

# SEISMIC DEFORMATION ANALYSIS OF AN EARTH DAM - A COMPARISON STUDY BETWEEN EQUIVALENT-LINEAR AND NONLINEAR EFFECTIVE-STRESS APPROACHES

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## SUMMARY

Equivalent-linear analysis of earth dams with QUAD4 is a state-of-practice approach which incorporates a cumulative level of knowledge in soil dynamics that is still used today in many organizations. Nevertheless, today's availability of more advanced nonlinear effective-stress analysis tools has improved significantly our estimates of shaking-induced permanent deformations of earth structures. In order to better understand the difference between, and facilitate a direct comparison of, the two different analysis methods, we analyzed an earth dam using both the equivalent-linear and the nonlinear effective-stress approach with the commercial finite difference code FLAC by focusing on computed shaking-induced cyclic shear stresses and permanent deformations.

## **INTRODUCTION**

We used FLAC to perform both equivalent-linear analysis and nonlinear effective-stress analysis for Stone Canyon Dam located in Los Angeles, California. The main objective of using FLAC for both types of analysis was to demonstrate that the difference between equivalent-linear and nonlinear, effective-stress analysis lies not in the different programs (i.e. QUAD4 vs. FLAC), per se, but in the soil constitutive models utilized. To this end, we reanalyzed the dam with the same equivalent-linear soil model with FLAC, which was analyzed using QUAD4. The histories of cyclic shear stresses at different locations of the dam computed with FLAC using the equivalent-linear soil model were found to be very similar to those computed using QUAD4.

The shear-stress histories at the above locations were further computed utilizing the nonlinear, effectivestress approach.

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In contrast to the rather uniform-amplitude, low-frequency cycles of the equivalent-linear runs, the nonlinear, effective-stress generated cycles start out with higher frequencies and amplitudes, both decreasing as shaking continues. This behavior reflects the gradual decrease of soil stiffness and shear strength due to buildup of excess pore-pressure, an important mechanism which significantly affects the dynamic response. Because the equivalent-linear analysis uses averaged linear-elastic properties (i.e. secant modulus), the computed dynamic response tends to be too soft in the beginning and too stiff towards the end of shaking.

## EQUVALENT-LINEAR ANALYSIS

## Stone Canyon Dam Geometry and Model Makeup

Stone Canyon dam, owned and operated by the Los Angeles Department of Water and Power (LADWP), is located on the south slope of the Santa Monica Mountains in Los Angeles, California. The original dam was built in 1924 as a hydraulic fill embankment with a maximum height of about 200 feet above bedrock. In 1956 the dam was partially reconstructed and raised as a rolled earth fill with a maximum height of 160 feet. With a crest elevation of 874 feet above mean sea level, the dam impounds 10,372 acre-feet of water with a design reservoir level at Elevation 865 feet. The downstream portion of the dam straddles a narrow canyon filled with alluvium susceptible to liquefaction under strong earthquake shaking.

The dam was analyzed in 1977 by LADWP [1] with the equivalent-linear finite element program QUAD4 [2]. For comparison, we used the same geometry and material properties for the FLAC analysis. Figure 1 shows the QUAD4 and corresponding FLAC model meshes, the material properties are summarized in Table 1. Strain-compatible shear modulus and damping for embankment and alluvium are plotted in Figure 2. The input ground motion developed in 1977 for local maximum credible earthquake (MCE) is plotted in Figure 3.

			Effective		Shear Modulus
Material	Description	Unit	Friction	Cohesion	
No.		Weight	Angle ø'	c'	
		(pcf)	(Deg.)	(psf)	(psf)
	Unsaturated 1956				0.400
1	embankment	138.8	35.7	204	1056*P <sub>a</sub> *(ơ' <sub>m</sub> /P <sub>a</sub> ) <sup>0.493</sup>
	Saturated 1956				0.400
2	embankment	141.8	35.7	204	1056*P <sub>a</sub> *(ơ' <sub>m</sub> /P <sub>a</sub> ) <sup>0.493</sup>
	Unsaturated 1924				
3	embankment	138.8	35.7	204	580* $P_a^*(\sigma'_m/P_a)^{0.71}$
4	Unsaturated alluvium	118.7	33.1	266	$580^{*}P_{a}^{*}(\sigma'_{m}/P_{a})^{0.71}$
5	Saturated alluvium	131.9	33.1	266	$580^{*}P_{a}^{*}(\sigma'_{m}/P_{a})^{0.71}$
Notes:	$\sigma'_{\rm m} = (\sigma'_{1\rm c}+\sigma'_{3\rm c})(1+\upsilon)/3$			$\sigma'_{1c}$ = Major effective principal stress	
	$\sigma'_{3c}$ = Minor effective principal stress			$P_a$ = Atmospheric pressure (=2116 psf)	

