NONLINEAR DYNAMIC RESPONSE ANALYSIS OF LEXINGTON DAM

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ABSTRACT

The dynamic response of Lexington Dam during the October 17, 1989 Loma Prieta earthquake and a smaller earthquake is analyzed using equivalent-linear and nonlinear procedures. The calculated motions at the dam crest are compared to the recorded motions during the earthquakes. The computed response of the dam using nonlinear procedures is in reasonable agreement with the recorded response and the response calculated using equivalent-linear methods.

INTRODUCTION

The seismic stability evaluation of earth dams generally requires an evaluation of their dynamic response to earthquake ground motions. An important requirement of analytical procedures for the dynamic response analysis of earth dams is that they consider the nonlinear stress-strain behavior of soils. Dynamic response analysis procedures which model the nonlinear behavior of soils using the equivalent-linear approach proposed by Idriss and Seed (1967) are now widely used. While these procedures provide an approximate representation of the nonlinear behavior of soils which is adequate for many practical purposes, they do not model the actual nonlinear stress-strain path of soils during seismic loading. For a given seismic loading the analysis is carried out using linear visco-elastic properties corresponding to an average level of strain during the loading. Because equivalent-linear procedures cannot model yielding of soils, they may lead to calculated stresses higher than may actually be possible, and they cannot model permanent deformations resulting from soil yielding.

Fully nonlinear two-dimensional procedures which can model the time-varying stress-strain behavior and yielding of soils are now becoming more widely available. The purpose of this paper is to present the results of equivalent-linear and fully nonlinear analyses of the dynamic response of Lexington Dam during the October 17, 1989 Loma Prieta (M_s 7.1) and August 8, 1989 Lake Elsman (M_L 5.2) earthquakes. The calculated motions at the crest of the dam are compared to the recorded motions during the earthquakes to evaluate the use of these types of analyses for calculating the dam's dynamic response.

DESCRIPTION OF LEXINGTON DAM

Lexington Dam is located in the Santa Cruz mountains of California about 15 miles north of Santa Cruz and about 13 miles and 5 miles northwest of the epicenters of the Loma Prieta and Lake Elsman earthquakes, respectively. The dam is a 207-foot-high zoned earthfill with upstream and downstream slopes of 5½:1 and 3:1, respectively. The crest of the dam is 40 feet wide and about 810 feet long. A plan view and the approximate maximum cross section of the dam are shown in Figures 1 and 2, respectively.

The dam is founded on Franciscan sandstone and shale with minor amounts of greenstone, chert and schist. It was built in 1953 of densely compacted local materials. The downstream shell consists of clayey sandy gravel with about 15 to 40% fines of low to medium plasticity. The materials in the upstream shell and the upper 80 feet of the core are generally similar and consist of clayey sands with about 15 to 35% gravel and 20 to 50% fines of medium plasticity. The materials in the core below 80 feet are clearly distinct from those above and consist of a clay of medium to high plasticity.

The results of insitu and laboratory tests presented by Wahler and Associates (1982) indicate that the materials are generally very stiff. However, because of the difficulty in sampling gravelly materials, the data on dynamic properties and strength from undisturbed samples is limited. Downhole and crosshole seismic wave velocity measurements indicate that the shear wave velocity of the materials at small strains increases with depth and may be reasonably approximated by the expression:

$$V_s = (k_{2max} \cdot (\sigma_m)^{½} \cdot g / \gamma)^{½}$$

where V_s is the shear wave velocity in ft/sec, k_{2max} is a constant, σ_m is the mean effective stress in psf, g is gravity in ft/sec^2, and γ is the unit weight in kcf. The ranges of shear wave velocities measured in the dam and the corresponding values of k_{2max} for the dam materials are presented in Table 1. Limited data is available regarding shear wave velocities of the foundation rock. The available data indicates that the average shear wave velocity of the foundation immediately beneath the main body of the dam is about 3,000 ft/sec. Towards the upper reaches of the abutments it is somewhat less than 2,000 ft/sec. Compression wave velocities of about 10,000 ft/sec were measured immediately beneath the main body of the shells and core.

The reservoir level at the time of the earthquakes was between 90 and 100 feet below the maximum storage level. The reservoir level at the time of the geophysical measurements was also low. Piezometer readings in the upstream shell and core of the dam indicate that the pore water pressures in the embankment fluctuate little in response to changes in the reservoir level and that they are generally less than hydrostatic. Water level readings in the downstream shell indicate that these materials are unsaturated and that the phreatic surface is near the foundation.

RECORDED RESPONSE

The strong motion instrumentation at the dam site consists of 3 accelerographs located as shown in Figure 1. The instruments are oriented to record motions transverse (0° component) and parallel (90° component) to the longitudinal axis of the dam and in the vertical direction. The instruments have recorded motions during several earthquakes including the October 17, 1989 Loma Prieta and the August 8, 1989 Lake Elsman earthquakes, and a small (M_L 5.0) nearby earthquake on June 27, 1988. The recorded motions from these three earthquakes were digitized and processed by the staff of the California Strong Motion Instrumentation Program (Shakal and others, 1989). Figure 6 shows the acceleration response spectra of the motions recorded in the transverse direction (0° component) at the left abutment and right crest accelerographs during the Loma Prieta and Lake Elsman earthquakes. The motions from the June 27, 1988 earthquake were not used in this study since the instruments appear to have triggered late during this event.

A summary and an analysis of the motions recorded at the dam site during the Loma Prieta and Lake Elsman earthquakes has been presented by Makdisi and others (1991). Evidence of the nonlinear behavior of the dam during the Loma Prieta earthquake can be directly observed in the earthquake records (Mejia and others, 1992).

Other instrumentation at the dam includes survey monuments along the crest, pneumatic piezometers in the upstream shell and core, and open standpipe piezometers in the downstream shell. Measured deformations at the survey monuments presented by Volpe and Associates (1990) indicate that crest settlements during the Loma Prieta earthquake varied from a maximum of 10 inches near the crest midpoint to about 1 inch near the left abutment and 4 inches near the right abutment. Horizontal deformations transverse to the dam axis varied from less than 1 inch (downstream) near the left abutment, to 3 inches (downstream) near the crest midpoint, to about 2 inches (upstream) near the right abutment. Deformations during the Lake Elsman earthquake were very small.

