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EARTHQUAKE RESPONSE OF ARCH DAMS TO SPATIALLY-VARYING GROUND MOTION

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ABSTRACT

The response of two arch dams to spatially-varying ground motions recorded during earthquakes is computed by a recently developed linear analysis procedure, which includes dam-water-foundation rock interaction effects and recognizes the semi-unbounded extent of the rock and impounded water domains. It is demonstrated that spatial variations in ground motion, typically ignored in engineering practice, can have profound influence on the earthquake-induced stresses in the dam.

Introduction

Ground motions recorded at arch dams exhibit spatial variation (or non-uniformity) along the dam-foundation rock interface. Such data include records obtained at two dams: (1) Pacoima Dam (California) during the magnitude 4.3 earthquake on January 13, 2001, and the magnitude 6.9 Northridge earthquake on January 17, 1994 (Hall 1996) (Alves and Hall 2006b); and (2) Mauvoisin Dam (Switzerland) during the magnitude 4.6 Valpelline earthquake on March 31, 1996 (Proulx et al. 2004).

Rarely are these spatial variations in ground motion considered in earthquake analysis of arch dams, and when they are included, dam-water-interaction is usually oversimplified. Water compressibility, foundation rock mass, and foundation rock damping (material and radiation) are ignored, and the semi-unbounded extent of the foundation rock and impounded water domains is not recognized (Alves and Hall 2006a) (Mohtahedi and Fenves 2000). All these factors are known to be important in determining the earthquake response of dams to spatially-uniform excitation (Chopra 1992), therefore, they should also be included in analyzing dam response to spatially varying ground motions. Utilizing a recently-developed linear analysis procedure and computer software (Chopra and Wang 2008) (Wang and Chopra 2008), which includes these interaction effects and recognizes the semi-unbounded extent of rock and impounded water domains, the response of the two dams to spatially-varying ground motion recorded during past earthquakes is investigated.

Earthquake Response of Mauvoisin Dam

Mauvoisin Dam and Earthquake Records

Located in the Swiss Alps, Mauvoisin Dam is a 250-meter-high double curvature arch dam. An array of 12 three-component strong-motion (SM) accelerographs has been operating at the dam since 1993. Motions of Mauvoisin Dam during the magnitude 4.6 Valpelline earthquake

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of March 31, 1996, centered 13 km away from the dam, were recorded by the accelerograph array. At the time of the earthquake, the water level was at El.1864, i.e., 112 m below the crest of the dam. The stream components of motions recorded at the accelerograph locations are shown in Figure 1; for brevity, similar figures for the cross-stream and vertical components are not included, but are available in Chopra and Wang (2008).

System and Excitation

Based on correlation of computed response with ambient vibration data and known concrete and rock properties, Proulx et al. (2004) selected parameter values for the dam-water-foundation rock system. These properties were adopted in the analysis reported herein; they are available in Chopra and Wang (2008). Ambient vibration tests led to a viscous damping ratio of 2-3% in the lower vibration modes of Mauvoisin Dam (Darbre et al. 2000). Damping values for the dam alone and foundation rock separately were selected for the EACD-3D-2008 model to achieve a viscous damping ratio of about 2% for the overall dam-water-foundation rock system. A viscous damping ratio of 1% (in all vibration modes) of the dam alone and 3% for the foundation rock led to a damping ratio of 2.2% in the first symmetric mode and 1.5% in the first-anti-symmetric mode, indicating that the chosen damping values for concrete and rock provide an overall damping of about 2% for the dam-water-foundation rock system, consistent with experimental data.

The records SM05, SM08, SM10, SM06, and SM01 were assumed to be free-field motions at locations on the interface that are closest to the recorders. Interpolating and extrapolating these records, the motions at all nodes (of the finite element mesh) around the canyon were determined (Chopra and Wang 2008), and the motions were assumed to be uniform over the thickness of the dam, thus defining the spatially-varying input motions in the EACD-3D-2008 computer program.

