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The strong motion observation investigation of cracks in Xinfengjiang dam

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ABSTRACT: Through original dam Strong Motion Observation, model test and structural dynamic response analysis, the dynamic characteristics and seismic resistance of Xinfengjiang dam before and after its cracking are emphatically investigated. Some processed results of the strong motion records on part of the cracks of the dam are shown. The existence of the cracks is considered to be of influence on the antiseismicity the dam. Recommendations on further reinforcement to the dam are made basing on the model test, the dynamic response analysis of the dam and the strength collation of the reinforced—bar.

1 PREFACE

1.1 Description of the dam and the Cracks

XINFENGJIAN reservior is at about 6 kilometers west of the city of HEYUAN, GUANGDONG province, with a reservior capacity of 11.5 billion cuicmeters. The dam is composed of a qravitybuttress dam with 19 monobuttresses of 18 m with each and two gravity dams at both banks. The dam is 105m high, 440m long and 107m in base width. Originally, seismic intensity of dam site was assessed as Ⅵ, so seismic protection was not provided. Rocks at the dam site are Jurasic—Cretaceous granite, less weathered on the left bank, more heavity weathered on the right bank. The reservior area is in the vicinity of the HEYUAN—SHAOWU major fracture zone and the rock is more fractured.

Soon after strong of water, a strong earthquake of Ms 6.1 happened on March 19 1962, with the epicenter at about 2 km north—west of the dam, a seismic source depth of 5 km and an epicentral intensity of Ⅷ odd. At that time, water level in the reservior was 110.6 m in elevation, meaning that the dam had passed the test on strong earthquake with high water level. Nevertheless, many cracks of different size and harmfulness were seen in some parts of the dam, mostly in the part of 97 to 112 m in elevation of the dam. The most serious condition was seen between No. 13 and 17 buttresses, where the 82 m long section was penetrated by a crack through which water oozed out. In the past 20 years, the cracks further developed due to the effect of variation in environmental temperature, water level and pressure, and of earthquake etc. Toensure safety operation of the dam, in addition to the second phase consolidation treatment, it was necessary to perform observation and investigation of the cracks in order to make clear their law of development and their risk, so as to provide a basis for the necessity of reinforcement for seismic resistance.

1.2 Observation and investigation

After the second consolidation, seismic resistance of the dam was obviously improved. To assess the effect of reinforcing, observation and investigation were further made to the dam—head. Items investigated were:

1. Observation of eismic response of the cracks so as to collect the valuable data on strong earthquakes motion;
2. Dynamic model test to obtain dynamic characteristics before and after cracking of the dam;
3. The dam's reinforcing, and safety factor calculation of the dam—head under the effect of different seismic intensity after dam's reinforcing, and calculation of reinforced bar strength for assessment of reinforcing effect of this dam.

In this paper Strong Motion records and preliminary analysis of crack seismic response observed since 1986 are summerized and the model tests and structural response analysis & calculation are also reported.

2 STRONG MOTION OBSERVATION OF DAM'S CRACKS

2.1 Instruments used and their specifications

For Strong Motion Observation, a CHINA—made REZ1 strong motion accelerograph was used, which is an multi-galvanometer type optical recording seismograph with wide passband, high range, auto—triggered recording and satisfactory performance. The 12 signals were recorded on the same photo—paper roll. Its specification is: pass-

band 0. 5-35Hz, recording sensitivity 0. 1—2mm/gal adjustable, maximum triggering sensitivity 1G, time scale 20 pulses per second. (1)

2. 2 Arrangement of measuring points

Observation station for the purpose has been set up since 1966 and 24 channels have been recorded during the past 20 years for monitoring seismic response of the dam's main body structure. To investigate the difference in seismic response between the upper and lower parts of the dam's cracked head, the variation in amplitude and frequency, the effect-of cracks on overall dam body chacteristics, etc. practical observation was imperative in order to obtain data. For observation of acceleration time—history, buttresses No. 14, 16 and 17 were selected, on which pick—ups were installed at 20cm above and under the crack of 108m elevation. Besides, observation points were also set at the top, the base and at 86m elevation, of the No. 14 buttress for monitoring its overall response. For detail of measuring points, see Table 1 and Fig. 1.