An apparent water level rise of about 6 feet was measured in two piezometers in the core and one piezometer in the upstream shell after the Loma Prieta earthquake. The piezometer readings decreased slightly during the following several months. A relatively large seep developed on the downstream face six weeks after the earthquake and lasted for a few months. The seep appears to coincide with an increase in water levels in one of the three observation wells in the downstream shell. No significant water level changes were measured after the Lake Elsman earthquake.

SOIL MODELS

Three stress-strain soil models are used to analyze the dynamic response of Lexington Dam: the equivalent-linear model proposed by Idriss and Seed (1967), a multiple-nested yield surface plasticity model presented by Salah-mars and Kavazanjian (1992), and a model based on the failure-seeking model proposed by Cundall (1979) and the bounding surface plasticity model proposed by Dafalias and Hermann (1982). This latter model is generally similar to the multiple yield surface model and will not be presented herein.

Equivalent-Linear Model

The equivalent-linear model is schematically illustrated in Figure 3. In this model the hysteretic stress-strain behavior of soils under symmetrical cyclic loading is represented by an equivalent modulus G corresponding to the secant modulus through the end points of the hysteresis loop and an equivalent damping ratio λ corresponding to the hysteretic damping (see Figure 3(a)). The equivalent modulus and damping typically vary with strain as shown in Figure 3(b). For a given seismic loading these relationships, usually known as the modulus reduction and damping curves, are used iteratively to select modulus and damping values which are compatible with the average strain induced by the loading. In the analyses presented herein the average strain was calculated as 0.65 times the peak maximum shear strain.

Multiple-Nested Yield Surface Model

In this model the stress-strain behavior of soils is represented by a family of circular yield surfaces which are nested in stress space as shown in Figure 4(a). The yield surfaces can be made to follow kinematic hardening rules which result in hysteretic stress-strain behavior under symmetrical cyclic loading as shown in Figure 4(b). The stress-strain relationship connecting the end points of the hysteresis loops at different strains, shown by the dashed line in Figure 3(a), is usually referred to as the backbone curve. Any backbone curve can be modeled by selecting an appropriate number of yield surfaces. The resulting amount of hysteretic damping will depend on the backbone curve selected and will correspond to Masing-type behavior. In the analyses presented herein a small amount of viscous damping was used so that the total damping at small strains would be similar to that used in the equivalent-linear analyses.

For a given seismic loading the model will track the stress-strain path of the soil with time and will accumulate permanent strains under sustained yielding. A tension stress cut-off can be modeled to prevent excessive tension stresses from developing in the soil. The analysis is conducted in terms of total stresses which seems reasonable for Lexington Dam in view of the dense and clayey nature of its materials. Degradation in soil stiffness and strength during the earthquakes was assumed to be small based on the high densities of the materials, the results of laboratory tests by Wahler and Associates (1982), and the moderate duration of the earthquakes. While the soil model can appropriately treat permanent volumetric strains under isotropic stress loading (i.e. volumetric plasticity) this option was not used in the present study and the bulk modulus of the materials was assumed to be elastic and equal to the bulk modulus used at small strains in the equivalent-linear analyses.

EQUIVALENT-LINEAR ANALYSES

The equivalent-linear analyses of Lexington Dam were performed using the computer programs FLUSH (Lysmer and others, 1975) and SUPERFLUSH (Udaka, 1989). FLUSH is a two-dimensional plane strain finite element code for the dynamic analysis of soil structures and the analysis of dynamic soil-structure interaction. The program assumes that the base of the finite element model is rigid. SUPERFLUSH is an enhanced version of FLUSH which allows use of a compliant boundary at the base of the model.

The finite element mesh used in the equivalent-linear analyses is shown in Figure 5. This mesh corresponds approximately to the maximum section of the dam and is near the location of the right crest accelerograph. The motions recorded at the abutment in the direction transverse to the axis of the dam (0° component) were used as input motions in the analyses. The acceleration response spectra of these motions together with the spectra for the recorded motions at the right crest accelerograph are shown in Figure 6.

The dynamic material properties required for the equivalent-linear analyses are the total unit weight, the shear modulus at small strains (G_{max}), Poisson's ratio, and the modulus reduction and damping curves. The values of G_{max} were calculated using the k_{2max} values estimated from the measured shear wave velocities. The values of Poisson's ratio and total unit weight were estimated from the measured shear and compression wave velocities and laboratory test results. A summary of these values is presented in Table 1.

Parametric dynamic response analyses performed by Makdisi and others (1991) using various modulus reduction and damping curves indicate that the average modulus reduction and the lower-bound damping curves proposed by Seed and Idriss (1970) for sands result in a calculated dynamic response of the dam which is in good agreement with the recorded response during the Loma Prieta and Lake Elsman earthquakes. Additional parametric analyses were performed in this study to supplement those presented by Makdisi and others (Mejia and others, 1992).

Figure 7 shows a comparison between the recorded and calculated response spectra at the dam crest using FLUSH for two assumptions of the modulus reduction and damping curves. In one analysis (labeled "clay curves" in Figure 7) the modulus reduction and damping curves proposed by Vucetic and Dobry (1991) for clays with a PI of 30 were used for the medium to high plasticity clays in the core below 80 feet. The average modulus reduction and lower-bound damping curves proposed by Seed and Idriss for sands were used in all other zones of the dam. In the second analysis (labeled "sand curves" in Figure 7) the Seed and Idriss curves were used in all zones of the dam. As shown in Figure 7, use of the Seed and Idriss curves in all zones of the dam leads to calculated response spectra which are in very good agreement with the recorded spectra at the right crest accelerograph. The spectra calculated using the

Vucetic and Dobry curves in the core below 80 feet are significantly higher than the recorded spectra and the spectra calculated using the Seed and Idriss curves.

Parametric analyses were performed with SUPERFLUSH to evaluate the effects of foundation flexibility on the computed dynamic response of the dam. Based on the geophysical measurements at the site a shear wave velocity of 3000 ft/sec and a Poisson's ratio of 0.4 were used for the foundation rock in the analyses. The motions recorded at the left abutment were input at an assumed rock outcrop with the same shear wave velocity as the foundation. Figure 8 shows a comparison between the recorded and calculated response spectra at the dam crest using a rigid base model and a compliant base model and the Seed and Idriss curves. It may be seen that for the Loma Prieta earthquake the spectra calculated with the two models are in good agreement. For the Lake Elsman earthquake the spectrum calculated with the compliant base model is slightly lower than that calculated with the rigid base model. Nonetheless, it appears that for the assumed rock characteristics and input motions the effects of foundation flexibility on the calculated dynamic response of the dam are relatively small.

