DYNAMIC PROPERTIES OF EARTH DAMS

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SUMMARY

Dynamic properties of three earth dams in a seismically active area (Southern California, USA) are estimated from their earthquake records (input ground motion and crest response). In addition, results of full-scale dynamic tests on one of the dams, involving different levels of excitations, and a comparison between the low-strain response characteristics during the tests and the relatively high-strain properties during two earthquakes are briefly presented. Suggested curves for shear moduli and damping factors (as functions of induced strains) as well as shear-wave velocity (as a function of dam depth), for the three dams, are included.

THE THREE DAMS

1 - Santa Felicia Dam "Fig. 1" is a modern rolled-fill earth dam constructed from well graded alluvial materials consisting of clay, sands, gravel, and boulders. The dam was equipped with two accelerometers "Table 1" that yielded data on how it responded to two earthquakes (with M_L = 6.3 and 4.7). In addition full-scale dynamic tests were performed on the dam including mechanical shaking, ambient vibration, and hydrodynamically generated forces (Ref. 1).

2 - Carbon Canyon Dam "Fig. 3" is a random earthfill structure resting on approximately 100 ft. of recent silt, sand and gravel. The San Fernando earthquake (Feb. 9, 1971, M_L = 6.3) was recorded only by the crest accelerograph while the Whittier earthquake (Jan. 1, 1976, M_L = 4.2) was recorded by three accelerographs "Table 1", two were mounted on the abutments to give some indication of the uniformity of conditions and the third was on the central region of the dam crest "Ref. 4".

3 - Brea Dam "Fig. 2" is a zoned earthfill embankment, with a central impervious core composed of graded material and two shells constructed of random material. Three accelerographs were installed on and around the dam; during the 1976 Whittier earthquake the left-abutment accelerograph was inoperative "Table 1 and Ref. 4".

ESTIMATION OF DYNAMIC PROPERTIES

Natural Frequencies: Amplification spectra (Figs. 4 and 5) of the dams' earthquake records were computed "Ref. 2 and 4" by dividing Fourier amplitudes of acceleration of the crest records "Fig. 6" by those of the abutment records to indicate the resonant frequencies and to estimate the relative contribution

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of different modes. Then two-dimensional continuous models were used to establish from the observed fundamental frequency a value for the shear wave velocity which was assumed, as a first approximation, constant throughout the dam and which was then used to calculate other frequencies higher than the fundamental. The natural frequencies in the two horizontal directions of a dam can be estimated by

$$\omega_{n,r} = \frac{v_s}{h} [\beta_n^2 + \eta(\frac{r\pi h}{\ell})^2]^{\frac{1}{2}}, \quad n,r = 1, 2, 3, 4, \ldots \qquad (1)$$

with

$\eta = 1$ for the upstream-downstream direction, and

$\eta = 2\ (1+\nu)$ for the longitudinal direction;

v_s is the shear wave velocity, h and ℓ are the height and length of the dam, β_n are roots of the Bessel function of zero order of the first kind and ν is the Poisson's ratio of the dam material. Tables 2, 3, 4 and 6 show comparisons between the observed resonant frequencies and estimated values computed from Eq. (1); they also show the estimated shear-wave velocities from the earthquake records. Observed resonant frequencies of Brea and Carbon Canyon Dams were compared only with the symmetric computed frequencies because the crest accelerograph was located at the crest mid-point of the two dams.

The results of full scale tests on Santa Felicia Dam indicated that there are many closely spaced frequencies not only in the two horizontal directions but also in the vertical direction, and some of the longitudinal resonant frequencies are very close (even identical) to some of the upstream-downstream frequencies which may suggest a strong coupling between these two horizontal directions. Thus three-dimensional analytical or finite element models are needed to realistically represent the prototype. Also, the correspondence between resonant frequencies from the tests and those estimated from earthquake records is reasonably good over the first few frequencies, but higher modes could not be reliably matched.

