International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics

1995 - Third International Conference on Recent Advances in Geotechnical Earthquake Engineering & Soil Dynamics

06 Apr 1995, 1:30 pm - 3:00 pm

Seismic Stability Analysis of a High Earth and Rockfill Dam

N. Deng
Bechtel Corporation, San Francisco, California

F. Ostadan
Bechtel Corporation, San Francisco, California

I. Arango
Bechtel Corporation, San Francisco, California

J. Marrone
Bechtel Corporation, San Francisco, California

Proceedings: Third International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics,
April 2–7, 1995, Volume I, St. Louis, Missouri

Seismic Stability Analysis of a High Earth and Rockfill Dam

Paper No. 6.18

N. Deng, F. Ostadan, I. Arango, and J. Marrone
Bechtel Corporation, San Francisco, California

SYNOPSIS Accumulation of knowledge on earthquake activity in California has lead to stronger ground motions being postulated for the evaluation of the seismic stability of dams. A recent regional seismicity study for a 555 ft high earth and rockfill dam in central California lead to a ground motion with peak ground acceleration (PGA) of 0.50g originating in a local fault system 3 miles from the dam site. This PGA is more than 6 times higher than the PGA=0.08g value originally adopted when the Dam was analyzed for seismic stability 20 years ago. Thus, as part of FERC Part 12 evaluation requirements, the seismic stability of the Dam was re-evaluated using the updated ground motion and state-of-the-practice technology. This paper presents the analysis procedures and the results.

INTRODUCTION

The Dam analyzed in this paper was constructed in 1960's. The zoned earth and rockfill embankment has an impervious central core, and earth and rockfill shells. The dam rests directly on rock. It rises about 555 ft above the original streambed and 585 ft above its deepest foundation. Total volume of the fill material is approximately 16,750,000 cubic yards. The maximum cross section is shown in Fig. 1.

A comprehensive seismic stability study of the Dam was performed in 1969. In that study, hyperbolic non-linear soil properties, strain-dependent dynamic shear modulus of soil materials, and the finite element method, were adopted. A recorded time history scaled to peak ground acceleration (PGA) of 0.08g was used for seismic performance study of the dam.

Accumulation of recorded earthquake motions in California for the last 25 years has lead to a better understanding of the regional seismicity. As a result, stronger ground motions have been postulated for the region in the seismic safety analysis of dams. A recent seismicity study of the Dam region, as required by the FERC Part 12 study, resulted in a design ground motion with PGA = 0.5g originating from a Magnitude 6.5 earthquake at a local fault system 3 miles from the dam site. Therefore, the seismic stability of the Dam was re-evaluated using the new ground motion and the current state-of-practice methodology and knowledge of the material properties.

METHODOLOGY

The methodology adopted in the current analysis followed, in general, the procedure summarized in Marcuson et al., (1990) and Seed and Harder (1990). It consists of the following major steps: (1) Determination of the design ground spectrum and generation of a spectrum-compatible time history for dynamic response analysis; (2) Determination of the material property parameters for both static and dynamic analyses considering their variation and uncertainty; (3) Computation of the static effective stresses existing in the embankment; (4) Computation of the dynamic response of the embankment to the input seismic excitations; (5) Determination of the generation and dissipation of pore water pressures in the embankment due to seismic shaking; and (6)

