14 Mar 1991, 2:00 pm - 3:30 pm

Inelastic Seismic Response of San Fernando and Santa Felicia Dams

Elsa Stara-Gazetas
Acres International, Amherst, NY

Ricardo Dobry
Rensselaer Polytechnic Institute, Troy, NY

Proceedings: Second International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, March 11-15, 1991, St. Louis, Missouri, Paper No. 7.41

nelastic Seismic Response of San Fernando and Santa Felicia Dams

Elsa Stara-Gazetas
Geotechnical Engineer, Acres International, Amherst, NY, USA

Ricardo Dobry
Professor of Civil Engineering, Rensselaer Polytechnic Institute, Troy, NY, USA

SYNOPSIS: A simplified method of inelastic seismic analysis of earth dams developed by the authors is used to study the response of the San Fernando and Santa Felicia dams to accelerograms recorded in the 1971 San Fernando Earthquake. The method involves two separate stages. In stage I, the dam is discretized into finite elements and is subjected to horizontal static inertia-like forces; its nonlinear deformation is computed using a plane strain code, while the applied horizontal forces are gradually increased until large enough strains develop in most elements of the dam. The results of this analysis are utilized to derive realistic nonlinear stress-strain relationships for layer super-elements consisting of horizontal rows of finite elements. Then, in stage II of the analysis, the dam is discretized as a one-dimensional layered triangular shear beam, in which each layer's constitutive relation stems from the nonlinear stress-strain super-element relation determined in the previous stage. The dynamic response of the dam is then computed using (with small modifications) existing nonlinear shear beam formulations. The results of the analysis for San Fernando and Santa Felicia Dams are presented and compared with the results of two-dimensional "equivalent-linear" and "kinematic-plasticity" methods. Considerable insight is gained into the nature of the nonlinear seismic response of embankment dams.

INTRODUCTION

The "shear beam" model of dynamic analysis assumes that only horizontal displacements and shear stresses are generated under seismic excitation, with both being uniformly distributed along the width of the dam(Gazetas, 1987). Its use is primarily justified by the simplicity of the model which makes analyses during early design stages and parametric studies feasible, compared with the "plane strain" model based on the finite-element discretization. The shear beam model, also gives results for natural frequencies, modal displacements and seismic strains which are in good agreement with the results of the finite element methods(Dakoulas and Gazetas, 1985).

It is well known that soil behaves nonlinearly when subjected to large strains, such as those induced by strong seismic excitation. Experimental evidence also suggests that soil exhibits inelastic behavior under cyclic seismic loading.

The nonlinear behavior of soil is, often, modeled as an "equivalent linear" one, while the inelastic soil behavior can be represented by plasticity based formulations. A two dimensional finite element "equivalent linear" method of dynamic analysis is presented by Idriss et al (1973) while a plasticity based finite element solution by Prevost et al(1985). Besides the considerable effort associated with their application, the extended computer requirements of the sophisticated methods may not allow their use in everyday engineering design.

This paper presents the application of the proposed simplified inelastic method to San Fernando and Santa Felicia dams and it tests its validity by comparing its results versus the "equivalent linear" and "plasticity based" finite element formulations.

OUTLINE OF "LAYERED-INELASTIC-SHEAR-BEAM"(LISB) METHOD OF ANALYSIS

The LISB method is a two stage procedure which involves: (i) a two-dimensional finite element static nonlinear analyses (Stage I) and (ii) a one-dimensional shear beam dynanic analysis (Stage II), as shown schematically in figure 1.

In Stage I, the dam is discretized into finite elements and is subjected to incrementally applied horizontal static forces which simulate the inertia forces generated by the seismic excitation; this simulation is in accordance with the main assumption of the shear beam model that only horizontal deformations develop. The estimation of the inertia-like forces is based on a triangular acceleration distribution along the depth of the dam, in accordance with the fundamental mode shape of inhomogeneous dams (Dakoulas and Gazetas, 1985 and Gazetas, 1982).