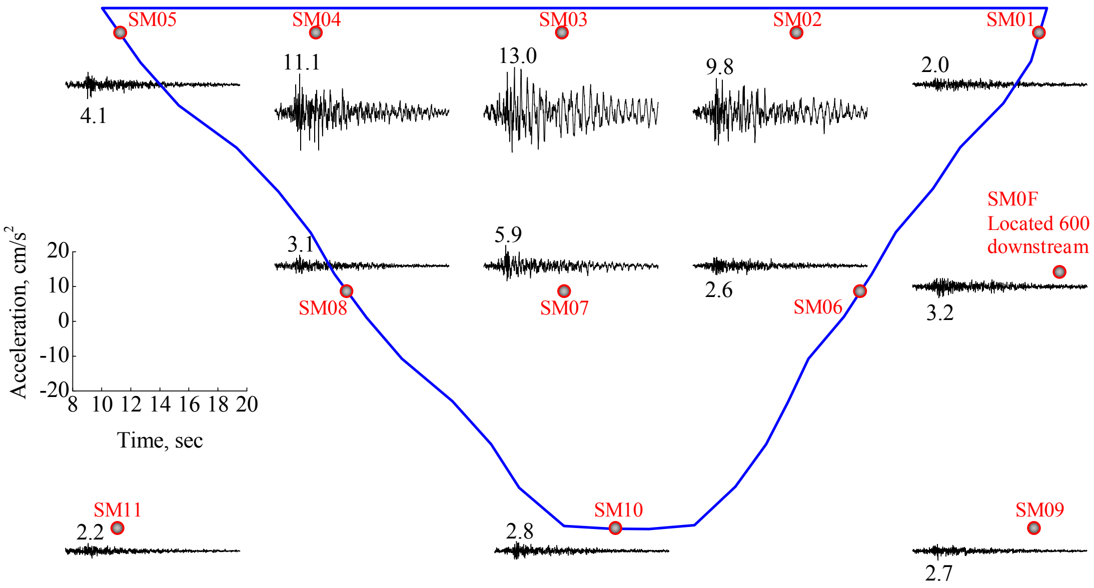


Figure 1. Recorded motions in stream direction; accelerations are in cm/sec^2; peak values are noted.

Influence of Spatial Variations in Ground Motion

With the spatially-varying excitation thus defined, the response of the dam was determined by the EACD-3D-2008 analysis procedure. The computed displacement responses of the dam were reasonably similar to the recorded displacements (Chopra and Wang 2008). Structural response to spatially-varying excitation may be split into two parts: quasi-static and dynamic response (Chopra 2007). The quasi-static component is the response due to static application of the prescribed displacements of the structural supports at each time instant. In the case of a dam, these are the nodal points (in the finite element model) at the dam-rock contact zone or interface. How significantly the dam response is affected by spatial variations in the ground motion along the dam-rock interface is closely tied to the importance of the quasi-static component of the response.

The quasi-static component is only a small part of the response of Mauvoisin Dam, and thus the influence of spatial variations in ground motion on stresses is relatively small. Figure 2 identifies the quasi-static component in the history of displacements at the center of the dam crest. Although the quasi-static component is a significant component in the cross-stream response and a major component in the vertical response, it is a relatively small part of the displacement in the stream direction, the direction of strongest response. Therefore, the spatial variations in ground motion are expected to only modestly influence stresses in the dam, which is confirmed by the results presented in Fig. 3 where the earthquake-induced stresses (excluding initial stresses) are presented for two excitations: spatially-varying and spatially-uniform (the excitation in the latter case is the SM10 record). Although spatial variations in the ground motion cause significantly larger values of some stress components, their overall influence on the distribution pattern (as indicated by the shapes of the stress contours) for stresses in the body of the dam is not large.