NONLINEAR ANALYSES

The nonlinear analyses using the multiple-nested yield surface model were performed using the computer program DYSLAND (Salah-mars, 1989). The bounding surface model is incorporated into the program DYNARD (Moriwaki and others, 1988). The results of analyses using the multiple-yield surface model are presented herein. A description of all analyses performed and additional results are presented by Mejia and others (1992).

The nonlinear analyses were performed using the same finite element mesh used for the equivalent-linear analyses (Figure 5). The recorded motions at the left abutment were input at the base of the model which was assumed to be rigid. Analyses were performed for the recorded polarity of the motions and for a reverse polarity (i.e. motions of opposite sign). Analyses were conducted with and without initial static stresses in the dam. The initial stresses were obtained from an analysis of the dam under gravity loads. The analyses without initial stresses simulate the equivalent-linear analyses since these do not consider the effects of initial stresses directly. Reversing the polarity of the motions had little effect on the calculated dam response in the absence of initial stresses.

Parametric analyses were performed for several backbone curve models. The parameters of these models were selected based on the available data regarding the dynamic stress-strain and strength characteristics of the dam materials. Analyses results for the backbone curves selected to be compatible with the modulus reduction curves used in the equivalent-linear analyses are presented herein. The backbone curves were developed from the estimated values of G_{max} and the modulus reduction curves assumed for the main zones of the dam. The resulting backbone curves are generally consistent with the available laboratory data regarding the stress-strain and strength characteristics of the materials.

Figure 9 shows a comparison between the recorded and calculated response spectra at the dam crest from the nonlinear analyses without initial stresses. In general, the spectra calculated for the Lake Elsman earthquake are in relatively good agreement with the recorded spectrum. For the Loma Prieta earthquake, the spectrum calculated using backbone curves in the lower core corresponding to the Vucetic and Dobry modulus curve is significantly higher than the recorded spectrum for periods less than about 0.5 seconds. The calculated spectrum for the backbone curves corresponding to the Seed and Idriss curve is in good agreement with the recorded spectrum. Figure 10 shows a comparison between the calculated response spectra from the equivalent-linear and the nonlinear analyses (for the backbone curves in the lower core corresponding to the Seed and Idriss modulus curve). It may be seen that the spectra calculated with these two types of analyses are in good agreement.

Figure 11 shows a comparison between the recorded and the calculated response spectra from the nonlinear analyses with and without initial stresses (for the backbone curves in the lower core corresponding to the Seed and Idriss modulus curve). It may be seen that the acceleration response spectra calculated at the dam crest are not very sensitive to the initial static stresses in the dam. This, however, is not the case for the calculated crest displacements.

Figure 12 shows the acceleration and relative displacement time histories calculated at the dam crest for the Loma Prieta earthquake using the lower-core backbone curves corresponding to the Seed and Idriss modulus curve. The calculated residual vertical and horizontal displacements at the crest are about 5½ and 2 inches, respectively. These displacements are somewhat smaller than the observed permanent displacements during the earthquake but are roughly in the same proportion and have the same relative sense. The calculated residual displacements for the Lake Elsman earthquake are less than ½ inch, in good agreement with the observed displacements. Further discussion of the calculated displacements is presented by Mejia and others (1992).

CONCLUSIONS

The dynamic response of Lexington Dam during the October 17, 1989 Loma Prieta earthquake and the August 8, 1989 Lake Elsman earthquake was analyzed using equivalent-linear and nonlinear procedures. The computed response of the dam using equivalent-linear procedures together with the average modulus reduction curve and the lower-bound damping curve proposed by Seed and Idriss (1970) for sands is in good agreement with the recorded response during the earthquakes. For the assumed rock characteristics the effects of foundation flexibility on the calculated response of the dam were found to be relatively small. The computed acceleration response spectra using fully nonlinear procedures are in reasonable agreement with the spectra recorded at the dam crest and the spectra calculated using equivalent-linear procedures. In addition, nonlinear procedures predict permanent deformations of the same order of magnitude as those observed at the dam crest after the earthquakes.

ACKNOWLEDGEMENTS

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TABLE 1

SUMMARY OF MATERIAL PROPERTIES FOR ANALYSIS

Zone of Dam	Measured Shear Wave Velocity (ft/sec)	Estimated k_{2max}	Total Unit Weight (pcf)	Poisson's Ratio
Upstream shell	600-1800	130	138	0.45
Core above 80 feet	900-1600	130	138	0.40
Core below 80 feet	900-1000	45	122	0.45
Downstream shell	1100-2200	235	138	0.35

