ANALYSIS OF PACOIMA DAM USING RECENTLY RECORDED SEISMIC MOTIONS: REPORT ON PROGRESS

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Abstract

Ground and structure motions were recorded on 17 channels at Pacoima Dam during a magnitude 4.3 earthquake on January 13, 2001. These data are examined by system identification and finite element modeling to quantify the effects of nonuniform ground motion and the level of damping exhibited by the dam. The system identification study indicates the dynamic response of the dam is due mostly to two modes which have frequencies close to 5hz and damping in the range of 4% to 7% of critical. The displacement histories of the dam are reproduced fairly well by the finite element model, but differences in amplitudes for some of the channels remain to be resolved. In addition, more work is needed to obtain confidence in the results, especially the relatively high level of damping which seems to be present.

Introduction

Pacoima Dam is a 113m high concrete arch dam located north of the city of Los Angeles. A well known ground motion record obtained above the south abutment during the 1971 San Fernando earthquake showed large accelerations of 1.25g horizontal and 0.70g vertical which have been attributed to topographical amplification. A more extensive 17-channel accelerograph array was installed later and was in place during the 1994 Northridge earthquake. Nine of these channels were located on the dam-rock interface in order to capture the spatially nonuniform features of the seismic input, and the remaining eight channels were located either on the dam crest or at 80% height on the downstream face of the dam. Unfortunately, middle portions of many of the 1994 records contained off-scale high frequency motions which could not be digitized. These motions probably resulted from impacts in the contraction joints between the blocks of the dam and at a thrust block on the south abutment. Movement of a rock mass occurred on the south abutment in both the 1971 and 1994 earthquakes, more severely in the latter. These movements opened and reopened a gap in the joint at the south thrust block. Repairs undertaken after both earthquakes included stabilization of the damaged abutment and filling the gap at the thrust block.

This paper is a progress report on an investigation into a set of records obtained at Pacoima Dam during a magnitude 4.3 earthquake on January 13, 2001 (CSMIP, 2002). By the time of this earthquake, the 17 analog channels at Pacoima Dam had been replaced by digital ones, and so the recent data is of high quality. Of principal interest in this study are the effects of non-uniformity in the ground motion and the level of damping present in the dam vibration. Both of these are important considerations in the earthquake response of dams, and neither has been adequately quantified to date.

The three sections that follow present a description of the records, an identification study in which best-fit parameters of a 2-mode linear system are determined, and an effort to calibrate a detailed finite element model using the recorded data. Future studies will employ the calibrated finite element model and stronger ground motions to evaluate the effects of cracking and joint opening on the dam response. The final report will also include an examination of records obtained on Pacoima Dam during the 1994 Northridge earthquake, which have been previously studied by others (Mojtahedi and Fenves, 2000).

Description of Records

Locations of the 17 channels at Pacoima Dam are shown in Figure 1. Channels 1 to 8 are on the body of the dam: six of these are radial in the horizontal plane with one each oriented tangentially and vertically. Channels 9 to 17 are located on the dam-rock interface in order to define the input motion to the dam. There are three channels each at stations on the north and south abutments and at the base. Acceleration and displacement time histories from the 2001 earthquake for all channels except vertically oriented ones are plotted in Figures 2 and 3. Peak values of acceleration, velocity and displacement are listed in Table 1 for each channel. The highest accelerations at the interface and on the dam are 0.10g and 0.16g, respectively. Since the level of shaking is much lower than during the 1994 Northridge earthquake, the acceleration records show none of the off-scale high frequency motions which characterized the Northridge earthquake accelerograms.

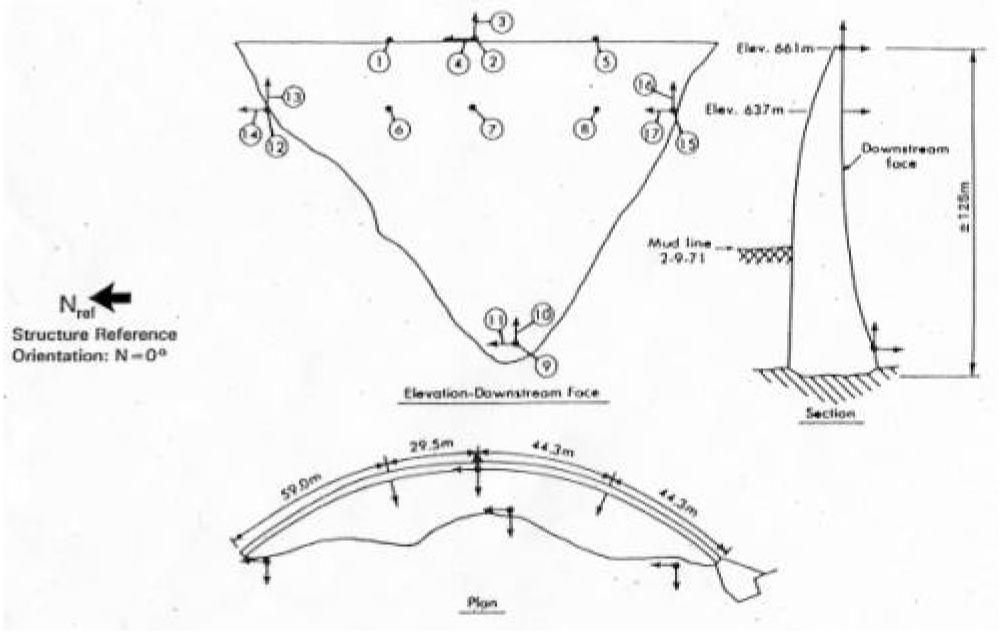

Figure 1. Location of the 17 recording channels at Pacoima Dam (CSMIP, 2002).

Although the intensity of the input motion from the 2001 earthquake is not high, the amplitude and phase variations around the canyon are probably more functions of frequency than amplitude, which means these characteristics of nonuniform input should be fully contained in the data and so can still be quantified. The moderate motions of the dam imply that it is vibrating in or near its linear range, and this simplifies the present study of the effects of nonuniform ground motion. Regarding damping, the data should lead to values appropriate for low-level vibration, which will be useful as a baseline. Another simplification arises from the water level being 41m below the crest during the 2001 earthquake, which is low enough so that it has only a minor effect on the dam response.

The recorded motions from the 2001 earthquake on the north and south abutments are of higher amplitude than those at the base. This amplification is shown in Figure 4 as a function of vibration frequency where plots of ratios of response spectra computed from the respective components of the abutment and base motions are presented. The most amplification is seen in the north-south component (close to cross-stream direction) at the south abutment, which is where the damage occurred in previous earthquakes. However, the other two components on the south abutment are amplified about the same, or even less, than the respective ones on the north abutment. At the fundamental frequency of the dam, which is shown to be about 5hz in the next section (actually two frequencies near 5hz), the amplification on the south abutment in the north-south direction is about 3.5, and for the other channels, the amplification ranges from 2 to 3. Amplification factors above four occur for two channels: the north-south component on the south abutment at frequencies around 4hz and 10hz, and the east-west component (close to the upstream-downstream direction) on the north abutment around 7hz.