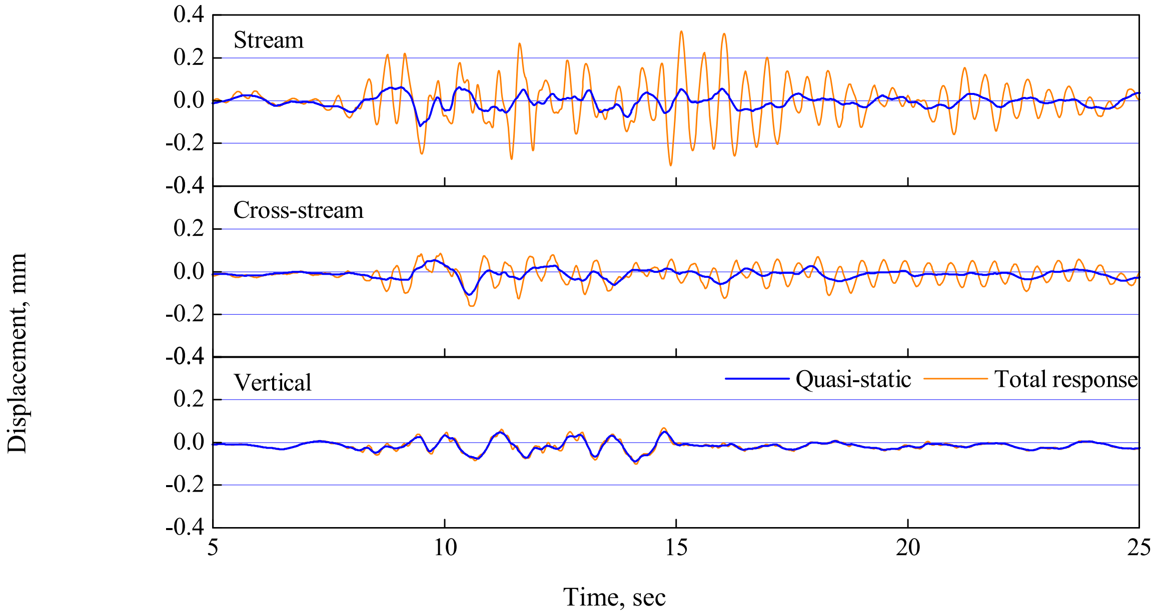
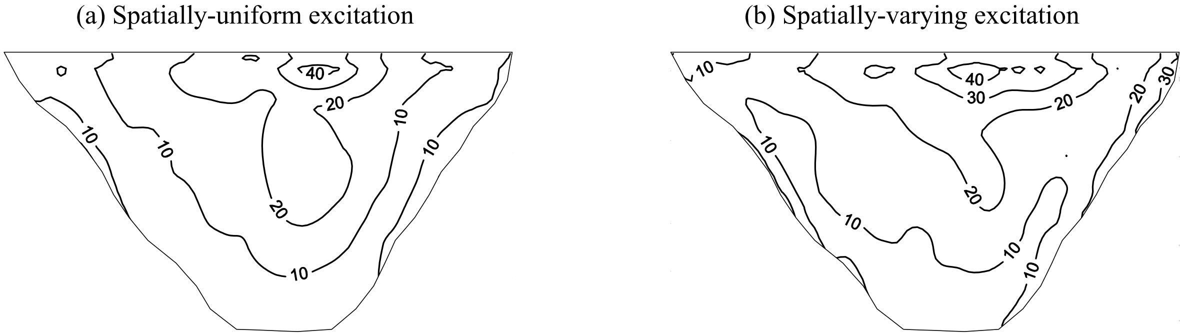


Figure 2. Quasi-static and total displacement histories at crest center due to spatially-varying ground motion; stream, cross-stream and vertical responses are included.



(a) Spatially-uniform excitation

(b) Spatially-varying excitation

Figure 3. Peak values of tensile arch stresses (kPa) on the upstream face due to (a) spatially-uniform excitation, and (b) spatially-varying excitation. Other stress components are available in Chopra and Wang (2008).

Response of Pacoima Dam to Two Earthquakes

Pacoima Dam and Earthquake Records

Located in the San Gabriel Mountains near Los Angeles, Pacoima Dam is a 113-meter high concrete arch dam, with a crest length of 180 m. Completed in 1928, the dam is instrumented with an array of accelerographs designed to record 17 channels of motions. On January 13, 2001, a magnitude 4.3 earthquake occurred, with its epicenter about 6 km south of Pacoima Dam and focal depth of about 9 km. The water level was 41 m below the crest at the time of this earthquake. The stream (or radial) component of the recorded motions is presented in Fig. 4; the cross-stream (or tangential) and vertical components are available in Chopra and Wang (2008). Spatial variation in ground motions along the dam-foundation rock interface is evident. In the stream direction, the peak acceleration of 13 cm/sec^2 at the base is amplified to 43 and 34 cm/sec^2 at the left and right abutments, respectively (Fig. 4). In the cross-stream direction, the peak acceleration of 20 cm/sec^2 at the base is amplified to 95 cm/sec^2 at the left abutment and to 50 cm/sec^2 at the right abutment; the large difference between the amplitudes of the motions at the two abutments is striking.

