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MODAL RESPONSES OF A LARGE EARTH AND ROCKFILL DAM

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SUMMARY

Analysis of strong-motion accelerograms recorded at Leroy Anderson Dam near Morgan Hill, California during two earthquakes provided the basis for estimating the vibrational modes of the dam which were excited by the earthquakes. Comparisons of Fourier amplitude spectra which were computed from the motions obtained at embankment and ground locations showed that significant amplification of certain frequency components of the ground motion occured in the embankment. These data were used to identify the modes of vibration of the structure. Observed natural frequencies were compared with frequencies predicted by 1- and 2- dimensional theories for earth dam vibrations.

INTRODUCTION

Leroy Anderson Dam, an earth and rockfill structure, was strongly excited by the Morgan Hill Earthquake ($M_L = 6.2$) of April 24, 1984. The Mt. Lewis Earthquake ($M_L = 5.8$) of March 31, 1986 also triggered strong-motion accelerographs at the dam site. Records obtained from these earthquakes provided a unique opportunity to analyse the response of a large embankment dam subjected to significantly different levels of excitation.

Several previous studies (Refs. 1,2,3,4,5) have used data of the amplification of the ground motion by the embankment to estimate modal responses during seismic events. However, in most of these cases only one level of excitation is considered, or the extent of the strong-motion instrumentation at the dam is minimal. The present study utilizes data from several embankment locations to estimate natural frequencies and to classify the modes. Furthermore, the study shows that 2-D models closely predict the observed natural modes.

DESCRIPTION OF DAM

Leroy Anderson Dam is a rolled earth and rockfill structure located in Santa Clara County, California, approximately 18 km southeast of San Jose. Construction initiated at the dam site in 1949 and was completed in 1950. The dam is operated by the Santa Clara Valley Water District as part of its water supply system.

The embankment at the dam site rises 72 m above stream bed level and the crest length is approximately 427 m. At the crest the dam is 12 m wide and the width of the dam at the maximum section is about 335 m.

Outer zones of the embankment are composed of dumped and sluiced rockfill material which contain a maximum rock size of approximately 0.9 m. Although no shear tests were performed on the rockfill material, it has been conservatively estimated that the fill has an effective friction angle of 35-40 degrees and a cohesion value of 12.0 kPa.

The central core of the dam is classified as a uniformly-graded, gravelly clayey sand to sandy clay. An average of the test results from six samples taken from the core show that this material is composed of 15% gravel, 32% sand and 53% fines. An average value of the dry density is 1772 kg/m^3 with a natural water content of 19.5%. Construction records reveal that the average relative compaction of the core material ranged from 95% to 98%. Laboratory test results of this soil indicate an effective friction angle of 28 degrees and a cohesive strength of approximately 43.1 kPa.

The entire foundation of the dam consists of Franciscan formations of serpentine, sandstone, shale, and greenstone. Serpentine and sandstone underly the main portion of the embankment. The serpentine is typically sheared and very weathered and significant amounts of it were excavated during construction. The right abutment also contains considerable amounts of soft serpentine. Additional information regarding embankment properties is found in Ref. 6.

DESCRIPTION OF STRONG-MOTION INSTRUMENTATION

The dam was initially instrumented by the U.S. Geological Survey (USGS) in 1983. A self-contained SMA-1 accelerograph was located on the floor of a small concrete vault on the embankment crest near the maximum section of the dam. An additional SMA-1 was placed approximately 152m downstream of the toe on an alluvial deposit.

In 1985 the strong-motion instrumentation was expanded by the USGS to include a central recording system with accelerometers placed at four embankment locations and the dam toe. The CRA-1 system contains 12 remote accelerometers connected to the recording unit which is located in the aforementioned concrete vault. A common trigger is provided for the CRA-1 system and the SMA-1 on the crest. An additional SMA-1 is located on a rock outcrop above the left abutment of the dam. Real time is provided by a WWVB receiver.

