in the recorded motion. The overestimation of the vibration is most likely caused by the lack of radiation damping in the model. The sliding of the foundation rock mass near the left abutment, not accounted for in the model, may also be responsible for the discrepancy.

Figure 7 shows the envelopes of the maximum tensile arch and cantilever stresses at the downstream face, viewed looking downstream. (Observations for upstream face stresses are similar.) The contours are different in distribution and magnitude for the two closed joint cases. For uniform input motion, the peak arch and cantilever stresses are 900 psi and 400 psi, respectively. The peak stress for the non–uniform case are more than three times larger.

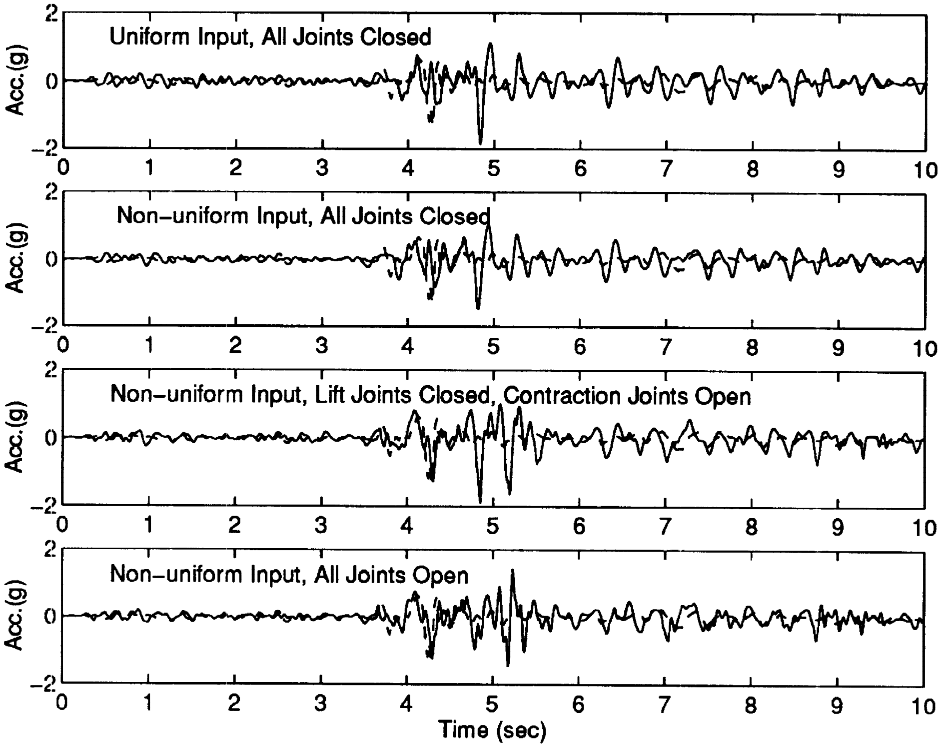


Fig. 6 Comparison of recorded acceleration for channel 8 (dashed line) with computed acceleration (solid line) at the same location.

Opening of Contraction Joints

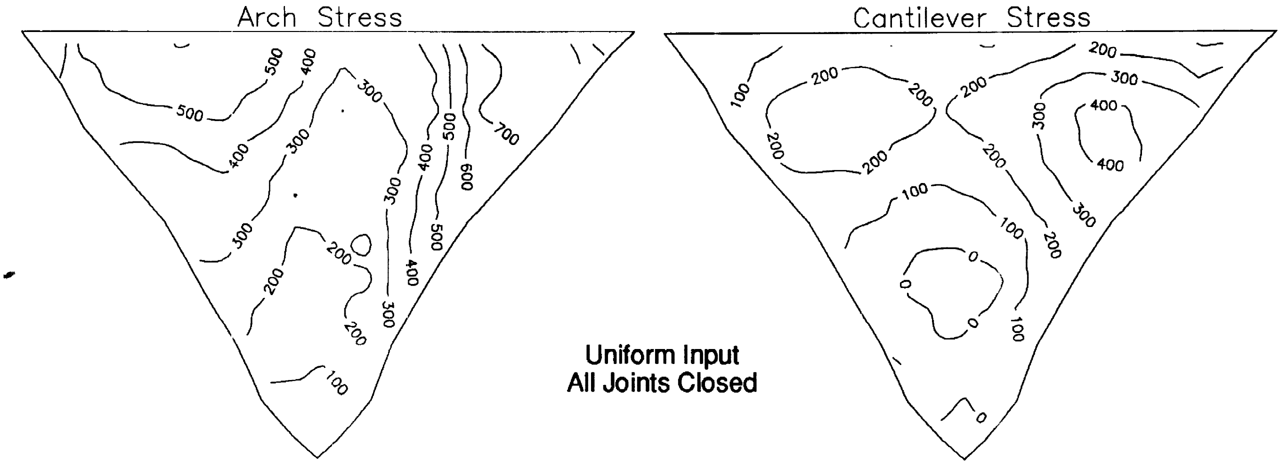
To examine the effects of contraction joints, as well as opening at the dam–foundation interface due to tensile stresses, the analysis with non–uniform input motion was repeated with these joints allowed to open. From the channel 8 acceleration comparison in Fig. 6, the agreement between computed and recorded acceleration improves significantly when the joints are allowed to open. However, the computed response again contains spikes not present in the recorded motion for the reasons mentioned previously.

