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EARTHQUAKE OBSERVATION AND THREE DIMENSIONAL MODAL ANALYSIS OF A ROCK FILL DAM

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ABSTRACT

Earthquake behavior of the rock fill dam which is constructed at the complex valley topography of narrow ridge of left bank is observed by many observation points at the dam body and abutment. The maximum acceleration of longitudinal direction at the center of dam crest is often larger than that of up-downstream direction. In order to evaluate the distribution of the dynamic elastic properties in the dam body, the elastic wave tomography using PS logging is measured. S wave velocity distribution of the core in the longitudinal direction and of the transition and rock zone in the vertical direction is modelled. The three dimensional dynamic analysis by mode superposition is performed taking account of the distribution of elastic properties calculated by the modelling. The fundamental eigen value mode of the results of this analysis is the mode of longitudinal direction at the maximum cross section. This analysis conforms well the results of the observations.

KEYWORDS

Earthquake observation; Maximum acceleration; Elastic wave tomography; PS logging; S wave velocity distribution; Dynamic elastic properties; Three dimensional analysis; Dynamic analysis by mode superposition

INTRODUCTION

Many of the methods now used to study dynamic problems with dams are the two dimensional analysis calculating stability by applying only horizontal load in the up-downstream direction to maximum cross section of dam body. In those methods, then, the horizontal vibration in the longitudinal direction and the vertical vibration acting during an earthquake can not be accounted for. This means that the rational method of studying dynamic problems with dams that accounts for three dimensional shape of a dam body and for earthquake motion has not yet been established.

This paper is intended as an investigation of clarifying the earthquake behavior of a fill dam constructed at complex valley topography. To achieve this, this investigation falls into four processes. First, many seismometers were installed in one of that kind of fill dam. Secondly, to estimate the dynamic elastic properties of the dam body, elastic wave exploration was performed. Thirdly, to reflect the elastic properties obtained in this way in the dynamic analysis, the three dimensional dynamic elastic property distribution of the dam body was modelled. Lastly, to predict earthquake behavior, the three dimensional dynamic analysis by mode superposition method was performed by programming this elastic property distribution. In this way, the authors succeeded in clarifying and predicting the earthquake behavior of a fill dam.

EARTHQUAKE OBSERVATION METHOD

Dam Profile

The dam selected for an earthquake observation was Ohgaki Dam (H = 84.5m, L = 262m, rock fill dam). It has a unique topography and constructed on the coast of the Pacific Ocean where earthquakes relatively often occur. Fig.1, Fig. 2 and Fig.3 show respectively the topography and layout, the maximum cross section, and the longitudinal section. Each of these figures also shows the locations of the embedded seismometers, and the locations of the holes used for the elastic wave exploration. As Fig.1 clearly indicates, the dam is constructed on the valley of the old S-shaped river (foundation geology biotite granite), the left bank is situated in a narrow ridge, and the dam axis and the narrow ridge cross rectangularly. As Fig.3 reveals, the gradient of the left abutment is steeper than that of the right one, so that the dam shape is not symmetrical in the longitudinal direction. In these ways, Ohgaki Dam is distinguished by a complex and asymmetrical dam body shape. The locations of the embedded seismometers were selected considering this characteristic valley topography and the dam body shape.