Another aspect of the non-uniformity in the input motions is time shift. This quantity can be found between any two motions by integrating their product as a function of time offset between the two. The offset for which this correlation integral is maximum is the time shift, which is listed in Table 2 for respective components of the motions from the base station to the two abutment stations. As seen, the abutment motions in the horizontal directions lag (positive time shift) the base motions by times ranging from 41 to 66 milliseconds. Time shifts for the vertical component are smaller. Although the largest time shifts are a significant fraction of the fundamental period of the dam, which is about 200 milliseconds, the shifts are not expected to affect the dam response in a major way. This is because the horizontal abutment motions excite most of the dam response, and they are actually time shifted relatively little with respect to each other. Some further work is in progress to quantify the frequency dependence of the time shifts.

A long range goal of collecting ground motion data at the base and sides of canyons, as at Pacoima Dam, is to develop rules for prescribing nonuniform seismic input in safety assessment analyses of dams. Based on the data presented here, one could propose that time shift be a function of elevation and shear wave speed in the rock. For Pacoima Dam, using the 84m elevation difference between the base and abutment recording stations and a shear wave velocity for rock of 1500 to 2000 m/sec (see section on Finite Element Model Calibration) results in a time shift of 0.042 to 0.056 milliseconds, which is in the range of that found for the horizontal components of

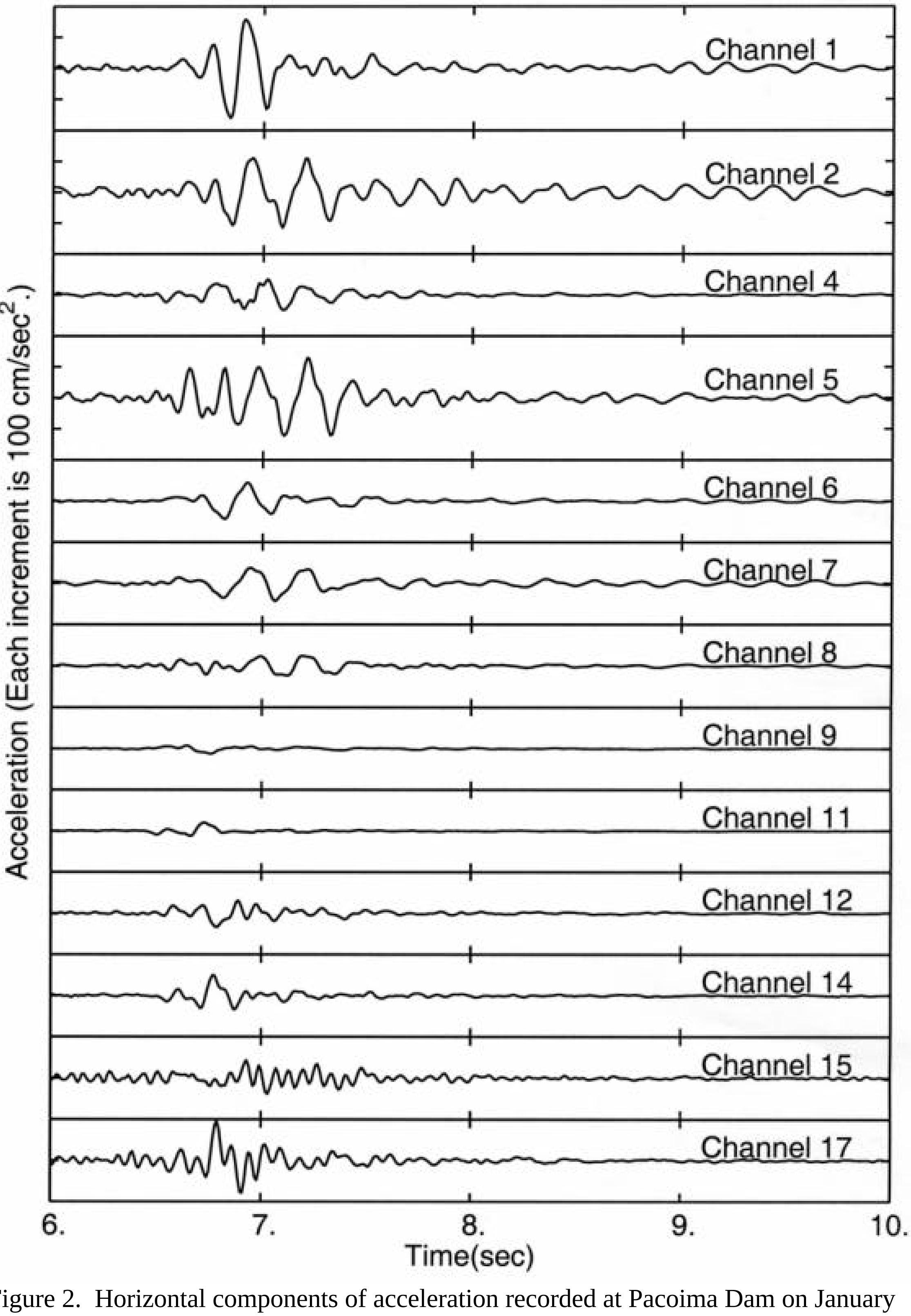

Figure 2. Horizontal components of acceleration recorded at Pacoima Dam on January 13, 2001.