When contraction joints are allowed to open, the peak downstream arch stress reduces to 1000 psi from 3400 psi and the peak cantilever stress increases to 1800 psi from 1400 psi. The maximum opening of the contraction joints is 4 in. Significant opening, however, occurs at the base of joint, in contrast with the case of uniform input. The upstream and downstream openings are in–phase for each joint indicating complete separation of the vertical joint. The opening of the right–most joint is almost entirely due to the pseudo–static response caused by the relative displacement along the foundation interface.

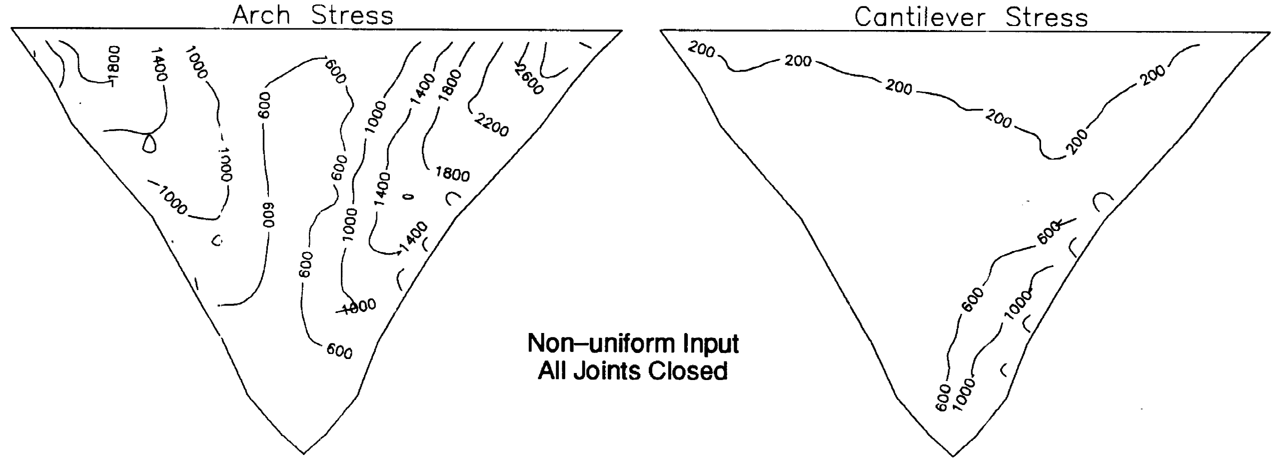
Effects of Lift Joints

The cantilever stresses computed for the case with contraction joint opening exceed the tensile strength of concrete and the lift joints. To account for the opening of lift joints, the dam was analyzed with all vertical, horizontal and abutment joints allowed to open, and considering the non–uniform input motion. In view of the permanent opening of the thrust block joint, tangential stiffness of the joint was omitted. The last history in Fig. 6 for non–uniform input and all joints open shows the best comparison between the computed and recorded acceleration at channel 8.

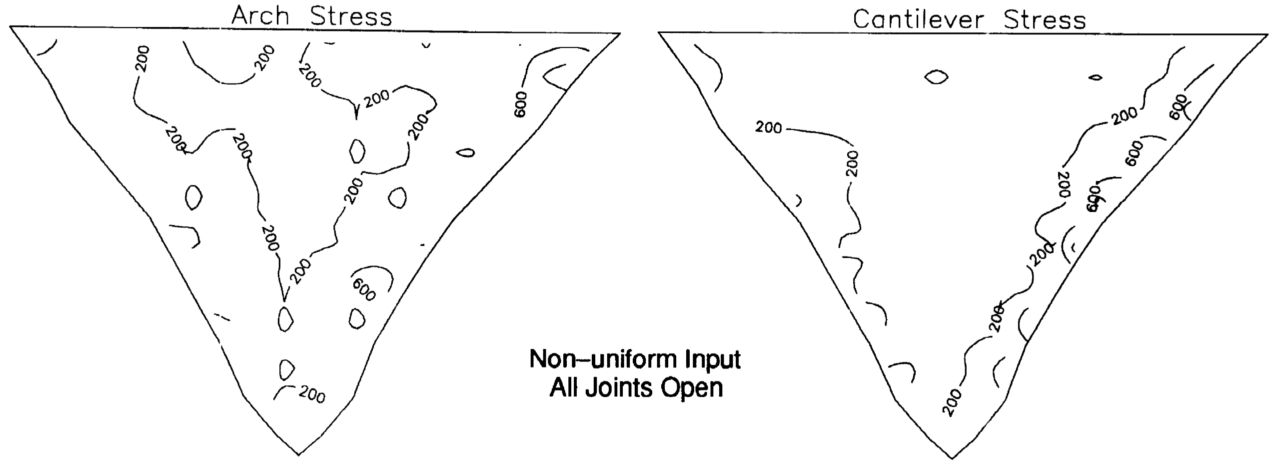
The opening of lift joints releases the cantilever stresses, as seen from contours in Fig. 7. The maximum cantilever stress of downstream face reduces to 1000 psi from 1800 psi for lift joints assumed closed. Significant opening occurs at the top lift joint with a maximum value of 2.6 in. at the base of thrust block on downstream face. The opening for all other locations is less than 0.5 in. Complete separation through the thickness occurs at a number of locations.