The nonlinear stress-strain relation is approximated by a hyperbola with the initial moduli and the ultimate strength being functions of the effective confining pressure(Duncan et al, 1970). The element stresses caused by the dam weight are estimated by means of the computer code FEADAM (Duncan et al, 1980). These stresses are used to estimate the tangent shear moduli of each element, which are then forced to be functions of the mean effective pressure rather that of the confining pressure; thus, even if the computer code operates with moduli dependent on the confining pressure, the hyperbolic stress- strain relationships are chosen in such a way that the shear modulus of each element vary with mean effective pressure.

Thus, for each increment of lateral loading the horizontal force-deformation relation of each element can be estimated.

In Stage II, the dam is discretized as a one-dimensional layered triangular shear beam, in which each layer's constitutive relation stems from the nonlinear shear stress-shear strain superelement relation determined in Stage I. The superelement (layer) average shear stress-average shear strain can be readily obtained by averaging the element force-displacement relations derived in Stage I and dividing it by the total horizontal area and by the thickness of the layer, respectively. The average shear stress-shear strain relation is the backbone curve of the superelement,which along with the extended Massing criterion (Massing, 1926 and Pyke,1979) leads to the complete hysteretic constitutive relation for each superelement. The dynamic response of the dam can then be readily computed using existing nonlinear formulations.
The analyses performed herein are based in a lumped mass formulation and a step by step integration by means of the Newmark's "b" method(Newmark, 1959). An additional 2% viscous damping was added to account for all nonhysteretic types of damping that may be present, especially at very small strains.

FIRST CASE STUDY: LOWER SAN FERNANDO DAM

The Lower San Fernando dam is a hydraulic-fill embankment with a height of 140 ft, a length of 2080 ft at the crest, an upstream slope of 2.5H:1V and downstream slopes of 2.5H: 1V to 4.5H:1V. During the 1971 San Fernando earthquake, the dam was subjected to strong excitation with an estimated peak ground acceleration of 0.60 g and suffered a major upstream liquefaction flow slide.

Seed and his coworkers (Seed et al, 1973) performed an "equivalent-linear" finite element dynamic analysis with the QUAD-4 code(Idriss et al, 1973). The initial static stresses caused by the dam weight were determined by the nonlinear incremental static method incorporated into the FEADAM computer code (Duncan et al, 1980); the required soil parameters were established from consolidated drained tests. The seismoscope record obtained at the dam abutment had been translated into an acceleration time history by R.F.Scott; its downstream component with a peak value of 0.60g was used as the input acceleration (LSFDA record).

The Layer Inelastic Shear Beam (LISB) procedur is applied herein to the same San Fernando dam with identical material properties an excitation as used in Seed's study. The dam wa discretized in elements built in 17 horizonta layers, as shown in figure 2.a. The (average shear stress-shear strain curves correspondin the bottom and top layers are shown in figur 2.b, where dots correspond to the value calculated with the FE code, and the soli lines are the best fitted shear stress- strai curves. Figures 3 and 4 display th acceleration and shear strain time historie along the height of the dam due to the LSFD excitation. Notice that the computed peak cres acceleration is also 0.60g, implying n amplification by the dam, contrary to wha usually happens with elastic response; als notice that high frequencies are retained i all motions at various depths in the dam; th computed layer (average) peak shear strain a the base of the dam reaches 1% at about 1 seconds(fig. 5).