The cross-stream (or tangential) component of the motions "recorded" during the 1994 earthquake are presented in Fig. 5; the stream (or radial) and vertical components are available in Chopra and Wang (2008). Spatial variation in ground motions along the dam-foundation rock interface is evident. In the stream direction, the peak acceleration of 429 cm/sec^2 at the base is amplified by a factor of approximately two at the abutments. In the cross-stream direction, the peak acceleration of 518 cm/sec^2 at the base is amplified to 1317 and 744 cm/sec^2 at the left and right abutments. The time variation of motions at the two abutments are similar, but the difference in amplitude is striking; in contrast, the stream motions at the two abutments are similar.

The system properties were chosen as those established by system identification using the earthquake records of January 13, 2001 (Alves and Hall 2004). Damping values for the dam alone and foundation rock were selected for the EACD-3D-2008 model to achieve damping in the overall dam-water-foundation-rock system consistent with the aforementioned system identification studies that had led to viscous damping ratios of 6.2% in the first symmetric

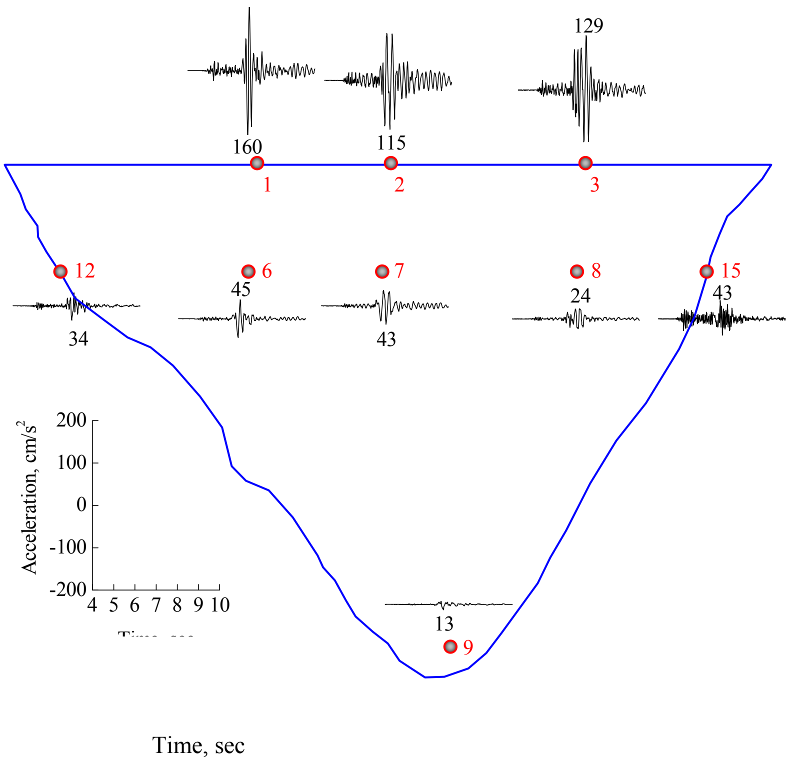


Figure 4. Recorded accelerations (cm/sec^2) in stream or radial direction at Channels 1-3, 6-8, 9, 12 and 15 during the January 13, 2001, earthquake.

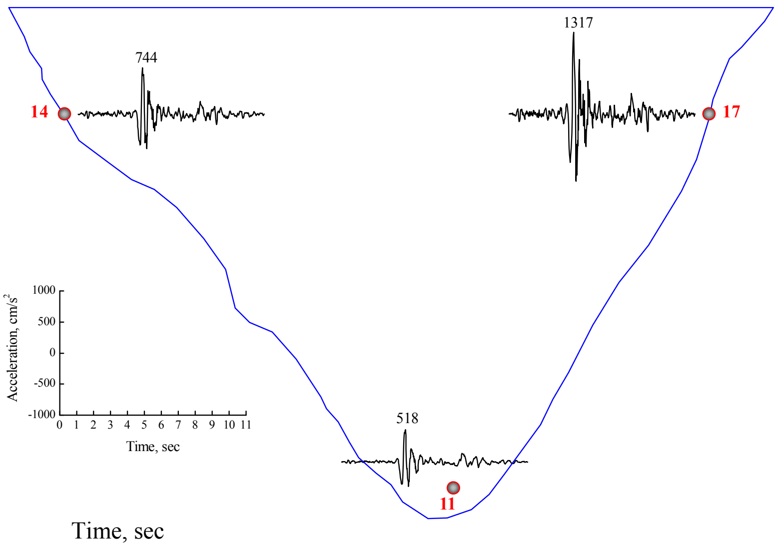


Figure 5. Accelerations (cm/sec^2) generated by Alves (2004) in cross-stream direction at Channels 11, 14, and 17 to represent motions during the Northridge earthquake.