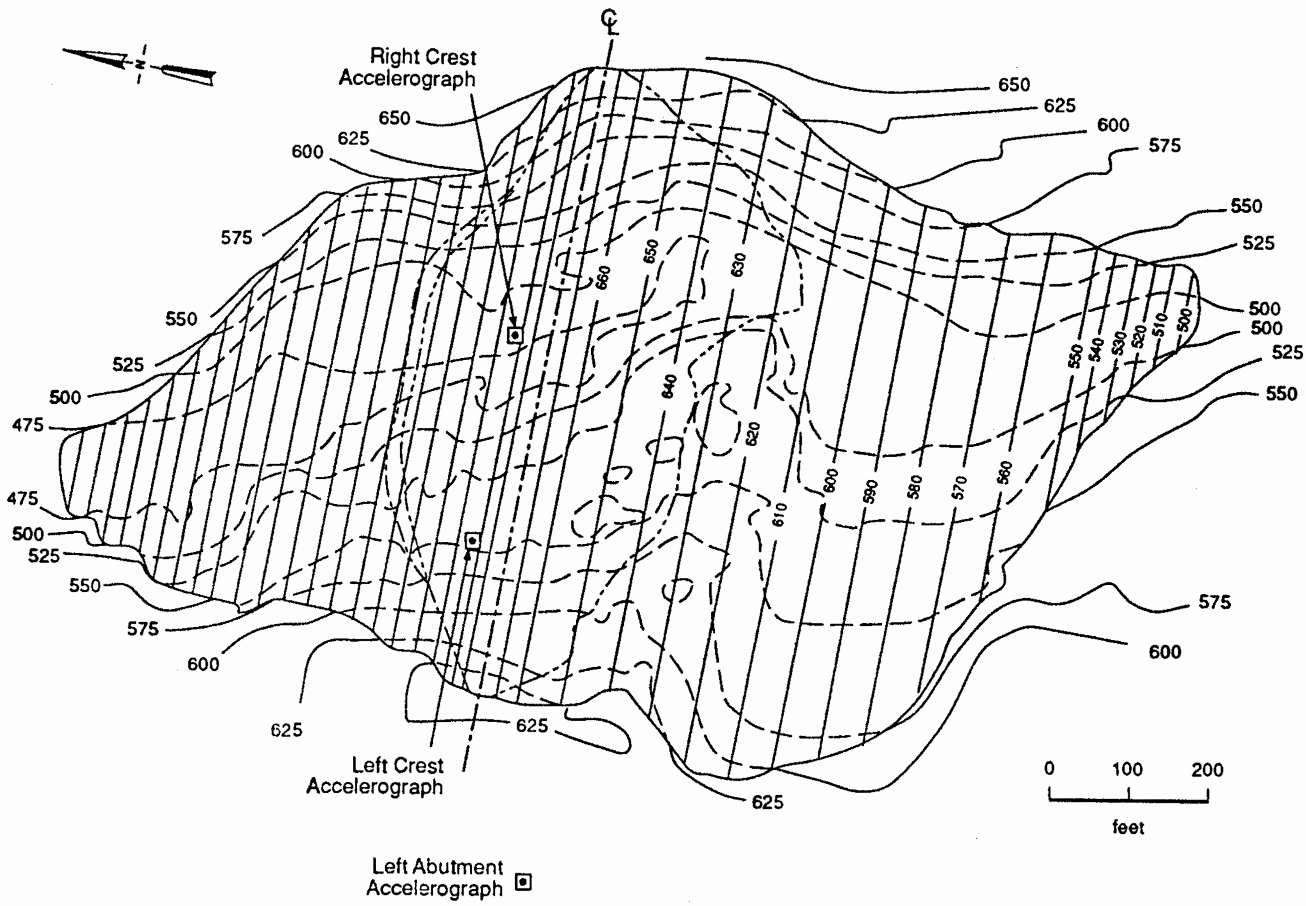


Figure 1. Plan view of Lexington Dam

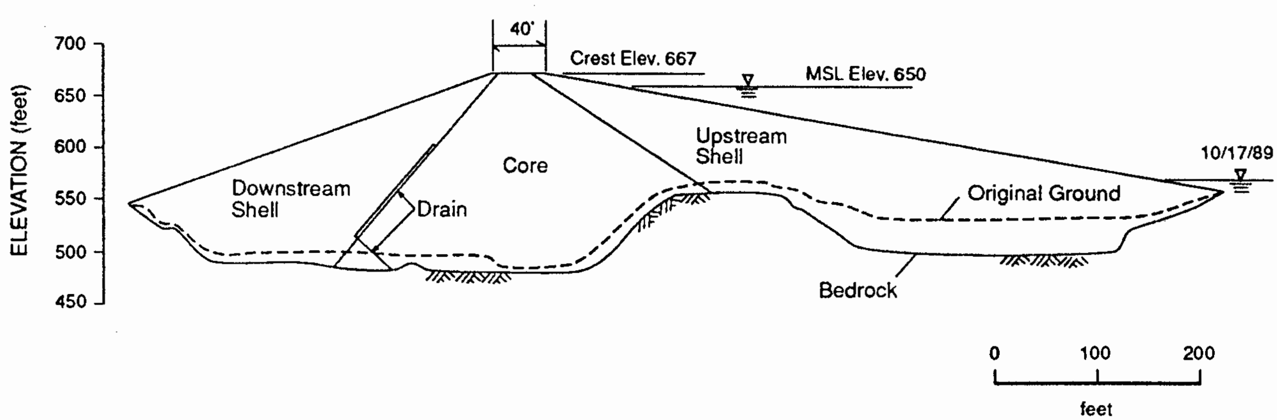
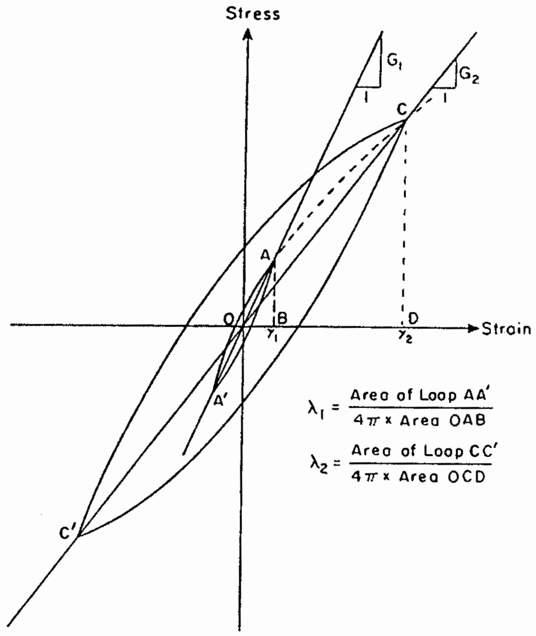
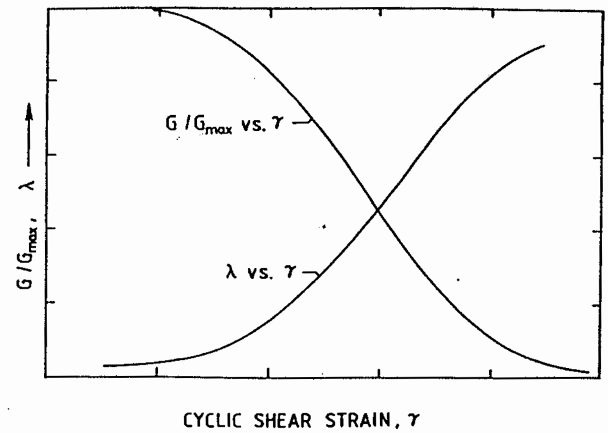


