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NONLINEAR SEISMIC ANALYSIS OF THE UPPER SAN FERNANDO DAM UNDER THE 1971 SAN FERNANDO EARTHQUAKE

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SUMMARY

The Upper San Fernando Dam was analyzed under an estimated shaking condition representing the 1971 San Fernando earthquake. The analysis used an explicit finite difference method and nonlinear soil models. The preliminary values of computed deformation appear to be consistent with the deformations of the dam observed following the 1971 earthquake. This type of analysis involving an actual case history provides confidence in using nonlinear methods to estimate seismically-induced deformations of earth dams in engineering practice.

INTRODUCTION

An evaluation of seismically-induced permanent deformations is becoming a critical part of investigations concerning earth dams in seismic regions. As this trend continues, one finds in the literature an increasing number of analytical procedures to estimate seismically-induced deformations of earth structures. One category of such procedures is time-domain dynamic response analyses of earth structures using nonlinear soil models to directly compute the deformations. However, many procedures in this category use very complicated soil models, often require long computational time on a large computer, and may not have been well-calibrated using actual case histories.

The main objective of this paper is to show that a nonlinear, explicit finite difference method can be used to calculate in a reasonable way the observed deformations of the Upper San Fernando Dam due to the 1971 San Fernando earthquake. The analysis was performed using only the available data and emphasizing simplicity in soil model and analysis. The results presented herein are considered to be preliminary at this time.

UPPER SAN FERNANDO DAM AND THE 1971 SAN FERNANDO EARTHQUAKE

The Upper San Fernando Dam, which was located northwest of Los Angeles, was an 80 foot-high hydraulic fill dam with a reservoir of about 1850 acre-feet. Many details of its construction, its damage due to the 1971 San Fernando earthquake, and its seismic analysis are presented in a report by Seed et al (1973).

The 1971 San Fernando earthquake had a surface wave magnitude of 6.6 and a focal depth of about 8 miles. The dam was about 8-1/2 miles from the source of this earthquake. The peak acceleration at the dam site was considered to have been no greater than 0.55 to 0.6 g (Reference 3).

The earthquake apparently created severe longitudinal cracks running almost the full length of the dam on the upstream slope slightly below the pre-earthquake reservoir level. The crest of the dam reportedly moved downstream about five feet and settled vertically about three feet. At the downstream toe of the dam a two feet high pressure ridge was observed. These major observations of the dam following the 1971 earthquake are summarized for a major section of the dam (Reference 4) in Figure 1.

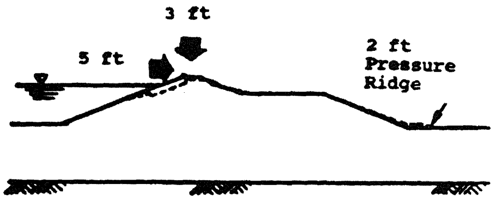

Figure 1 - Observed Deformations After 1971 Earthquake

ANALYSIS

The seismic analysis of the dam was performed using the computer program DYNARD, which is being developed by the authors. The analysis section is discretized into elements and nodal points similar to those in the finite element method. The program uses the explicit finite difference method (Reference 6) to solve the equations of motion at nodal points and to calculate acceleration, velocity, and displacement at those points. Nonlinear constitutive relationships are used to calculate stresses in elements using incremental strains obtained for each element from incremental velocity data at nodal points surrounding the element. Figure 2 shows the finite difference mesh used in the dynamic analysis of the Upper San Fernando Dam. In the analysis mesh shown in Figure 2, the sides consist of energy absorbing boundaries, and the bottom has a compliant boundary.

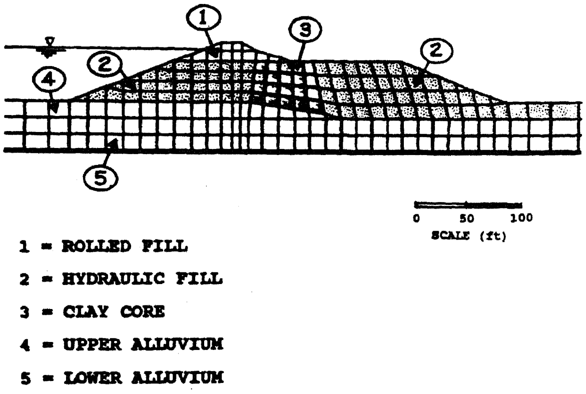

Figure 2 - Analysis Mesh and Material Types

A modified Pacoima accelerogram (Reference 1) scaled to a peak acceleration of 0.6 g was used as an input accelerogram at the base. This input motion is considered to represent in a reasonable way the 1971 shaking conditions at the site of the Upper San Fernando Dam.