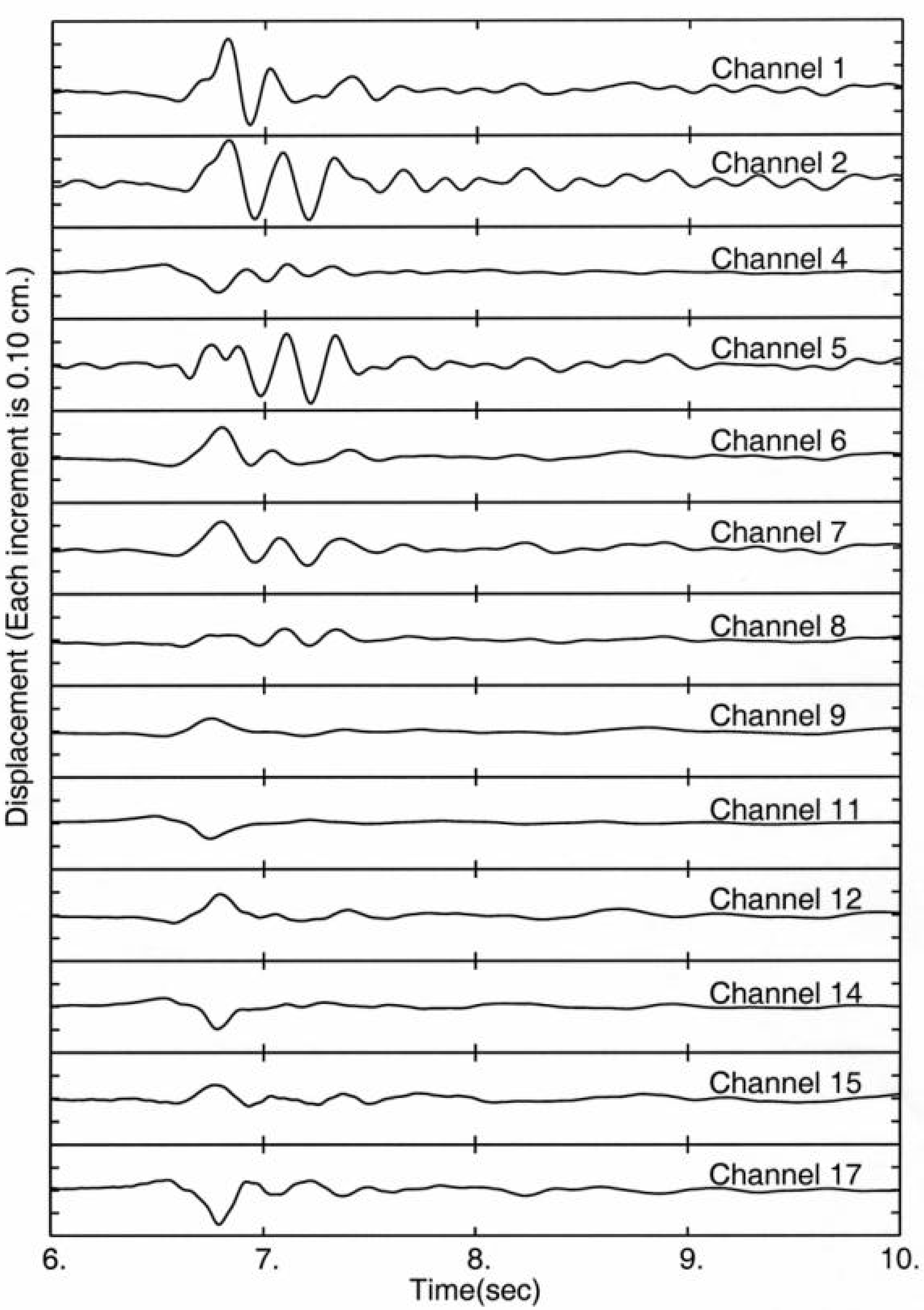

Figure 3. Horizontal components of displacement recorded at Pacoima Dam on January 13, 2001.

Channel	Location/Orientation	Acceleration	Velocity	Displacement
1	crest at north thrd point/radial	-0.16g	-6.2 cm/sec	0.22 cm
2	center crest/radial	-0.12g	-4.7 cm/sec	0.18 cm
3	center crest/up	-0.02g	0.6 cm/sec	0.02 cm
4	center crest/tangential	0.04g	1.3 cm/sec	-0.09 cm
5	crest at south qtr point/radial	0.13g	-3.9 cm/sec	-0.17 cm
6	80% height at north thrd pt/radial	0.05g	-2.0 cm/sec	0.13 cm
7	80% height at center/radial	-0.04g	-1.7 cm/sec	0.12 cm
8	80% height at south qtr pt/radial	0.02g	-1.1 cm/sec	0.05 cm
9	base/west	-0.01g	0.6 cm/sec	0.06 cm
10	base/up	0.01g	-0.2 cm/sec	0.02 cm
11	base/north	0.02g	-0.9 cm/sec	0.07 cm
12	north abutment/west	-0.03g	1.2 cm/sec	0.09 cm
13	north abutment/up	-0.01g	-0.5 cm/sec	0.03 cm
14	north abutment/north	0.05g	1.5 cm/sec	-0.10 cm
15	south abutment/west	0.04g	-0.9 cm/sec	0.06 cm
16	south abutment/up	0.02g	-0.3 cm/sec	0.03 cm
17	south abutment/north	0.10g	2.3 cm/sec	-0.15 cm

Table 1. Peak values of acceleration, velocity and displacement from the 17 channels on Pacoima Dam during the 2001 earthquake.

	East-west comp	Vertical comp	North-south comp
Base to north abutment	0.049 sec	0.024 sec	0.048 sec
Base to south abutment	0.041 sec	-0.008 sec	0.066 sec

Table 2. Time shifts from the base station to the stations on north and south abutments for east-west, vertical and north-south components of the 2001 earthquake records. Lag is positive.

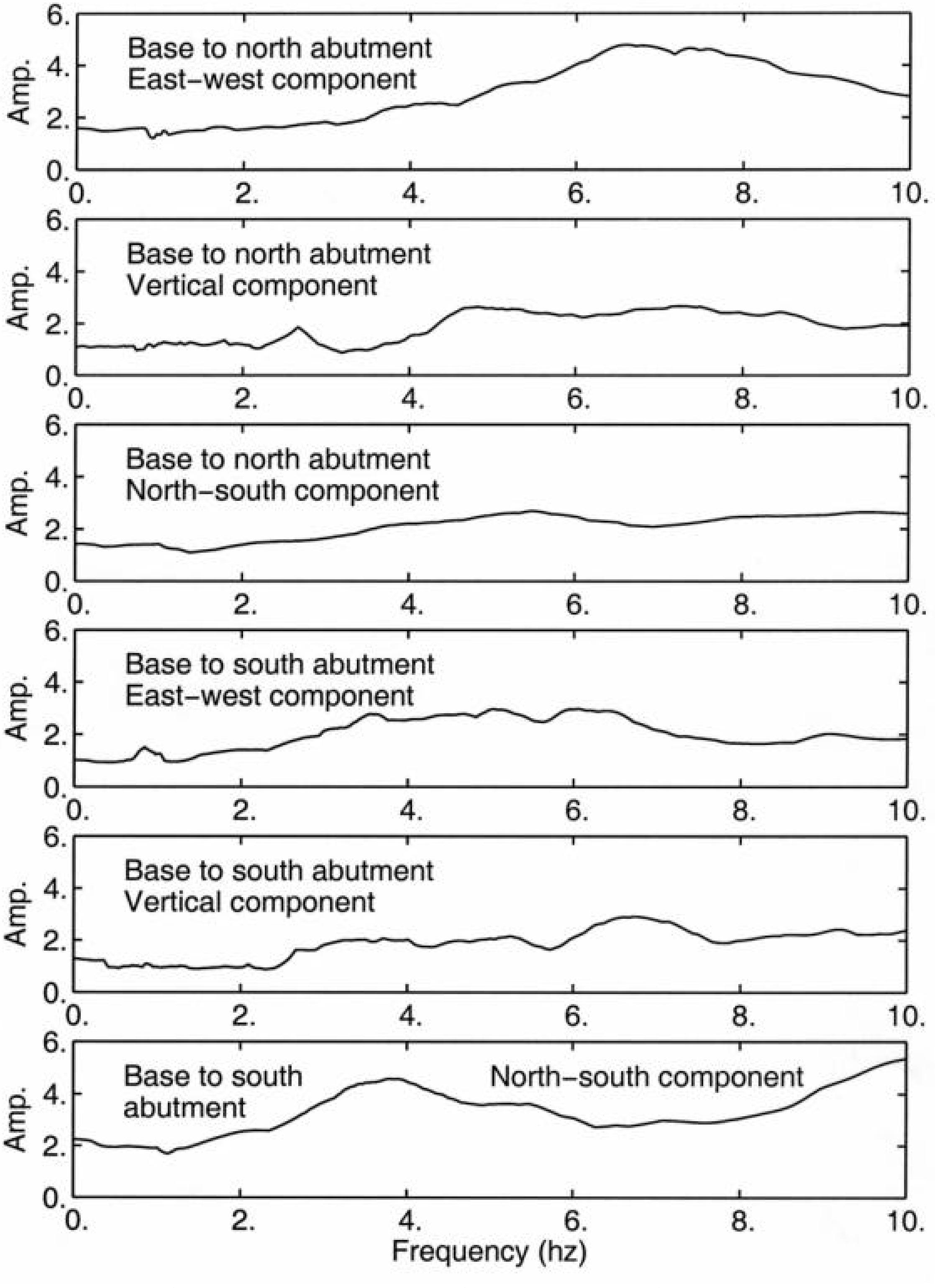

Figure 4. Amplification on the abutments of Pacoima Dam referred to motion at the base of the dam in terms of ratios of response spectra (5% damping).

