Seismic Analysis of Concrete Face Rockfill Dams[a]

Discussion by George Gazetas,[5] M. ASCE

The authors have presented an interesting study on the seismic analysis and performance of rockfill dams, with particular attention to the CFRD. In this writer's opinion, the contributions of the paper include: the development of the "Earthquake Severity Index" for estimating the relative crest settlement (Fig. 1), the discussion on the performance of 14 embankment dams (in California, Latin America, and Japan) during weak and moderately strong seismic ground shaking (Table 1), and the presentation of numerical results illustrating the potential effects of reservoir hydrodynamic pressures and of inelastic tensionless soil behavior on dam accelerations and permanent deformations.

In an attempt to provide a somewhat broader perspective on the subject, this discussion outlines the effects of some other potential factors influencing the seismic performance of CFRDs, presents an overview of some recent theoretical formulations for the nonlinear inelastic response of embankment dams, and points out some possible limitations of the methods and concepts advanced in the paper.

Effect of Narrow Canyon Geometry. The assumption of plane-stain conditions (which forms the basis of the two sophisticated codes used in the paper) is exactly valid only for infinitely long dams subjected to a "synchronous" base excitation (i.e., identical motion of all points along the base). For dams built in narrow valleys, as is often case with rockfill dams, the presence of relatively rigid abutments creates a three-dimensional (3D) stiffening effect, whereby natural periods decrease and near-crest accelerations increase sharply as the canyon becomes narrower.

Theoretical results and full-scale measurements suggest that the significance of such 3D narrow-canyon effects may be far greater than any possible hydrodynamic effects (48–57). Figs. 12 and 13 illustrate the

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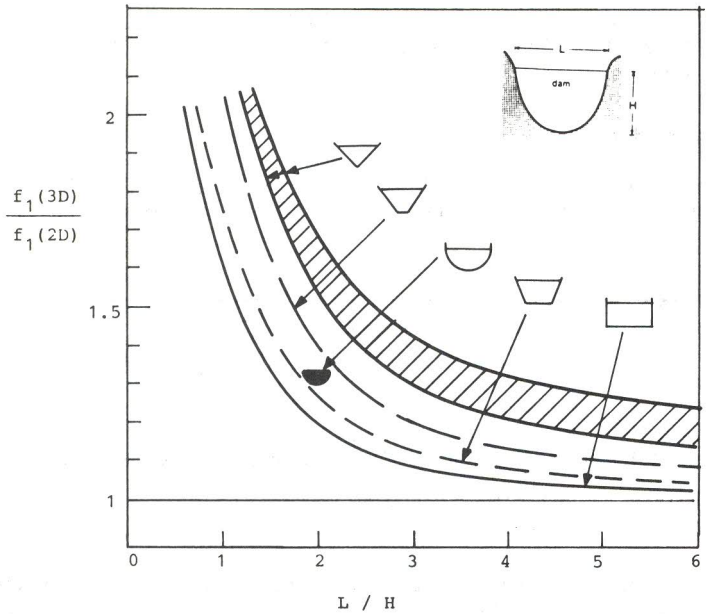

FIG. 12. Effect of Canyon Geometry on Fundamental Natural Frequency of Dam; Scatter, Shown Only for Triangular Canyon, Corresponds to Different Slopes, Methods of Analysis, and Size of Soft Core

importance of canyon geometry on fundamental frequency, steady-state crest amplification function, and acceleration seismic histories.

Evidently, plane solutions may easily underestimate the fundamental frequency by 30–50% for dams in narrow canyons. For example, two of the dams considered in the discussed papers, the Kisenyama (Japan) and El Infiernillo (Mexico) rockfill dams, are built in narrow valleys, the cross-sectional shape of which is between a semicircle ($L/H = 2$) and a triangle with $L/H = 2.50$. One would thus expect f_1 (3D)/f_1 (2D) = 1.40.

It is also evident from Fig. 13 that merely adjusting the shear modulus—so that the 2D model duplicates the fundamental frequency of the 3D dam—would hardly lead to identical (or even similar) seismic responses. Plotted in this figure, as a function of excitation frequency, is the amplitude of crest acceleration for a harmonic unit-amplitude base excitation (traditionally called "amplification" function). The results (from Ref. 49) are for three dams in a rectangular, a semicylindrical, and a triangular canyon, all with aspect ratio $L/H = 2$, as well as for an infinitely long dam responding in plane strain (2D case). It is clear that, in addition to predicting lower natural frequencies, 2D models would underpredict all the amplification resonant peaks and the relative importance of the higher harmonics (i.e., while the second and third resonant peaks of the 3D dams are of about the same amplitude with the first peak, the 2D model predicts a rapidly declining peak for higher resonances).