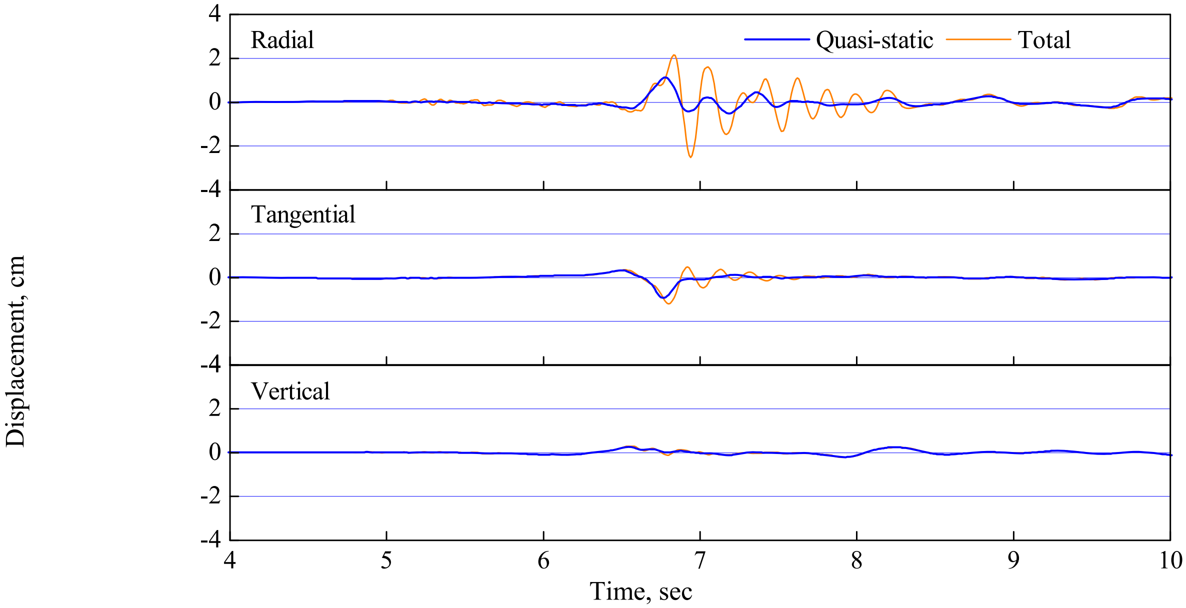


Figure 6. Quasi-static and total displacement histories at crest center (node 211) due to spatially-varying ground motion during the January 13, 2001, earthquake: (a) radial component; (b) tangential component; and (c) vertical component.

vibration mode and 6.6% in the first anti-symmetric vibration mode (Alves 2004). Assuming a viscous damping ratio of 2% (in all vibration modes) of the dam alone and 4% for the foundation rock, the viscous damping ratio was 7.0% in the first mode and 6.7% in the first anti-symmetric mode (second mode of the dam), values that are close to the identified values.

