PROTOTYPE DYNAMIC TEST AND THEORETICAL ANALYSIS
OF A CONCRETE GRAVITY DAM

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SUMMARY

In this paper, the results of the prototype dynamic test and the finite element analysis for a concrete gravity dam with wide joints are presented. The first six frequencies and the corresponding mode shapes and damping ratios of the dam were obtained from this test. The three mathematical models of the dam were used for investigating behavious of the dam. The calculated results of the three models are compared with those of the field test of the dam.

INTRODUCTION

Fengshuba Dam is situated in Longchuan County in the upper reasches of the Dongjiang River in Guangdong Province, China. It is composed of three types of blocks: two hollow gravity blocks, eight solid gravity blocks and fourteen gravity blocks with wide joint. The height of the tallest block is 95.3m. The crest length is 400 m and the crest width is 6.5 m. The power plant is located in hollow Block Nos. 6 and 7. The dam is shown in Fig. 1.

The dam site is in zone of high intensity of earthquake. The design earthquake of the dam is designated as MM VIII. Thus, the purpose of prototype dynamic test and theoretical analysis of the dam is used for checking its capacity resistant to strong ground motion. The field tests on Fengshuba Dam were conducted during March and April 1982 (1). During the testing period the water in reservoir was near full and not changed significantly. Most tests were conducted in period of time from midnight to four o'clock of next morning. Therefore influence of the environment state on the field test was decreased as possible. The finite element analyses, including eigenvalue computation, response spectrum analysis and static analysis, were performed for three theoretical models by means of computer program SAP IV (2) on IBM-4341 Computer. Only the results of prototype dynamic tests and eigenvalue computations were described here. From the results of both two aspects of the test and computation it is shown that the whole property of Fengshuba Dam is of more important rather than the action of single block when the vibration amplitude are small.

PROTOTYPE DYNAMIC TEST

Forced Vibration Testing Equipment and Measuring Instrument

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Two new vibration generators of Type 635 were used for the test. The main features of the vibration generator are as follows (1):

- Operating frequency range: from 0.5 to 30 cps, in step of 0.001 cps;
- The maximum force obtained: 6 ^{T} in the frequency range 4.2 - 30 cps;
- Force factor accuracy: K < 0.02, where K = $4\pi^2$ W R, W—equivalent weight, R - equivalent radius;
- During synchronized operation, accuracy of the phase of each generator can be controlled to 10° bellow 30 cps;
- Drive motor: 5.5 KW, 3000 rpm.

Vibration displacements of the dam were measured with a set of instrument consisted of thirty-two Type - 701 electro-magnetic pickups, five Type- CZT -1 six-channel amplifiers, and two Type SC - 18 electro - magnetic oscillographs with twenty - four channels. The pickup has three measuring modes: small displacement, large displacement and velocity. Small displacement mode is always used for field test on concrete dam. The main features of the pickup in this mode are as follows:

- Natural period: 1.0 ± 10% (Sec.);
- Damping constant: 0.55 - 0.65;
- Sensitivity: > 180 (m v/mm);
- Range of measurable frequency: 1 - 20 cps, error 10%;
- Range of measurable displacement: 5x10^5 - 1.0 (mm), (peak-peak).

Arrangement of Exciting and Measuring Points

As a matter of experience of prototype tests on dams conducted past, it is known that exciting points should be arranged on the proper locations of the dam crest in order to obtain the symmetrical and antisymmetrical modes. For obtaining better results of mode shape measurements, the more exciting points should be arranged so long as conditions of field tests permit. In this test, one exciting point was located at the centre of crest on Block Nos. 5, 7, 10, 13, and 16, respectively. Moreover, two exciting points were also located at the foundation gallery of Block Nos. 9 and 11 so as to explore the feasibility and effect of exciting through foundation of the dam and to make comparision with the results obtained from on crest.

Measuring points were arranged on various heights of the dam, such as crest and four inspection galleries at different levels, the number of measuring points at each block is one at least at different levels.

In adition, some measuring points were located at both sides of vertical construction joints at the crest and inspection gallery (elevation 145 m) for investigating the behavior of joints between blocks. The dynamic behavior of some main attached srtuctures at the dam crest, such as crane-houses located at Block Nos. 6, 7, 12 and 13 were measured. The effect of these structures on dynamic behavior of the dam was discussed.

