SEISMICALLY INDUCED DEFORMATIONS IN EARTHDAMS

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SUMMARY

A method is presented for calculating the permanent deformations induced in an earth dam structure, embankment or cut slope due to earthquake loading. The method involves the concept that seismic deformation of a dam is due to softening of the soil by seismic shaking and the resultant settling of the dam to a new condition compatible with the changed stress-strain properties of the embankment soils. The method is illustrated by analyzing two different dams which have undergone permanent deformations by previous earthquakes.

INTRODUCTION

In seismically active areas, numerous cases are reported in which failure or severe damage to earth dams and embankments have resulted from earthquake ground shaking (Ref. 1, 2). For this reason, earth dam structures in seismically active areas require an evaluation of the degree of stability or potential instability which the embankment will experience during an earthquake.

. The degree of stability of an embankment is normally evaluated by employing a factor of safety based on the principal of limiting equilibrium, in which the strength available is compared with the applied stress. Two distinct procedures have developed which both utilize finite element calculations in which the dam structure is modeled as a series of individual elements. The first method (Ref. 3) uses a calculated seismic factor of safety for each element. The second method (Ref. 4) is based on an evaluation of the potential strain experienced by each element.

While the above two methods of seismic stability evaluation are useful indicators of the overall stability, unless the elements all show very low or very high factors of safety, the methods do not provide an estimate of whether the dam will deform a large or a small amount as a result of an earthquake. The methods only present information on the "potential" for an isolated element to deform, if subject to cyclic loads equivalent to those acting on individual elements in the dam.

Lee (Ref. 5) and later Serff (Ref. 7) have developed more rigorous methods of estimating the permanent deformations experienced by saturated earth structures during a seismic loading. Both methods follow the basic Seed approach for calculating the factor of safety and strain potential for individual elements (Refs. 3 and 4). Differences between the two methods depend on procedures used to calculate deformations from the strain potential values. Chaney (Refs. 7 and 8) later extended the work of Lee (Ref. 5) to

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include the effect of non-saturated zones.

PERMANENT DEFORMATION ANALYSIS

The permanent deformation method involves the use of finite elements, to model the embankment configuration under study. Each element in the embankment has a shearing stiffness and volume compressibility defined by an appropriate secant modulus which are changed as a result of the seismic disturbance. Values of the apparent changes in soil shearing stiffness and volume compressibility are evaluated from the results of cyclic triaxial (CTX) tests on laboratory samples of soil. The permanent deformations at the grid nodal points resulting from the earthquake are calculated on the basis of the effect the gravity loading has on a soil whose apparent shearing stiffness and volume compressibility has decreased due to the earthquake.

Using the apparent element stiffnesses and volume compressibilities defined in terms of E_{ip} and B_{TOT} (Figs. 1 and 2 respectively) along with the static gravity loads in a gravity-turn-on analysis will lead to total displacement at each nodal point (U_T) from the beginning of construction to the end of the earthquake. Finally by subtracting the calculated initial displacements (U_i) from the total displacements, the net nodal point displacements (U_p) due only to the earthquake are obtained:

$$U_p = U_T - U_i \qquad (1)$$

CASE STUDIES

Over the years, a number of earth dams have undergone earthquake loading and experienced the resulting permanent deformations. To illustrate the deformation method described above, analyses were made of the following two dams: (1) Hebgen Dam, and (2) Lower Van Norman Bu-Pass Reservoir Dam. Each of these dams have been studied previously and the results reported in the literature. Space here permits only a brief description. The soil data used for these studies was either developed from CTX tests on soil from the dams studied or the parameters were estimated from the trends indicated by the available laboratory data. Parameters developed in this manner for each of the case studies are presented in (Ref. 7). The significant results of the studies on the two dams are summarized on Table 1 and presented graphically in Figs. 3 and 4.

SUMMARY AND CONCLUSIONS

A method has been presented for calculating the permanent deformations induced in an earth dam structure due to an earthquake. The method involves the concept that seismic deformation of a dam is due to a softened pseudo stiffness of the soil by seismic shaking and the resultant settling of the dam to a new condition compatible with the changed stress-strain properties of the embankment soils. The method has been used to calculate the deformations of one older dam (constructed prior to 1935). The two dams studied had both experienced various known amounts of deformations during earthquakes in the past. Results obtained showed reasonable agreement with both the magnitude and direction of observed movement.