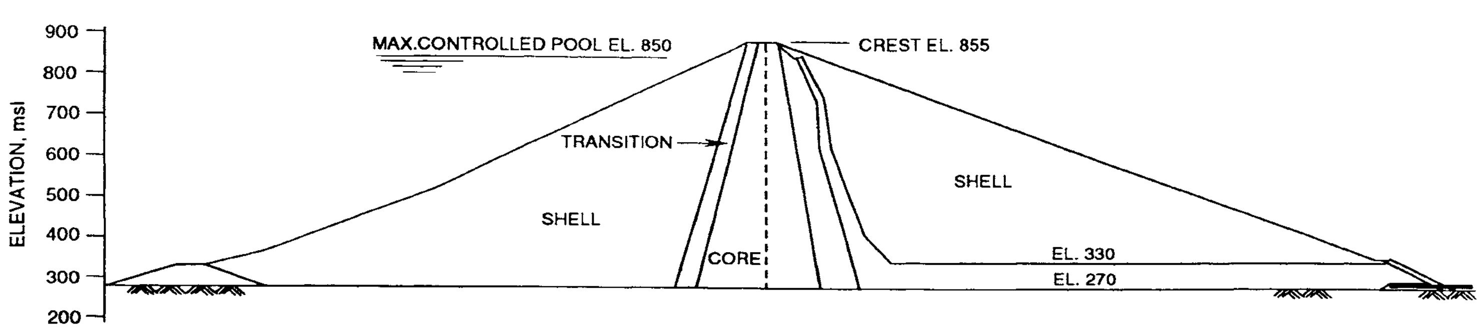

Fig. 1. Maximum Cross Section of the Dam

Evaluation of the slope stability and determination of the possible permanent deformation of the dam crest and slopes.

The static stress analysis was performed using the program FEADAM84 (Duncan et al, 1984) in which the behavior of soil materials is simulated by a hyperbolic non-linear elastic model. The dynamic analysis was performed using the program FLUSH (Lysmer et al., 1975) in which the dynamic soil behavior is simulated by the equivalent linear method with strain-dependent shear modulus and damping properties.

MATERIAL PROPERTIES

The central core material is a silty to clayey sand compacted to ≥98% relative compaction at ±2% of optimum moisture content. The transition zones and the shell regions are composed of gravel and cobbles up to 12 inches in diameter from gold dredge tailings. The shells were compacted to 100% relative compaction.

The hyperbolic stress-strain parameters required to model each material for the static stress analyses were selected based on the construction records and the available laboratory test results. To account for possible variations and uncertainty, upper and lower bound values were established as shown on Table 1.

The properties required for dynamic analyses include the low-strain shear modulus G_{max}, and its dependency with strain amplitude γ, and the damping ratio β. For the core material, G_{max} was obtained from the relationship $750 \leq G_{max}/S_u \leq 1400$ (Egan and Ebeling 1985), where the undrained shear strength S_u = 4.5 ksf was determined from the laboratory tests. The G-γ curve for a Plasticity Index PI = 10 was selected based on laboratory test results. For the shell material, the shear modulus was determined from $G_{max} = 1000.K_2.(\sigma'_m)^{1/2}$ (Seed et al., 1984) where σ'_m is the mean effective stress in psf and is obtained from static stress analysis, and the K_2 is a parameter depending on the relative density and particle size of the material. Since the shells were compacted to 100% relative compaction, an equivalent relative density of Dr = 90% was conservatively assumed for the material. A K_2 value ranging from 130 to 200 for the shell material was considered in the dynamic response analysis.

FINITE ELEMENT ANALYSES

Two plane strain finite element models were prepared for the full-height and mid-height sections of the Dam. These models were used in both the static stress and dynamic response analyses. The model for the full-height cross section consists of 1016 elements and 1050 nodes and has a height of 555 ft and a baseline length of 2465 ft. The model for mid-height section was similar in geometry to the full-height model from the crest elevation of 855 ft to elevation 576.5 ft. This paper will discuss only the analysis results from the full-height cross-section model.

TABLE 1 - Static Material Properties

	Symbol	Shell Material		Core Material	
		L.B.	U.B.	L.B.	U.B.
Friction Angle	ϕ	40	40	30	30
Cohesion	C	0	0	0	0
Modulus Coefficient	K	780	1300	350	700
Modulus Exponent	n	0.20	0.40	0.40	0.80
Unload-Reload Modulus	K_{ur}	780	1300	350	700
Failure Ratio	R_f	0.70	0.80	0.60	0.80
Bulk Modulus	K_b	500	1300	100	300
Bulk Modulus Exponent	m	0.15	0.22	0.40	0.80
Total Unit Weight	γ_{total}	135 (pcf)	135	137	137
Buoyant Unit Weight	γ_b	84 (pcf)	84	75	75