Experimental Procedure and Main Results

Forced vibration test procedure was as follows: First, frequency scanning test was conducted to determine resonant frequenies of the dam; Second, based on the results of the scanning tests, a cross-calibration was performed for the total set of measuring equipment in order to obtain the convertible relationship among the amplitudes recorded by various channels; Finally, for

each resonant frequencies forced vibration tests were conducted to measure corresponding mode shapes respectively.

The exciting force of vibration generator is proportional to the square of the exciting frequency. For certain eccentric load, the exciting force acted on dam increases with the square of the exciting frequency. To obtain the so-called normalized resonant curves for constant force, each displacement amplitude recorded should be divided by the square of its corresponding exciting frequency. The resonant frequencies obtained from sweeping test are listed in Table I. Fig. 3 shows the typical resonant curves.   It may be seen from Table I. and Fig. 3 that the first six natural frequencies are 4.9 5.3, 6.2, 7.2, 8.1 and 10.1 cps.

Based on resonant frequencies measured, the mode shape tests were conducted. Since a large number of the pickups and the recording channels were used, the mode shape testing program could be accomplished in a short time. A measuring point must at least remain fixed as a reference point throughout the mode shape tests, so that amplitude and phase of each measurement could be identified according to the same standard. Then the spatial mode shape of the overall vibration of the dam could be determined. Fig. 4 shows the mode shapes corresponding to the first six natural frequencies. It is shown from the Fig. 4 that the 1st, 3rd and 5th mode shapes are symmetric and the 2nd, 4th and 6th are antisymmetric. (The 5th and 6th modes were omitted in Fig. 4)

In prototype dyanmic tests, damping ratios were usually found from the normalized resonance curves by the band-width method. In the case of civil engineering structures, it is important to know how range an equivalent viscous damping coefficient lies in. Meaningful ranges may be defined as under 1%, 1-2%, 2-5%, 5-10% and over 10%(3). The damping ratios of the first six modes of the dam are listed in Table I. their values are 3.8%, 3.1%, 2.3%, 3.4%, 3.5% and 3.1% in order. The damping ratios of crane-houses on Blocks 7 and 13 are 1.9% and 2.1% respectively. It is shown that the damping ratios of Fengshuba Dam are in the range of 2-5%, the average value for the first six damping ratios is 3.2% which nears the damping ratio of arch dams (4).

In this test, two vibration generators were also mounted on the foundation gallery in Block Nos. 5 and 7   to excite the dam. The results obtained from this test are ploted in Fig. 4.

It is shown from the Fig. 4 that the results obtained from foundation exciting test are in agreement with those obtained from crest exciting tests. Some mode shapes of the former seem even to be better than those from the later.

As stated above, the maximum output force of one generator is 6^T. What is the deformation property of the dam body in resonance condition when the dam is excited by one or two vibration generators mounted on the crest ? What is the behaviour of the construction joints between blocks? In order to investigate the deformation characteristics of the dam at resonance, the displacement response of Block Nos. 5 and 7 was measured when vibration generator was located on the crest of Block No. 5 to excite the dam with various exciting forces at 4.8 cps. The measured results are ploted in Fig. 5. It is shown from the Fig. 5 that the deformation of the block is appearently in linear elastic state at resonant condition, excitation load vs. displacement is nearly in linear. The displacement responses measured on both sides of construction joint are ploted in Fig. 6. It is shown that in general

the displacements on both sides of the vertical joint are somewhat different at the lower frequencies and difference is a little more at higher frequencies than at lower frequencies.