Table 1. Measuring point arrangment and preliminary analysis

Elevation	Buttress position	Horizontal Am	Vm	Dm	F	Vertical Am	Vm	Dm	F
124	14, top	408	14. 5	1. 72	5. 8	165	4. 4	0. 5	7
108	14, above	103	2. 5	0. 3	5. 8	99	2. 9	0. 2	7
108	14, under	107	3. 1	0. 3	5. 9	109	2. 9	0. 4	7
108	16, above	107	5. 1	0. 6	5. 4				
108	17, under	121	3. 6	0. 22	7. 9	85	2. 0	0. 2	7
86	14, waist	85	2. 7	0. 11	5. 8				
43	14, base					32	1. 4	0. 1	5

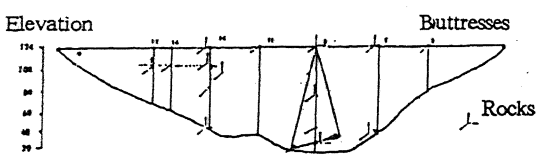

Fig. 1. Arrangement of Measuring Points

3 DAM'S STRONG MOTION RECORD & DATA POINTS

Since the setting up of crack observation station in 1986, 48 curves of acceleration records of dam's cracks and other records of dam body response were obtained. Here as an example, preliminary processing and ananlysis of records for the crack are made.

3. 1 Earthquakes

At zero o'clock on 26th November 1989, a moderate strong aftershock of magnitude = 4. 6 happened at about 2km lower reaches of the reservior, i. e. at 114°40′e and 23°41′n, with a seismic source depth of 9. 5km, an epicentral intensity of Ⅵ and a water level of 92m in elevation. Seismic source was deeper than before, and the sensible sphere and area of intensity Ⅵ were larger.

3. 2 Record processing

Strong motion observation records for the cracked dam were digitalized and spectrally analyzed by conventional methods(2).

During record processing, zero point adjustment of the digitalized strong motion acceleration records and instrument calibration had been made. For the former, band—pass filter was made by Ormsby filter of rapid faltung. The processed records are expressed in the form of the time—history of the corrected acceleration, velocity and displacement, and the response spectra, and the fourier spectra; and these data are provided by 5. 5″ floppy discs.

3. 3 Preliminary analysis of crack acceleration

The maximal peak value on the earthquake of M = 4. 6 was at the dam top (at 124m elevation), where an acceleration of 400 gal, a velecity of 14. 5cm/s, a displacement of 1. 72cm and a horizontal—to—vertical acceleration ratio of 1 : 0. 4 were recorded. Table 1 is the principal result: The maximal values of acceleration Am (gal), velocity Vm(cm/s) displacement Dm(cm) as well as frequency F(Hz). In Fig. 2 the time—history curves of the acceleration, velocity and displacement, for records of channels 11 and 14 are shown. The acceleration curves for other record channels are shown in Fig. 3.

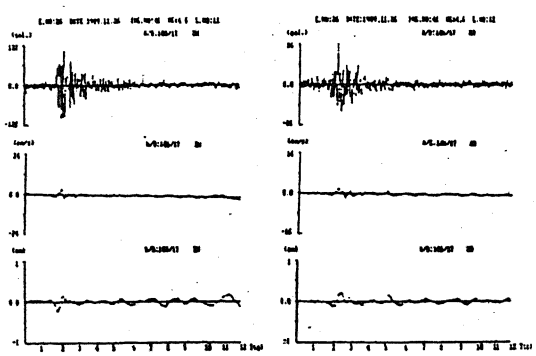

Fig. 2. Rectified Acceleration of Buttress No. 17, and velocity and displacement integrated from it.

For better explanation, Am, Vm, and Dm of the measuring points on buttress No. 14 is plotted in Fig. 4. From the figure it may be seen that the crack does have an influence on the response of dam body to earthquake.

This is manifested in:

1. Comparison of Am, Vm, and Dm values between the points above and under the crack shows a slight reduction for Am and Vm above crack and a variation in Dm, meaning that the energy absorption by the crack was still existence under such earthquake (M—4.6); and

2. From Table 1 it is seen that the first order horizontal frequency of dam body is 5.8Hz, conforming to the original observation result (3) in the past with a little variation. So it is clear that the dam's overall characteristics may yet be considered as stable. The minor difference in frequency components of Fourier Amplitude spectra (Fig. 5) founded upon comparison of records between upper and lower measuring points may be attributed to the effect of the crack. And it may be conjectured that the higher the seismic intensity is, the higher will be the influnece of the crack.