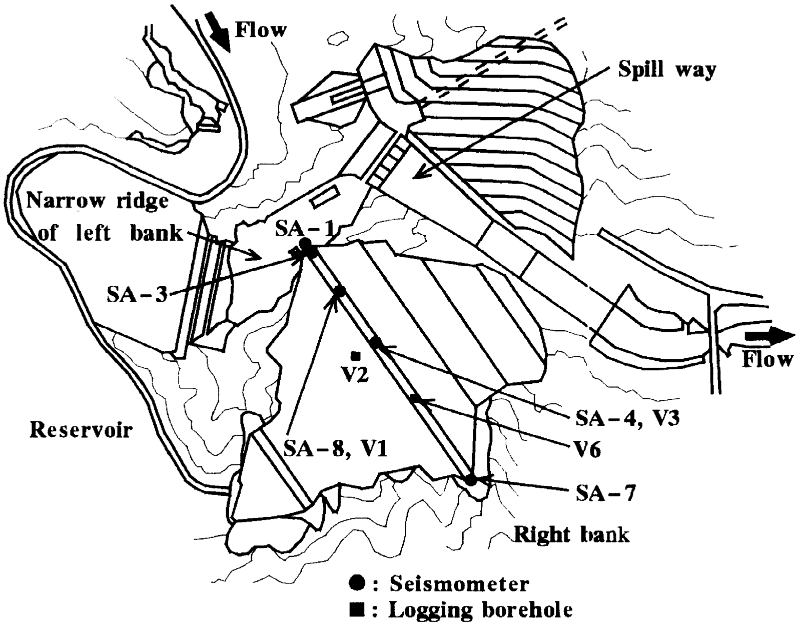


Fig. Topography and layout

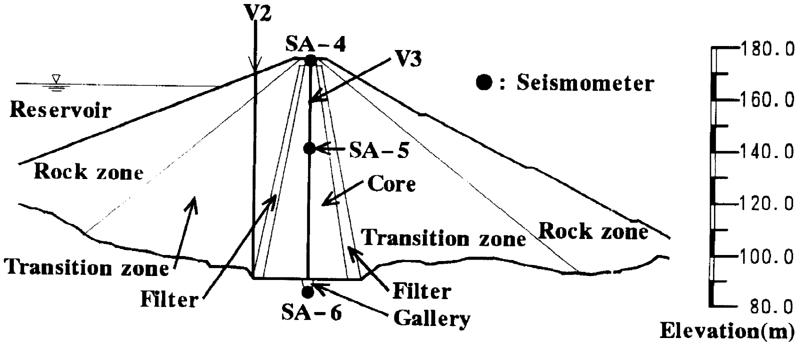


Fig. Maximum cross section

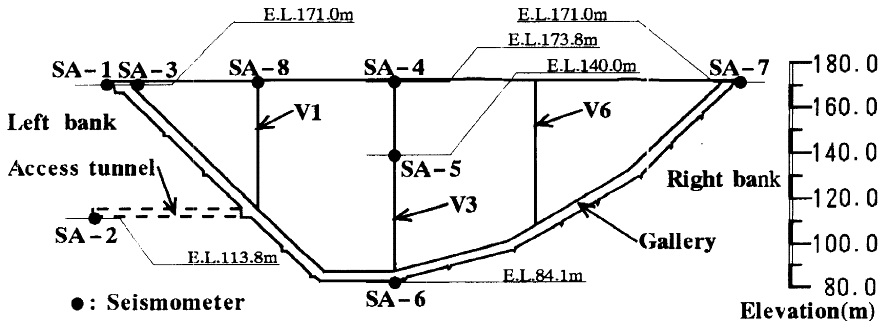


Fig.3 Longitudinal section

Results

Table 1 presents the maximum accelerations recorded at the observation points of the dam crest (SA-3, SA-8 and SA-4). The largest value of acceleration was 341.7Gal at SA-3 in the longitudinal direction. It was recorded at Off Fukushima Pref. Earthquake (1987.4.7) was recorded. The direction with the greatest maximum acceleration of the three directions at the various measurement points was frequently the longitudinal direction at SA-4 and almost always the up-downstream direction at SA-8. At SA-3, it appeared in both the directions. This means that in the dam crest of Ohgaki Dam, the dominant vibration was, in the longitudinal direction near the center, in the up-downstream direction near the left bank. Consequently, there were differences in the direction of the maximum acceleration at the observation points of the dam crest, demonstrating the complexity of earthquake behavior in this dam body.

Table 1 Maximum acceleration at the dam crest

	SA-3			SA-8			SA-4		
	X	Y	Z	X	Y	Z	X	Y	Z
1985.04.11	6.0	7.7	5.8	29.0	21.2	9.3	27.0	28.3	11.8
1985.05.11	27.9	19.2	20.5	51.9	33.5	17.4	37.1	39.6	36.8
1985.07.29	19.4	65.2	37.4	64.2	72.2	64.6	72.2	84.3	102.0
1985.08.12	45.3	37.3	28.0	47.8	64.7	39.3	52.4	86.8	67.9
1985.10.04	9.8	12.5	5.5	26.0	31.5	13.5	26.8	44.0	19.0
1986.07.10	19.5	21.9	12.3	36.2	32.2	14.4	28.1	53.8	24.4
1986.10.14	45.1	24.8	39.1	39.5	34.5	32.5	40.5	55.9	31.8
1987.02.06 [1]	29.5	21.0	19.5	66.5	39.0	21.0	46.5	70.1	45.5
1987.02.06 [2]	91.4	129.5	44.2	127.2	119.9	85.9	110.2	172.4	109.0
1987.04.07	196.5	341.7	222.9	278.9	210.9	208.2	121.1	308.9	145.2
1987.04.23	166.0	133.0	91.0	129.0	108.0	75.0	108.0	158.0	125.0
1993.01.15	13.9	17.8	6.7	43.6	27.8	11.4	18.5	32.6	16.8