Figure 2. Maximum section of Lexington Dam

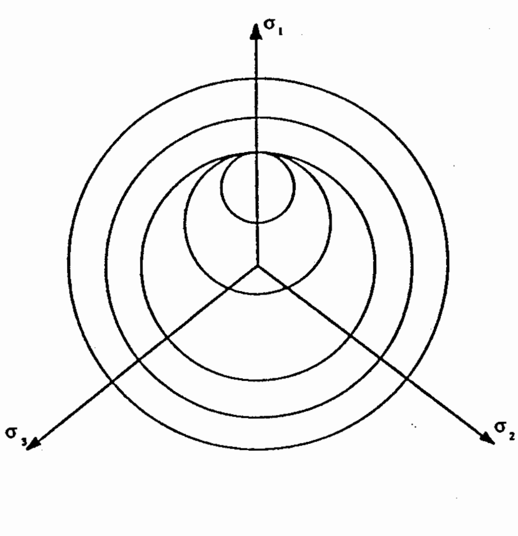


(a) Equivalent modulus and damping

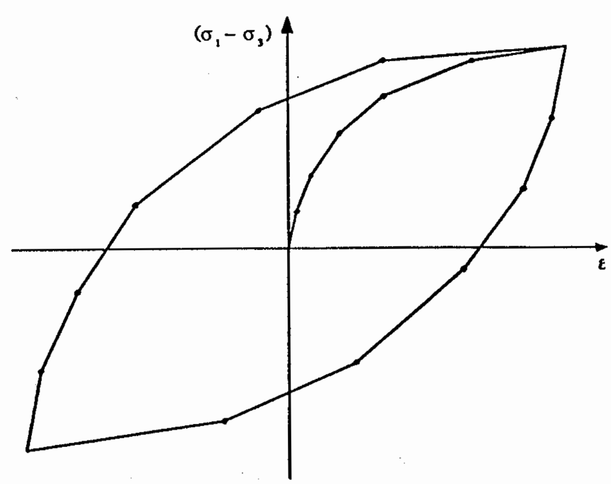


(b) Modulus reduction and damping relationships with strain

Figure 3. Equivalent-linear model



(a) Yield surfaces



(b) Example hysteretic loop

Figure 4. Multiple-nested yield surface model

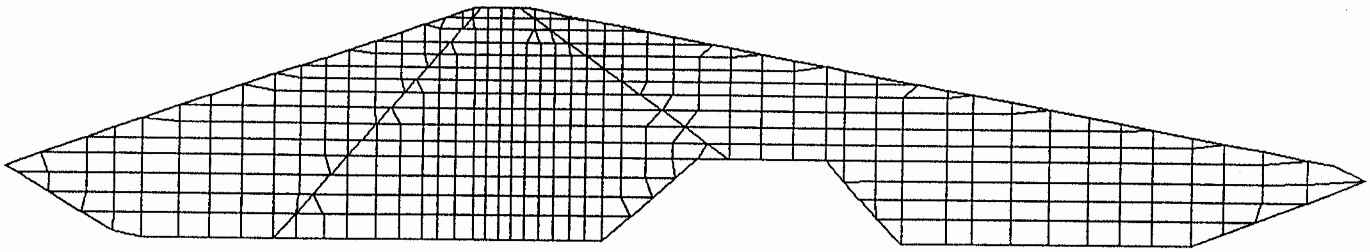


Figure 5. Finite element mesh used in analyses

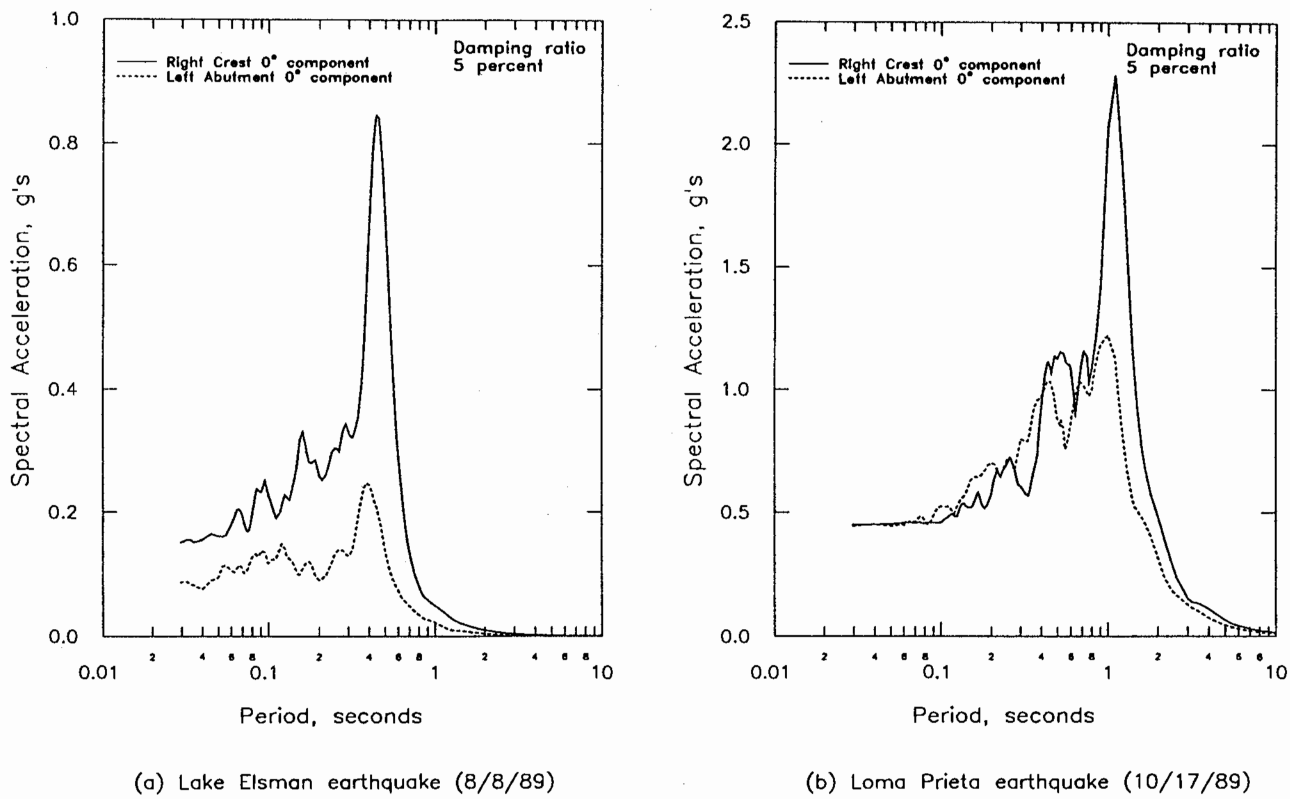
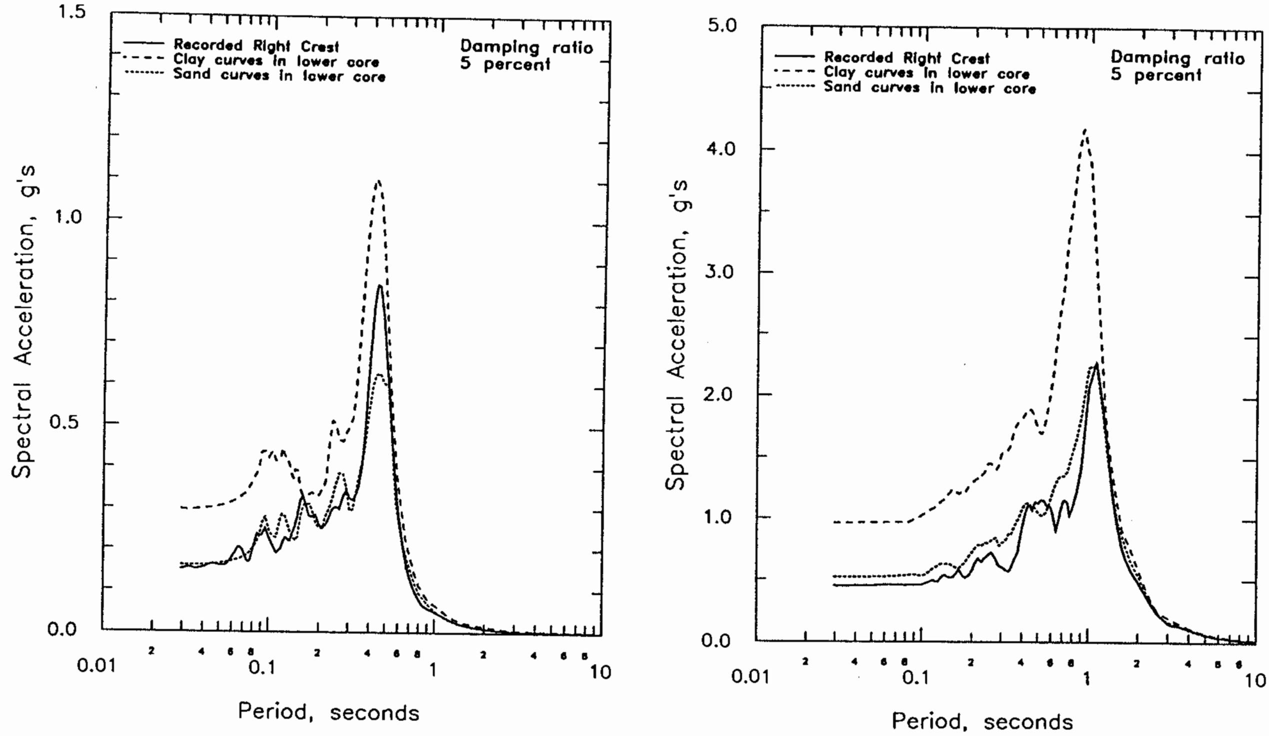