Shear Moduli and Damping Factors

Examination of the earthquake records indicated that the dams responded primarily in their fundamental modes of vibration in the two horizontal directions (Ref. 2 and 4) although there was some contribution of the higher modes apparent in the responses (e.g. Figs. 3, 4 and 5). To determine the shear moduli and damping factors, the fundamental mode response was treated as that of a single-degree-of-freedom hysteretic structure. The crest and base records were digitally band-pass filtered to isolate the hysteretic response of the fundamental mode, and a method using the 2-D analytical models was used (Ref. 3) to enable the shear stress and strain and, consequently the shear modulus to be evaluated from each hysteresis loop; the equivalent viscous damping factor is calculated from the area inside each loop. Both shear moduli and damping factors were determined as functions of the induced dynamic strains in the dam. The data obtained for the three dams (for the upstream-downstream direction) is shown in Tables 5 and 7 and in Figs. 7 and 8. For the Santa Felicia Dam, the estimated shear moduli and damping factors from low-strain full-scale tests, which revealed changes in these properties, are consistant with those determined from the relatively larger strains induced by the two earthquakes (Fig. 7 and 8). By interpolating and extrapolating the low-and high-strain data the curves of Figs. 7 and

8 were arrived at; they provided reasonable estimates of the dynamic properties of the dam's constituent material. The type of behavior indicated is typical of a softening dynamic system such as the soil of an earth dam which is known to be extremely nonlinear but has seldom been examined at full-scale. In addition, the variation of shear-wave velocity with depth (based on in-situ *measurements on Santa Felicia Dam and on the representative value (≈850 ft/sec* and estimated at $(\frac{2}{3} - \frac{3}{4})h$) determined from earthquake records (Ref. 2) is shown in Fig. 9. The dynamic properties estimated from the earthquake records (shaded areas) for the Brea and Carbon Canyon Dams are also shown in Figs. 7 and 9; behavior similar to Santa Felicia Dam is proposed (the dashed curves) for the region not covered by the shaded areas.

The data presented indicates that nonlinear (or piece-wise linear) models must be used to predict the effect of an earthquake on an earth dam due to the nonlinearity of the material degradation, and the variation of the material properties with depth should be taken into account.

ACKNOWLEDGMENTS

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Table 1

Summary of the Three Earth Dams Accelerographs

DAM (Name, Location and Type)	Height (ft)	Crest Length (ft)	Earthquake (Magnitude)	Location of Accelerograph	Epicentral Distance (km)	Recorded Peak Acceleration (g) U-D(a)	L(b)	V(c)
Santa Felicia Dam			1971 San Fernando (M_L = 6.3)	Crest	33.4	0.21	0.18	0.07
				Outlet Works		0.22	0.20	0.07
Ventura County, CA Modern rolled-fill embankment (well graded alluvial material with some binder, and compacted gravelly clays)	273	1,275	April 8, 1976 (M_L = 4.7)	Crest	14.0	0.05	0.05	0.03
				Outlet Works		0.05	0.04	0.03
Carbon Canyon Dam			1971 San Fernando (M_L = 6.3)	Crest	74.0	0.07	0.07	0.04
Orange County, CA	100	1,925	January 1, 1976	Crest		0.10	0.06	0.05
A random fill earth dam (compacted silty and sandy clays)			(M_L = 4.2)	R. Aubtment	7.4	0.13	0.08	0.04
				L. Abutment		0.12	0.10	0.05
Brea Dam Orange County, CA Zoned earth-fill with central impervious core of graded material	90	1,765	January 1, 1976 (M_L = 4.2)	Crest	9.3	0.09	0.11	0.05
				Downstream		0.08	0.05	0.04

(a) Upstream-Downstream Component
(b) Longitudinal Component
(c) Vertical Component

Table 2

Comparison Between Resonant Frequencies from Earthquake Records, Full-Scale Dynamic Tests and Existing Shear-Beam Theories (Santa Felicia Earth Dam)