ground motion (Table 2). An additional rule expressing amplification as a function of frequency and elevation could be formulated by averaging the results shown in Figure 4. Such rules would be applied to components of a reference motion to generate a suite of motions around a canyon. A major difficulty is how to select the reference motion. Should it be considered representative of a bottom site, in which case it would be amplified and time lagged up the canyon, or a site near the crest of the dam, in which case it would be de-amplified and time forwarded down the canyon, or somewhere in between? If the reference motion is to be selected by current standard procedures, this becomes an interesting question.

System Identification

System identification is performed using the computer program MODEID (Beck and Jennings, 1980) which models the structure as a linear system in modal coordinates excited by spatially nonuniform ground motion. To run MODEID, the user specifies the number of modes to be included and supplies the motions recorded on the structure (channels 1 to 8 in the present case) and at the "base" of the structure (channels 9 to 17 in the present case). Using the “base” motions as input, the program determines the frequencies, damping, shapes and participation factors for each mode, as well as the pseudo-static response matrix, which produce the best fit to the recorded structural motions.

For a two-mode solution, MODEID converged to modal frequencies of 4.8hz and 5.1hz with damping of 6.8% and 4.6% of critical, respectively. As shown from experience in forced vibration testing (Hall, 1988), arch dams typically have two closely spaced modal frequencies, and these correspond to mode shapes which can be classified as symmetric and antisymmetric. Previous forced vibration tests on Pacoima Dam in 1980 revealed frequencies of 5.4hz and 5.6hz (ANCO Engineers, 1982), higher than the MODEID values. Reasons for this difference are not clear. Damping values from the 1980 tests were also higher than those from MODEID, but data from those tests were of poor quality and this made it difficult to accurately determine damping. However, even the 4% to 7% damping from MODEID seems on the high side compared to forced vibration results from other dams (for example, 1.4% to 4.0% at Morrow Point Dam and 1.8% to 3.1% at Monticello Dam; see Hall, 1988). And it should be noted that MODEID identifies the fixed-base modal properties, ie, foundation interaction is not represented, and so there is no energy radiation from this source.

Figure 5 plots the recorded accelerations from channels 1, 2, 4 and 5 along with the best-fit responses of the MODEID model. The agreement is very good. However, because MODEID does not enforce "realistic" conditions in its parameter determination, the identified mode shapes appeared to violate orthogonality, and they did not match the expected symmetric and antisymmetric profiles. In addition, some terms of the pseudo-static response matrix were much too large. Because of these problems, a question arises about the accuracy of the damping values. (Modal frequencies are well determined.) In fact, there is a kind of ill-posedness between modal damping and participation factor, as a higher value of one can be significantly compensated by a lower value of the other.

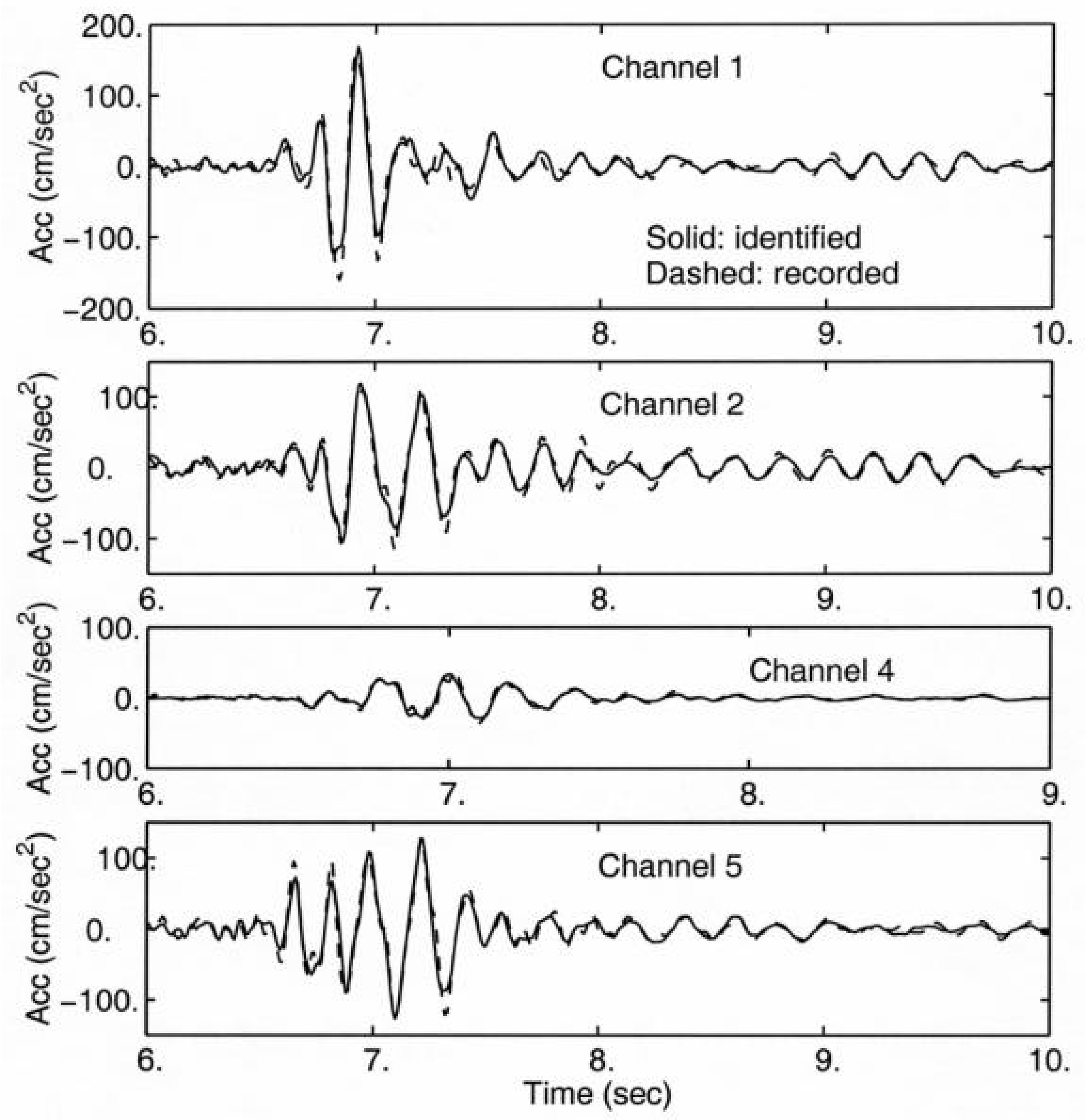

Figure 5. Comparison between the recorded accelerations at channels 1, 2, 4, and 5 and the best-fit accelerations from the MODEID system identification study.