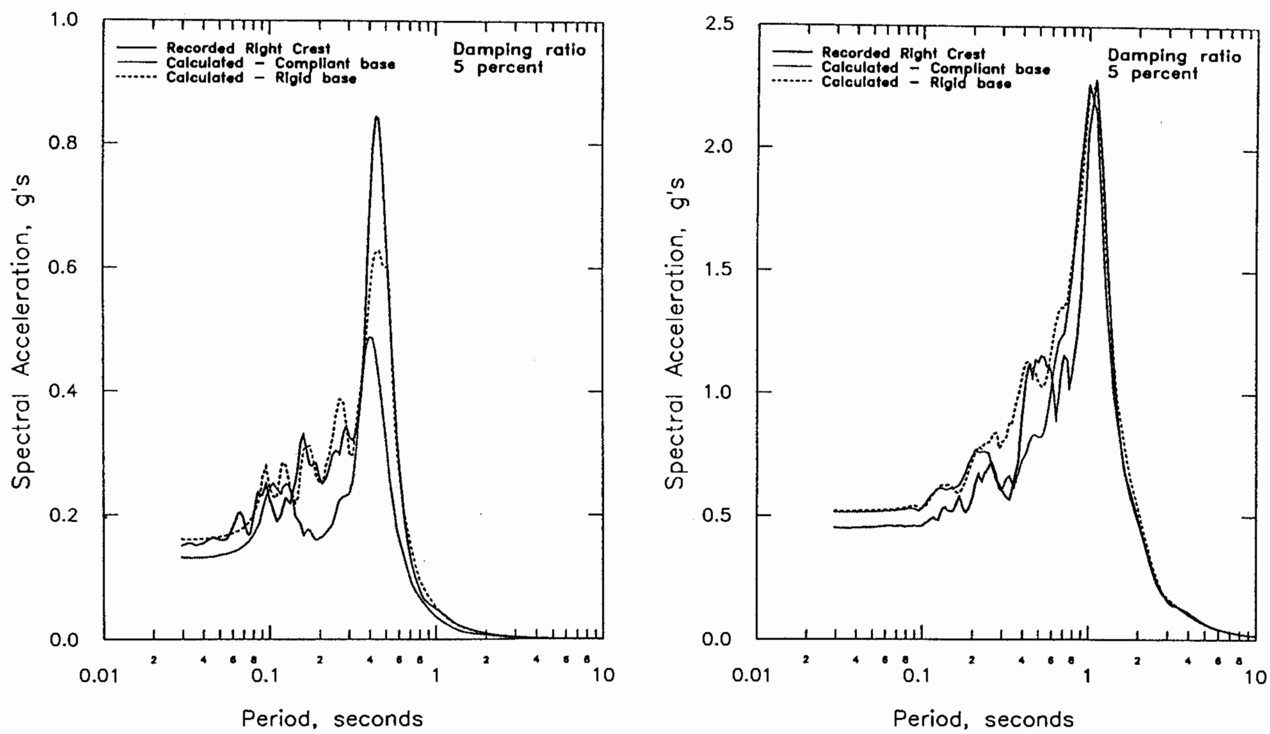
Figure 6. Acceleration response spectra of motions recorded at Lexington Dam



(a) Lake Elsman earthquake (8/8/89)

(b) Loma Prieta earthquake (10/17/89)

Figure 7. Comparison between recorded and calculated response spectra at the dam crest using FLUSH



(a) Lake Elsman earthquake (8/8/89)

(b) Loma Prieta earthquake (10/17/89)

Figure 8. Comparison between recorded and calculated response spectra at the dam crest using rigid base and compliant base models