Upstream-Downstream Direction

EARTHQUAKE RECORDS: San Fernando E.Q., 1971 Observed Frequency (Hz)	Southern California E.Q., 1976 Observed Frequency (Hz)	2-D SHEAR-BEAM THEORY (Based on the Observed First Frequency 1.45 Hz) Mode n,r	Frequency $f_{n,r}$ (Hz)	FORCED VIBRATION TESTS: Symmetric Shaking Measured Frequency (Hz)	Designation	Remarks	Antisymmetric Shaking Measured Frequency (Hz)	Designation	Remarks	2-D SHEAR BEAM THEORY (Based on the Observed First Frequency 1.635 Hz) Mode n,r	Frequency $f_{n,r}$ (Hz)
1.44	1.46	1,1	1.45	1.635	S1(1,1)	Shear	-	-	-	1,1	1.635
-	1.66	-	-	1.850	R1	Rocking	-	-	-	-	-
1.81	1.86	1,2	1.67	-	-	-	1.875	AS1(1,2)	Shear	1,2	1.872
-	-	-	-	-	-	-	2.025	AR1	Rocking	-	-
2.03	2.08	1,3	1.95	2.100	S2(1,3)	Shear	-	-	-	1,3	2.209
-	-	-	-	2.270	R2	Rocking	-	-	-	-	-
2.27	2.25	1,4	2.32	-	-	-	2.300	AS2(1,4)	Shear	1,4	2.610
2.47	-	-	-	2.600	R3	Rocking	-	-	-	-	-
-	-	-	-	-	-	-	2.650	AR2	Rocking	-	-
2.88	2.73	1,5	2.71	2.840	S3(1,5)	Shear	-	-	-	1,5	3.048
-	-	-	-	2.920	R4	Rocking	-	-	-	-	-
3.10	3.13	1,6	3.11	-	-	-	3.100	AS3(1,6)	Shear	1,6	3.510

AMBIENT VIBRATION MEASUREMENTS: Average Measured Frequency (Hz) from the Fourier Amplitude Spectra 3-13-78	3-14-78	3-15-78	3-16-78	3-17-78	3-24-78	3-27-78	Average Measured Frequency (Hz) "7 days"	THE POPPER TESTS: Average Measured Frequencies From the Fourier Amplitude Spectra (in Hz) Test I	Test II	Test III	Average
1.620	1.621	1.586	1.619	1.603	1.620	1.626	1.614	1.513	1.503	1.512	1.509
1.753	1.779	1.792	1.773	1.745	1.787	1.780	1.773	1.727	1.719	1.677	1.708
1.934	1.884	1.924	1.835	1.916	1.881	1.924	1.900	1.892	1.802	1.831	1.842
2.025	2.020	2.030	1.978	-	2.035	2.044	2.022	1.954	1.922	-	1.938
2.130	2.130	2.097	2.044	2.050	2.111	2.119	2.097	2.062	2.027	2.027	2.037
2.224	2.244	2.168	2.161	2.225	2.237	2.229	2.213	2.133	2.141	-	2.137
2.368	2.350	2.395	2.333	2.377	2.367	2.320	2.359	2.355	2.307	2.354	2.339
2.591	2.611	2.549	2.540	2.587	2.568	2.500	2.564	2.489	2.522	2.520	2.510
2.680	2.693	2.680	2.695	2.632	2.699	2.646	2.675	2.659	2.604	2.659	2.641
2.900	2.809	2.783	-	2.842	2.869	2.859	2.844	2.778	2.805	2.735	2.773
3.010	2.942	2.903	-	3.038	2.970	2.989	2.975	2.954	2.920	2.897	2.924
3.091	3.230	3.128	-	3.190	3.214	3.135	3.165	3.093	3.057	3.062	3.071

Table 3

Santa Felicia Dam

Comparison Between Resonant Frequencies from Earthquake Records, Full-Scale Tests and Theory

Longitudinal Direction

Observed Frequencies (1971 E.Q.) (Hz)	Computed Frequencies Hz	n,r	Observed Frequencies (1976 E.Q.) (Hz)	Computed Frequencies Hz	n,r	Measured Frequencies (Forced Vibration) (Hz)	Computed Frequencies Hz	n,r	Measured Frequencies (Ambient Vibration) (Hz)	Computed Frequencies Hz	n,r
1.35	1.35	1,1	1.27	1.27	1,1	1.43	1.44	1,1	1.45	1.45	1,1
1.70			1.66			1.68			1.64		
1.86	1.79	1,2	1.86	1.68	1,2	1.85	1.88	1,2	1.85	1.91	1,2
-			-			1.95			1.99		
2.15			2.15	2.2	1,3	2.16			2.18		
2.32	2.34	1,3	-			2.28			2.32		
						2.42	2.47	1,3	2.45	2.5	1,3
			2.64	2.6	2,1	2.63			2.64		
V_s = 723 ft/sec			V_s = 600 ft / sec			V_s = 703 ft/sec			V_s = 774 ft/sec		