Table 1 Stone Canyon Dam Material Properties



Figure 1 LADWP Finite Element QUAD4 Model and the Reproduced Model with FLAC



Figure 2 Shear Strain Compatible Shear Modulus and Damping Ratio



Figure 3 Input 1977 Local MCE Ground Motion [1]

#### **Equivalent-Linear Reanalysis with FLAC**

LADWP performed a QUAD4 analysis in 1977 to evaluate seismic deformation of the dam. Due to QUAD4's elasticity-based formulation, shaking-induced permanent deformations could not be computed directly, but were evaluated by post-processing the total-stress-oriented QUAD4 results. First, "strain potentials" were obtained for each element of the model by relating computed shear-stress cycles to accumulated shear strains based on cyclic-triaxial test data. Shaking-induced permanent deformations were then derived by "making compatible" these strain potentials with the continuum of the embankment model. This was achieved by performing a gravity-turn-on analysis with hypothetically reduced shear moduli derived from the strain potentials [3]. The computed seismic crest settlement using this method was less than 1 foot.

In comparing the results of these analyses we focused on computed shaking-induced cyclic shear stresses and permanent deformations. In Figure 1, the marked locations A, B, C and D indicate those elements for which QUAD4-computed shear-stress histories were presented in the 1977 LADWP report. These stress histories were compared with the results from the same equivalent-linear soil model in the new analysis with FLAC. The objective of using FLAC, in lieu of QUAD4, WAS to demonstrate that the difference between equivalent-linear and nonlinear, effective-stress analyses, lies not in the different programs (i.e. QUAD4 vs. FLAC), per se, but in the soil constitutive models utilized.

As presented in Figures 4 through 7, the top three history plots depict the input motion, QUAD4computed shear stresses, and shear stresses obtained with the equivalent-linear FLAC analysis, respectively, at the four locations marked in Figure 1. With the exception of Location A in the upstream portion of the 1956 embankment, the shear-stress histories computed with the two programs are nearly identical. The existing minor deviations could reflect slight differences in the input-motion histories, since the FLAC input motion was digitized from a hard-copy plot in the 1977 LADWP report. Also, the FLAC model mesh is somewhat finer than the QUAD4 mesh used in 1977.

## NON-LINEAR EFFECTIVE-STRESS ANALYSIS

## **Analysis Approach**

We used a Mohr-Coulomb (linear elastic/perfectly plastic) soil model coupled with a practice-oriented pore-pressure generation model [4] which was implemented using the programming language FISH that is embedded within FLAC. Pore pressures are generated in response to shear stress cycles, as illustrated schematically in Figure 8, which follow the cyclic-stress approach developed by Seed and coworkers [5][6]. However, unlike the standard approach where liquefaction potential is assessed as a post-processing step to equivalent-linear analysis, pore-pressure generation in FLAC is incremental and fully integrated with the nonlinear dynamic analysis. As effective stresses decrease with increasing pore water pressure, the soil begins to yield and increments of permanent deformation are accumulated during shaking. The simultaneous coupling of pore-pressure generation with nonlinear, plasticity based, stress analysis produces a more realistic dynamic response than can be achieved with equivalent-linear method. Specifically, the plastic strains generated as a result of increased pore pressures significantly contribute to the internal damping of the modeled earth structure.

The analysis approach described above has been verified by analyzing well documented seismicperformance case histories of dams [7][8], as well as performing validation analyses of centrifuge shaking tests as part of the NSF-sponsored VELACS program [9][10]. It has been utilized in practice for various earth fill dams [11] and for dynamic soil-structure interaction analyses of pile-supported wharf structures [12][13].









Figure 4 Location A – Shear-Stress Histories - QUAD4 vs. FLAC









Figure 5 Location B – Shear-Stress Histories - QUAD4 vs. FLAC









Figure 6 Location C – Shear-Stress Histories - QUAD4 vs. FLAC









Figure 7 Location D – Shear-Stress Histories - QUAD4 vs. FLAC

#### **Cyclic-Strength Parameters**

The pore-pressure generation scheme utilized in the nonlinear effective-stress analysis requires as input a cyclicstrength curve, a relation between the cyclic-stress ratio and the number of cycles required to reach liquefaction. The cyclic triaxial test data reported by LADWP [1] were obtained with remolded samples of blended material from both the alluvium and embankment. These data are believed to be reasonably representative of the embankment material. For the alluvium, however, the cyclic strength used in this study was derived from SPT data collected in the 2000 and 2001 field explorations [14].

The SPT-based cyclic-strength curves are shown in Figure 9. The dashed line represents the cyclic-strength curve for the alluvium derived from the corrected SPT blow counts for clean sand  $(N_1)_{60cs}$  using the empirical relationships by Youd and Idriss [15]. For our analysis, this curve was approximated by a best-fit straight-line shown as a solid line. The cyclic-strength curve for the embankment was obtained from triaxial test data for a confining pressure of 2,045 psf. Curves for higher confining pressures were obtained using correction factors,  $K_{\sigma}$ , proposed by Youd and Idriss [15]. The effect of pre-shaking static shear stress ( $K_{\alpha}$  correction) was ignored [9].

