

Seismic response analysis of a filldam with three-directional input of earthquake motion

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ABSTRACT : A three-dimensional seismic response analysis with the mode superposition method is presented in this paper. A series of case studies of the analytical procedure was carried out applying the actual earthquake behavior observed at Fukada earthfill dam. The results from the P-S loggings were used to determine the elastic properties of the dam body. The damping factor of the lowest mode is assumed to be 5%, and 30 modes were used for superposition. Under these conditions, the analytical results revealed that the procedure introduced here could give a good estimation on eigen frequencies and response accelerations of the dam body.

1 INTRODUCTION

Many of present analytical methods on dynamic problems of filldams normally deal with two-dimensional cross section of a dam only. In these analyses with two-dimensions cannot predict the influence of abutments. Although actual dam body is of three-dimensional. In case of Japan, 60% of filldams are located on narrow valleys having low L/H ratio (length of the dam / height of the dam) of less than 5. Therefore, it was thought necessary to develop a practical three-dimensional seismic analysis procedure for filldams.

This paper introduces a three-dimensional seismic response analysis developed by the authors, with mode superposition method, and a series of case studies applied for the actual earthquake behavior of a filldam. In the case studies, the analytical results obtained with three-directional (upstream-downstream, left-right, up-down) earthquake waves input are compared with the observed earthquake motions of Fukada earthfill dam. The capability of the numerical procedure is verified by this comparison.

2 THREE-DIMENSIONAL MODE SUPERPOSITION METHOD

The dynamic equilibrium equation is basically written as

$$M\ddot{U} + C\dot{U} + KU = R, \quad (1)$$

where M is the mass matrix, C is the damping matrix,

K is the stiffness matrix, \ddot{U} is the acceleration vector, \dot{U} is the velocity vector, U is the displacement vector and R is the earthquake force vector. The approach to solve Eq.(1) is usually divided into two, i.e. the step-by-step integration method and the mode superposition method.

In case of three-dimensional seismic analysis of a large-scale structure like a filldam, the mode superposition method is more economical than the step-by-step integration method. The treatment of the mass matrix and the stiffness matrix, and the selection of the eigenvalue analysis are important in the mode superposition analysis of the three-dimensional structure, as they have great influence on its accuracy and efficiency.

In order to grasp the three-dimensional vibration of a filldam, a computer program (code name : POETICS) was developed taking above mentioned matters into consideration. The functions and the characteristics of POETICS are as follows;

1. 2D plane strain 2nd-order variable nodal point isoparametric element, 3D isometric 1st and 2nd-order variable nodal point isoparametric element are available.
2. Active column scheme is adopted in the treatment of global stiffness matrix.
3. Special mass lumping scheme, developed by Hinton and Owen (1980) is adopted in the calculation of the element mass matrix. In this scheme, the diagonal terms of the consistent mass matrix are scaled to preserve the total mass.
4. Subspace iteration method is adopted in the eigenvalue solver (see Bathe and Wilson (1976)).
5. Central difference method, Wilson θ method (see Wilson et. al. (1973)) and Newmark method (see Newmark (1959)) are available as a numerical integration of the modal equilibrium equation.

3 CHECK OF THE ANALYTICAL PROCEDURE BY SIMPLIFIED DAM MODELS

3.1 Analytical conditions

Analytical models are the pseudo two-dimensional model (2D model) shown in Fig.1 and the simplified three-dimensional model (3D model) shown in Fig.2. Both models have same cross section, and use the 3D 1st-order element. The 3D model has three longitudinal sections whose L/H values are 6, 4 and 2. The material properties were determined based on the material tests of the actual earthfill dam, i.e. the elastic modulus : 5000 kgf/cm², Poisson's ratio : 0.4, and the density : 2.0 t/m³.

The input wave in the analyses of these models was of a sine wave with a frequency of 2Hz and an amplitude of 20 gal. The input was acted on to upstream-downstream direction (y component of Fig.1, x component of Fig.2) only. The Newmark method was used in the calculation of the response, with a time step of integration of 0.005 sec and ignoring viscous damping.