In the static stress analysis, the construction of the dam was simulated incrementally from the baseline to the crest, one layer at a time, and the stress distributions in lower portions were recalculated each time a new soil layer was placed on the top. After this step, the hydrostatic pressure was applied incrementally on the upstream slope of the central impervious core until the water level reached the normal operational maximum level. Both the upper and lower bound material properties were used in the analysis. The results in terms of contours of α-values, i.e., the ratio between shear stress and the vertical effective stress, corresponding to the upper bound material properties case are shown in Fig. 2.

For the dynamic responses, and to account for uncertainties in material properties, several cases were analyzed using appropriate combinations of static and dynamic soil properties. Maximum horizontal acceleration results corresponding to the upper-bound static soil parameters and upper-bound dynamic soil parameters case are shown in Fig. 3. The results showed a significant amplification of the ground motion with a maximum crest horizontal acceleration of 1.37g.

PORE WATER PRESSURE GENERATION

The dynamic response analysis revealed that significant amplification of the postulated ground motion would occur in the Dam. Consequently, high level of dynamic shear stresses would have to be expected to develop in the embankment, raising the question of possible significant pore water pressure generation in the upstream shell. However, based on the laboratory test results and construction records, it was found that the shells and transition zones were compacted to at least 90% relative density. Granular materials at this relative density would behave dilatively under shear stresses. Consequently, the pore water pressure generated in the embankment, if any, would be negligible. (Seed et al., 1985, Marcuson et al., 1990).

STABILITY AND DEFORMATION ANALYSES

Slope stability analyses were performed on both the maximum and mid-height sections of the Dam assuming both circular and wedge slip surfaces. Minimum factors of safety of 2.0 and 2.1 were