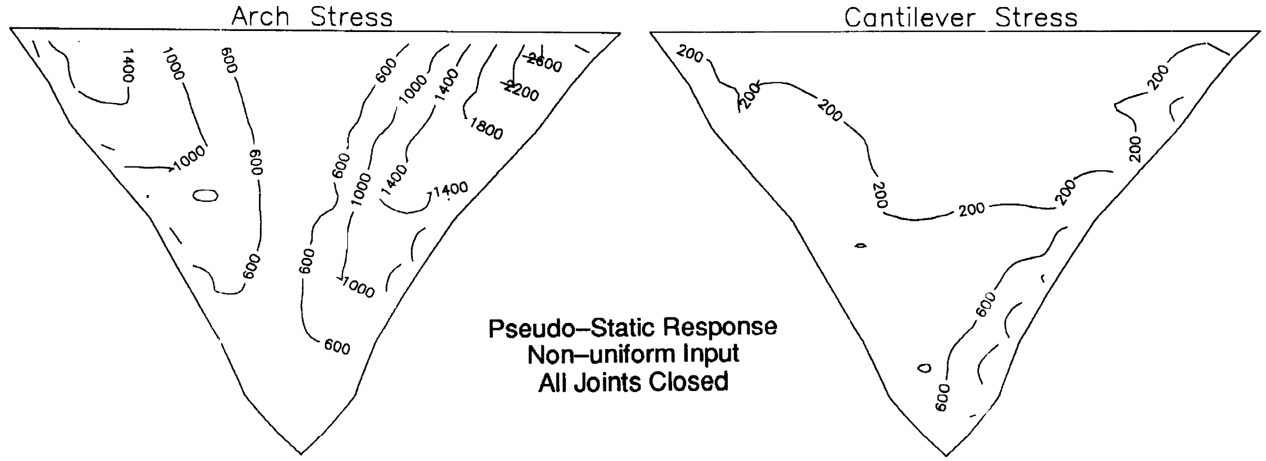
Uniform Input
All Joints Closed



Non–uniform Input
All Joints Closed



Non–uniform Input
All Joints Open



Pseudo–Static Response
Non–uniform Input
All Joints Closed

Fig. 7 Envelopes of maximum tensile stress on downstream face (in psi).

Pseudo–static Response

For a better understanding of the response to non–uniform input motion, the seismic response to the non–uniform input motion was computed with all joints prevented from opening and the inertial effects omitted, to compute the pseudo–static response of the monolithic model. From contour plots of the maximum stress in Fig. 7, the peak stresses associated with the pseudo–static response are largest near the abutments with relatively small stresses in the central portion of the dam. The peak stresses near the abutments are similar to the corresponding stresses which are shown in the same figure for the total dynamic response computed with all joints assumed closed. For the assumed non–uniform input motion the pseudo–static response is significant and the contribution from the vibration in total response is limited to the upper center of the dam.

CONCLUSIONS

Seismic analysis of Pacoima dam using the processed strong motion records from the 1994 Northridge earthquake shows that amplification of seismic waves due to canyon topography has important effects on the response of the dam. An analysis with uniform input motion underestimates the stresses, particularly near the abutments. The stresses are dominated by the pseudo-static response caused by relative displacements of the non–uniform free-field motion. The contribution of dam vibration to the stresses is smaller.

A finite element procedure incorporating discrete joint elements for representation of the discontinuities of the dam can simulate the actual response of the dam. According to the model, the maximum joint opening is 4 in. for the contraction joints and 2.6 in. for the lift joints. In view of the opening of the lift joints, the seismic analysis procedure can be improved by including slippage of the open joints. The dam response is over-estimated unless the loss of energy due to the radiation damping is accounted for.

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