Table I   Frequencies (cps) and Damping Ratios (%)

from the Field Test on Fengshuba Dam

(in upstream–downstream direction)

Record No.	Measured Values on Dam Body												Crane-house on Block 7		Block 13	
	F	D	F	D	F	D	F	D	F	D	F	D	F	D	F	D
3-18-02					6.2	1.2			8.1	3.8	10.0	1.3				
3-18-03									8.2	2.9						
3-23-01	4.9	4.5														
3-23-02			5.4	2.4												
3-23-03							7.4	2.8	8.2	4.0						
3-23-04											10.2	4.8				
3-26-01							7.2	3.2								
3-26-02	4.9	4.4	5.3	3.9	6.4	1.4							4.2	1.8		
3-27-01	4.9	3.7											4.2	2.0		
3-27-02					6.4	2.3										
3-27-03					6.3	2.0										
3-27-04	4.9	4.4	5.3	3.0									4.1	1.9		
3-27-05							7.2	3.1	8.1	3.4						
3-27-06							7.3	3.8								
3-28-02											10.0	1.3				
3-30-01			5.4	3.2	6.4	2.3	7.2	4.1	8.0	3.3	10.1	4.9				
3-31-01			5.4	3.2											4.6	2.1
4-04-02	5.0	4.1														
4-04-03	5.0	3.4														
4-05-02	4.9	3.4														
4-06-01	5.0	3.4			6.1	3.1										
4-06-02	4.9	3.1			6.1	3.1										
4-06-03			5.3	3.2												
4-06-04			5.4	2.7												
4-07-01	4.9	3.4														
4-07-03					6.1	1.8										
Average	4.9	3.8	5.3	3.1	6.3	2.3	7.3	3.1	8.1	3.5	10.1	3.1	4.1	1.9	4.6	2.1

Note: F — Frequency

D — Damping Ratio

DYNAMIC FINITE ELEMENT ANALYSIS

As stated above, Fengshuba Dam consists of three types of blocks, the configuration of the dam is complex, therefore the amount of computational effort is larger and the cost of computation is higher. In the analysis, the bedrock underlaying the dam is assumed to be rigid and the influence of water in reservoir is neglected; the concrete of the dam body is assumed to

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be homogeneous solid, the elastic modulus for the concrete materials was taken as 3×10^5 and 2×10^5 (kg/cm²), for dynamic and static analysis respectively, the concrete density as 2.4 T/m and Poisson's ratio as 0.167. The three mathematical models of the dam, namely three-dimensional model of the whole dam (Model I), plane stress model of single block (Model II), three-dimensional model of single block (Model III),were considered. For each model, eigenvalue computation, response spectrum analysis and static analysis for the dam have been performed by means of computer program SAP IV (2) on IBM - 4341 computer. The influence of elastic foundation and water in reservoir are intended for later stage. Only the results of eigenvalue computations are described below.

Model I: Three-dimensional Finite Element Idealization of the Whole Dam

For Model I, it is assumed that the whole dam is homogeneous and relative motion between blocks is neglected. The dam is divided into five layers along its height (in Y axis direction) and one to three layers along the upstream - downstream (in Z axis) direction. The total structure of the dam is discretized as thirty-one 8-node solid elements and four hundred and fifty-nine 21-node elements. Total number of nodes is 1549 and the number of equations is 3993. In order to present the actual situation of the dam,the configuration of the dam and its foundation, bollows in the blocks, and wide joints between blocks were modelled as really as possible. The first ten frequencies and corresponding mode shapes were determined for the Model I. These frequencies are listed in Table II. In order to save space,only the first four mode shapes are shown in Fig. 4.

Model II: Plane Stress Model of Single Block

The assumptions adopted in Model II and properties of the concrete materials are the same as above. Five blocks are computed by Model II. The number of nodes and elements is different for these elements, the largest number of node is 340 for Block 8, the least number of node is 183 for Block 14. The first ten frequencies computed from the five blocks are listed in Table II, respectively.

Model III: Three-dimensional Model of Single Block

Three blocks among five blocks stated above were computed by Model III. In computation, the half of each block is included because each one of these blocks is almost symmetrical about centre plane in upstream-downstream direction. The node number of finite element idealization among these blocks is 448 at most for Block 7 and 252 at least for Block 12. The first ten frequencies and their associated mode shapes were determined for the three blocks. These frequencies are also listed in Table II.