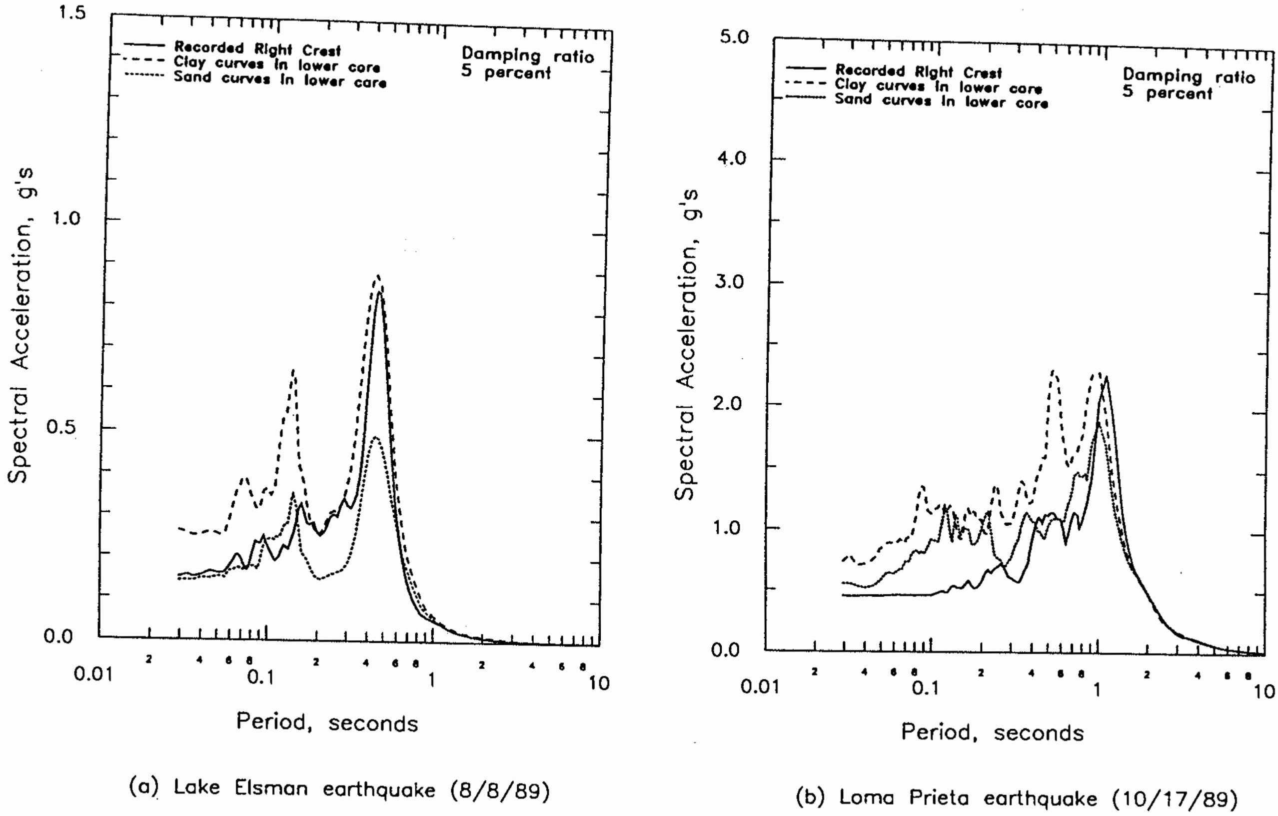


Figure 9. Comparison between recorded and calculated response spectra at the dam crest using DYSLAND without initial stresses