Unit : Gal, X = up-downstream direction, Y = longitudinal direction, Z = vertical direction
Underline : the largest acceleration of the three points on the dam crest
1 : recording time = 21:24:27, 2 : recording time = 22:16:36

Fig.4 and Fig.5 show the relationships of the maximum accelerations in the up-downstream direction and the longitudinal direction at SA-4 and at SA-8 respectively. In both figures, the straight forty-five degree line passing through the zero point is an equivalent acceleration line when the maximum accelerations in the two directions are equal. When measurement value is above this line, the maximum acceleration in the longitudinal direction is greater than it is in the up-downstream direction, and when it is below, the situation is reversed. At SA-4, the maximum acceleration in the longitudinal direction is clearly greater than it is in the up-downstream direction. At SA-8 on the other hand, the maximum acceleration in the up-downstream direction is greater than it is in the longitudinal direction. These figures reveal that the maximum acceleration in the up-downstream direction is frequently the maximum value at SA-8. The maximum acceleration in the longitudinal direction on the other hand frequently appears at SA-4. This means that when the maximum acceleration at the dam crest was high, vibration in the longitudinal direction dominated near SA-4, and vibration in the up-downstream direction dominated near SA-8.

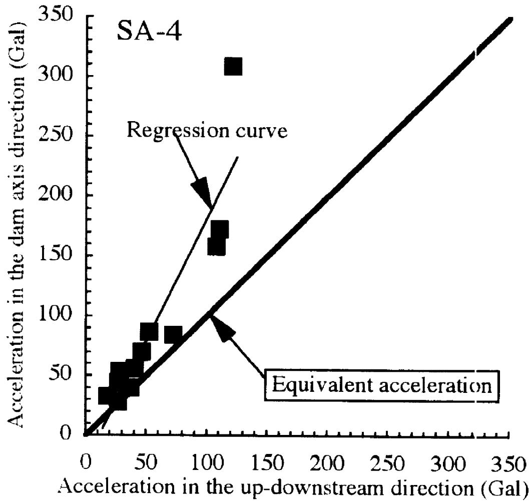


Fig. 4 Maximum accelerations in the up-downstream and the longitudinal direction (SA-4)

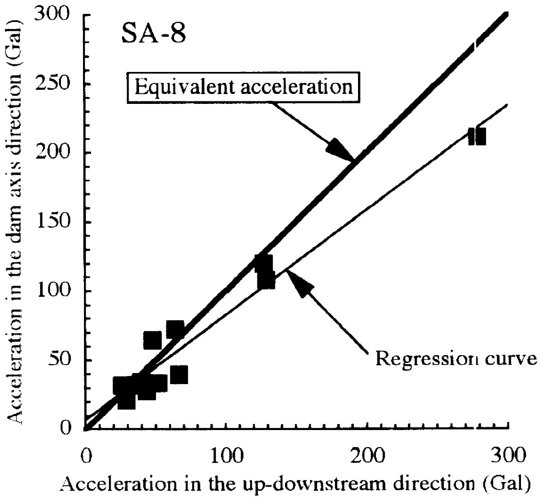


Fig.5 Maximum accelerations in the up-downstream and the longitudinal direction (SA-8)

It is generally assumed that the earthquake behavior at the dam crest is marked by the dominance of unconfined up-downstream direction vibration. But the earthquake observations at Ohgaki Dam clearly show that vibration in the up-downstream direction is not necessarily dominant at the dam crest, and that earthquake behavior marked by dominant longitudinal direction vibration does occur in parts of a dam crest. The earthquake behavior of a dam is more complex than being considered normally because of the effects of the shape of valley and of the dam body. The stability analysis which is based solely on the maximum cross section can not be used to assess earthquake behavior in the longitudinal direction. Consequently, it is necessary to take account of three dimensional earthquake behavior including the vibration in the longitudinal direction in order to perform rational safety assessment.

