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System identification of nonlinear seismic response of earth dams

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ABSTRACT: A system identification technique, developed to provide dynamic properties of earth dams from their seismic records, is utilized to assess the capabilities and limitations of analytical models in terms of dynamic nonlinear constitutive relationships and damping. The technique is based on the least square method using the Gaussian hypothesis. Earth dams are modeled as three-dimensional nonhomogeneous visco-elasto-plastic structures and the spatial variation of the excitation on the dam boundaries is considered. The forward problem is solved using a Galerkin-Ritz formulation in which the solution is expanded using eigenmodes as basis functions. The constitutive model is used to accommodate the nonlinear path dependent behavior of the dam material as well as coupling between different constituents of the soil mixture. The model is implemented using the Druker-Prager multi-yield surface model and a linear Kelvin-Voigt model. Application to two instrumented dams, shaken in recent strong earthquakes, showed a significant match between the recorded response and the optimal estimated response, it also sheds some light on the salient features of the nonlinearity of these dams.

1 INTRODUCTION

The system identification problem can be viewed as a process of four main steps, as follows [Tarantola (1987)]:

1. Performing a series of experiments on the structure.
2. Selection of a mathematical model for the physical system based on the observed experimental data.
3. Estimation of the unknown parameters using a proper optimality condition.
4. Assessment of the quality of the identified model.

Recorded earthquake recorded motion, as a full-scale large-amplitude experiment, gives a unique opportunity to make a quantitative study on the structure behavior. However, often the sensors are not optimally placed to monitor the behavior of the whole structure under investigation. Such a limitation hinders making a concrete statement about the structural properties. Finally, a mathematical model for the earth dam problem (Fig. 1) is chosen based on the preliminary analysis of the observed and synthesized data. A visco-elasto-plastic, three dimensional model is found to be the most convenient model to accommodate most of the response features of earth dams.

2 THE INVERSE PROBLEM

2.1 *Gaussian hypothesis*

The inverse problem can be approached by a combination of the state information (which can be viewed over the parameter and observation spaces) and of the theoretical model state. Herein, the Gaussian hypothesis is considered in order to describe the statistical distribution -using a mean and a covariance operator- for each piece state information.

2.2 *Problem solution*

The most comprehensive way to evaluate the parameters is by choosing them in such a way that the true model parameters lie in a given range in which the probability density function of the parameters is optimized in a certain sense. Herein, the chosen optimality criterion is the maximum likelihood criterion which leads to the least square approach. Basically, the solution of the inverse problem using the least square approach requires minimizing a cost function which is done by cumulating the square of the error vector norm via a covariance operator combining both the mobilization and the observation uncertainties. The error vector is defined as the vector measuring the deviation between the estimated and the measured displacement response in the time domain.

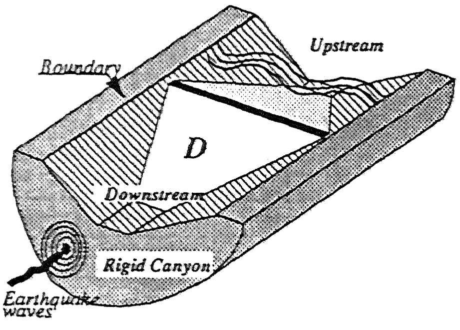


Figure 1. 3-D configuration of earth dams.

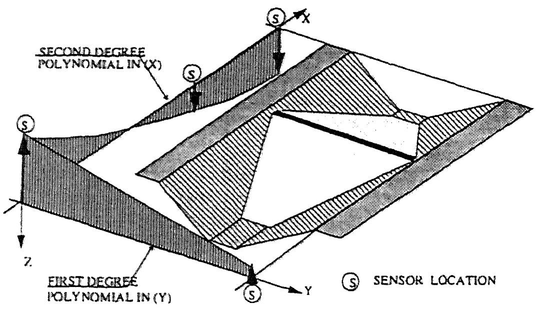


Figure 2. Ground motion spatial variation shape functions.