<u>Comparison Of LISB And Equivalent Linear Analyses</u>

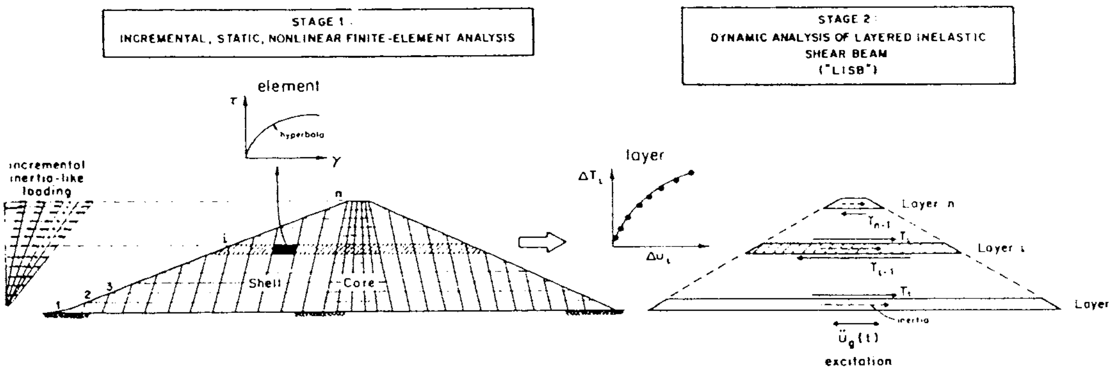
The crest acceleration time historie calculated by the LISB and the equivalent linear finite element (EQLFE) methods have nearly the same peak value of 0.60g ; however, their details and frequency characteristics are dramatically different (Stara-Gazetas, 1986). LISB predicts a substantial number of high frequency cycles which are suppressed by the EQLFE method (the thickness of the crest elements in EQLFE analysis are about double the layer thickness used by LISB); notice, also, that the LISB histories exhibit a "clipped" form, which is mainly attributed to the existence of a limiting value for the shear stress in the hyberbolic formulation.

Figure 5 compares the shear stress time histories for four elements at the base of the dam, obtained by EQLFE, and the layer(average) shear stress obtained by LISB. The LISB peak shear stress in the layer is about 2.4 ksf, while the EQLFE shear stress varies from 3 ksf at the core to 1.5 ksf at elements close to the slope. Thus, the LISB stress is, indeed, not far from the average value predicted by the FE formulation across the width of the dam. However the number of cycles is fairly different, as are the prevailing frequencies of oscillation.

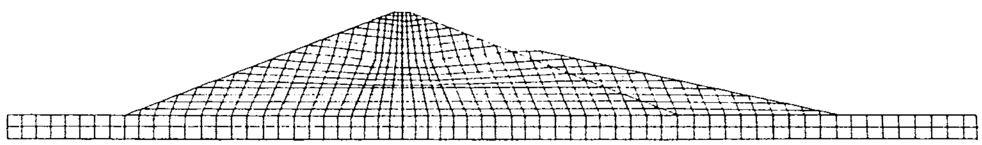
Figure 6 compares the shear strain time history of an element near the slope surface at the bottom of the dam. The LISB method predicts a layer(average) peak shear strain of .9%, while the EQLFE method predicts a peak element strain of .9% for the near slope element and a value of 1.3% near the center of the dam element.

SECOND CASE STUDY: SANTA FELICIA DAM

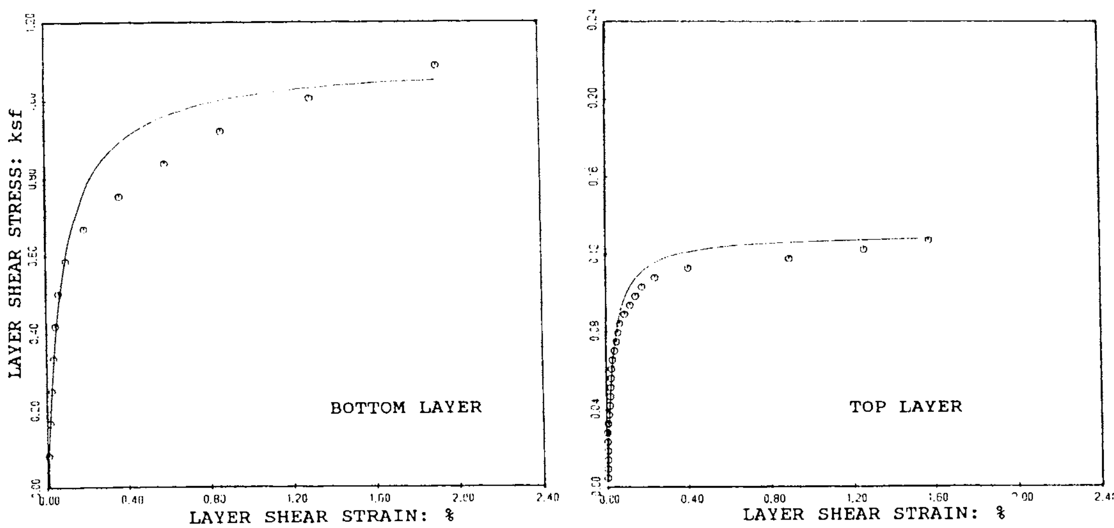
The Santa Felicia dam is approximately 275 ft in height with upstream and downstream slopes of 2.25H:1V and 1H:1V, respectively, and a length at the crest of 1275 ft. The dam