Influence of Spatial Variations in Excitation

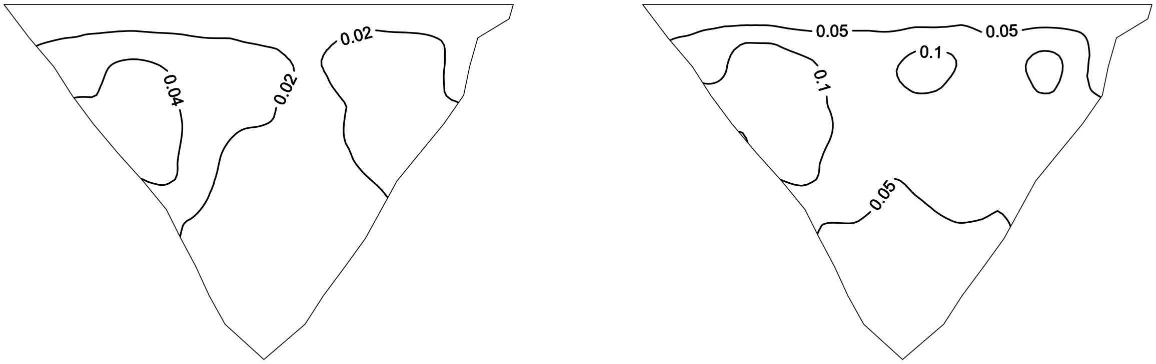
January 13, 2001, Earthquake

The response of the dam to spatially-varying excitation recorded during the 2001 earthquake was determined by the EACD-3D-2008 analysis procedure. The computed displacements compared well to the recorded displacements (Chopra and Wang 2008). The quasi-static component is a significant but not a dominant part of the displacement response of Pacoima Dam to the January 13, 2001, earthquake records. Figure 6 identifies the quasi-static component in the history of displacements at the center of the crest. Although the quasi-static component is dominant in the tangential and vertical responses, it is not a major part of the displacement in the radial direction, the direction of largest response.

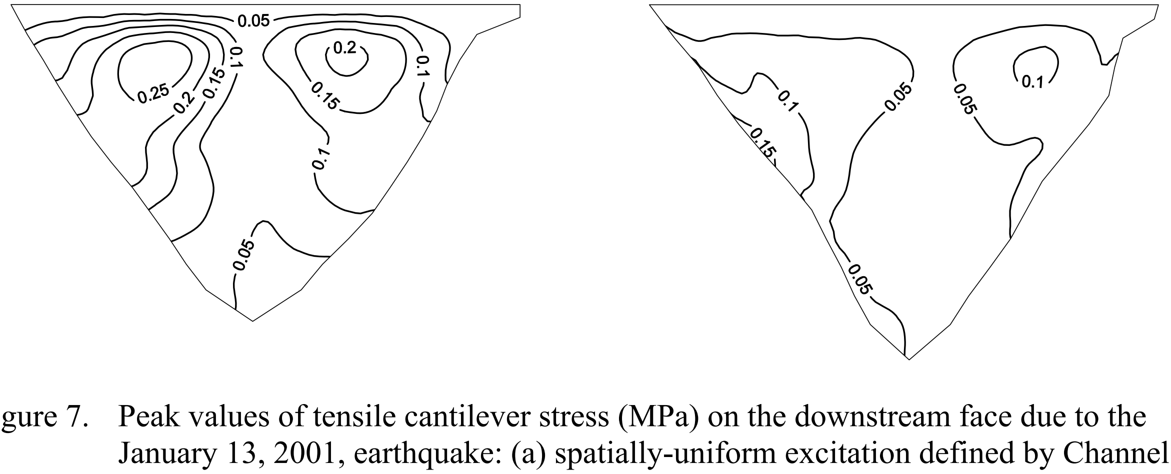
Therefore, the spatial variations in ground motions are expected to significantly influence—but not dominate—the stresses in the dam, as shown in Fig. 7, where the peak values of the tensile stresses in the cantilever direction on the downstream face of the dam are presented; similar figures for arch and cantilever stresses on both faces of the dam are available in Chopra and Wang (2008). Presented are stresses due to four different excitations; the first three are spatially-uniform excitations defined by ground motions recorded at the base of the dam (Channels 9-11), the right abutment (Channels 12-14), and the left abutment (Channels 15-

17). The fourth excitation is defined as the recorded (and interpolated or extrapolated) spatially-varying ground motions. Among the three spatially-uniform excitations, the stresses are smallest due to ground motions recorded at the base of the dam, they are the largest due to excitation defined by the left abutment records, and between these two extremes due to ground motions recorded at the right abutment. This ordering of the stress values correlates well with the relative intensity of ground motions at the three locations: the peak accelerations in the stream direction are 12.8 cm/s^2 at the base, 33.8 cm/s^2 at the right abutment, and 43.3 cm/s^2 at the left abutment.

The stresses due to spatially-varying excitation may be smaller or larger than those due to spatially-uniform ground motion, depending on the intensity of the latter. They are larger when compared to the stresses due to the base motion—the least intense of the three spatially-uniform excitations—but are generally smaller than the stresses due to the abutment motions. Comparing the four parts of Fig. 7 also reveals that spatial variations in ground motion significantly influence—but not dominate—the stresses in Pacoima Dam due to the January 13, 2001, earthquake.


