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System Identification and Seismic Performance Evaluation of Earth Dams

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System Identification and Seismis Performance Evaluation of Earth Dams

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SYNOPSIS A system identification technique is developed to provide dynamic properties of earth dams from their seismic records. The technique is utilized to assess the capabilities and limitation of analytical models in terms of dynamic nonlinear constitutive relationships as well as damping. The technique is based on the least square method using Gaussian hypothesis. Earth dams are modeled as a three-dimensional nonhomogeneous visco-elasto-plastic soil structure. The forward problem is solved using a Galerkin-Ritz formulation in which the solution is expanded using basis function, which are selected to be the eigenmodes. The spatial variation of the excitation is considered by using global shape functions defined on the boundary domain to interpolate the input motion on the dam boundaries using recorded motion at discrete locations. The constitutive model is used to accommodate the non-linear path dependent behavior of the dam material as well as coupling between different constituent of the soil mixture. The model is implemented using Druker-Prager multi-yield surface model and linear Kelvin-Voigt model. Application to instrumented dams, in recent earthquake, showed significant match between the recorded response and the optimal estimated response.

INTRODUCTION

System identification is the process of evaluating a model of a real system state from experimental records measuring the output (response) of the system due to known or even unknown input (excitation). What is meant by the model in the previous definition is the class of theoretical or mathematical relation by which the output of the system can be computed with a minimum level of uncertainty. 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.

Earthquake recorded motion 'as a full-scale, large-amplitude experiment', gives a unique opportunity to make a quantitative study on the structure behavior. However, usually a few transducers may not be optimally placed to monitor the behavior of the whole structure under investigation. Such limitation hinders making a concrete statement on the structure properties.

The mathematical model for the earth dam problem (figure 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 the following features of the earth dams:

1. The material nonlinearity of the soil.
2. The behavior of the soil as a multi-phase material which has a similar behavior as a one phase viscous material [Bardet et al. (1990)].
3. The geometric three dimensional nature of these dams.
4. The spatial variation of the excitation along the dam boundaries.

The parameters estimation is achieved using the least square criterion based on the Gaussian hypothesis and the assessment of the solution quality is achieved by evaluating the model covariance operator as well as the behavior of the objective function.

THE INVERSE PROBLEM

Gaussian Hypothesis

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

Problem Solution

The most comprehensive way to evaluate the parameters is by choosing them in such way the true model parameters lie in a given range at which the probability density function (p.d.f.) of the model 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 least square approach requires minimizing a cost function which is performed by cumulating the square of the error vector norm via a covariance operator combined both the modelization and the observation uncertainties. The error vector is defined as the vector measuring the deviation between the estimated and the measured displacement response in time domain. The observation covariance operator is assumed to be null, since this study concerns only one earthquake for each dam.
However, the modelization covariance operator is still debated. It can be evaluated by repeating the forward problem for a given set of parameter 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.

OPTIMIZATION TECHNIQUE

The solution of the inverse problem based on Gaussian hypothesis requires minimizing an objective function using an unconstrained optimization technique in which three methods were used in order to assure efficient convergence. Some of them have a slow but steady convergence (cyclic method), others have fast convergence if the current parameters values are close enough to the optimal solution such as Newton method and conjugate directions method. These three methods are described in any nonlinear programming reference (e.g.Bazaraa (1979)). Finally, the line search technique is implemented using an adaptive discrete steps in the selected feasible and improving direction.

COMPUTATIONAL SCHEMS FOR FORWARD PROBLEM

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

Earth dams are modeled as a three-dimensional nonhomogeneous structures [Abdel-Ghaffar et al. (1987)] subjected to nonuniform ground motion at their boundaries. The material nonlinearity is considered using constitutive model (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 results from the diffusion of pore water pressure through the porous media is considered. Thus multi-phase analysis of the soil should be utilized. To simplify the problem an analog one-phase viscous model is used to simulate the multi-phase model behavior using only one parameter η(equivalent viscosity coefficient). Hence a visco-elasto-plastic model can accommodate the previous essential features of earth dams.

In order to reduce the computational efforts and to accommodate complex boundary conditions, a hybrid global finite element method which in effect combines the finite element and Galerkin-Ritz method is used in the solution of the forward problem [Mote (1971)]. Global boundary shape functions are used to interpolate the ground motion on the dams boundaries to allow the seismic wave propagation (figure 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 linear mode shapes as admissible shape functions reduces tremendously the number of degree of freedom describes the system and hence the computational time.