THREE DIMENSIONAL ELASTIC PROPERTIES OF DAM BODY

Elastic Wave Exploration

The dynamic modulus of elasticity of dam body are usually evaluated indirectly from the element tests of embankment materials such as triaxial compression test under repeated loading. Direct assessments of the elastic properties of a constructed fill dam are rarely done (Yasunaka et. al. (1992)). And the elastic properties of dam body have never been evaluated three dimensionally. The evaluation is necessary to assess the three dimensional earthquake behavior of a fill dam including the longitudinal direction. The elastic properties of the longitudinal section of the core and that of vertical direction of the rock and the transition zones of Ohgaki Dam were measured by PS logging. The PS logging of the core was done at the V3 hole shown in Figs. 1, 2, and 3. That of the rock and transition zones were done at the V2 hole. The V1, V3 and V6 holes were used to measure the S wave velocity in the longitudinal section of the core.

Results

Table 2 shows the results of the PS logging at hole V2. This table also shows the results of a PS logging done when the dam was constructed. Fig. 6 shows the S wave velocity distribution in the longitudinal section of the core. Fig. 6 indicates that S wave velocities up to 500m/s were distributed almost horizontally, but the nearer was a measurement point excavation line, the deeper the location where those in excess of 500m/s appeared. It is assumed from this result, that the S wave velocity distribution near the excavation is distributed in accordance with the shape of the excavation line.

Table 2 Dynamic elastic properties (hole V2)

Depth (m)	Vp (m/s)	Vs (m/s)	Poisson's ratio	G (MPa)	E (MPa)
0 ~ 12	2,000	700	0.430	1,060	3,010
	2,000	600	0.450	775	2,250
12 ~ 18	1,000	420	0.393	375	1,040
	2,000	460	0.472	449	1,320
18 ~ 22	1,000	420	0.393	375	1,040
	1,250	280	0.473	167	490
22 ~ 32	1,000	420	0.393	375	1,040
	850	250	0.452	132	385
32 ~ 40	700	340	0.346	245	660
	1,800	580	0.442	714	2,060
40 ~ 52	1,440	600	0.395	829	2,314
	1,800	520	0.454	623	1,810
52 ~ 68	2,300	500	0.475	576	1,700
	2,300	620	0.460	885	2,590

Upper values at the dam constructed (1986.5)
Lower values at this time (1991.5)

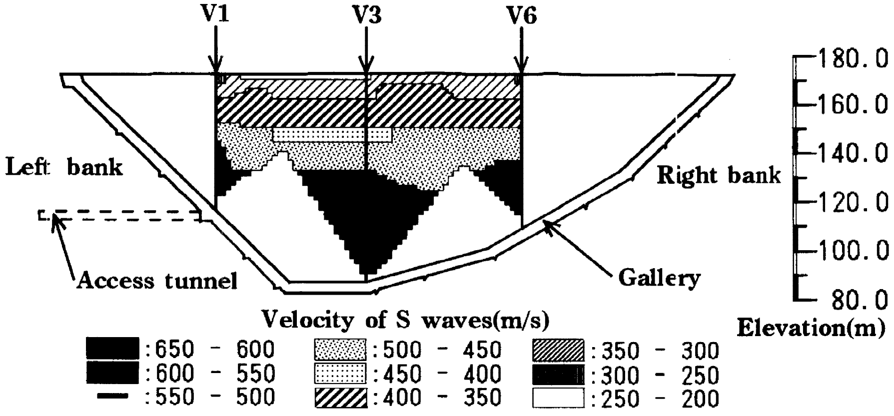


Fig.6 Distribution of S wave velocity

The term "depth ratio" can be defined as the dimensionless value (h/H) obtained by dividing the depth (h) of measurement points of S wave velocity by the height of dam (H). Fig.7 shows the changes of the S wave velocities for the three holes when the vertical axis is the depth ratio and horizontal axis is the S wave velocity.

This figure indicates that while the S wave velocity rises to a certain depth ratio, it does not increase very much over it. Changes in the simplified S wave velocity shown in Fig.8 were found from Fig.7. The changes in the S wave velocity shown in this figure are treated as a model of S wave velocity distribution. The model of S wave velocity distribution of the transition and rock zones was found from in the same manner.