RESPONSE OF DAM

The Morgan Hill Earthquake occurred at an epicentral distance of 16 km N-NW of the dam. Two sets of longitudinal cracks on the crest, centered over the buried shoulder of the core, were observed after the seismic event. These cracks extended the majority of the crest length but excavations showed that the vertical extent of the cracks was minor. It was concluded that the cracks developed due to differential settlement between the rockfill shells and the core (Ref. 7). The two SMA-1 instruments installed at the time triggered and operated properly for the duration of the event.

For the Mt. Lewis Earthquake, epicentral distance was 36 km and no damage was observed at the dam. The crest SMA-1 and CRA-1 system recorded the event but the downstream and left abutment SMA-1's did not trigger because of the low amplitude of the motions. A summary of peak motions obtained for the two earthquakes is shown in Table.1.

FREQUENCY DOMAIN ANALYSIS OF DATA

Fourier amplitude spectra (FAS) were calculated from the motions recorded at all the embankment locations and the ground stations. For the Morgan Hill Earthquake, the Fourier amplitudes of the crest records at specified frequencies were divided by those of the downstream site records in corresponding directions to determine the degree of amplification of the dam's responses. These amplification ratio spectra were smoothed and peaks in these spectra were used to estimate natural modes of the dam that were significantly excited by the earthquakes. Similarly, the FAS of the embankment records were divided by those of the toe records in corresponding directions to obtain amplification spectra for the Mt. Lewis Earthquake.

Modes were classified as symmetric shear(S) or anti-symmetric shear(AS) for which the predominant motion was in the transverse (T) direction. Longitudinal(L) and vertical(V) modes were also identified. For responses in which there was strongy coupled T and V motion on the crest and middam locations, the identified modes were classified as rocking(R).

COMPARISON OF OBSERVED BEHAVIOUR WITH THEORY

In order to compare natural frequencies estimated from amplification spectra and those predicted by various theories of earth-dam behaviour, two-dimensional (2-D) homogeneous models were used to estimate the average shear-wave velocity of the embankment material. Once these values were established, analytical expressions for earth-dam vibrations in the T, L, and V directions were used to calculate natural frequencies corresponding to these directions.

For transverse vibrations, the average shear wave velocity within the dam, v_s, is determined from

$$v_s = \frac{\omega_{n,r} \quad H}{\sqrt{\beta_n^2 + (r\pi \; H/l)^2}} \; ; \qquad n,\ r = 1,\ 2,\ 3,\ldots \quad (1)$$

in which H = height of dam, $\omega_{n,r}$ = natural frequency in the n,r mode, β_n = roots of the Bessel function of zero order of the first kind, and l = length of the dam for an assumed rectangular canyon.

For Leroy Anderson Dam, H = 72 m and l = 230 m. This average length was determined from A/H in which A is the longitudinal cross-sectional area of the embankment.

The fundamental frequency observed in the crest record in the T direction for the Morgan Hill Earthquake was used to determine the value of $\omega_{1,1}$ in Eq. (1). Visual anlaysis of the record shows that the dam was vibrating with a period of approximately 0.67 sec during the strongest portion of the response. If it is assumed that this response corresponds to the fundamental T mode, then from Eq. (1), v_s = 259 m/sec. This value was selected to represent the average shear wave velocity of the embankment material for this event.

For the Mt Lewis Earthquake, the longitudinal record at the centre crest was used to estimate the fundamental mode because the transverse record did not appear to have a predominant frequency. This L record clearly shows a fundamental period of 0.50 sec. The average shear wave velocity, v_s is determined from:

$$v_s = \frac{\omega_{n,r} \quad H}{\sqrt{\beta_n^{\,2} + 2(1+\nu)(r\pi \; H/l)^2}} \quad ; \qquad\qquad n,\ r = 1,\ 2,\ 3,\ldots \quad (2)$$

in which ν represents Poisson's ratio and is assumed to be 0.45 for the Anderson Dam embankment material. Eq. (2) results in an average shear wave velocity of 308 m/sec. These shear wave velocities obtained for both events are in reasonable agreement with those suggested for a dam of this type (Ref.2).

Various 1- and 2-dimensional models were used to compute natural frequencies in the T, L, and V directions. Both homogeneous and non-homogeneous conditions were considered, and the values of the average shear wave velocities determined from Eq. (1) and (2) were employed in these models. Details of the models are found in Refs. 1,2,3,4,8,9. The comparisons between the estimated natural frequencies excited during the two earthquake events and the frequencies determined by the various theories of earth dam behaviour are shown in Table 2.