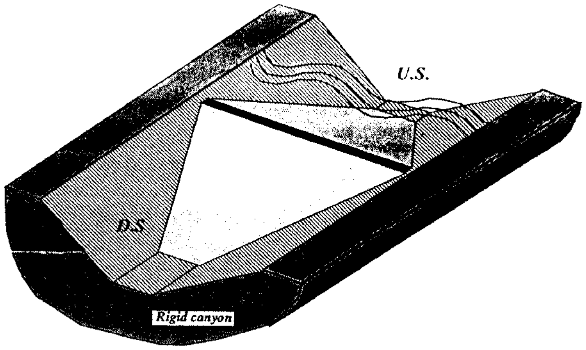


Figure 1: 3-D configuration of earth dams.

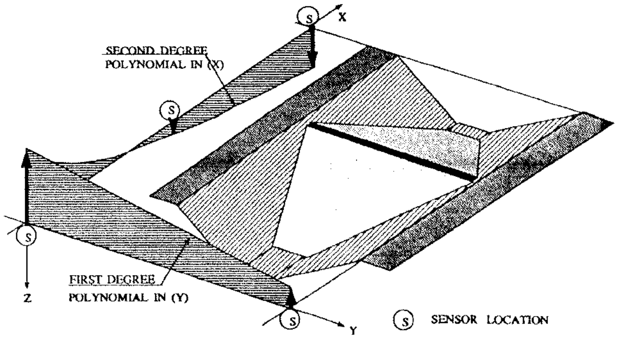


Figure 2: Ground motion spatial variation shape functions.

The multi-yield surface plasticity theory is used with Druker-Prager yield criterion (figure 3) [Prevost et al. (1985)]. For updating the yield surfaces the Ziegler's 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) G_0 and (low-strain shear modulus). Nonhomogenity is considered with the variation of confining pressure in the spatial domain.

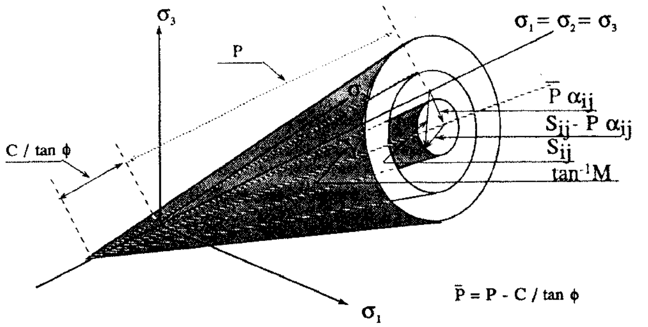
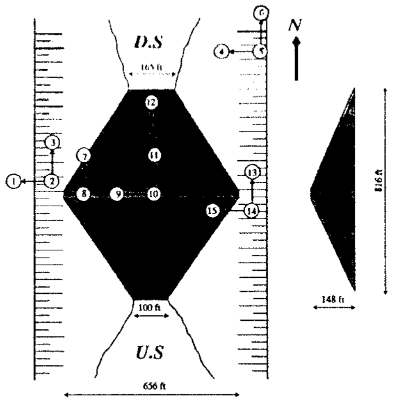


Figure 3: Druker-Prager multi-yield surface model.

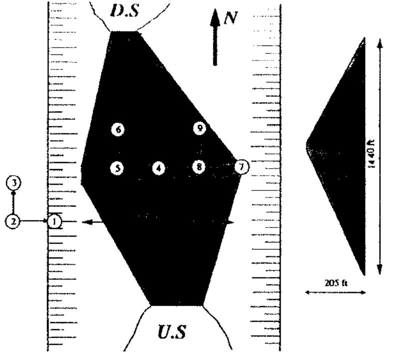
APPLICATIONS

Several well-instrumented earth dams were strongly shaken by the recent Whittier (Oct. 1987) and Loma Prieta (Oct. 1989) earthquake.The parameters identification of two existing earth dams are considered. The first is Puddingstone earth dam using 1987 Whittier earthquake (5.9 ML) and the second is Lexington dam using 1989 Loma-Prieta earthquake (ML=7.0).