A post-liquefaction residual strength of 800 psf was derived for the saturated embankment and the alluvium residual strength was derived from SPT blow counts using a relationship after Seed and Harder [16].

#### **Damping Ratio**

Damping in soils is primarily hysteretic, since energy

dissipation occurs when grains slide over one another. In the Mohr-Coulomb law utilized herein, energy is dissipated by shaking-induced plastic flow when shear stresses reach the yield strength. For smaller stress cycles remaining in the elastic range, energy dissipation is achieved by viscous damping. Raleigh damping is adopted in FLAC by means of two viscous elements. For one element, damping increases linearly with frequency (stiffness damping as a function of strain rate); for the other, damping decreases exponentially with increasing frequency (mass damping as a function of particle velocity). By choosing a center frequency,





Figure 8 Pore Pressure Generation Scheme (after Dawson et al.)



Figure 9 Cyclic-Strength Curves for Embankment and Alluvium

at which the combined gradients of the two curves balance out, it is possible to have damping that is nearly independent of frequency over a fairly wide spectrum on either side of the center frequency. The center frequency is usually chosen in the range between the natural frequency of the model and the predominant frequency of the input motion. Elastic-range damping ratios were assigned for each element of the dam model based on expected elastic shear-strain amplitudes for a given earthquake. Magnitudes of these strain amplitudes were estimated by performing a linear-elastic analysis run before the actual nonlinear, effective-stress analysis. Damping ratios were then derived for uniform (i.e. 65% of peak) strain levels based on the relationships plotted in Figure 2. The damping ratios obtained with this procedure ranged from 2% to 9% for the dam model.

Shear moduli and other material properties are as listed in Table 1.

#### **Analysis Results**

Shear-stress histories computed with FLAC utilizing the nonlinear, effective-stress approach, are plotted at the bottom of Figures 4 through 7. In contrast to the rather uniform-amplitude, low-frequency cycles of the equivalent-linear runs, the nonlinear, effective-stress generated cycles start out with higher frequencies and amplitudes, both decreasing as shaking continues. This behavior reflects the gradual decrease of soil stiffness and shear strength due to the buildup of excess pore-pressure, an important mechanism which significantly affects the dynamic response of the embankment. Because the equivalent-linear analysis uses averaged linear-elastic properties (i.e. secant modulus), the computed dynamic response tends to be too soft in the beginning and too stiff towards the end of shaking.

The stiff response of the equivalent-linear approach at the end of shaking tends to compensate for its soft initial response, such that total accumulated pore pressures at the end of shaking may not differ too much from those obtained with nonlinear, effective-stress models. When it comes to estimating permanent shaking-induced deformations, however, the difference between these two approaches is much more significant. As shown in Figure 10, the settlement of the dam crest computed with the nonlinear, effective-stress analysis is about 6 feet. This compares with less than 1 foot of settlement derived in 1977 from QUAD4-generated strain potentials! Considering the fact that these analyses were performed using the same cross section and material properties of the dam, as well as the same boundary conditions and input motion, this difference in results is quite dramatic. Also shown in Figure 10 are the input motion history, computed displacement vectors and excess pore pressure ratios.

The most likely explanation for the discrepancy in computed crest settlement is the fact that the strainpotential post-processing procedure [3], which was utilized in the 1977 study, merely addresses gravitydriven slumping of the embankment as a result of soil softening due to cyclic loading. This approach ignores the inertial driving forces during shaking, which can accumulate large permanent deformations with a down-slope bias. In contrast, the plasticity-based, effective-stress approach not only takes into account these important driving forces, but also produces more realistic pore-pressure histories and associated dynamic response of the embankment.



Figure 10 Nonlinear Effective-Stress Analysis Results of Stone Canyon Dam

#### **CONCLUDING REMARKS**

This paper presents a comparison study of seismic deformation analysis of an earth dam using equivalent linear and nonlinear effective-stress approaches. The computed shaking-induced cyclic stresses and permanent deformations were compared. The stiff response of the equivalent-linear approach at the end of shaking tends to compensate for its soft initial response, such that total accumulated pore pressures at the end of shaking may not differ too much from those obtained with nonlinear, effective-stress models. When it comes to estimating permanent shaking-induced deformations, however, the difference between these two approaches is much more significant.

The 2-D analysis of Stone Canyon Dam described in this paper was merely used as an example to demonstrate the difference of seismic deformation analysis between equivalent-linear and nonlinear effective-stress approaches. For a more realistic evaluation of the seismic performance of this dam it was reanalyzed using a 3-D FLAC model to take into account the arching across the narrow alluvium canyon beneath the base of the dam; and the buttressing effect due to the turning of the alluvium canyon at the downstream toe of the dam [17]. This 3-D analysis, resulted in a maximum shaking-induced crest settlement of about 1 foot.

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