Table 4

Brea Dam

Comparison Between Observed and Computed Resonant Frequencies

Upstream-Downstream Direction				Longitudinal Direction			
Computed Symmetric Frequencies		Difference Between Two Adjacent Frequencies	Observed Frequencies (1976 E.Q.)	Computed Symmetric Frequencies		Difference Between Two Adjacent Frequencies	Observed Frequencies (1976 E.Q.)
(n,r)	(Hz)		(Hz)	(n,r)	(Hz)		(Hz)
1,1	2.73		2.73				
				1,1	2.75		2.75
1,3	3.18	0.45	-				
				1,3	3.81	1.06	3.91
1,5	3.90	0.72	4.10				
1,7	4.79	0.89	4.69				
				1,5	5.32	1.51	4.88
1,9	5.76	0.97	5.86				
				2,1	6.01	0.69	5.45
1,11	6.79	1.03	7.03	1,7	7.01	1.00	7.03
V_s=677 ft/sec				V_s=661 ft/sec			

Note: the frequency resolution used to compute the Fourier amplitude spectra is 0.0977 Hz (time duration of the records was 12 seconds)

Table 5

Comparison Between the Dynamic Properties (of an Earth Dam) Estimated From Earthquake Records and Those Determined From Full-Scale Dynamic Tests.

Source of Data (Different Levels of Excitation)	Upstream-Downstream Direction							Longitudinal Direction
	SYMMETRIC VIBRATION						ANTISYMMETRIC VIBRATION	Natural (First) Frequency
	First Shear Frequency	Estimated Shear Modulus	Estimated Shear Strain	Estimated Damping Factor	Max. Acceleration at the Crest	Max. Displacement at the Crest	First Shear Frequency	
1971 San Fernando Earthquake M_L = 6.3	1.440 Hz	Ranges from 2.4×10^6 lb/ft^2 to 4.5×10^6 lb/ft^2	Ranges from 0.4×10^{-2} % to 5.5×10^{-2} %	Ranges from 5.0% to 15.0%	20% g	13.30 mm	1.81 Hz	1.35 Hz
1976 Southern California Earthquake M_L = 4.7	1.460 Hz	Ranges from 3.4×10^6 lb/ft^2 to 4.8×10^6 lb/ft^2	Ranges from 0.10×10^{-2} to 0.40×10^{-2} %	Ranges from 1.5% to 5.0%	5% g	0.85 mm	1.86 Hz	1.27 Hz
Forced Vibration Tests (Mechanical Shaking)	1.635 Hz	4.10×10^6 lb/ft^2	0.716×10^{-5} %	3.0%	.0037% g	0.00336 mm	1.875 Hz	1.425 Hz
Ambient Vibration Tests (Wind and Spilling of the Reservoir)	Ranges from 1.570 Hz to 1.670 Hz	Ranges from 3.6×10^6 lb/ft^2 to 4.3×10^6 lb/ft^2	-	Ranges from 2.3 to 3.6%	-	-	Ranges from 1.85 Hz to 1.95 Hz	Ranges from 1.44 Hz to 1.48 Hz
Hydrodynamically Generated Force (Popper Tests)	Ranges from 1.50 Hz to 1.63 Hz	-	-	Ranges from 2.9% to 4.2%	-	-	Ranges from 1.76 Hz to 1.93 Hz	-

Table 6
Carbon Canyon Dam
Comparison Between Observed and Computed Resonant Frequencies