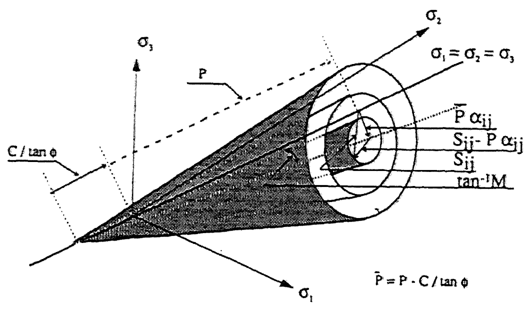


Figure 3. Druker-Prager multi-yield surface plasticity model.

The observation covariance operator is assumed to be null, since this study concerns only one earthquake for each dam. However, the mobilization covariance operator can be evaluated by repeating the forward problem for a given set of parameters with different degrees of sophistication (e.g. with different numbers of global shape functions, yield surfaces,...etc.) in order to evaluate the uncertainty inherent in the modelization state.

3 OPTIMIZATION TECHNIQUE

The solution of the inverse problem based on the Gaussian hypothesis requires minimizing an objective function using an unconstrained optimization technique in which three different methods are used in order to assure efficient convergence. Some of them have a slow but steady convergence (such as the cyclic method); others have fast convergence if the current parameter values are close enough to the optimal solution (such as the Newton method and the conjugate directions method). Finally, the line search technique is implemented using adaptive discrete steps in the selected feasible and improving direction.

4 COMPUTATIONAL SCHEMES

System identification problems require solving the forward problem (the equation of motion) in iterative ways. This problem should be solved in such a way the level of mobilization uncertainty is minimized.

Earth dams are modeled as three-dimensional nonhomogeneous structures [Abdel-Ghaffar et al. (1987)] subjected to nonuniform ground motion at their boundaries. The material nonlinearity is considered using a constitutive model (the Druker-Prager multi-yield surface) which is able to simulate the soil behavior under highly cyclic loading.

Since the hysteretic damping is not sufficient to fully account for the energy dissipation mechanism of the dam material [Zegal 1990], energy dissipation resulting from the diffusion of pore water pressure through the porous media is considered. To simplify the problem, an analog one-phase viscous model is used to simulate the multi-phase model behavior using only one parameter η (the equivalent viscosity coefficient).

In order to reduce the computational efforts and to accommodate complex boundary conditions, a hybrid global-local finite element method (which in effect combines the finite element method and the Galerkin-Ritz method) is used in the solution of the forward problem [Mote (1971)]. Global boundary shape functions are used to interpolate the recorded ground motions on the dams boundaries (Fig. 2). This technique enables a cost-effective computational scheme, particularly when one considers the iterative nature of the inverse problem which requires solving the forward problem repeatedly. Moreover, the choice of natural mode shapes as admissible shape functions tremendously reduces the number of degrees of freedom of the system.

The multi-yield surface plasticity theory is used with the Druker-Prager yield criterion (Fig. 3) [Prevost et al. (1985)]. For updating the yield surfaces, the Ziegler hardening rule [Chen (1988)] is utilized. Furthermore, the hyperbolic model describes the shear modulus variation with the level of shear stress via two parameters τ_r (ultimate shear stress) and G_0 (low-strain shear modulus). Nonhomogenity