More work on system identification is planned, especially to achieve confidence in the damping. First, sensitivity of the quality of the fit to the damping values will be examined. Second, the terms of the pseudo-static response matrix will be computed by the finite element program discussed in the next section and input as set quantities to MODEID. Constraining MODEID in this way should result in more realistic values for the remaining parameters to be determined. It should also be noted that the input motion is known to MODEID only at three locations, which could be a source of error. So, a third task is to investigate this issue through simulations using the finite element model.

Finite Element Model Calibration

A finite element model of Pacoima Dam, massless rock foundation, and incompressible water reservoir was constructed with the computer program SCADA (Hall, 1996). Shell elements are used for the dam, solid brick elements for the foundation, and pressure brick elements for the water (Figure 6). Rayleigh damping is employed using the stiffness and mass matrices of the dam and the stiffness matrix of the rock to construct a proportional damping matrix. The foundation model is connected only to the dam, and for modeling purposes the south thrust block is considered to be part of the foundation. Nodes of the water mesh are fixed down to the surface elevation at the time of the 2001 earthquake. SCADA uses the smeared crack method to model opening, closing and sliding nonlinearity associated with contraction joints and cracks in the dam, or it can operate in a linear mode.

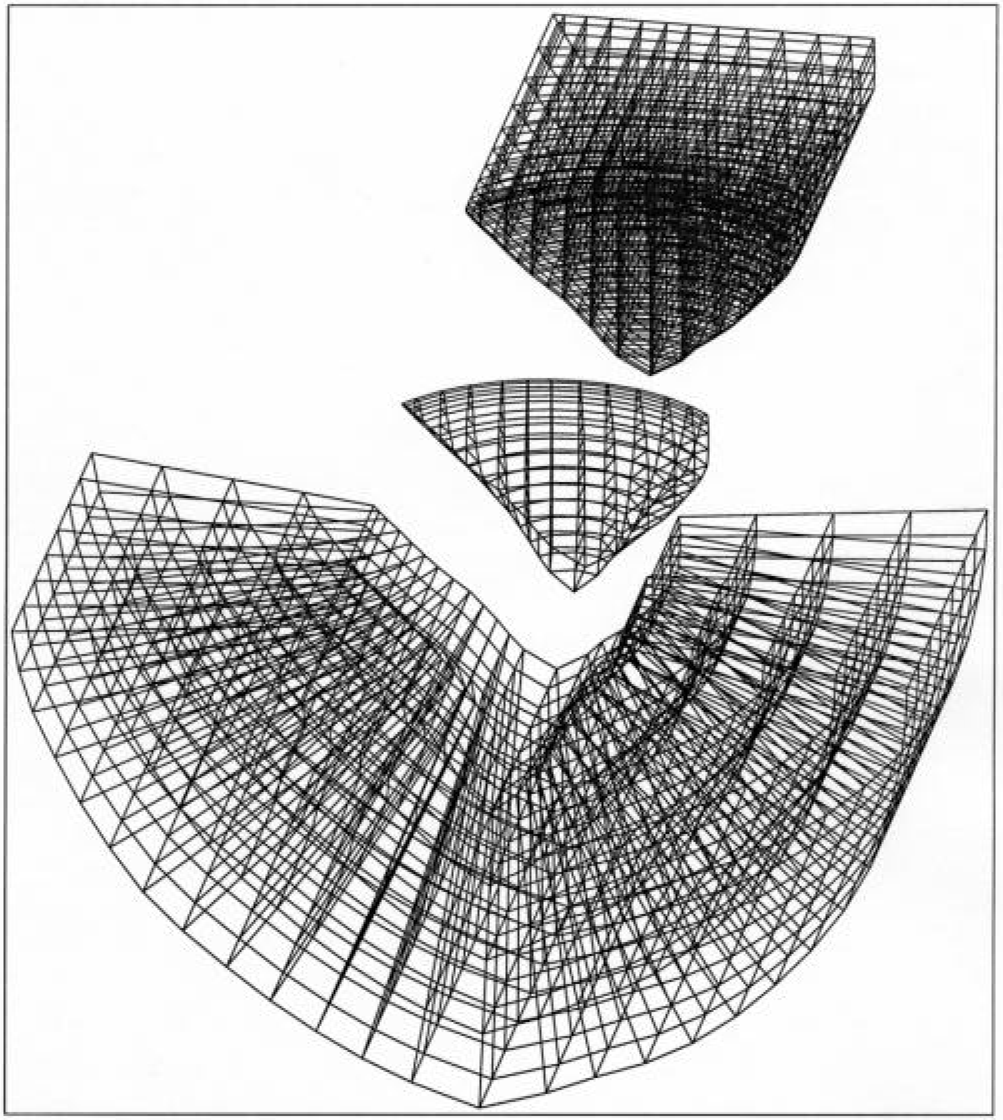

Figure 6. Finite element meshes for Pacoima Dam, water reservoir and rock foundation.

For the present study, SCADA was modified to accept nonuniform input. Earthquake loads are computed as those which when applied to the foundation mesh alone cause the interface to move at the desired motions. For the Pacoima Dam analysis, this requires that the recorded accelerograms at the abutments and base of the dam be interpolated to each dam node on the interface. Motions at nodes on the north side of the canyon are interpolated from the north abutment and base records, similar for the south side of the canyon using the south abutment and base records. Interpolation is performed channel by channel, and the interpolation at a node is weighted according to the elevation of the node. Before interpolation, any time shift is eliminated, and then the interpolated record is appropriately re-shifted based on its nodal elevation. For nodes located higher than the abutment stations, larger amplitudes and time shifts result. The interpolated motions, as a function of elevation, are applied to the water mesh as well.

Since channels 9 to 17 are located practically on the dam-rock interface, they should not be treated as free-field motions. That is, the dam nodes at the interface should be forced to move at the interpolated motions. To accomplish this, large stiffness terms were assembled into the foundation mesh for the translational degrees of freedom on the interface with the dam before the earthquake loads were computed. With this modification, the rock mesh provides flexibility only to the rotational degrees of freedom on the interface, as these are left free.

Material properties for the finite element model were chosen as follows: Young's moduli of 17,900 MPa (2600 ksi) for the concrete and 13,800 MPa (2000 ksi) for the rock, and unit weights of 23.6 kN/m^3 (150 lb/ft^3) for the concrete and 9.8 kN/m^3 (62.4 lb/ft^3) for the water. The rock modulus is in the range of a rather large variation of field data (Hall, 1988); it corresponds to a shear wave speed of about 1500 m/sec. The concrete modulus was selected to give natural frequencies close to those determined by MODEID. The frequencies resulting from this value, which is in the typical range for dam concrete, are 4.9hz for the first antisymmetric mode and 5.1 hz for the first symmetric mode. Also, based on the results of the system identification study, the damping level was set to 6% of critical.