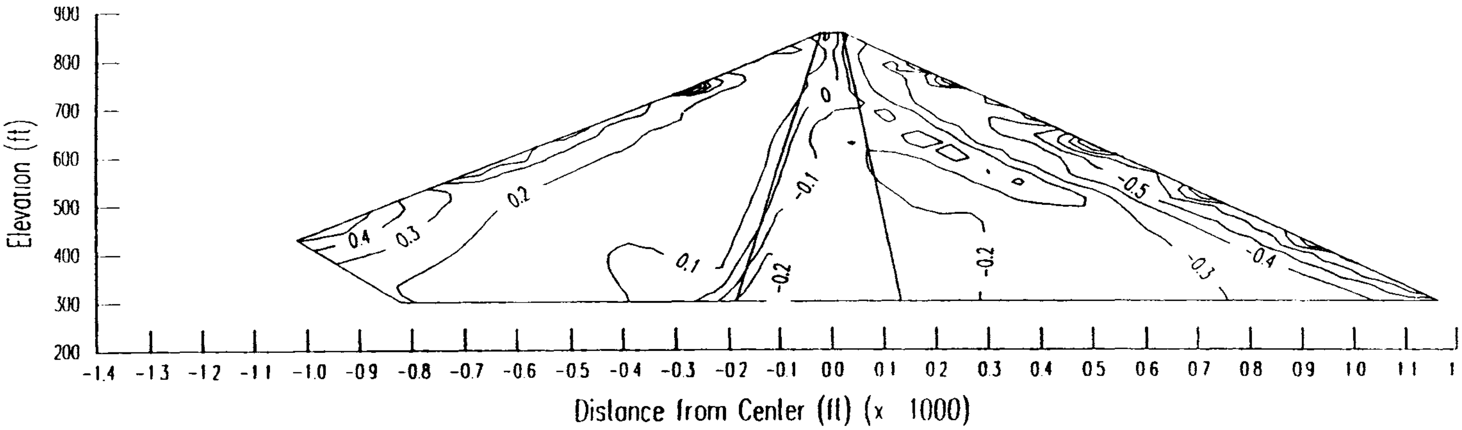

Fig. 2. Contours of α-Values - Upper Bound Material Property Case

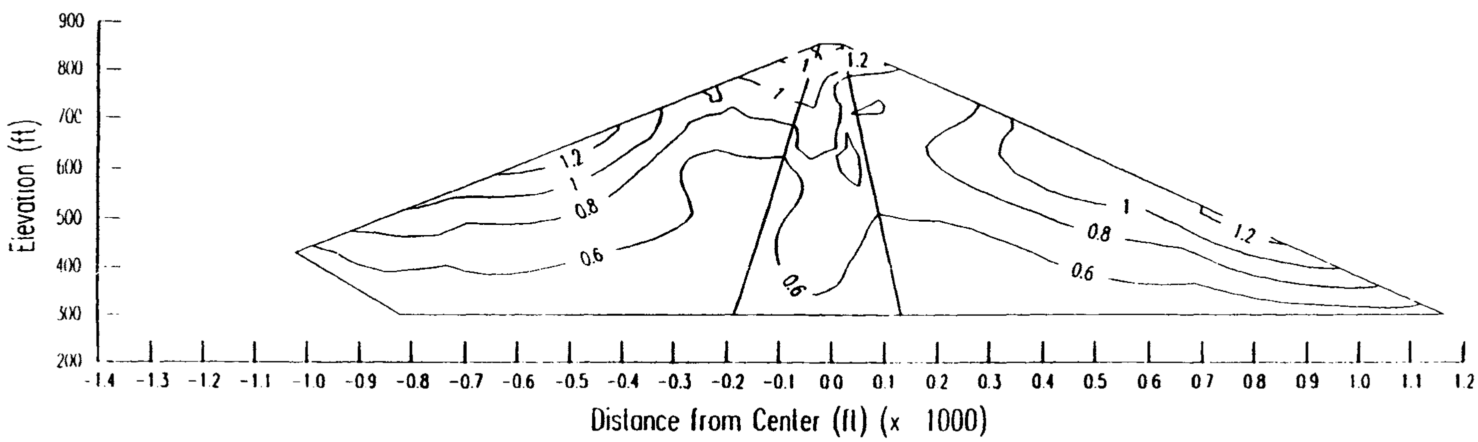

Fig. 3. Contours of Maximum Horozontal Acceleration in g - Upper Bound Material Property Case

obtained for the upstream and downstream slopes, respectively. Pseudo-static analyses resulted in the yield acceleration of 0.36g and 0.38g for the upstream and downstream slopes, respectively. The permanent deformations for the potential slip surfaces were evaluated using the procedures developed by Makdisi and Seed (1978). In addition, the maximum crest settlements of the Dam were evaluated using the empirical relationship developed by Bureau et al., (1985). Under the worst possible combination of the conditions, the Makdisi-Seed approach gave a permanent crest deformation ranging from 6 to 50 cm (0.2 - 1.6 ft). Bureau et al.'s relationship gave a crest settlement range of 6 - 82 cm (0.2 - 2.7 ft). Considering the height of the Dam (555 ft) and the minimum height of the free-board for the maximum water surface (25 ft), the computed deformations were judged to be small and tolerable.

A summary of observed seismic performance of other high earth and rockfill dams in terms of crest deformations is presented on Table 2. It is clear from the summary that the theoretically computed values (6 - 82 cm) for the dam are comparable to those observed.