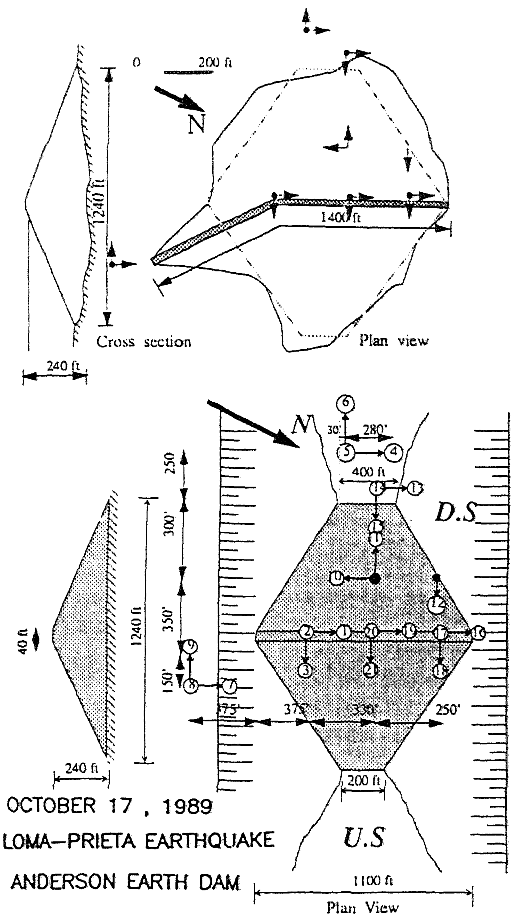


Figure 4-a. Sensor locations on Anderson Dam.

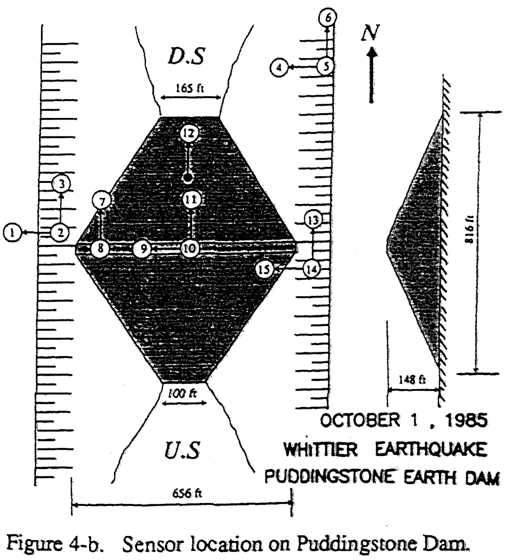


Figure 4-b. Sensor location on Puddingstone Dam.

is considered by the variation of confining pressure in the spatial domain.

5 APPLICATIONS

Several well-instrumented earth dams were strongly shaken by recent earthquakes. The parameters identification of two existing earth dams is considered. The first is Puddingstone earth dam using the 1987 Whittier, California, earthquake ($M_L = 5.9$), and the second is Anderson dam which was strongly shaken by the 1989 Loma Prieta, California, earthquake, ($M_L = 7.0$). The Anderson dam represents a unique case in which ground shaking caused permanent deformations and severely excited the nonlinear range of the dam material. Moreover, the seismic records showed evidence of spatial ground motion variability along the dam boundaries (Sayed et al, 1991).

Puddingstone dam is located 25 km northeast of the 1987 earthquake epicenter. The dam material is 60 to 90% sandy, silty clay and 10 to 40% sand and gravel. The Anderson dam is located 26 km northeast of the 1989 earthquake epicenter. The dam core is made of compacted gravelly, clayey sand and is surrounded by sluiced rockfill shells. A total

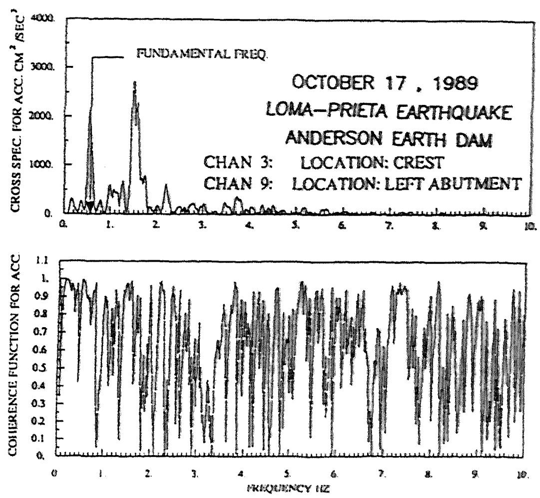


Figure 5-a. Spectral analysis of recorded motion.