Figure 7 shows a comparison between the recorded accelerations for channels 1, 2, 4 and 5 on the crest with ones computed by SCADA operating in the linear mode. The agreement is not particularly good, except for channel 4 where the motion is relatively small. The responses from the finite element model are too high for channels 1 and 2, and they contain a high frequency component at channel 5 not seen in the record (although it is present in the nearby station on the south abutment, see Figure 2). When displacements are compared (Figure 8), the agreement is better, although the response at channel 2 is still noticeably too high. In order to improve the performance of the finite element model, several modifications were tried: altering Young's modulus of concrete, raising the damping level, allowing full interaction between the dam and foundation rock, and permitting the contraction joints to open. None of these proved to be entirely successful; for example, increasing the damping to 12% of critical improved the agreement for channels 1 and 2 but worsened it for channel 5 (Figure 9).

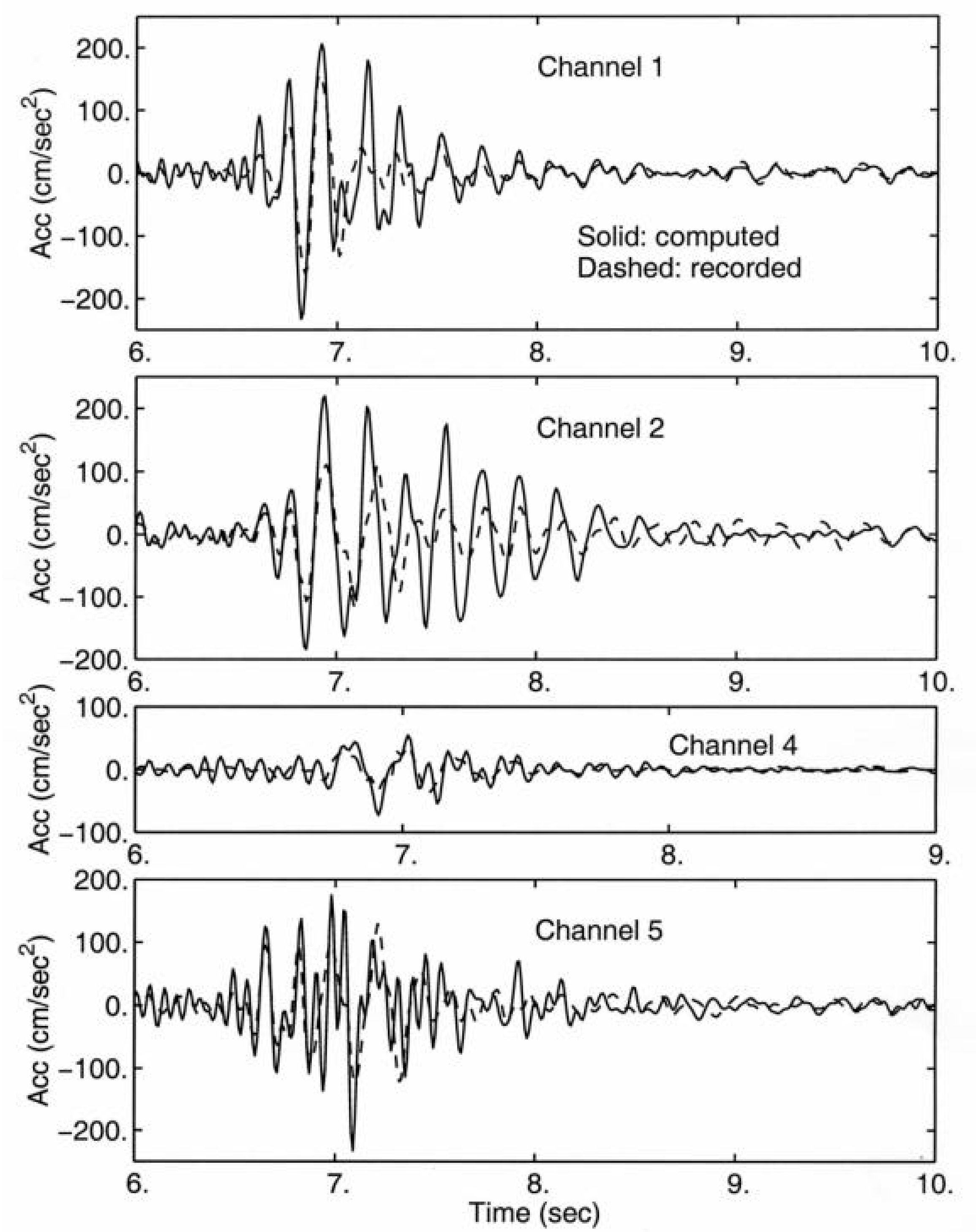

Figure 7. Comparison between the recorded accelerations at channels 1, 2, 4 and 5 and the computed accelerations from the SCADA finite element model with 6% damping.

Further work is underway to explain the differences between the recorded and computed responses of the dam. The first step of this effort is to examine in detail the behavior of the finite element model. Figure 10 shows computed displacement responses for channels 1, 2, 4 and 5 (same parameters as used for Figures 7 and 8) separated into the pseudo-static response and the dynamic responses from the first symmetric and