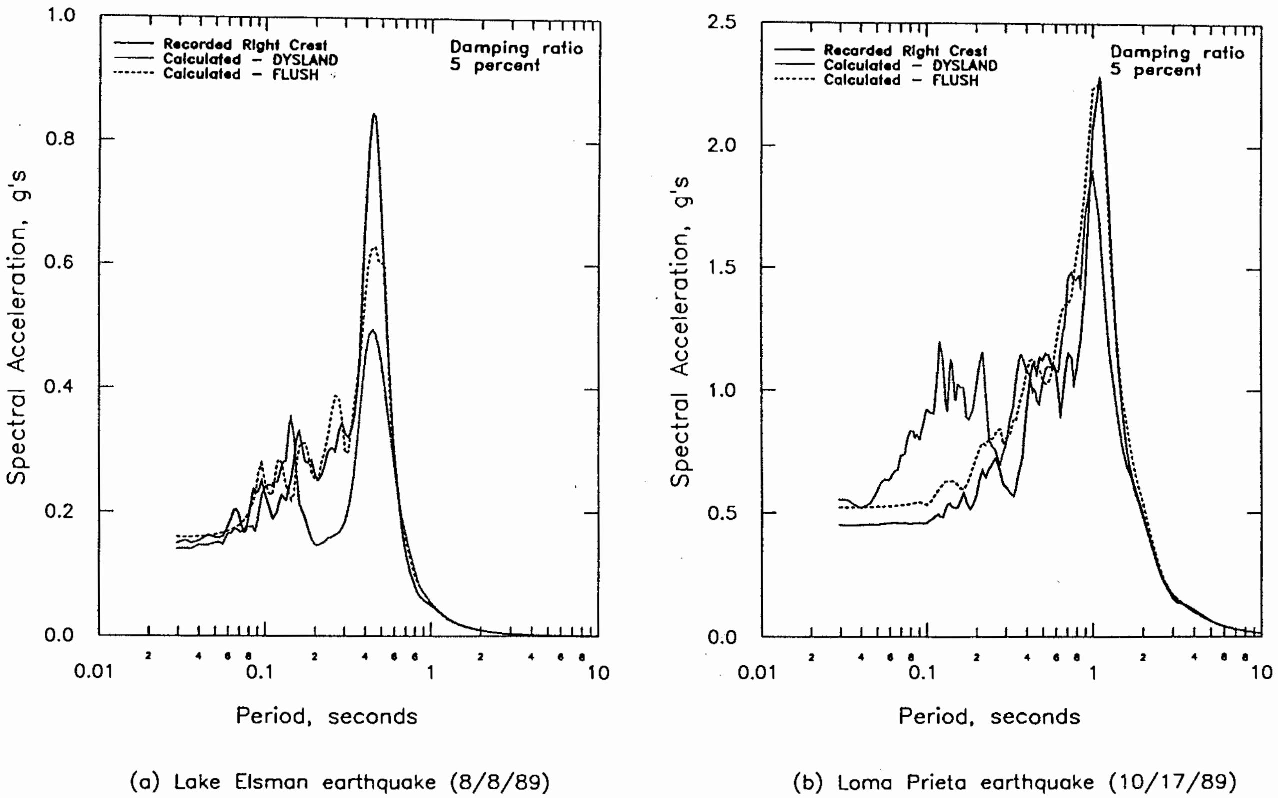
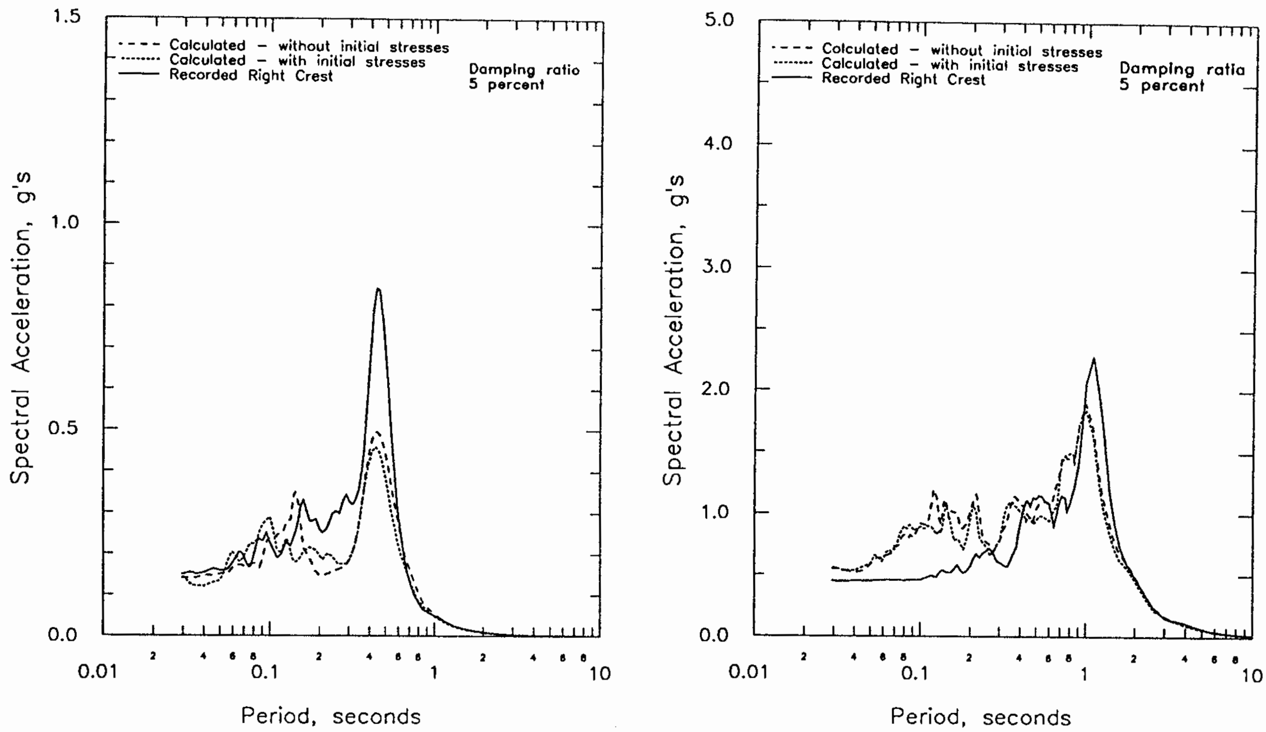


Figure 10. Comparison between recorded and calculated response spectra at the dam crest using FLUSH and DYSLAND without initial stresses



(a) Lake Elsman earthquake (8/8/89)

(b) Loma Prieta earthquake (10/17/89)

Figure 11. Comparison between recorded and calculated response spectra with and without initial stresses

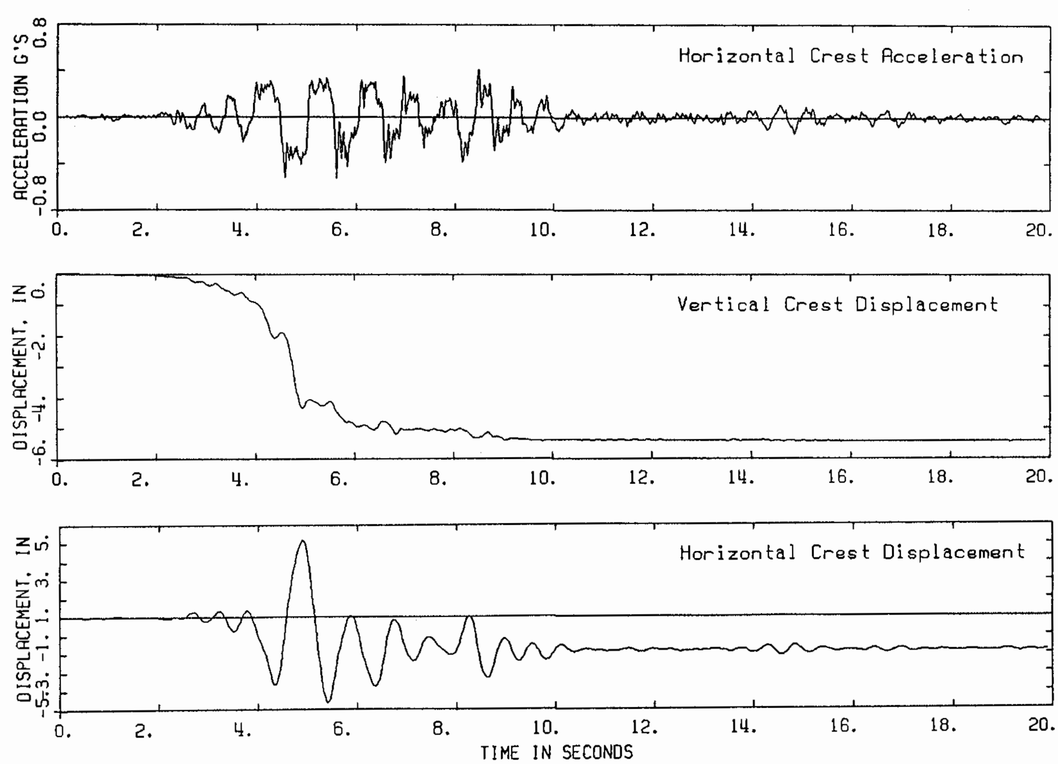


Figure 12. Calculated acceleration and relative displacement time histories for Loma Prieta earthquake