TABLE 2 - Measured Crest Movement of Rockfill Dams Due to Earthquake Shaking

Dam	Height (ft)	Downstream Slope	Earthquake Magnitude	Peak Ground Acceleration (g)	Crest Movement (cm)	
					Vertical	Horizontal
Cogoti (Chile)	275	1 on 1.8	8.3	0.20	38	—
Miboro (Japan)	430	1 on 1.75	7.0	0.20	3	5
Minese (Japan)	220	1 on 2.0	7.5	0.08	6	4
Oroville (California)	770	1 on 2.0	5.7	0.10	0.9	—
El Infiernillo (Mexico)	485	1 on 1.75	7.6	0.12	13.5	4.5
El Infiernillo (Mexico)	485	1 on 1.75	6.5	0.05	3.5	—
El Infiernillo (Mexico)	485	1 on 1.75	7.2	0.12	6.5	—
El Infiernillo (Mexico)	485	1 on 1.75	8.1	0.20	5.0	—
La Villita (Mexico)	197	1 on 2.5	7.6	0.10	4.5	3.0
La Villita (Mexico)	197	1 on 2.5	6.5	0.08	2.5	—
La Villita (Mexico)	197	1 on 2.5	7.2	0.13	14.4	—
La Villita (Mexico)	197	1 on 2.5	8.1	0.25	30.0	15.0
Leroy Anderson (California)	235	1 on 2.0	6.2	0.41	1.5	0.9

(Adopted from Ref. 1 and Ref. 2)

SUMMARY AND CONCLUSIONS

A study of the seismic stability of an existing high earth and rockfill dam is presented in this paper which used state-of-practice methodology. Material properties were determined based on construction records and laboratory test results. Finite element techniques were used in the static stress and dynamic response analyses. The stability of the slope was studied by the conventional limit equilibrium approaches and the permanent deformation to seismic motions evaluated by approaches based on both numerical calculation and field observation. Analysis results were compared with the observed performance of dams of similar type. It was concluded from the study that the dam will be capable of resisting the postulated PGA=0.5g earthquake motion without incurring unacceptable deformation.

REFERENCES

Bureau, G., R. L. Volpe, W. H. Roth and T. Udaka (1985), "Seismic Analysis of Concrete Face Rockfill Dams", Proceedings of the Symposium on Concrete Face Rockfill Dams, Annual Convention, ASCE, Detroit.

Centro Editorial de la Commission Federal de Electricidad, "Performance of El InFiernillo and La Villita Dams Including the Earthquake of March 14, 1979", Rodano No. 14, Mexico, S.D.F., Mexico.

Duncan, J. M., R. B. Seed, K. S. Wong and X. Ozawa (1984), "FEADAM84 - A Computer Program for Finite Element Analysis of Dams", Report No. SU/GT/84-03, Department of Civil Engineering, Stanford University, November.

Egan, J. A. and R. M. Ebeling (1985), "Variation of Small-Strain Shear Modulus with Undrained Shear Strength of Clays", Proceedings, 2nd International Conference on Soil Mechanics and Earthquake Engineering on board of the liner Queen Elizabeth 2, June.

Lysmer, J., T. Udaka, C.-F. Tsai and H. B. Seed (1975), "FLUSH - A Computer Program for Approximate 3-D Analysis of Soil Structure Interaction Problems", Report No. EERC-75/30, University of California at Berkeley, November.

Makdisi, F. I. and H. B. Seed (1978), "Simplified Procedure for Estimating Dam and Embankment Earthquake-Induced Deformations", Journal of Geotechnical Engineering Division, ASCE, Vol. 104, No. GT7.

Marcuson, W. F., M. E. Hynes and A. G. Franklin (1990), "Evaluation and Use of Residual Strength in Seismic Safety Analysis of Embankments", Earthquake Spectra, Vol.6, No.3.

Seed, H. B., K. Tokimatsu, L. F. Harder and R. M. Chung (1985), "Influence of SPT Procedures in Soil Liquefaction Resistance Evaluations", Journal of Geotechnical Engineering, Vol. 111, No. 12, December.

Seed, H. B., R. T. Wong, I. M. Idriss and K. Tokimatsu (1984), "Moduli and Damping Factors for Dynamic Analysis of Cohesionless Soils", Report No. UCB/EERC-84/14, September.

Seed, R. B. and L. F. Harder (1990), "SPT-Based Analysis of Cyclic Pore Pressure Generation and Undrained Residual Strength", Proceedings, H. B. Seed Memorial Symposium, Vol. 2. May.