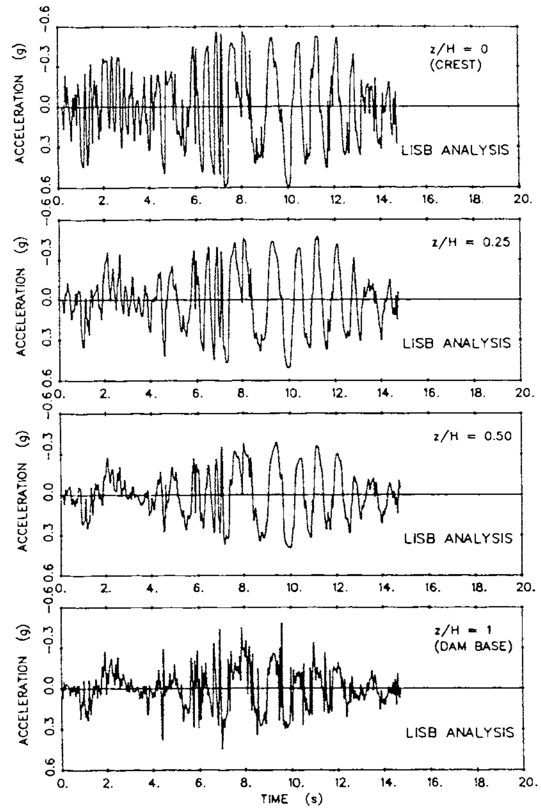
1. Illustration of the LISB 2-staged method



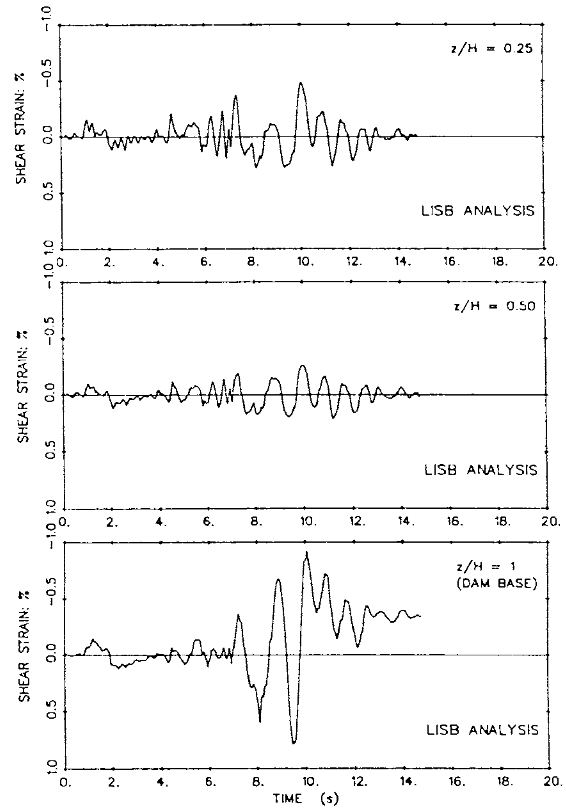
2.a. Finite element discretization of Lower San Fernando dam



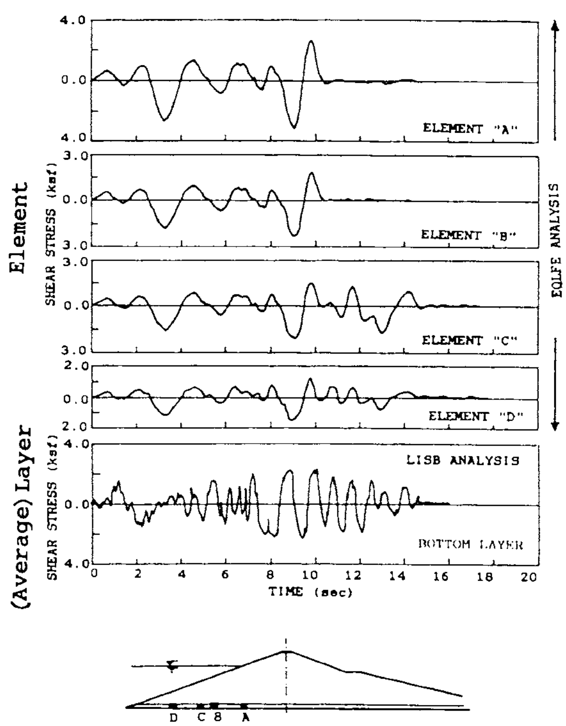
2.b. Layer shear stress-strain hyperbolic approximation for bottom and top layers of Lower San Fernando dam