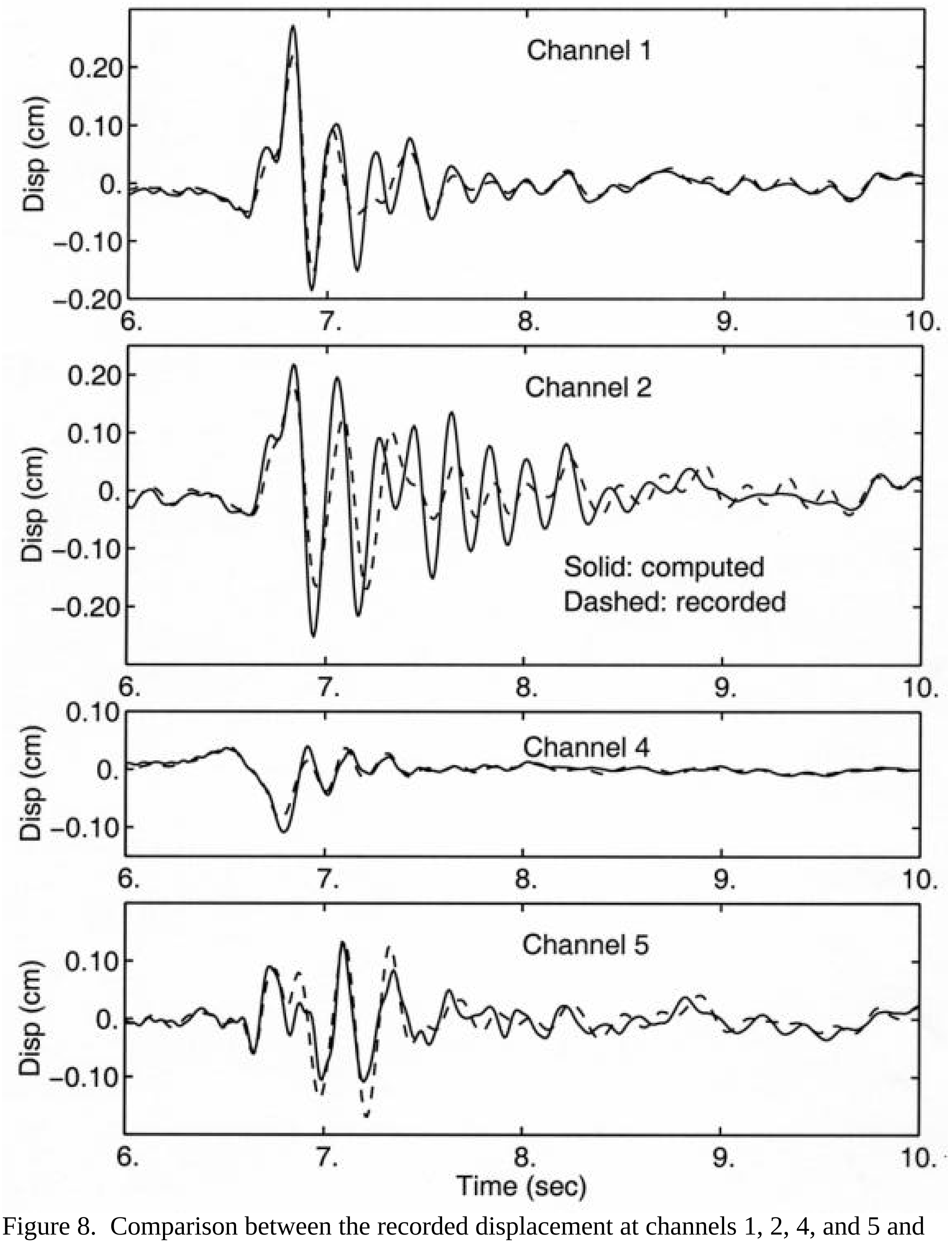

Figure 8. Comparison between the recorded displacement at channels 1, 2, 4, and 5 and the computed displacements from the SCADA finite element model with 6% damping.

antisymmetric modes. The largest contributions are made by the symmetric mode for channel 2, the antisymmetric mode for channels 1 and 5, and the pseudo-static response for channel 4; however, all three parts are important for each channel. It is expected that

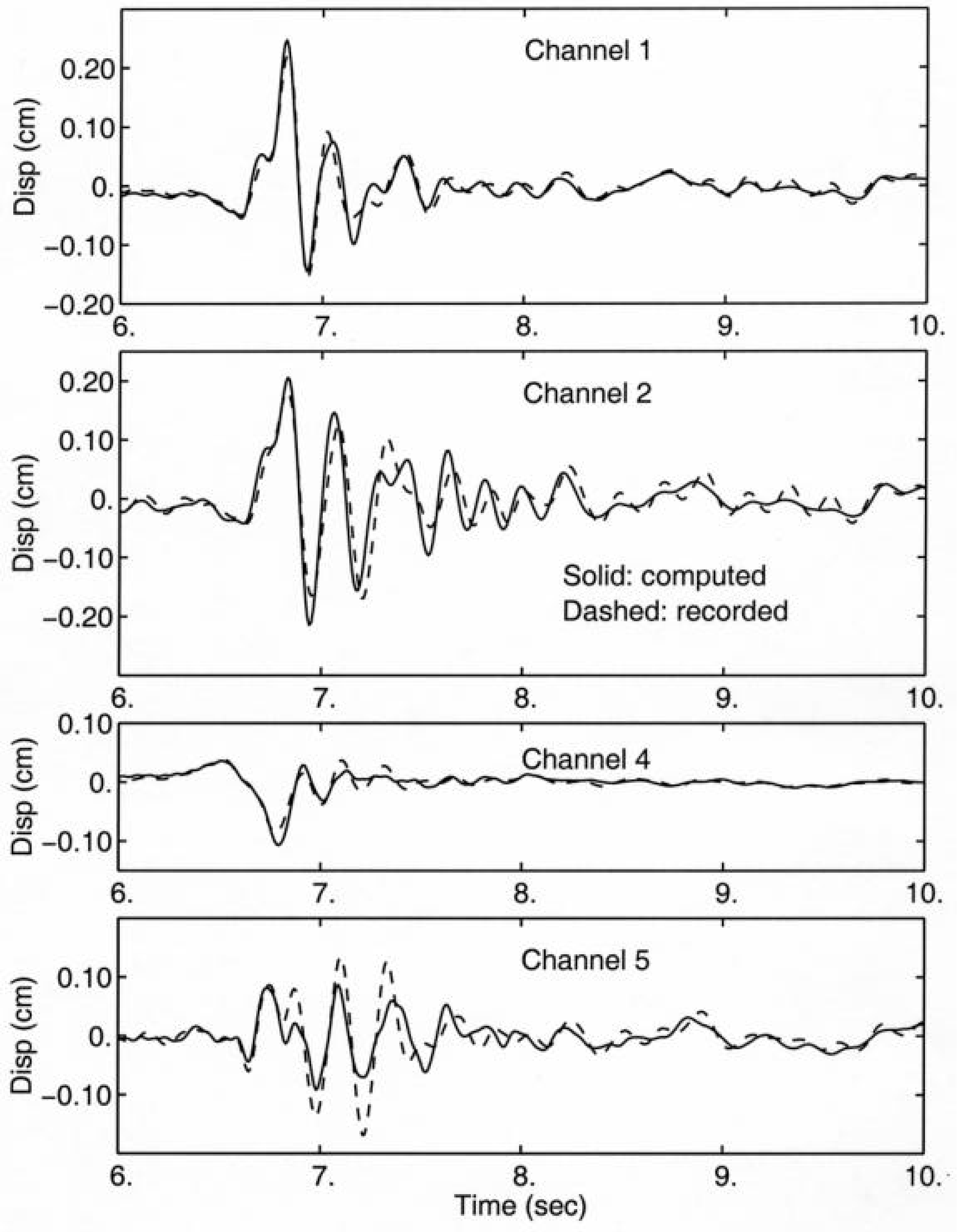

Figure 9. Comparison between the recorded displacements at channels 1, 2, 4 and 5 and the computed displacements from the SCADA finite element model with 12% damping.

the symmetric mode is excited mainly by ground motion in the upstream-downstream direction and the antisymmetric mode is excited mainly by cross-stream ground motion.