(a) Spatially-uniform excitation: Channels 09-11

(b) Spatially-uniform excitation: Channels 12-14


(c) Spatially-uniform excitation: Channels 15-17

(d) Spatially-varying excitation

Figure 7. Peak values of tensile cantilever stress (MPa) on the downstream face due to the January 13, 2001, earthquake: (a) spatially-uniform excitation defined by Channels 09-11; (b) spatially-uniform excitation defined by Channels 12-14; (c) spatially-uniform excitation defined by Channels 15-17; and (d) spatially-varying excitation.

January 17, 1994, Northridge Earthquake

The quasi-static component is dominant in the displacement response of Pacoima Dam to the January 17, 1994, Northridge earthquake records, therefore the spatial variations in ground motion have profound influence on the computed stresses in the dam. Figure 8 identifies the quasi-static component in the history of displacements at three locations on the dam crest. Consequently, the spatial variations in ground motion are expected to profoundly influence the stresses in the dam. Figure 9 confirms this expectation, where the peak value of the tensile stresses in the arch direction on the downstream face of the dam are presented; similar figures for arch and cantilever stresses on both faces of the dam are available in Chopra and Wang (2008). Presented are the stresses due to four different excitations. The first three are spatially-uniform excitations defined by ground motion at the base of the dam (Channels 9-11), the right abutment (Channels 12-14), and the left abutment (Channels 15-17). The fourth excitation is defined as the "recorded" (and interpolated or extrapolated) spatially-varying ground motion. The distribution pattern of stresses due to the three spatially-uniform excitations is similar, although the magnitude of stresses due to ground motions recorded at the base of the dam is much smaller than those due to motions at the left or right abutment; the stresses due to the two abutment excitations are similar in magnitude. By comparing the stresses due to spatially-varying and spatially-uniform excitations, clearly the spatial variations in ground motion had profound influence on the magnitude and the distribution of arch stresses (Fig. 9). Spatial variations in ground motion cause much larger cantilever stresses on both faces (compared to all three spatially-uniform excitations) in portions of the dam adjacent to the dam-foundation rock contact (Chopra and Wang 2008).

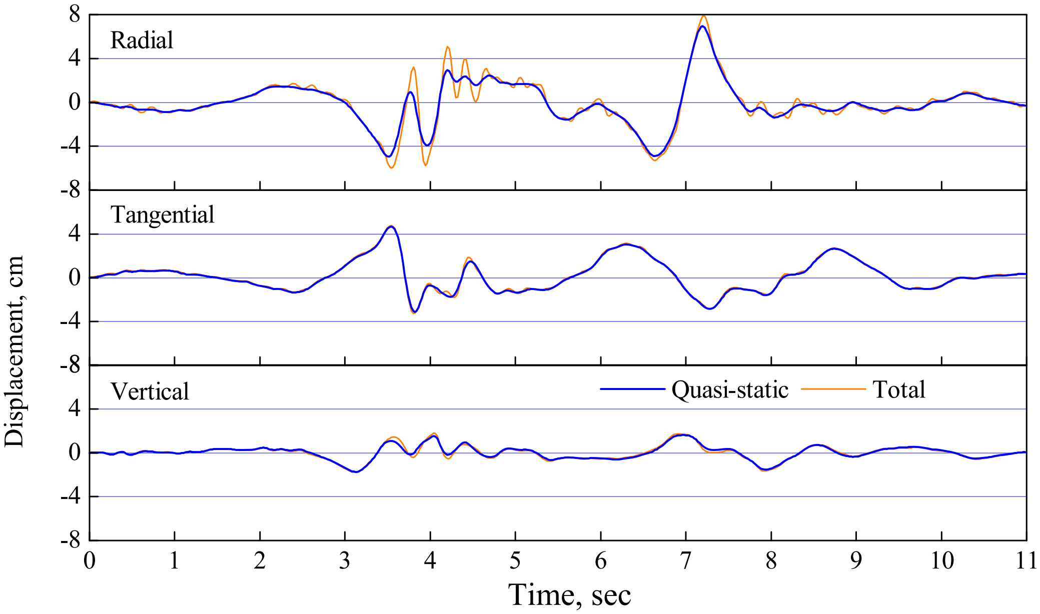
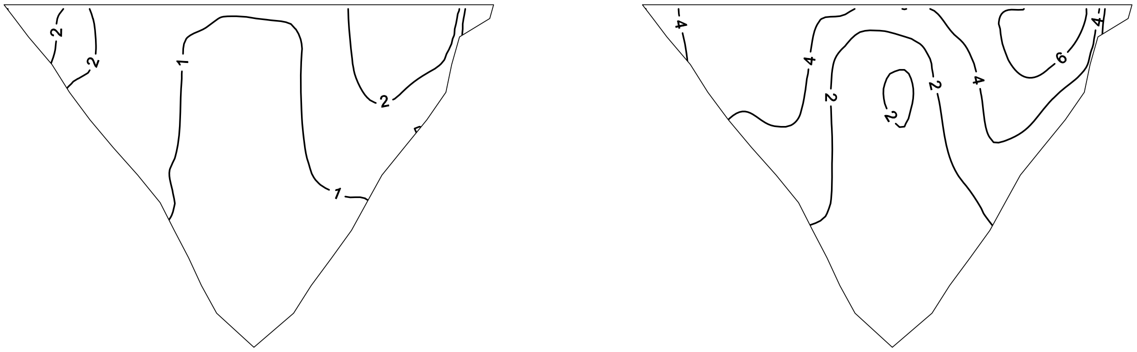