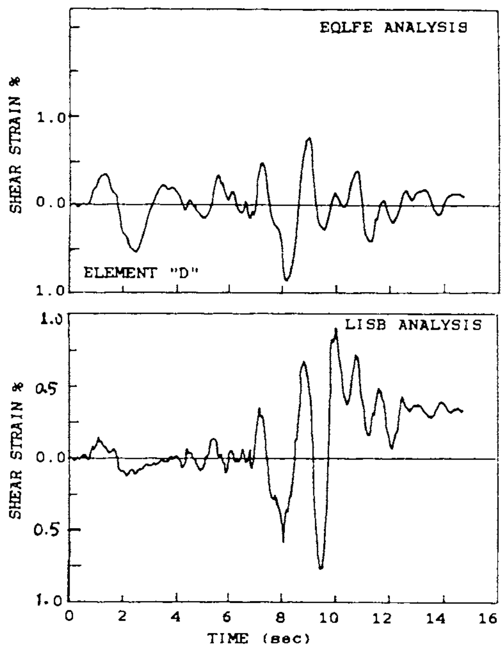
3.Acceleration time histories along the depth of the Lower San Fernando dam subjected to 1971 LSFD record at the abutment



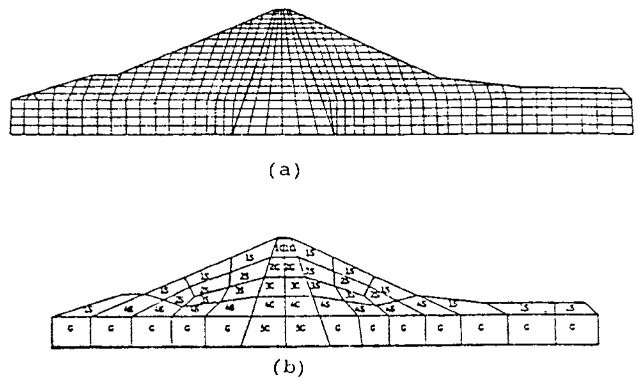
4.Shear strain time histories along the depth of the Lower San Fernando dam subjected to 1971 LSFD record at the abutment



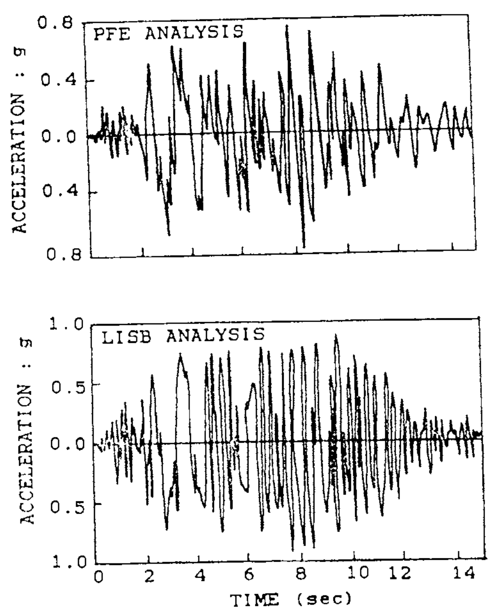
5.Shear stress time histories at the bottom layer of Lower San Fernando dam, subjected to 1971 LSFD record at the abutment, as predicted by the EQLFE and LISB methods