STRESS-STRAIN RELATIONSHIPS

A version of the "failure-seeking" model (Reference 2) was used as the basis of the nonlinear stress-strain relationships for soils. The basic failure-seeking model as used in this study is specified by a low-strain maximum shear modulus, an initial undrained shear strength, and the variations of the modulus from the low-strain region to point where the stress-strain curve reaches the specified initial undrained strength. It is noted that these parameters are relatively easy to estimate.

The maximum shear modulus and the initial undrained shear strength of the key soils in the dam were selected using the data presented in Reference 4. The generation of excess pore water pressures was incorporated in the soil model using a procedure developed by Vicente and Dobry (1983). Given a value of cyclincally-induced excess pore water pressures expressed in terms of pore pressure ratio (r_u), the maximum shear modulus (G_i) and the initial undrained shear strength (Su_i) of soils were degraded using the following equations:

$$G = G_i(1-r_u)^n$$

$$S_u = S_{ui}(1-r_u)^m \qquad (1)$$

The values of parameters in the Vicente-Dobry procedure to generate pore water pressures as well as the degradation parameters (n, m) shown in Equations 1 were obtained as follows: assuming initial parameter values, simulating a series of stress-controlled cyclic tests, and repeating the process until the computed relationship between the cyclic stress ratio and the number of cycles becomes sufficiently close to that for the soils under consideration as obtained in cyclic testing and evaluation.

In this study, we obtained the model parameter values using the relationships between the cyclic stress ratio and the number of cycles to reach one-way cyclic shear strain of 2.5 percent (or initial liquefaction) for the selected soils of the Upper San Fernando Dam (Reference 4). Figure 3 shows an example of such relationship for the hydraulic fill material to reach initial liquefaction. Also shown in Figure 3 are the computed results of simulation using the soil model and the selected values of the model parameters.

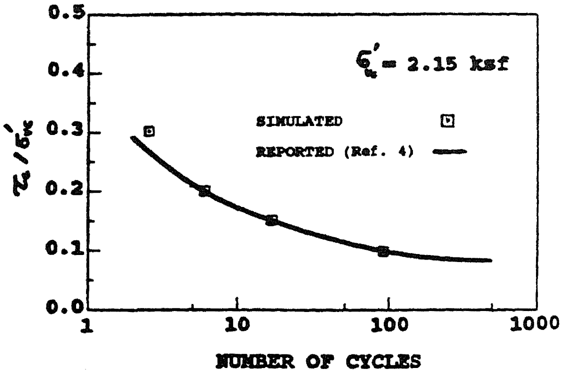

Figure 3 - Comparison of Reported and Simulated Soil Data

RESULTS

The results of the computed deformation at the end of shaking are summarized in Figure 4 in terms of a deformed finite difference mesh (using an exaggerated scale of two). Also shown in Figure 4 are the amount of computed deformations at key locations comparable to those shown in Figure 1.

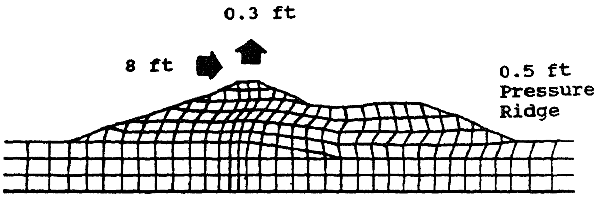

Figure 4 - Computed Deformation Results

CONCLUSIONS

Preliminary results of an analysis using a nonlinear explicit finite difference method correspond in a reasonable way the observed deformation pattern of the Upper San Fernando Dam following the 1971 San Fernando earthquake. Modelling the effects of degradation appears to be important in computing realistic permanent deformations of an earth dam under seismic loading conditions. The type of evaluation discussed herein provides confidence in using nonlinear seismic response analyses in engineering practice to evaluate seismically-induced permanent deformations of earth dams.

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