CONCLUSIONS

The accelerograms obtained from the strong-motion instrumentation located at Anderson Dam during the Morgan Hill and Mt. Lewis Earthquakes represent a valuable data set for engineering studies of the seismic response of earth dams. These records provided a unique opportunity to analyze the response of a large earth and rockfill structure subjected to significantly different levels of excitation. The following conclusions can be drawn from this investigation:

1. Amplification spectra can be used to adequately estimate the modes of vibration that were substantially excited during the two earthquakes. Although some peaks in the spectra will result from the yielding response of the dam and do not correspond to linear natural frequencies (Ref. 10), judgement can be used to identify the spectral peaks.

2. There was a significant change in the natural frequencies from one event to the next. This change implies that there was a corresponding difference in the stiffness characteristics of the embankment materials between the two events. The method used to estimate the average shear wave velocity appears to adequately reflect this difference.

3. On the basis of the comparisons between observed and computed natural frequencies, the non-homogeneous models appear to provide a slightly better representation of the seismic behaviour of the embankment than do the homogeneous models. However, no theory that was used accurately predicts all the modes that were identified by using amplification spectra.

4. Finally, the strong-motion instrumentation scheme at the dam was crucial to the determination of the dam's behaviour. Records obtained from the various sensor locations were critical in the identification of rocking behaviour and in the classification of some of the modes. Further analysis of these records should provide much insight into the behaviour of the embankment, and can be used to develop a more realistic model of the dam.

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Morgan Hill Earthquake			Mt. Lewis Earthquake		
Location	Orientation	Max Acc (g)	Location	Orientation	Max Acc (g)
Crest	T	0.64	Crest (SMA-1)	T	0.022
	L	0.38		L	0.017
	V	0.19		V	0.011
			Right Crest	T	0.023
Downstream	T	0.42		L	0.011
	L	0.29		V	0.010
	V	0.21			
			Centre Middam	L	0.016
			Right Middam	T	0.013
			Toe	T	0.012
				L	0.007
				V	0.009

Table 1: Summary of Corrected Peak Accelerations

Morgan Hill Earthquake						Mt. Lewis Earthquake					
Estimated Modes		1-D Theories		2-D Theories		Estimated Modes		1-D Theories		2-D Theories	
Mode Type	Freq. (HZ)	(1)	(2)	(3)	(4)	Mode Type	Freq. (HZ)	(1)	(2)	(3)	(4)
S1	1.46	1.38	1.47	1.49	1.49	S1	1.76	1.64	1.78	1.78	1.81
L1	1.70	-	-	1.68	1.65	L1	2.00	-	-	2.00	2.00
AS1	1.78	-	-	1.78	1.74	AS1	2.06	-	-	2.12	2.10
R1	1.96	-	-	-	-	R1	2.22	-	-	-	-
S2	2.16	-	-	2.18	2.08	S2	2.52	-	-	2.60	2.52
L2	-	-	-	2.36	2.23	L2	2.66	-	-	2.81	2.71
AS2	2.42	-	-	2.64	2.47	R2	2.72	-	-	-	-
V1	2.62	-	-	-	2.68	AS2	2.90	-	-	3.14	3.00
S3	3.00	-	-	3.14	2.89	V1	3.20	-	-	-	3.19
S4	3.12	3.17	3.17	3.22	3.06	S3	3.40	-	-	3.73	3.51
V2	3.22	-	-	-	2.94	R3	3.60	-	-	-	-
AS3	3.34	-	-	3.37	3.19	S4	3.72	3.77	3.83	3.83	3.71
R2	3.44	-	-	-	-						
S5	3.70	-	-	3.59	3.39						

(1) Homogeneous model - Ref. 8
(2) Non-Homogeneous model - Ref. 8
(3) Homogeneous models - Refs. 1,3
(4) Non-Homogeneous models - Refs. 2,4,9

Table 2: Comparisons of Estimated Natural Frequencies with Existing Theories