Puddingstone dam is located 16 miles northeast the Whittiers California. The dam material is 60 to 90% sandy silty clay and 10 to 40% sand and gravel. Lexington dam is located 13.5 miles from the epicenter of the main shock of the 1989 Loma-Prieta earthquake. The dam material is composed of relatively sandy gravelly clay core boarded by random materials of clay, sand, and gravel. Figure 4 shows the geometry and the model dimensions of the two dams.



a) PUDDINGSTONE EARTH DAM SENSORS LOCATIONS



b) LEXINGTON EARTH DAM SENSORS LOCATIONS

Figure 4: Model dimensions and sensor locations. for Puddingstone and Lexington dams.

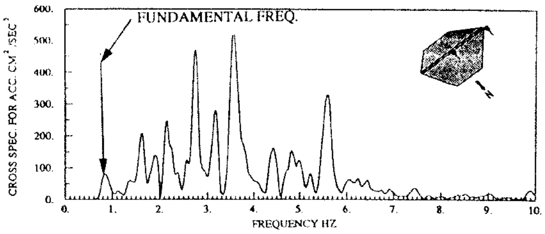


Figure 5: Cross correlation between channel 11 and 13 for Puddingstone dam.

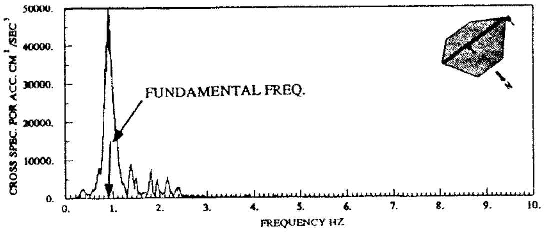
Pattern Recognition

The a priori information in the observation and model space are assessed using Fourier amplitude spectrum, cross spectrum, and coherence spectrum. 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. Figures 5 and 6 show the cross correlation spectrum between an input and an output station in the transversal direction of the dam. The analysis of the cross correlation spectrum revealed that the fundamental frequencies of each dam is approximately 1.9HZ for Puddingstone dam and 0.9HZ for Lexington dam. The coherence function analysis between input and output stations detect a nonlinearity sources inherent in the physical system as well as nonuniform boundary motion in Lexington dam (see figure 7).

System Identification for Puddingstone Dam and Concluded Remarks

The constitutive model parameters of the dam material (G_o, τ_r, η) are identified using 20 global shape functions to discretize the spatial domain (figures 8,9) and 11 yield surfaces to discretize the stress space. Only the most informative time period of the record 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. Howev-



Fiqure 6: Cross correlation between channel 3 and 9 for Lexington dam.

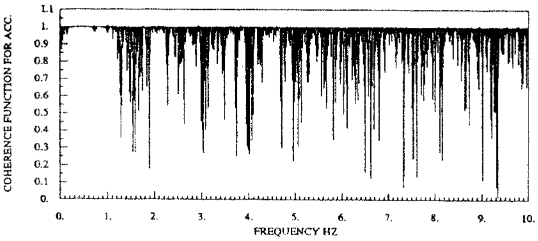


Figure 7: Coherence spectrum between channel 3 and 9 for Lexington dam.

er, Two different initial values are used to assure convergence to a global minimum. The maximum likelihood estimator is given by:

$$\begin{array}{lll} G_o & = 4.30386\times10^{6} \pm 0.00261\times10^{6} \text{ psf} & \\ \tau_r & = 6.54710\times10^{5} \pm 4.55274\times10^{5} \text{ psf} & (1) \\ \eta & = 8.72702\times10^{6} \pm 0.02122\times10^{6} \text{ psf.sec} & \end{array}$$

Figures 10,11,12 depict the variation of the objective function with the number of iteration and parameters paths.

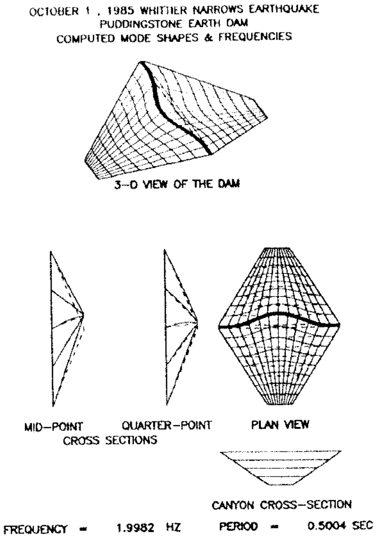


Figure 8: Global shape function # 1.