Plots of the two computed mode shapes at crest level appear in Figure 11, and the symmetric and antisymmetric features are evident. These shapes explain why the symmetric mode contributes more to the channel 2 response, and why the antisymmetric mode contributes more to the others. It is also evident that the presence of the antisymmetric mode in the channel 2 response, which is not insignificant, is sensitive to the location of this mode's cross-over point for radial motion (where the radial motion is zero). A small shift of the cross-over point toward the location of channel 2 would significantly reduce its contribution to the channel 2 response. This suggests that

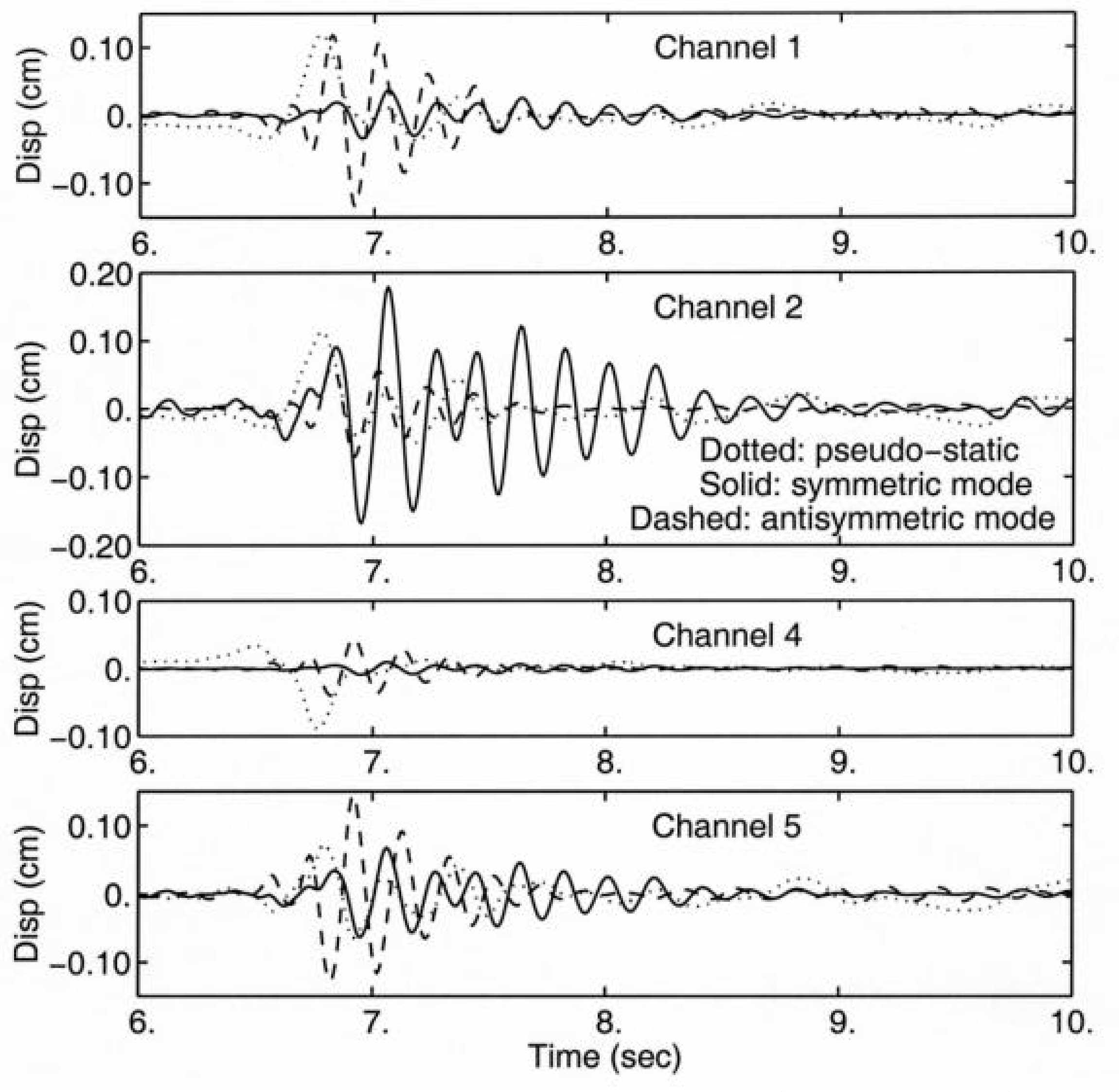

Figure 10. Computed displacements at channels 1, 2, 4 and 5 from the SCADA finite element model with 6% damping, separated into the pseudo-static response and the dynamic responses from the first two modes.

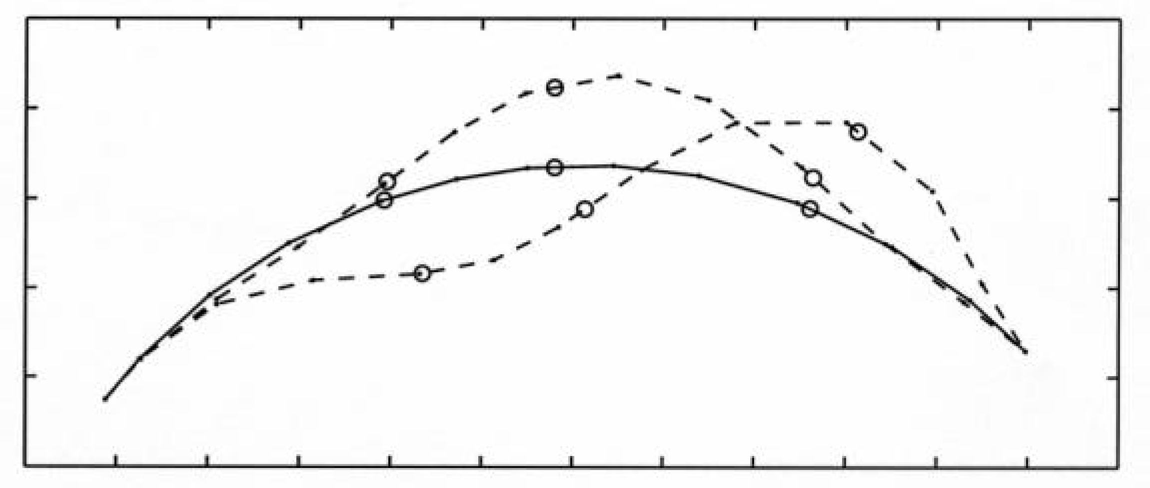

Figure 11. Plan view of the crest of the Pacoima Dam finite element model showing the fundamental symmetric and antisymmetric mode shapes (dashed lines). The open circles denote the three recording stations on the crest of the dam.

improvements to the finite element mesh, such as explicitly modeling the thrust block on the south abutment instead of treating it as part of the foundation rock, could be effective in obtaining better agreement to the recorded motions.

To be realistic, the ability of a finite element model to reproduce the recorded responses of an arch dam will always be less than that, say, for a building where uniform ground motion can often be assumed. Nonuniform ground motion can only be measured at a limited number of recording stations, meaning that a complete definition of the seismic input is subject to interpolation error. And the pseudo-static response associated with nonuniform ground motion involves deformation of the structure and so is different from point to point; whereas, the pseudo-static response to uniform ground motion is also uniform and identical to the ground motion itself. Finally, the presence of two modes which have nearly equal natural frequencies and which can contribute significant amplitude to the same line of motion over much of the structure is an additional complication not typically found in buildings.

Conclusions

For this progress report, some preliminary conclusions and suggestions for continuing work have been given in the preceding sections. As is apparent, there are several directions of research which can exploit the data obtained at Pacoima Dam on January 13, 2001. Of primary interest in these studies are the effects of nonuniform ground motion and the level of damping. In these respects, the data are proving to be extremely valuable even though they were generated by a minor earthquake of magnitude 4.3. Study of the records from the Northridge earthquake at Pacoima Dam as well as additional records obtained from future earthquakes will help to expand the conclusions reached by the present investigation.

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