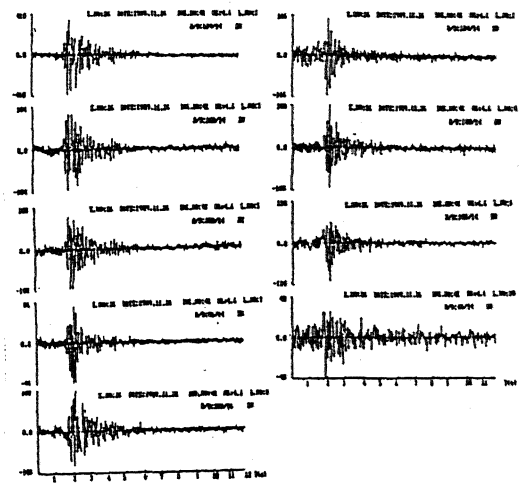

Fig. 3. Acceleration versus time for other channels

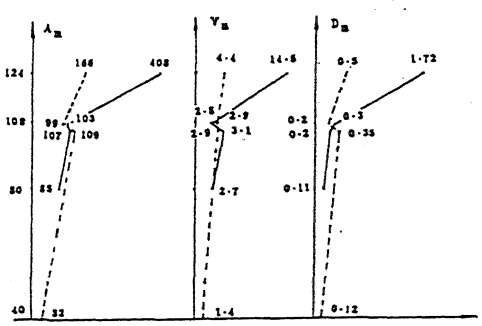

Fig. 4. Comparison of Am, Vm and Dm for buttress No. 14

4 DAM MODEL DYNAMIC TEST(4)

To get mechanical paremeters of the original structure through structural model test is one of the fundamental methods in strutural dynamic of model was taken along several different himics. The model test for XIN-FENGJIANG dam was carried out taking buttress No. 14 as the object.

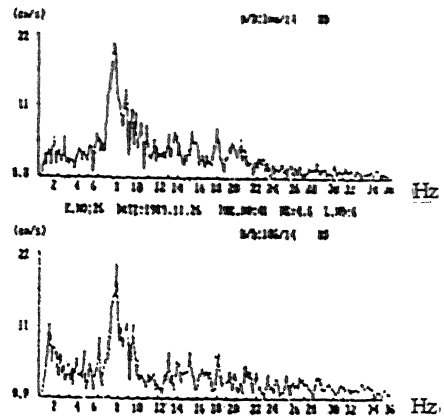

Fig. 5. Fourier acceleration spectrum above and under the cracks

4.1 Model design

In model making, taken into account was conditions of gravity similarity in addtion to the similarity of elastic force and inertia force, which must be met. In this test, material used for the model was weight—added sulphurized rubber which was similar in volume weight and of a modulus of dynamic. First, a cantilevershape sample was used to determine the free frequency by method of knocking and then the modulus of eleasticity was calculated as:

$$F=\frac{3.52}{2\pi L^2}\sqrt{\frac{EILG}{Q}}$$

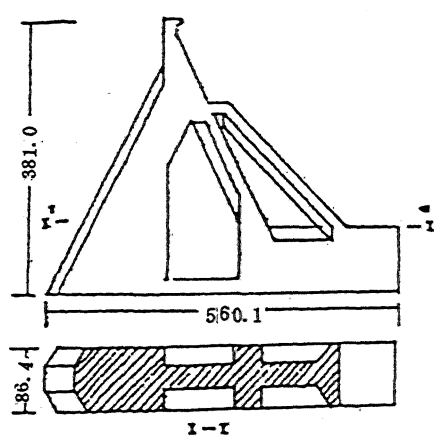

Fig. 6. Model dimensions

Where: Q=total weight, L=sample length, I=moment of inertia, F=measured frequency, and E=modulus of dynamic elasticity.

By this method, material volume weight $\rho_m = 2.49 kg/m^3$ and modulus of elasticity $Em = 2481.8 kg/cm^2$ were obtained. Here the similarity scales are listed in Table 2 and dimensions of the model are shown in Fig. 6.

Table 2. Scale of similarty

Physical quan.	Symbol Scaling	forula	Quantity
Ratio of volume	P	ρ/ρ_m	0.96
Ratio of elastic	Q	E/Em	120.9
Geomtric ratio	λ	L/Lm	209
Ratio Acc. of	A	A/Am	1.0
Ratio of period	τ	P/Q	18.63

4.2 Measuring technology and method

Free frequency of the model was determined by the resonance method, and response components of model was taken along several different highness of this model, thus corresponding vibration patterns were obtained.

First, vibration tests were made in the conditions of empty reservior and full reservior respectively when the model was intact. When complete result was got, cracked dam was simulated by sawing the model apart in the position corresponding to elevation 108m of the original, then vibration tests were performed under empty and full reservior conditions with the dam reinforced, thus results for the 4 conditions were got.