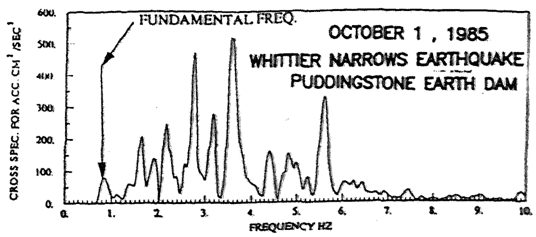


Figure 5-B. Cross correlation between channels 11 and 13 for Puddingstone Dam.

of 21 strong-motion accelerographs were installed on and near the Anderson dam in eight different locations. Figure 4 shows the geometry and the model dimensions of the two dams.

5.1 *Pattern recognition*

The a priori information in the observation and model space are assessed using Fourier amplitude cross and coherence spectra. The spectral analysis of the records provided valuable information on the dynamic properties of the dam materials (the a priori information) as well as the dynamic response characteristics (modelization information). Nonuniform ground motion along the dams boundaries, natural frequencies, and mode shapes as well as nonlinearity can all be detected from the spectral analysis. The analysis of the cross correlation spectrum revealed the fundamental frequencies of each dam; it is approximately 1.90 Hz for Puddingstone dam and 0.60 Hz for Anderson dam. The coherence function analyses between input and output stations detect nonlinearity sources inherent in the physical system as well as nonuniform boundary motion in Anderson dam (see Fig. 5).

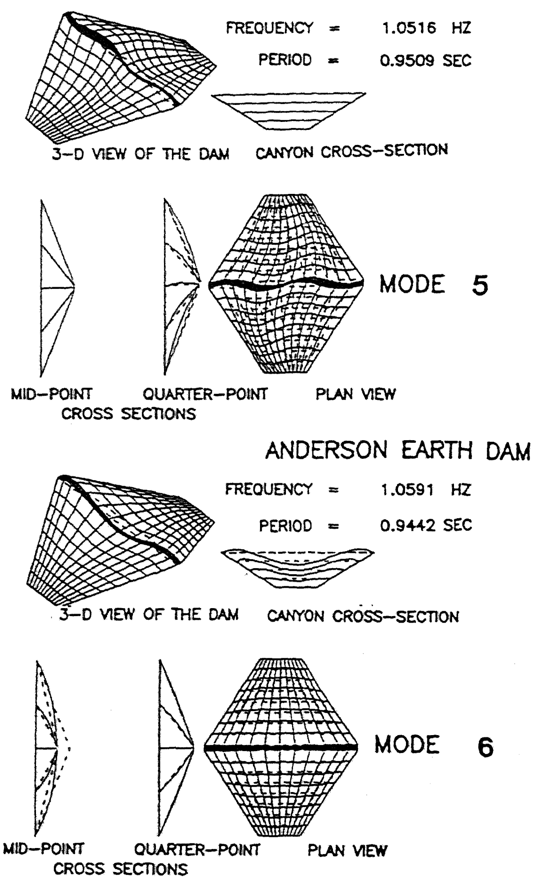


Figure 6. Samples of the global (mode) shape functions.

5.2 *System identification for the two dams*

The constitutive model parameters of the dam material (G_0, τ_r, η) are identified using 20 global shape functions to discretize the spatial domain of each dam (Figs. 6) and 11 yield surfaces to discretize the stress space. Only the most informative time period of the

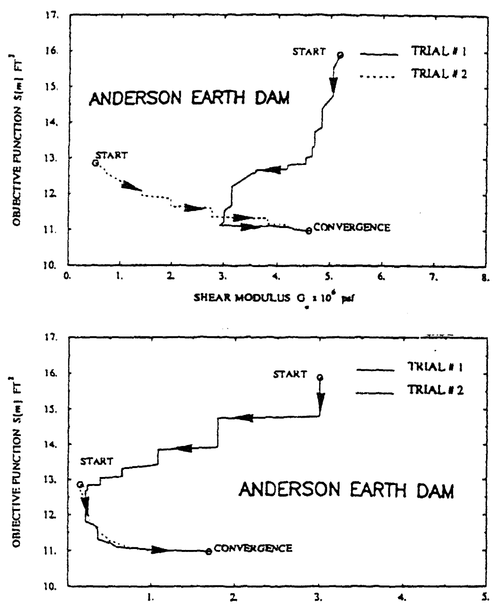


Figure 7.