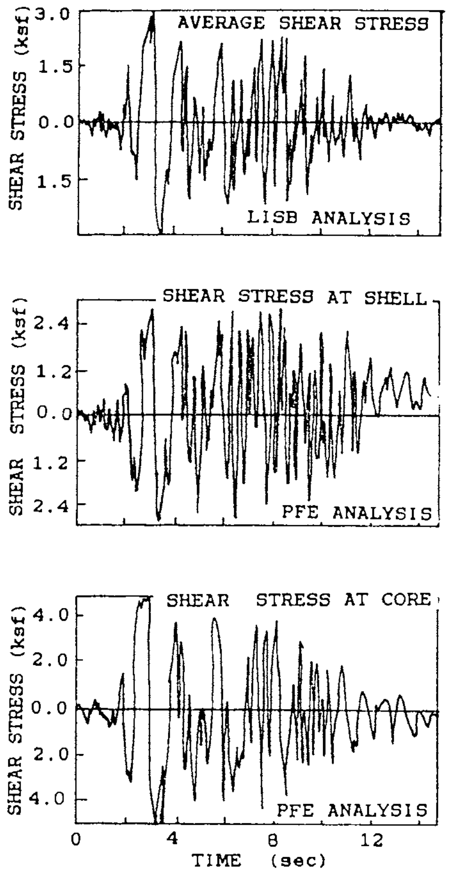
6. Shear strain time histories at an element near the slope of the bottom layer of the Lower San Fernando dam, subjected to 1971 LSFD record at the abutment, as predicted by the EQLFE, (a), and the layer strain history as predicted by LISB, (b).



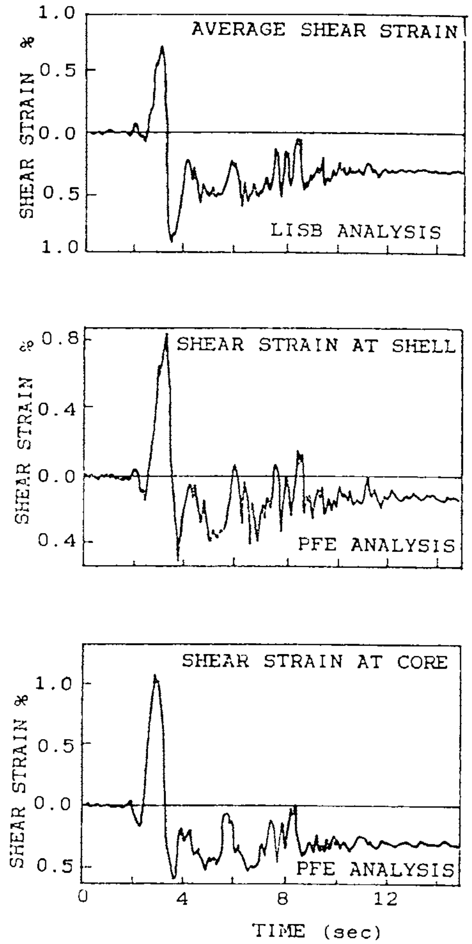
7. Santa Felicia dam finite element discretization used in: (a) LISB analysis, and (b) PFE analysis



8. Crest acceleration time histories of Santa Felicia dam as predicted by LISB and PFE analyses



9. Shear stress time histories: (a) of elements at shell and core at the bottom layer of the Santa Felicia dam subjected to the SFEP record as predicted by PFE and (b) of the bottom layer as predicted by LISB



10. Shear strain time histories: (a) of elements at shell and core at the bottom layer of the Santa Felicia dam subjected to the SFEP record as predicted by PFE and (b) of the bottom layer as predicted by LISB

consists of an impervious core, pervious upstream and downstream shells and is founded on a 75 ft deep alluvium.

Prevost et al (Prevost et al, 1985) performed nonlinear plasticity-based two-and three-dimensional finite analyses (PFE) for an idealized Santa Felicia dam model. The nonlinear hysteretic stress-strain behavior of the dam material was modeled according to the multisurface plasticity theory and use of a purely kinematic hardening rule. The Santa Felicia dam model was subjected to the 1971 San Fernando Earthquake record obtained at the Pacoima dam site (SFEP) with a peak acceleration of 1.2g.

The same idealized dam was analyzed by the authors with LISB method using the same SFEP seismic excitation; efforts have been made to duplicate the material properties used by Prevost et al(1985) as closely as possible.