DISCUSSION AND CONCLUSIONS

From the results of field test on Fengshuba Dam, it may be seen that at small amplitudes of forced vibration although the small relative motions on both sides of joints between blocks exist, deformation properties of the dam are in linear limit of elasticity, the dam with wide joints behaves as vibration of an overall structure. As stated previously, the main assumptions

| Type of Model	Measured Values	Model I	Model II			Model III				
Block No.			7	8	12	5	7	8	12	14
Mode No. 1	4.9	5.317	4.074	4.835	4.532	5.27	4.74	4.82	4.49	4.85
2	5.3	6.073	8.942	10.32	10.66	10.62	9.39	10.57	10.59	10.70
3	6.2	7.168	9.533	11.30	11.54	12.76	10.7	11.76	11.83	13.38
4	7.2	7.475	9.558	11.45	11.82	19.44	17.0	17.89	18.89	18.20
5	8.1	7.542	16.88	17.15	18.89	24.28	20.3	22.97	26.68	27.90
6	10.1	7.576	19.26	22.36	26.37	29.66	23.9	24.87	27.81	31.95
7		7.626	19.90	22.66	26.46	31.48	25.6	27.42	30.35	36.67
8		7.662	20.48	23.16	27.28	32.36	29.9	30.04	33.73	38.55
9		8.219	25.75	29.01	32.47	35.88	30.5	30.94	35.66	39.80
10		8.715	27.74	31.69	38.63	39.87	32.6	33.66	39.61	43.52
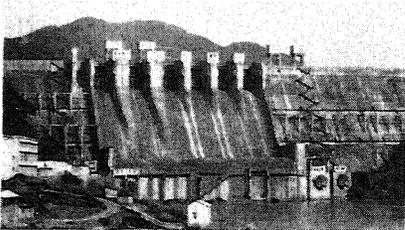
Fig. 1   Fengshuba Dam
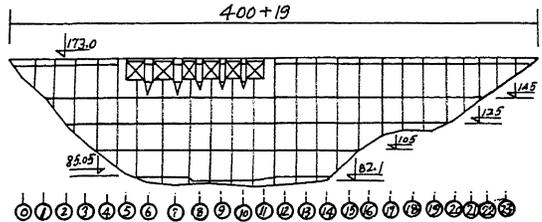
Fig. 2   Arrangement of measuring points

and the material properties adopted in computation are the same for three
mathematical models of the dam. However, it is shown from Table II that only
the results obtained from three-dimensional model of the whole dam, namely
Model I, near comparatively to those obtained from field tests. The first
three mode shapes obtained from Model I are agree with measured from field
tests, although the fourth to sixth modes computed are different from the
results of the field test in the amplitudes and phases. For the plane stress
model and the three-dimensional model of taller blocks (namely Model II and
Model III), the foundamental natural frequencies computed from these two
models are near to those obtained from field tests in general, but the higher
order frequencies from computation are by far larger in comparision with those
from the field tests. Of course, the mode shapes of the both two models are
not represented those of the dam. Thus, in view of the results of theoretical
models in agreement with results of the field test, a three-dimensional model
of whole dam is better appropriate to simulate dynamic behaviour for the dam
with wide joints.

It is suggested that at small amplitudes of motion a concrete gravity
dam is best idealized by a three-dimensional model and that at large enough
amplitudes a two-dimensional model appears to be the most appropriate model
(5). Up to the present, there are only a few strong earthquake records
obtained on concrete gravity dams, therefore dynamic behavior for concrete
gravity dam with wide joints is not well understood. If a concrete gravity dam
is not suffered from failure during a large earthquake, then interaction be-
tween blocks always exists. In addition, interaction of the dam-bedrock and

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the dam-reservoir still exist. Therefore, a concrete gravity dam with wide joints may behave as action of overall structure to a great extent under condition of strong earthquake. It is assumed that Model I may be improved if joint between blocks is simulated by some of special elements.

Finally, based on the results of the field test and the three mathematical models on Fengshuba Dam, some of elementary conclusions may be drawn as follows:

. The dynamic prototype tests of concrete gravity dam are necessary and meaningful for studying its dynamic behavior and improving its mathematical model further. The results from field test show that at small amplitudes of motion the deformation properties of the dam are within linear limit of elasticity and that in spite of small relative motion on both sides of the joints the dam is well modelled by Model I. From the point of view of mathematical model in agreement with experimental results the only Model I among the three models is suitable. If some of reasonable factors mentioned above are included and simulated, Model I may be improved further at large enough amplitudes of motion.

. From the results of field test on Fengshuba Dam, it may be seen that that average value of the damping ratios for the first six modes is 3.2%. This value is less than average value of Xinfengjiang Dam (6) and the specified value 5% in reference (7). It is meaningful _ for earthquake resistant design of the type of concrete gravity dam.