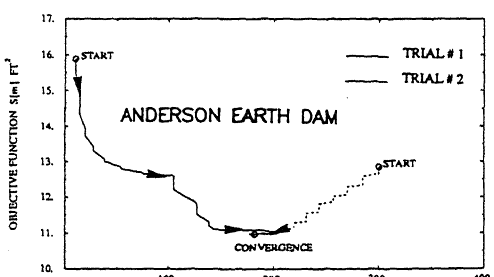


Figure 8.

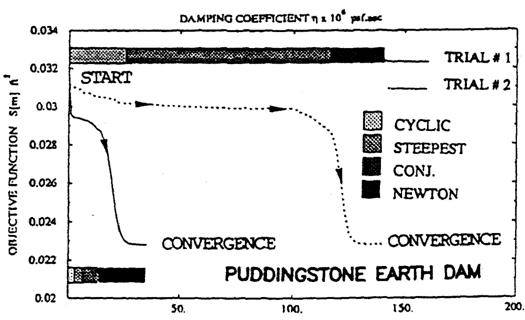


Figure 9

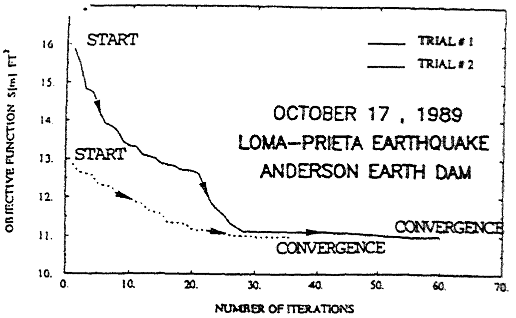
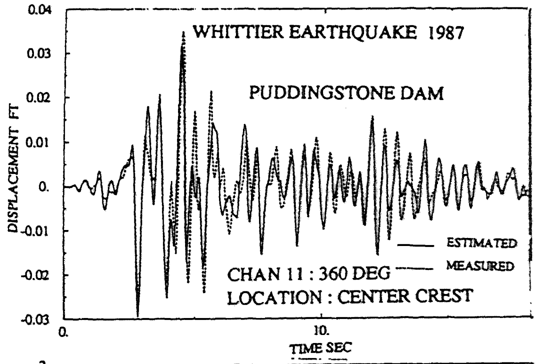
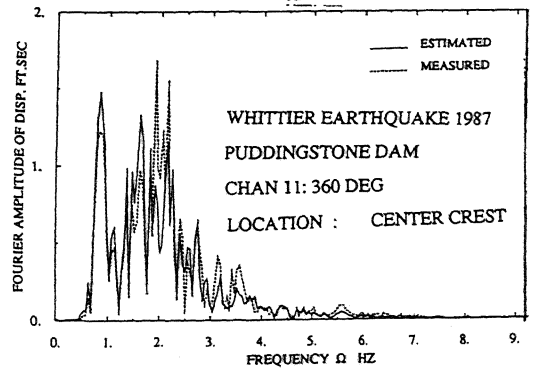


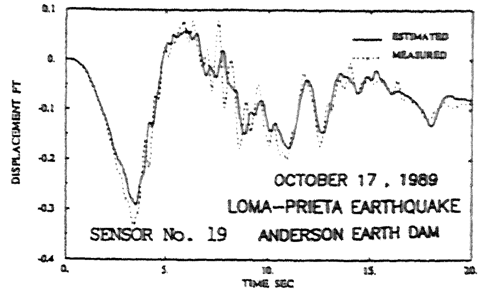
Figure 10.