Figure 12: Optimization path for the viscous damping coefficient parameter η.

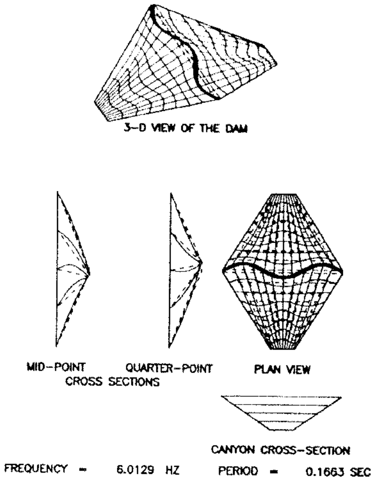


Figure 9: Global shape function # 20.

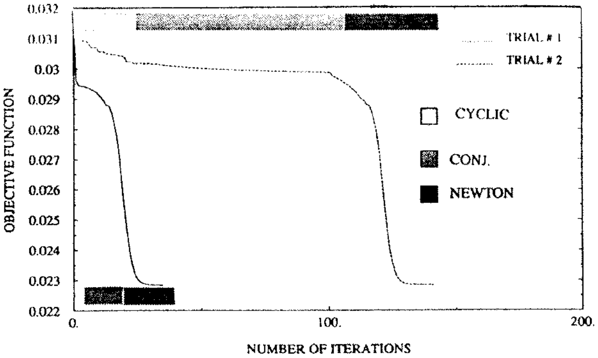


Figure 10: Optimization path for the objective function.

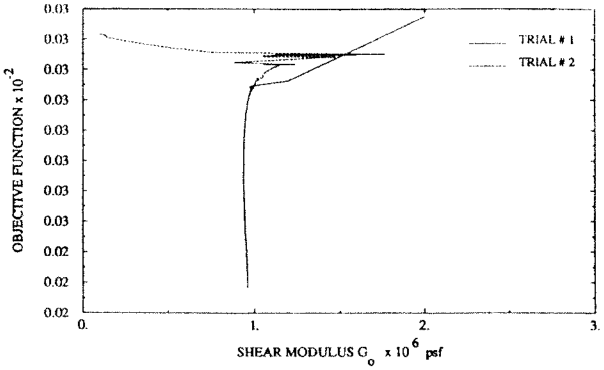
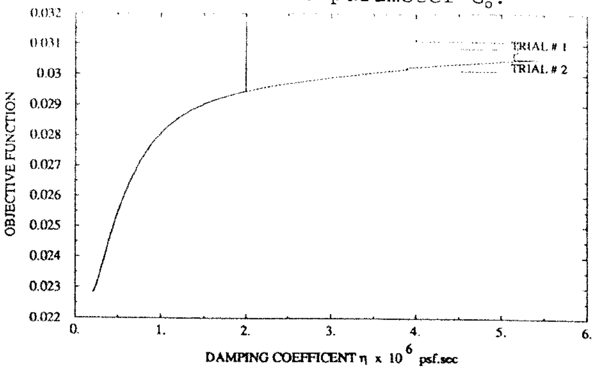


Figure 11: Optimization path for the low strain shear modulus parameter G_o.



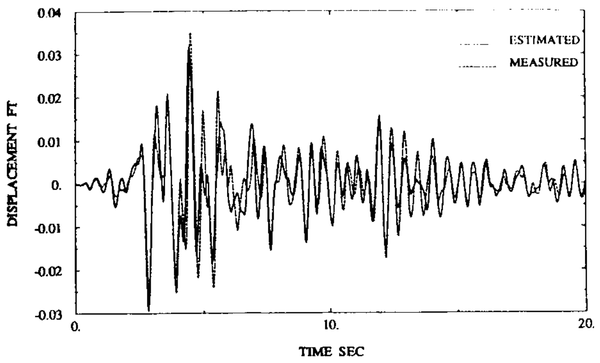


Figure 13: Time history of channel 11.