ACKNOWLEDGEMENTS

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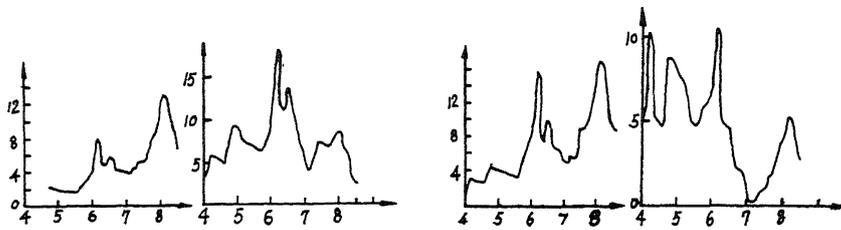7. Earthquake Resistant Design Code for Hydraulic Structures, China, 1982.

Fig. 3   Relations of displacement vs. frequency

Mode 1

Mode 2

Mode 3

Mode 4

——— test (exciting at crest)
– – – computation (Model I)
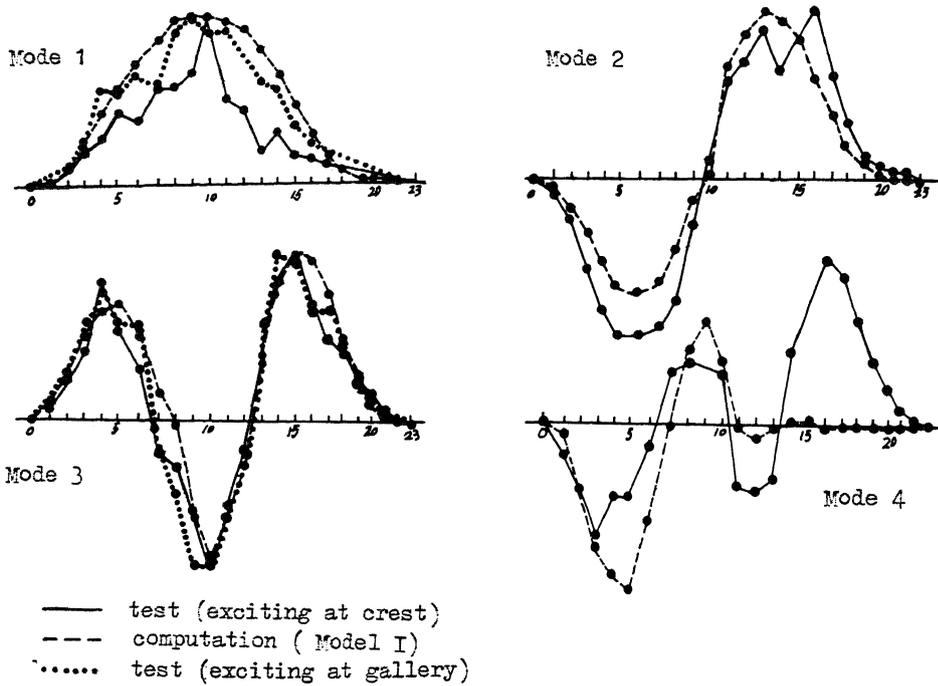······ test (exciting at gallery)
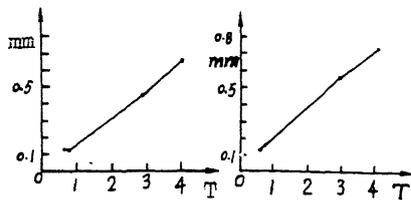
Fig. 4   Mode shapes

Fig. 5 Relations of exciting force
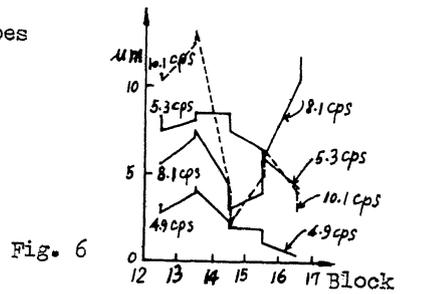vs. displacement (4.8 cps.)

Fig. 6

Displacement distribution
on both sides of
the construction joints

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