Upstream-Downstream Direction					Longitudinal Direction				
Computed Symmetric Frequencies		Difference Between Two Adjacent Frequencies	Observed Frequencies (1976 E.Q.)	Observed Frequencies (1971 E.Q.)	Computed Symmetric Frequencies		Difference Between Two Adjacent Frequencies	Observed Frequencies (1976 E.Q.)	Observed Frequencies (1971 E.Q.)
(n,r)	(Hz)		(Hz)	(Hz)	(n,r)	(Hz)		(Hz)	(Hz)
					1,1	1.37		1.37	1.37
					1,3	1.47	0.10	1.47	1.47
1,1	1.56	-	1.56	1.55					
1,3	1.60	0.04	-						
1,5	1.68	0.08	-						
1,7	1.80	0.12	1.76	1.75	1,5	1.66	0.19	1.75	1.75
1,9	1.94	0.14	1.86	1.86	1,7	1.90	0.24	1.86	1.86
				2.00	1,9	2.19	0.29	1.95	-
1,11	2.10	0.16	2.25	2.25					
					1,11	2.50	0.31	2.30	2.3
1,13	2.28	0.18	2.34	2.34					
V_s=376 ft/sec					V_s=328 ft/sec				

Table 7

Dynamic Properties of two Earth Dams Estimated From Earthquake Records (Jan. 1, 1976 Earthquake)

(Upstream-Downstream First Symmetric Shear Mode)

Property	Carbon Canyon Dam	Brea Dam
First Upstream-Downstream Shear Frequency	1.56 Hz	2.73 Hz
Estimated Shear Modulus	Ranges from 0.55×10^6 lb/ft^2 to 1.53×10^6 lb/ft^2	Ranges from 1.85×10^6 lb/ft^2 to 2.45×10^6 lb/ft^2
Estimated Shear Strain	Ranges from 0.3×10^{-2}% to 2.1×10^{-2}%	Ranges from 0.29×10^{-2}% to 1.13×10^{-2}%
Estimated Shear Stress	Ranges from 57.4 lb/ft^2 to 114.8 lb/ft^2	Ranges from 77.8 lb/ft^2 to 209.4 lb/ft^2
Estimated Dumping Factors	Ranges from 0.09% to 2.5%	Ranges from 1.0% to 3.0%
Max. Crest Acceleration (Absolute)	0.10 g	0.09 g
Max. Crest Displacement (with respect to base)	2.0 mm	1.2 m

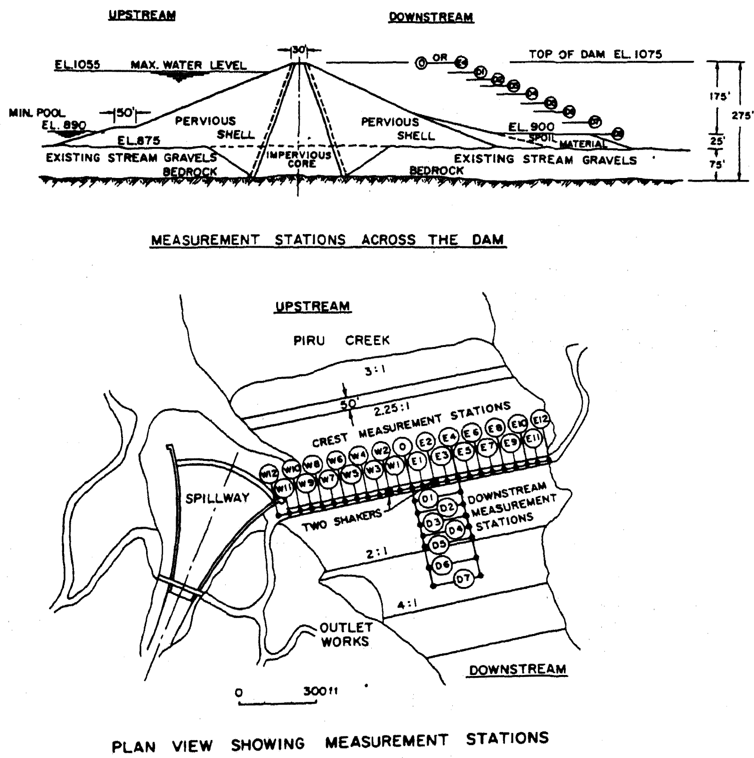

Fig. 1 Cross section and plan view of Santa Felicia Earth Dam showing the measurement stations of the full-scale dynamic tests.