The number of modes used in the mode superposition was set at 20 from the lowest mode, and total number of degrees of freedom in the 2D and 3D model was 108 and 309 respectively.

The thickness of the 2D model is thicker than the plain strain condition. However, the behavior of the 2D model was expected to be same as the plain strain condition, because the x-directional degrees of freedom of each nodal point were fixed.

3.2 Analytical results

The response acceleration time history at the dam crest of the 2D model is shown in Fig.3. The amplitude

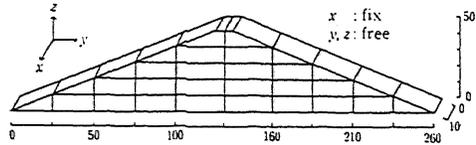


Fig. 1 2-D dam model with 3-D finite element

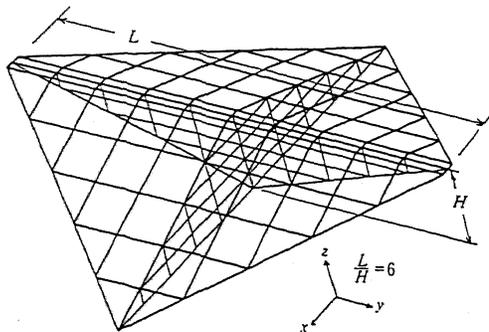


Fig. 2 3-D dam model

of acceleration appears to constantly increase as a result of the resonance. The response waves at the crest calculated by Wilson θ method and the central difference method were similar to the wave shown in Fig.3.

The response acceleration time histories at the crest in upstream-downstream direction are shown in Figs. 4, 5, 6. Along with the decrease of L/H from 6 to 2, the maximum value of acceleration amplitude appears to become low, and frequency of the wave high, gradually.

3.3 Accuracy and efficiency of the analyses

Two waves of response acceleration obtained from the superposition of 200 modes and 309 modes are also drawn in Fig.6. The result of the superposition of 309 modes is equal to the result obtained with the

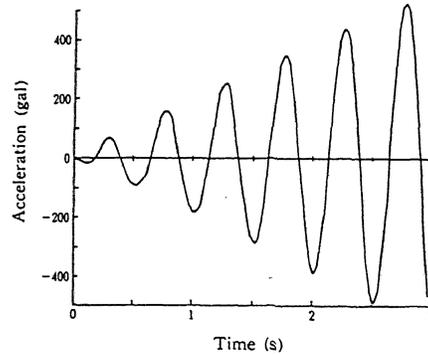


Fig. 3 Response acceleration at the crest nodal point (2-D dam model)

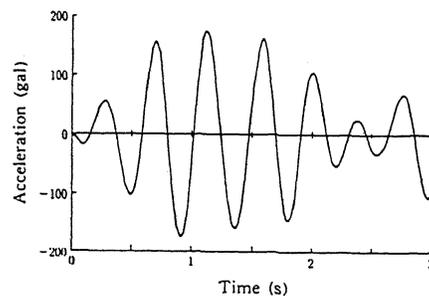


Fig. 4 Response acceleration at the crest center nodal point (3-D, L/H=6)

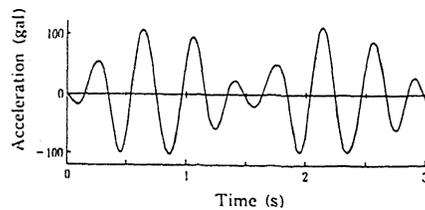


Fig. 5 Response acceleration at the crest center nodal point (3-D, L/H=4)