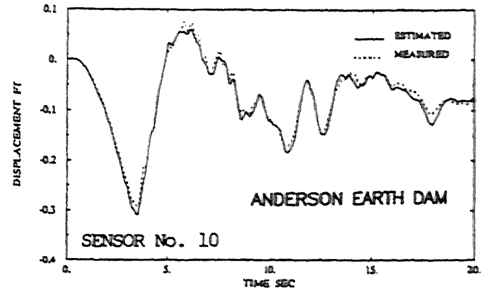
recorded response - 0 to 10 sec. (strongest shaking) - is used in the system identification process and the rest is used to assess the quality of the solution. The initial values of the parameters are chosen based on the a priori and pattern recognition information. However, two different initial values for each dam are used to assure convergence to a global minimum. The maximum likelihood estimator for the Puddingstone dam is given by:

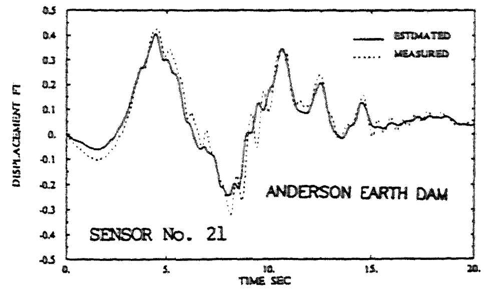
$$\left.\begin{aligned} G_0 &= 4.30386 \times 10^6 \pm 0.00261 \times 10^6 \ psf \\ \tau_r &= 6.54710 \times 10^5 \pm 4.55274 \times 10^5 \ psf \\ \eta &= 8.72702 \times 10^6 \pm 0.02122 \times 10^6 \ psf.sec. \end{aligned}\right\} \quad (1)$$

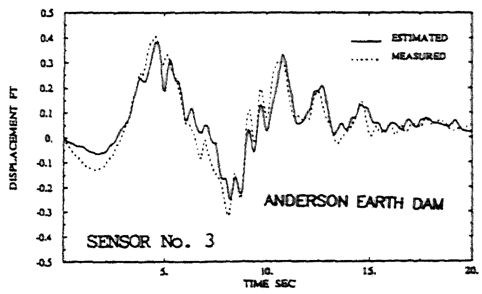


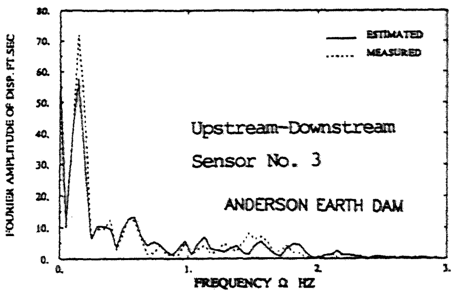












Figures 11, 12, 13. Measured and computed response quantities.

For the Anderson dam the values are given by:

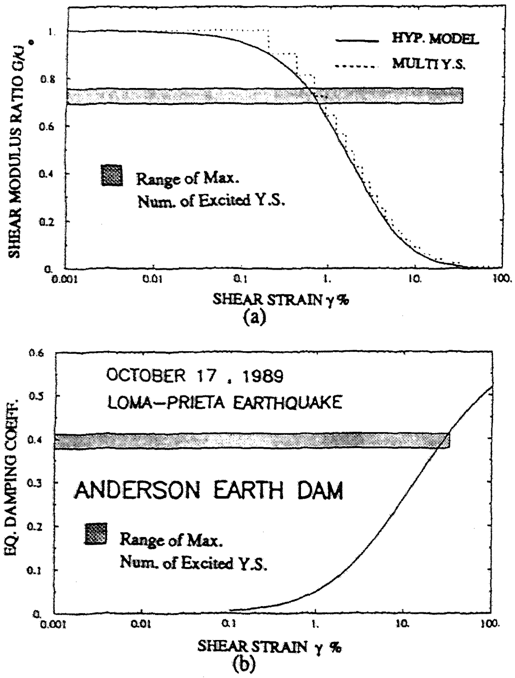
$$\left.\begin{aligned} G_0 &= 4.5934 \times 10^6 \pm 0.00750 \times 10^6 \; psf \\ \tau_r &= 1.7027 \times 10^5 \pm 0.02618 \times 10^5 \; psf \\ &= 1.8229 \times 10^6 \pm 0.00422 \times 10^6 \; psf.sec. \end{aligned}\right\} \quad (2)$$

Figures (7, 8, 9) depict the variations of the objective function along the optimization path as a function of the model parameters.