Table 3. Dam model free frequncy, downstreamwards

	Con.	Model'mea. val.			Converted val.		
		1	2	3	1	2	3
Intact Filled Empty	Mea.	145	220	373	7.79	11.87	20.03
	Calcu.	131.7	243.1	363	7.62	13.5	20.79
	%	9.0	11.0	1.6	2.2	14.2	3.8
	Mea.	142	222	362	7.62	11.92	19.04
	Calcu.	124.1	236.2	352.2	7.16	13.09	19.86
	%	12.6	6.4	2.7	6.0	9.8	2.2
Sawed—model Filled Empty	Mea.	170	340	450	9.13	18.26	24.16
	Calcu.	147.3	340.7	517.7	8.61	20.25	32.75
	%	13.4	0.1	27.0	5.7	10.9	35.6
	Mea.	168	342	454	9.02	18.36	24.38
	Calcu.	138.3	352.1	544.3	8.06	19.28	31.25
	%	18.0	2.9	20.0	10.6	5.0	28.2

4.3 Simulation of the insertion of reinforced bar in the cracked dam head and of dynamic water pressure

In consideration that the dam head was reinforced by reinforced bars, the sawed model was also strengthened by sticking and by anchoring with 6 lengths of steel wire of steel wire of dia. 0.8mm.

To simulate dynamic water pressure in full condition of the reservior, additional masses were used, i.e. masses of 57 to 370 grams each were added to 7 positions on model.

4.4 Experimental result

By model test, frequencies of 1st, 2nd and 3rd orders, as well as corresponding vibration patterns were determined, as shown in Table 3. From Table 3 it is known that dynamic water pressure has little effect on free frequency of the model, while the model's free vibration characteristics exhibit an obvious change when the model is cracked and then reinforced by steel wires—an increase of frequency by 17% to 54% is seen. The curve of resonance obtained is shown in Fig. 7.

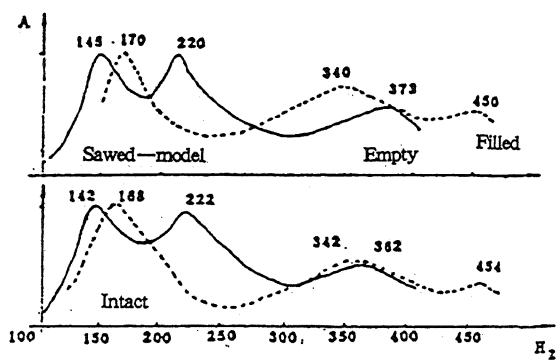

Fig. 7. Resonance curve of the model

4.5 Dam's Dynamic analysis and reinforced bar's strength calculation

In calculation, the two recorded accelerations fos M=4.5 earthquake at XINFENGJIANG dam area were imput, because the reinforced bar would not share seismic stress if seismic intensity was low. For empty reservior, only if rectified horizontal acceleration was over 0.15G and vertical acceleration was over 0.075G, and for full reservior only if rectified horizontal acceleration was over 0.1G and vertical acceleration was over 0.05G can the reinforced bar bear the earthquake effect.

5 CONCLUSIONS

Summing up the above strong motion observation, model tests and dynamic calculation & analysis, the following conclusion may be drawn:

1. Original observation show that the mainvibration frequency of the dam varies little, the maximal accelera-

tion is still not large and the dam's overall characteristics are still stable. However, since the cracks do have some influence on both vibration amplitude and freqency of the dam during earthquakes, close attention should be paid to the cases of strong earthquake.

2. The difference in free frequency before and after cracking of the dam reaches 20 to 50 percent as shown by the model test. This means that the influence of the crack is valid and innegligible.

3. The dynamic analysis for gravity dam performed by unidimensional finite element method yields dam—body's vibration characteristics conforming to model test result, proving that the simplified calculation is rational. The free frequencies obtained by test and calculation are both higher than those of the original obtained by observation. This may be attributed to three causes; the model (test and calculation) does not take into account the space effect of the dam; the softening effect arising from the inabsolute rigidity of the dam foundation was not taken into account; the influence of additional masses simulationg reservior water was not best considered in making simplifications for test and calculation.

4. As shown by dynamic stability analysis, the reinforced bar on the dam's cracked head can endure earthquake of M=7.5 in the case of empty reservior and of M=7 in the case of full reservior.

5. through calculation and analysis of stresses in the reinforced bars and in cosideration of bar's position and the influence of cracks in case of a earthquake, it is considered that the present arrangement of bars is not favourable for resistiong downstream wards capsize moment, and it is recommended that an additional row of bars be installed on the upstream side at 113m elevation to enhance seismic resistance of the dam.

* Co—workers include Zhang Da—ming, Yie Wei—yuan, Li Fa—guo, Cheng Xao—jiang, Chui Fa—zheng, Dai Guo—zhang, Wu Zhang—zhu, Tang Xuan—chu.

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