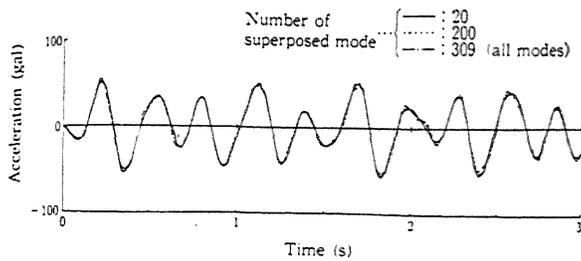


Fig. 6 Response acceleration at the crest center nodal point (3-D, L/H=2)

direct integration method in principle. The response wave of 309 modes almost overlapped with the response wave of 20 modes under the condition of $L/H=2$ in which the influence of high-order modes should be larger than other cases. It is found from these natures and trends, that the three-dimensional response of a dam could be predicted with satisfying accuracy by means of the mode superposition with small numbers of mode.

The cpu-times needed in the calculations of response analyses shown in Fig.6 were 3.2 minutes for 20 modes and 444 minutes for 309 modes for a computer whose MIPS-value was 15. It was become clear from this fact that the mode superposition with an appropriate numbers of mode is substantially economical.

4 EARTHQUAKE OBSERVATION OF FUKADA DAM

4.1 The dam profile

Fukada dam is a zoned-type earthfill dam, built for irrigation. It is 55.5m high and 340m long, the highest earthfill dam in Japan. The behavior of the dam during construction and first impounding has been summarized by Yasunaka et.al.(1985).

The materials of the embankment are weathered granite and weathered sandstone. A relatively clayey soil was used in the core zone, and a relatively granular soil was used in the shell zone.

Cross section of the dam is shown in Fig.7, and the plan in Fig. 8. Fukada dam has been instrumented with 3 strong motion seismographs and 10 accelerometers for earthquake observation. Each of the instrument can record three-directional accelerations of earthquake motion. The locations of them are also shown in these figures.

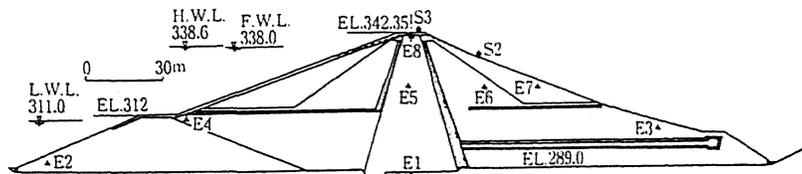


Fig. 7 Maximum cross section of Fukada Dam and location of seismographs

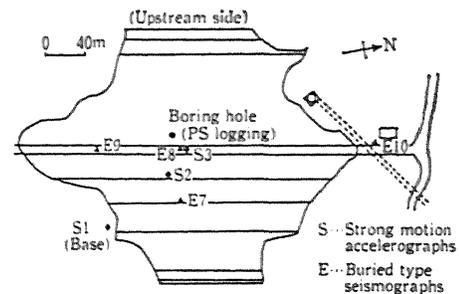


Fig. 8 Plan of Fukada Dam and location of seismographs

4.2 Results of the earthquake observation

The dam foundation experienced a seismic shock of 26 gal in the upstream-downstream direction during an earthquake occurred off-Ibaraki pref. in 1981, with Magnitude 7.0 and epicentral distance 189km. The seismograph on the dam crest (S3) recorded 128 gal in the same direction which was about 5 times the acceleration at the foundation. The records of the other components in the foundation (S1) were 19 gal in the left-right direction and 11 gal in the vertical direction. The magnification at the crest of both components was 3 and 4.4 times, respectively. The observed acceleration time histories at the foundation (S1) are shown in Fig.9.

Before this earthquake, the largest acceleration at Fukada dam had been recorded in 1978. The amplitude of acceleration at the foundation (S1, X) and the crest (S3, Y) was 35 gal and 210 gal respectively. It was reported by Tanaka and Yasunaka (1988) that the dam body had shown elastic behavior during this earthquake.