Figure 8. Quasi-static and total displacement histories at crest center (node 211) due to spatially-varying ground motion during the Northridge earthquake: (a) radial component; (b) tangential component; and (c) vertical component.

(a) Spatially-uniform excitation: Channels 09-11

(b) Spatially-uniform excitation: Channels 12-14



(c) Spatially-uniform excitation: Channels 15-17

(d) Spatially-varying excitation

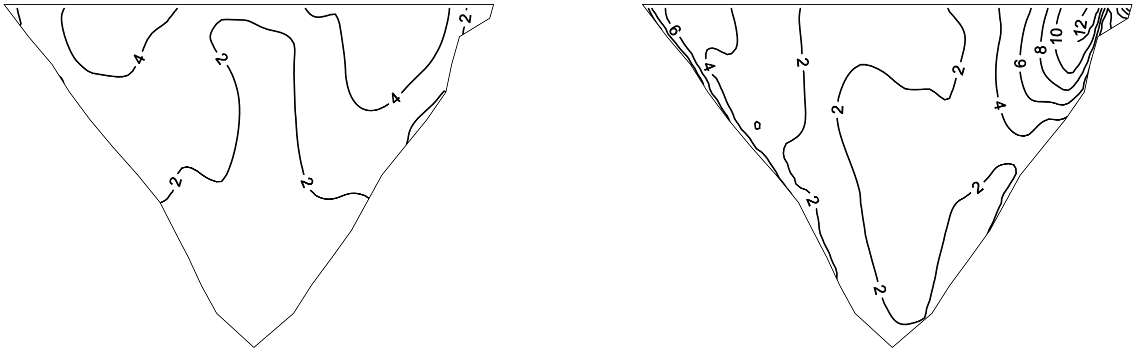


Figure 9. Peak values of tensile arch stress (MPa) on the downstream face due to the Northridge earthquake: (a) spatially-uniform excitation defined by Channels 09-11; (b) spatially-uniform excitation defined by Channels 12-14; (c) spatially-uniform excitation defined by Channels 15-17; and (d) spatially-varying excitation.

Because these stresses were computed by linear analysis, they are not indicative of actual stresses that developed in the dam because vertical contraction joints opened and cracking occurred during the earthquake. However, the large arch stresses computed in the thrust block between the dam and the left abutment and the portion of the dam adjacent to the thrust block [see Fig. 9 and additional figures in Chopra and Wang (2008)] suggests that cracking would occur in these areas, which is what actually happened during the earthquake.

Conclusions

Spatial variations in ground motion, typically ignored in dam engineering practice, can have profound influence on the earthquake-induced stresses in the dam. This influence obviously depends on the degree to which ground motion varies spatially along the dam-rock interface. Thus, for the same dam, this influence could differ from one earthquake to the next, depending on the epicenter location and focal depth of the earthquake relative to the dam site.

Acknowledgments

We are grateful to Georges Darbre for authorizing the use of earthquake motions recorded at Mauvoisin Dam, to Jean Proulx for advising us on the myriad details of his previous analyses of Mauvoisin Dam, and to Steven W. Alves and John F. Hall for advising us on the implementation of the procedures they had developed for interpolation of ground motions and for providing their finite element model of Pacoima Dam.

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