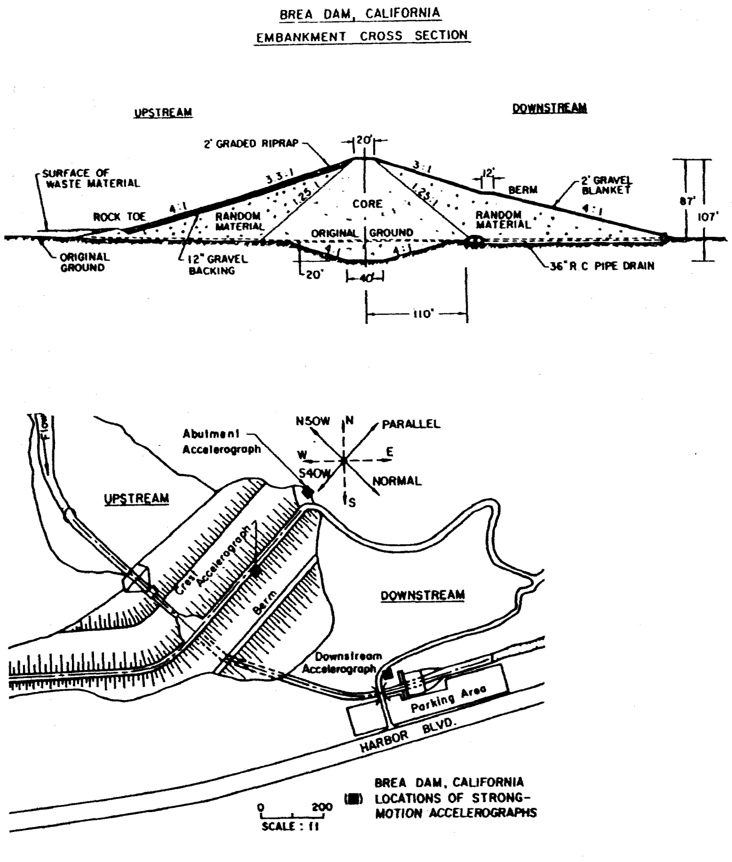

Fig. 2 Cross section and plan view of Brea Dam showing location of accelerographs.

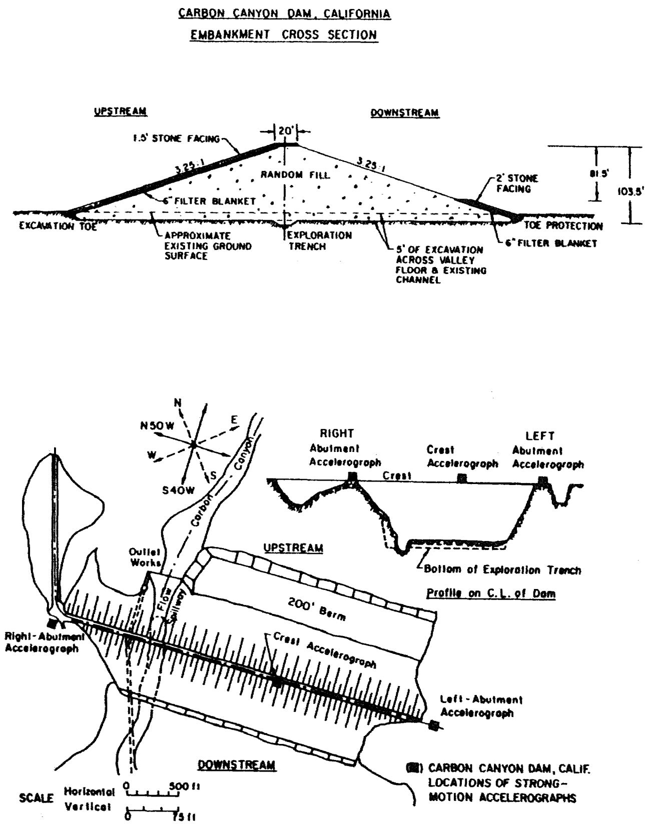

Fig. 3 Cross section and plan view of Carbon Canyon Dam showing location of accelerographs.