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 dam within the quasi-linear range so that the model could not predict accurately the ultimate shear strength.
Figures 13,14,15, and 16 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. Evidently, the identified response has less energy contents in the high frequency range rather than the measured response. This is attributed to the discretization of the spatial domain using finite number of global shape functions by truncating the higher order modes.

Figures 17 and 18 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.

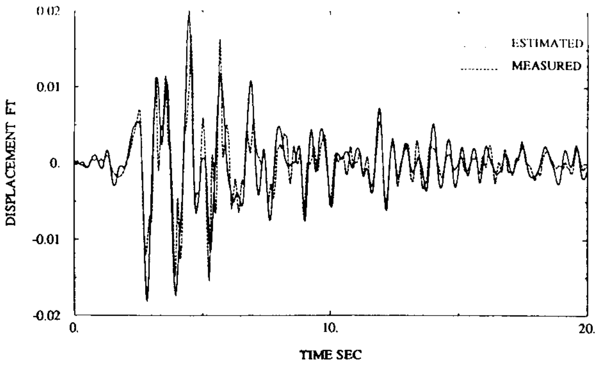


Figure 14: Time history of channel 12.

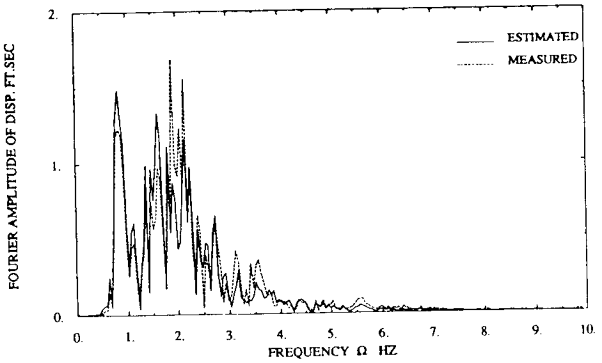


Figure 15: Fourier amplitude spectrum of channel 11.

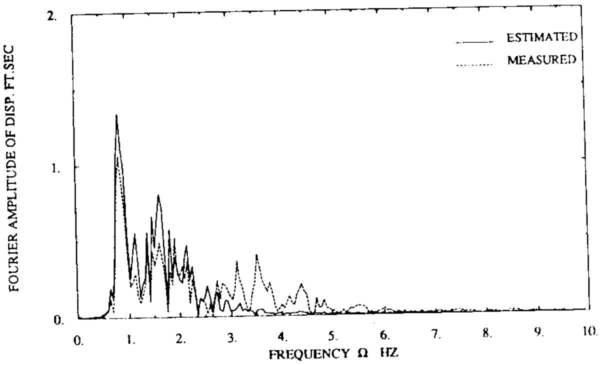


Figure 16: Fourier amplitude spectrum of channel 12.

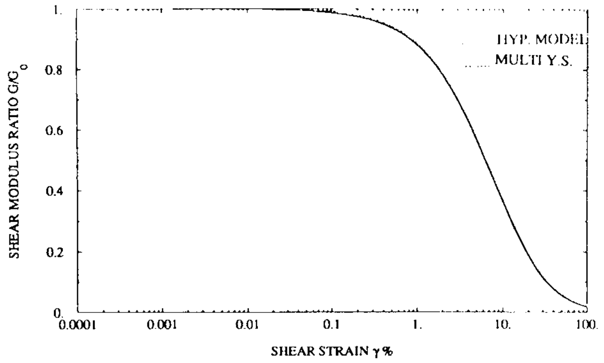


Figure 17: Estimated tangential shear modulus.

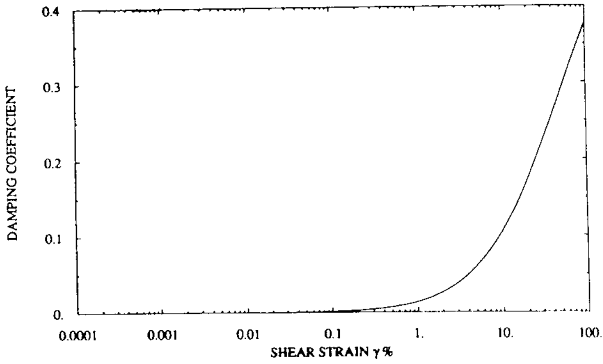


Figure 18: Estimated equivalent structural damping coefficient.

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