5 SEISMIC RESPONSE ANALYSIS OF FUKADA DAM UNDER THREE-DIRECTIONAL EARTHQUAKE MOTION INPUT

5.1 Analytical conditions

The finite element mesh for the analysis of Fukada dam is shown in Fig.10. The 1st-order isoparametric elements were applied to the model which had 288 nodal points, 299 elements and 498 degrees of freedom. During 10 seconds from second 5 of the acceleration records shown in Fig.9 were used as input waves for the analysis.

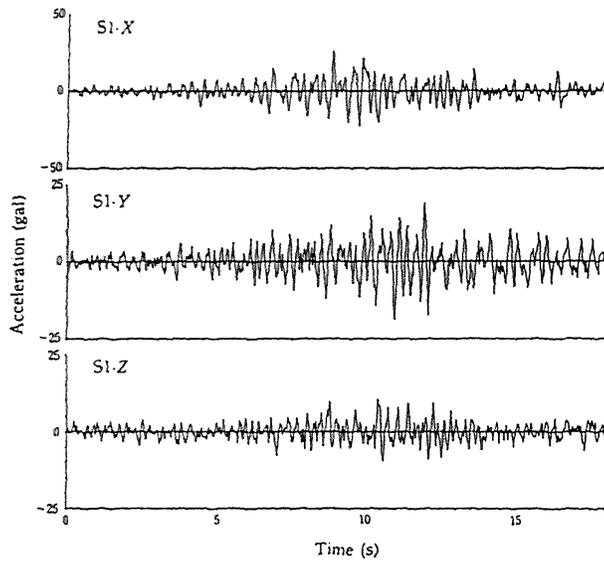


Fig. 9 Ground acceleration records of 1982 Off Ibaraki pref. Earthquake

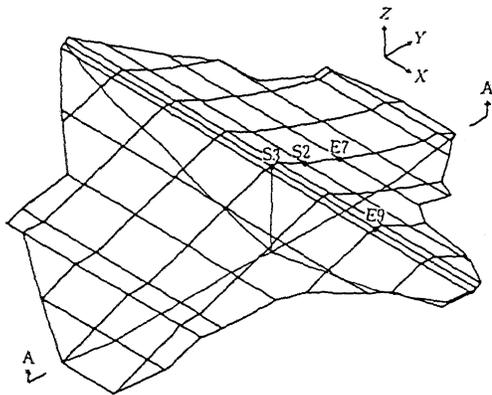


Fig. 10 3-D finite element mesh of Fukada Dam

Newmark method was applied to the integration scheme for the calculation of the modal responses, and the time step was set at 0.01 second in the integration. The number of modes for superposition was set at 30 from the lowest mode, on account of that the eigen frequency of 30th mode could cover almost entire range of predominant frequencies of the responses observed at the seismographs.

Elastic properties were obtained from the P-S logging. The results of the P-S logging at a boring hole located at almost the center of the dam are shown in Fig.11. In this figure, the dots indicate the reaching time of the elastic waves, and the solid and broken lines are the velocities of the waves. The elastic properties of the dam material were calculated by substituting the S-wave velocity (V_s) and the P-wave velocity (V_p) for the following well-known equations,

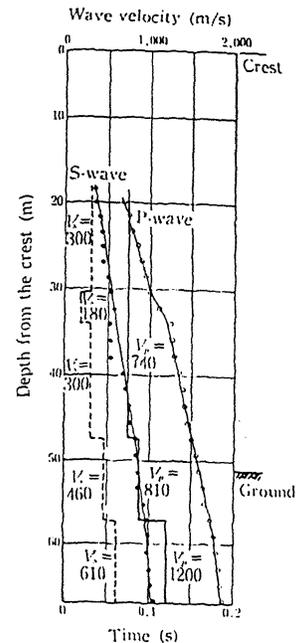


Fig. 11 Results of P-S logging (Boring hole)

$$\nu = \frac{2(V_s/V_p)^2 - 1}{2(V_s/V_p)^2 + 2} \quad (2)$$

$$G = \rho V_s / g \quad (3)$$

$$E = 2(1 + \nu)G \quad (4)$$

where ν is Poisson's ratio, G is the shear modulus, E is Young's modulus, ρ is the density (1.95 t/m^3) and g is acceleration of gravity (9.8 m/s^2). The average value of density during construction of Fukada dam was adopted as the density. The elastic properties were distributed as Fig.12 taking the results of the P-S logging into account.