Methods of Inelastic Response Analysis. The finite/difference code DSAGE presented by the authors models each soil element as elastic-

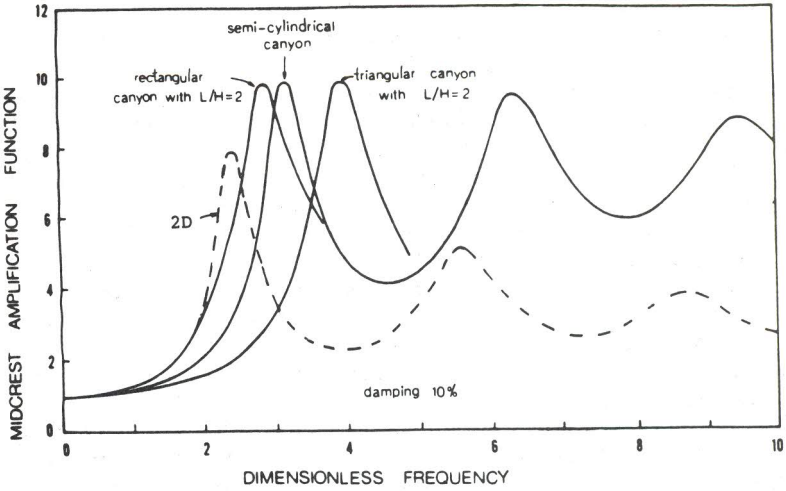

FIG. 13. Effect of Canyon Shape on Midcrest Steady-State Response Acceleration

perfectly plastic tensionless material obeying Coulomb's failure law, with a normal stress-dependent angle of shearing resistance. Some other formulations for inelastic response of embankment dams have also been developed in recent years, with pros and cons compared to the authors' formulation. They include, in order of sophistication:

1. The 2D and 3D finite-element inelastic code developed by Prevost (58) and applied to earth dams by Prevost, et al. (59). The hysteretic cyclic stress-strain behavior of each soil element is modeled rigorously in a very realistic way by using elastoplastic constitutive relations, based on multi-surface kinematic plasticity theory. Any "backbone" curve can be fitted to the soil model; results so far have been published for a hyperbolic curve.
2. The "Nonlinear Hysteretic Galerkin" formulation of Elgamal, Abdel-Ghaffar, and Prevost, an approximate method in which the solution is expanded using, as basis functions, the eigenmodes of the corresponding linear problem. Soil behavior is modeled using the aforementioned multi-surface kinematic plasticity theory with a hyperbolic uniaxial backbone curve.
3. The "layered inelastic shear beam" (LISB) of Stara-Gazetas (60), an approximate method which utilizes the results of a *static* incremental nonlinear finite element analysis, develops shearing stress-strain relations for a number of horizontal layers (superelements) into which the dam is divided. Then, a *dynamic* 1-D analysis is performed with the dam modeled as a layered shear beam with the developed superelement constitutive relations.

Additional reference is made to Gazetas (51) for a review and comparison of the foregoing, as well as some other methods of nonlinear response of embankment dams. It is worthy of note that the hyperbolic monotonic

stress-strain curve used in all these methods is a more realistic approximation for rockfill than the bilinear elastic-perfectly-plastic curve incorporated in the authors' code, DSAGE.

One objection to the Mohr-Coulomb relation used as yield criterion is that the associated flow rule implies very large extensional volumetric plastic strains—much greater than those observed even with very dense soils. However, the authors were careful to ensure that no such (spurious) dilation was allowed to occur. Was this accomplished through a nonassociated flow rule? If yes, what was used as the loading function?

"Earthquake Severity Index" (ESI). There is undoubtedly merit in the authors' observation that permanent crest settlements as a percentage of dam height are solely a function of the product $A(M - 4.5)^3$, where A = peak ground acceleration at the dam site, and M = earthquake magnitude. The writer believes that use of this concept and the developed chart (Table 1) could prove valuable in the preliminary design of CFRDs.

One word of caution: Near-source motions, recorded within a few miles of the causative fault of a strong earthquake, are very sensitive not only to magnitude, but also to unpredictable details of the earthquake source mechanism. For instance, *source directivity*, i.e., the direction of propagation of the fault rupture, often plays a dominant role on the motions recorded near the source.

Conclusion. The authors have presented an interesting study which complements recent work that has been overviewed in this discussion.

Appendix. References

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