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DAM	TYPE	HEIGHT (ft.)	EARTHQUAKE	MAG.	HORIZ. a_{max} (g)	CREST DEFORMATION- ft. OBSERVED (CALCULATED-2D)		REMARKS
						VERTICAL	HORIZONTAL	
Hebgen Lake Sta. 5+00	Loose soil and rock fill	87	Montana 1959	7.1	0.4	2.8D (2.01D)	0.8DS (0.61US)	Crest settled by core wall, core wall deformed horizontally in S shape, a_{max} middle of range
Lower Van Norman By-Pass Reservoir	Rolled earth fill, homogeneous dam	63	San Fernando 1971	6.6	0.60	0.42D (0.44D)	---- (0.24DS)	a_{max} upper limit of range

Note: D - Vertically down DS - Horizontally downstream US - Horizontally upstream

TABLE 1 - SUMMARY OF PERMANENT DEFORMATIONS AND OBSERVATIONS

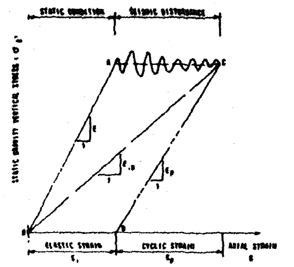


FIGURE 1 DETERMINATION OF EARTHQUAKE SOFTENED YOUNG'S MODULUS

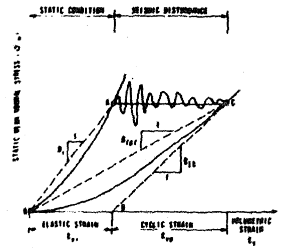
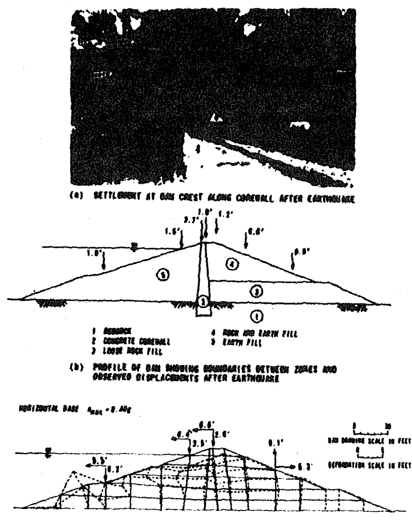


FIGURE 2 DETERMINATION OF EARTHQUAKE SOFTENED BULK MODULUS

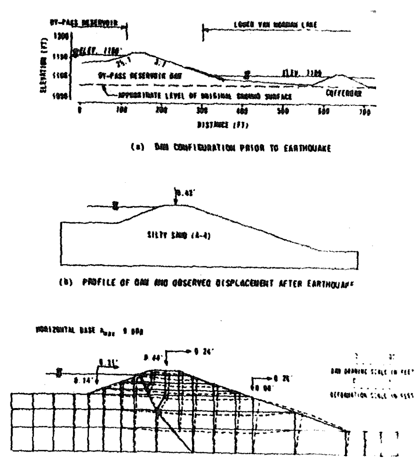


(a) SETTLEMENT AT DAM CREST ALONG COREWALL AFTER EARTHQUAKE

(b) PROFILE OF DAM SHOWING BOUNDARIES BETWEEN ZONES AND OBSERVED DISPLACEMENTS AFTER EARTHQUAKE

(c) PREDICTED PERMANENT DISPLACEMENTS, 2D ANALYSIS

FIGURE 3 COMPARISON OF PREDICTED AND OBSERVED DEFORMATION OF HEBGEN DAM AT STATION 5+00 UNDER 1959 EARTHQUAKE



(a) DAM CONFIGURATION PRIOR TO EARTHQUAKE

(b) PROFILE OF DAM AND OBSERVED DISPLACEMENT AFTER EARTHQUAKE

(c) PREDICTED PERMANENT DEFORMATIONS, 2D ANALYSIS

FIGURE 4 COMPARISON OF PREDICTED AND OBSERVED DEFORMATION OF LOWER VAN NORMAN BY-PASS RESERVOIR DAM UNDER 1971 SAN FERNANDO EARTHQUAKE