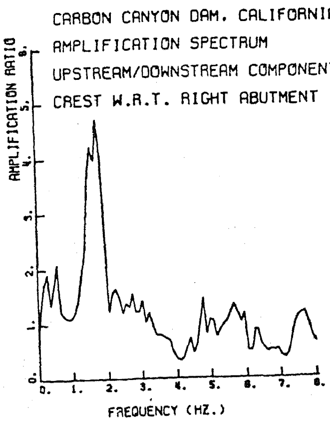

Fig. 4

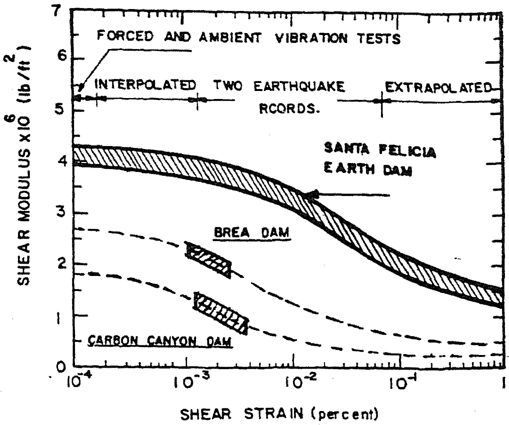

Fig. 7

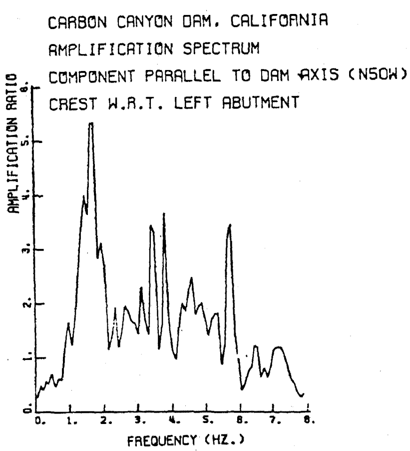

Fig. 5

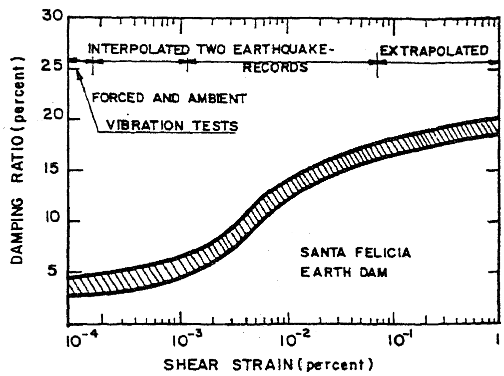

Fig. 8

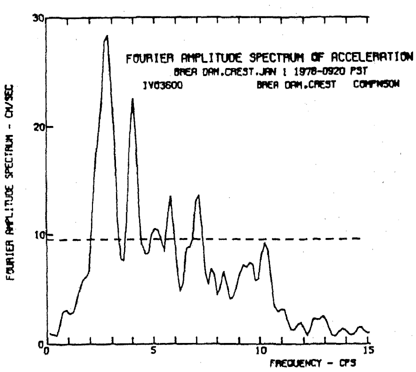

Fig. 6

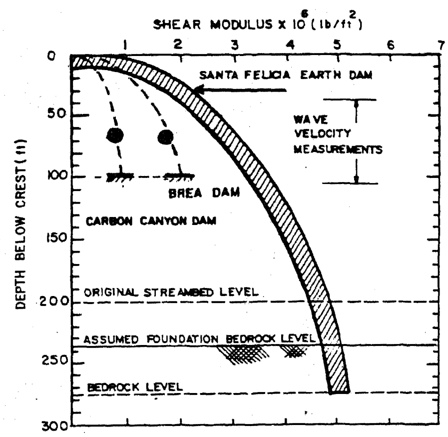

Fig. 9