5.3 *Assessment of the identified model quality*

Equation (1) shows that G_0 and η have a reasonable resolution around the mean value. On the other hand, τ_r has a very a wide resolution around the mean value, which is attributed to the low level of earthquake shaking which excited the Puddingstone dam within the quasi-linear range so that the model could not accurately predict the ultimate shear strength. By contrast, all parameters of Anderson dam (Eq. 2) have reasonable resolution around the mean values. The estimated and measured responses are approximately identical over the wide range of frequencies.

Figures 10, 11, 12, and 13 show the time history as well as the Fourier amplitude spectrum for the measured and identified responses. A good match is obtained even in the time range 10 to 20 sec. which is not used in the identification process.

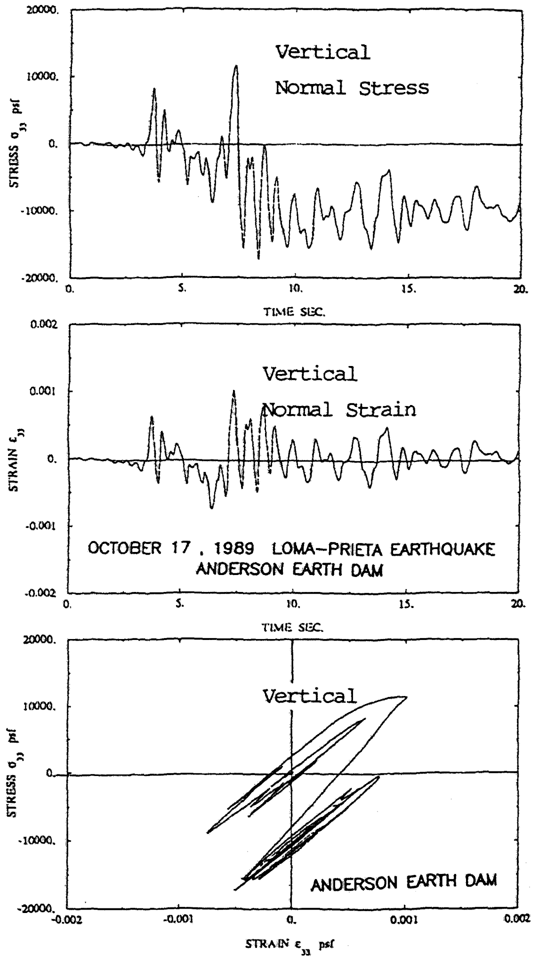


Figures 14, 15. Range of earthquake-induced dynamic shear strain: (a) with shear modulus, and (b) with hysteretic damping coefficient.

Figures 14 and 15 show the estimated tangential shear modulus and the equivalent structural damping coefficient, induced by the hysteretic behavior of the constitutive model, as a function of the shear strain. In addition, the maximum level of excitation, in terms of the maximum number of excited yield surfaces, during the earthquake is indicated. It is obvious, from these figures, that the Loma Prieta earthquake induced a wide range of dynamic shear strains. Finally, Figs. 16 and 17 show the time history of the normal stress and strain components at a point near the mid crest of the Anderson dam; these stresses contributed to the longitudinal cracks found along the crest.

6 CONCLUDING REMARKS

A cost-effective analytical-numerical procedure is developed for modelling and identifying the main phenomenological parameters that control the visco-



Figures 16, 17. Computed vertical normal stress and strain (with the hysteresis loop) near the crest level of Anderson Dam.

elasto-plastic seismic response of earth dams subjected to non-uniform ground motion along their boundaries.

The dam parameters (such as the low-strain shear modulus, the ultimate shear strength, and the viscous damping coefficient) that control its nonlinear seismic behavior were identified with good resolution around their mean values. The application, which showed significant agreement between the optimal computed time-history and the recorded motion, demonstrates the ability and effectiveness of the proposed modelling and identification technique to accurately predict the system parameters and the seismic behavior of earth dams.

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