The 1st and 2nd modal damping factors were assumed to be 5%. The other modal damping factors were calculated with the following equation,

$$\xi_i = \frac{\alpha + \beta \omega_i^2}{2\omega_i} \quad (5)$$

where ξ is Rayleigh's damping factor, ω is the eigen frequency and subscript i indicates the order of mode.

5.2 Analytical results

Eigen frequencies obtained from the analysis are shown in Table 1. It is understood that the vibrations other than that of the upstream-downstream direction appear to be of relatively low order in modes.

Response accelerations and their power spectra are shown in Fig.13, 14. The result of the response analysis

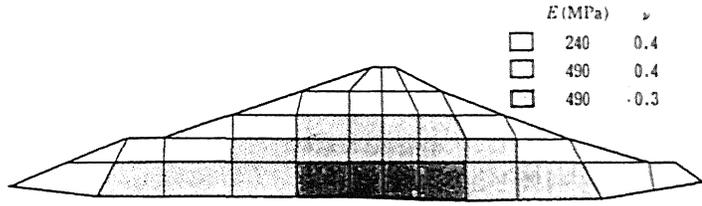


Fig. 12 Distribution of material parameters

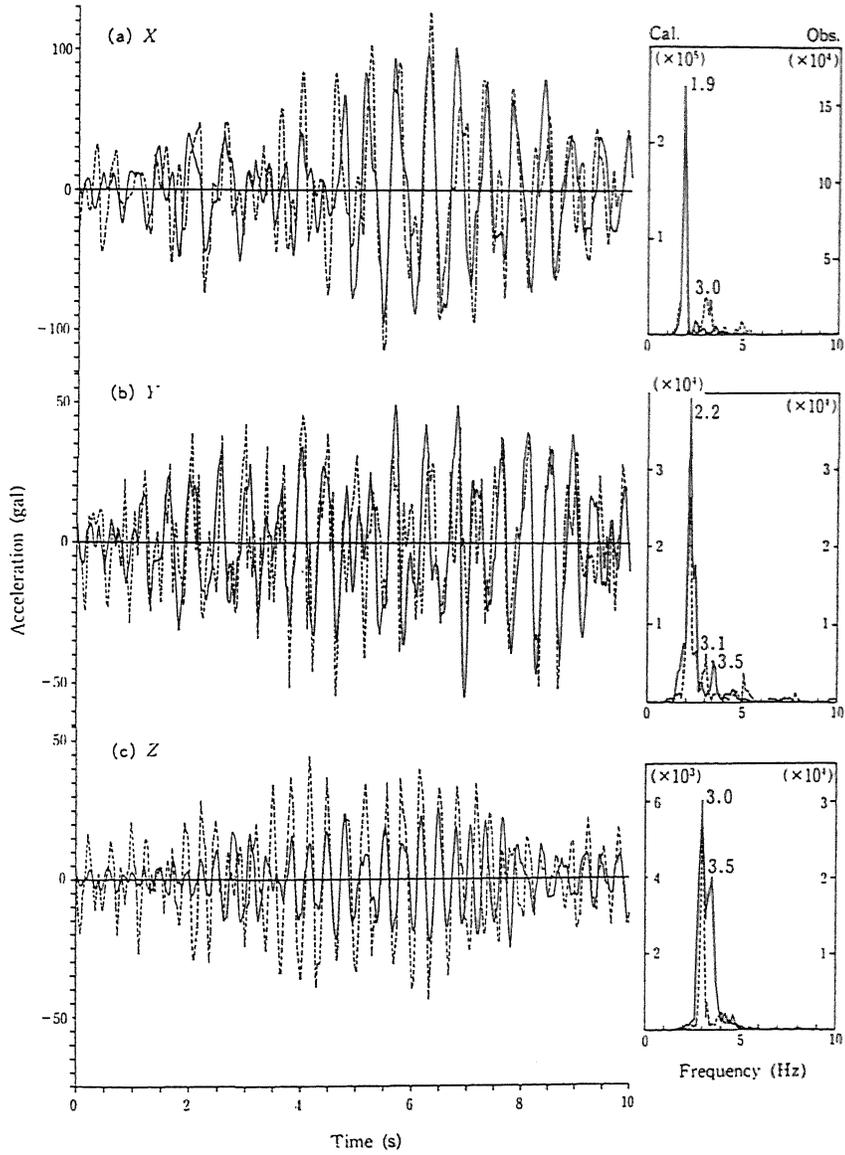


Fig. 13 Response acceleration and power spectra at S 3

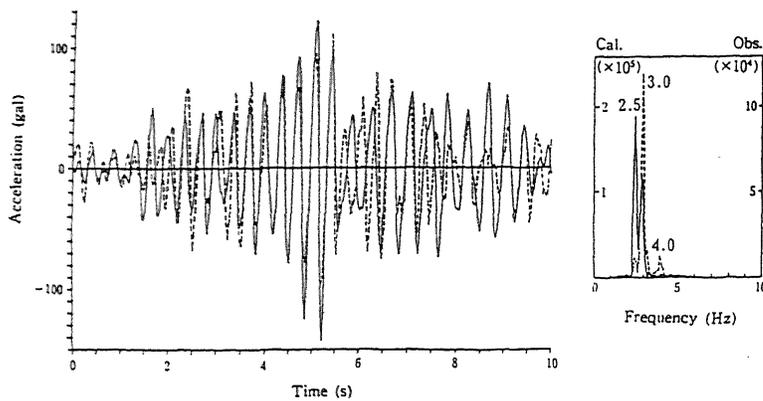


Fig. 14 Response acceleration and power spectra of upstream-downstream direction at E 9

Table 1 Eigen frequencies of Fukada Dam model

Mode	Eigen frequency (Hz)	Mode	Eigen frequency (Hz)
1	1.87 (X)	16	2.71
2	1.98 (X)	17	2.91
3	2.03 (Y)	18	2.95
4	2.14 (X)	19	2.97
5	2.38 (Z)	20	2.99
6	2.39	21	3.01
7	2.48	22	3.02
8	2.52	23	3.17
9	2.56	24	3.19
10	2.60	25	3.21
11	2.76	26	3.22
12	2.78	27	3.25
13	2.83	28	3.27
14	2.85	29	3.28
15	2.88	30	3.31

(X),(Y),(Z) : Predominant direction of each mode

was newly coded by the authors, in order to estimate the three-dimensional behavior of a filldam during an earthquake, and the case studies carried out have been presented in this paper.

The concluding remarks obtained from the investigations are summarized as follows;

1. The results of P-S loggings are adequate to estimate the elastic properties of dam materials.

2. The adequate number of modes for superposition can be determined by adopting the order of eigen frequency which cover almost entire range of predominant frequencies of the response waves.

3. The presented analytical procedure can predict the actual three-dimensional seismic behavior of a filldam with acceptable accuracy and practically applicable efficiency.

and the observation are indicated by the solid line and the broken line respectively in both figures. Fig.13 is for the response of the center of the crest (S3), and Fig.14 for the response of E9-point of the crest.

As concerns two horizontal responses (X and Y direction) at S3-point, the analytical results of the amplitude of acceleration and predominant frequencies showed a good agreement with the observed results. The analytical result of the amplitude of acceleration in vertical direction was relatively small, compared to the observed one.

The salient characteristic of the responses by this earthquake was the occurrence of large amplitude of acceleration at E9-point that was similar level to S3-point. The comparison between the calculated and observed responses at E9-point demonstrates this tendency clearly as shown in Fig.14.

6 CONCLUSIONS

The three-dimensional seismic response analysis which

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