The dam was discretized in 19 layers, four of which correspond to the foundation soil, as shown in figure 7.a. Figure 7.b depicts the dam discretization used in the PFE analysis. Figure 8 compares the crest acceleration histories computed with the LISB and the PFE methods. Clearly, LISB succeds in reproducing well the peak crest acceleration of 0.90g, as well as the detailed characteristics of the acceleration history obtained with the more sophisticated PFE method. Figures 9 and 10 compare the element shear stress and strain time histories computed with the PFE method in a core and a shell element located at an elevation of one-third of the dam height with the layer (average) shear stress and strain calculated with the LISB method. LISB and PFE are in good overall agreement. LISB predicts a peak value of layer shear strain of 0.95% compared with values of 1.08% and 0.90% for the core and shell elements,respectively, calculated with the PFE. Also, LISB predicts a 3 ksf layer shear stress compared with 5 ksf and 3ksf for the core and shell element, respectively. Moreover, both methods exhibit similar frequency characteristics. In fact, some higher frequency components are preserved only in the LISB's results, which did not filter out the high frequency components in the way that the finite-element study seems to have done due to its much coarser discretization of the embankment.

CONCLUSIONS

Results from "equivalent linear" finite element and LISB analyses of the Lower San Fernando dam reveal that both methods predict about the same values for peak acceleration, shear stress and strain. However, the detailed characteristics are remarkably different, with the prevailing frequencies determined by LISB being much higher and with the LISB response containing a significantly greater number of cycles.

Comparison of results from "plasticity based" finite element and LISB analyses of the Santa Felicia dam lead to the conclusion that both the peak values agree and the frequency characteristics of the calculated time histories are in good accord.

REFERENCES

Dakoulas, P. and Gazetas, G., "Nonlinear response of embankment dams", Proc. 2nd Int. Conf. Soil Dyn. and Earthq. Engr., 1985, Springer-Verland, 5/29-44.

Duncan, J.M. and Chang, C.Y., "Nonlinear analysis of stress and strain in soils", Journal of Soil Mechanics and Foundation Division, ASCE, Vol. 96, No. SM5, Proc. Paper 7513, 1970, 1629-1653.

Duncan, J.M., Wong, K.S. and Ozawa, Y. "FEADAM: A computer program for finite element analysis of dams", Reprt No. UCB/GT/80-02, Dept. of Civil Engrg, Univ. of Calif., Berkeley, 1980.

Gazetas, G. "Shear Vibrations of vertically inhomogeneous earth dams", Int. Journal of Num. and Anal. Methods in Geomech., 1982, 6, 67.

Gazetas, G. "Seismic response of earth dams : Some recent developments", Soil Dynamics and Earthquake Engrg, Vol.6, No. 1,1987.

Idriss,I.M., Lymer, J., Hwang,R. and Seed, H.B. "QUAD-4, a computer program for evaluating the seismic response of soil structures by variable damping finite element procedures", Report No. EERC 7316, Univ. of Calif., Berkeley, 1973.

Massing, G. "Eigenspannungen und Verttestigung beim Messing, Proc. 2nd International Congress on Applied Mechanics, Zurich, 1926, 332-335.

Newmark, N.M., " A method of computation for structural dynamics", Journal of Engineering Mechanics Div., ASCE, Vol. 85, No. EM3, 1959, 67-94.

Prevost, J.M., Abdel-Gaffar, A.M. and Lacy, S.J.,"Nonlinear dynamic analysis of earth dam: A comparative study". Journ. of Geotech. Engrg, ASCE, 1985, 111, 882-897.

Pyke, R. "Nonlinear soil models for irregular cyclic loading", Jour. Geotech. Engr. Div., ASCE, Vol. 105, No.GT6, 1979,715-726.

Seed, H.B., Lee, K.L., and Idriss, I.M. and Makdisi, F.I.,"Analysis of the slides in the San Fernando dams during the earthquake of Feb. 9, 1971", Report No. EERC 73-2, Univ. of Calif., Berkeley, 1973.

Stara-Gazetas, E. "A method for inelastic response analysis of earth dams", Ph.D thesis, Rensselaer Polytechnic Institute, 1986.