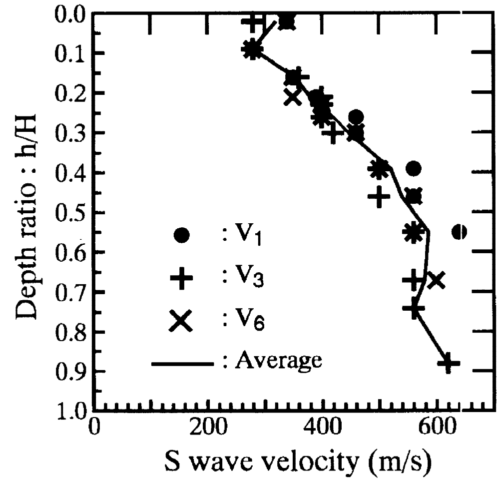
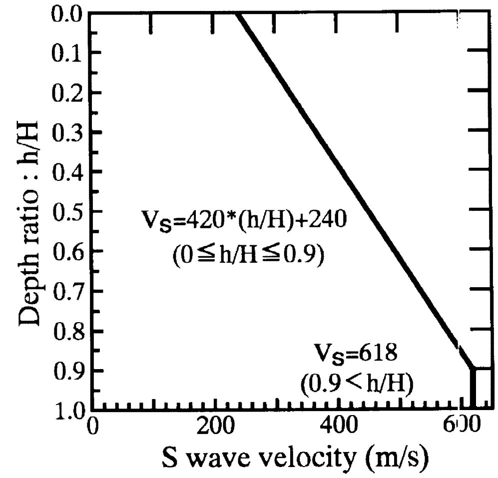


Fig. 7 S waves velocity at V1, V3 and V6 holes



$E = 0.2*(1+\nu)*\rho*V_S*(1/g)$

ν : Poisson's ratio
ρ : Density
g : Gravitational acceleration

Fig.8 Model of S wave velocity at the core

THREE DIMENSIONAL DYNAMIC ANALYSIS

Analysis Method

When the step-by-step integration method is used for three dimensional dynamic analysis of a large-scale structure like a fill dam, the amount of memory needed and the time required to complete the analysis increase as the number of nodes and the number of degrees of freedom rise. To settle these problems, therefore, a computer program by mode superposition method (code name: POETICS) was developed (see Yasunaka et. al. (1992)).

The dynamic modulus of elasticity in analysis was found by applying the model of S wave velocity distribution. The depth ratios for the center of gravity of each element were calculated in the program, and the S wave velocities of each element based on these depth ratios were also calculated by using the model of S wave velocity distribution. The dynamic modulus of elasticity at the core was determined from these S wave velocities based on the formula shown in Fig 8. The dynamic modulus of elasticity of the transition and rock zones was calculated in the same manner.

Results

Fig 9 shows the response waves in the up-downstream direction at SA-4. Fig 10 shows the eigen value modes obtained from the analysis. Fig 9 demonstrates that the maximum accelerations of the observations conform almost perfectly with those of the analysis. And the waves also do. Resonant frequencies of the analysis conform almost perfectly with those of the observations. It is correct to state that the results for the longitudinal direction conform with the resonant frequencies, but the absolute value of the power spectrum of the longitudinal direction was not reproduced so well. Fig 11 demonstrates that in the fundamental eigen value mode, the eigen value mode in the longitudinal direction is dominant. This conforms well with the observations which show that in many cases at Ohgaki Dam, the largest maximum acceleration at SA-4 was recorded in the longitudinal direction.

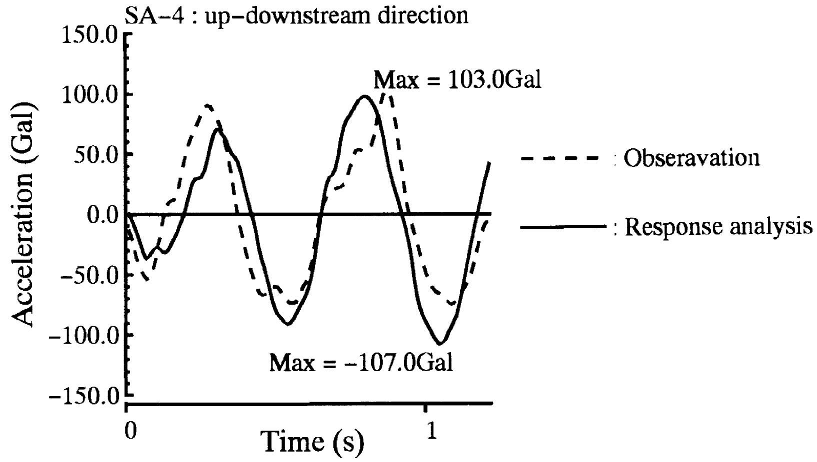


Fig.9 Response acceleration waves

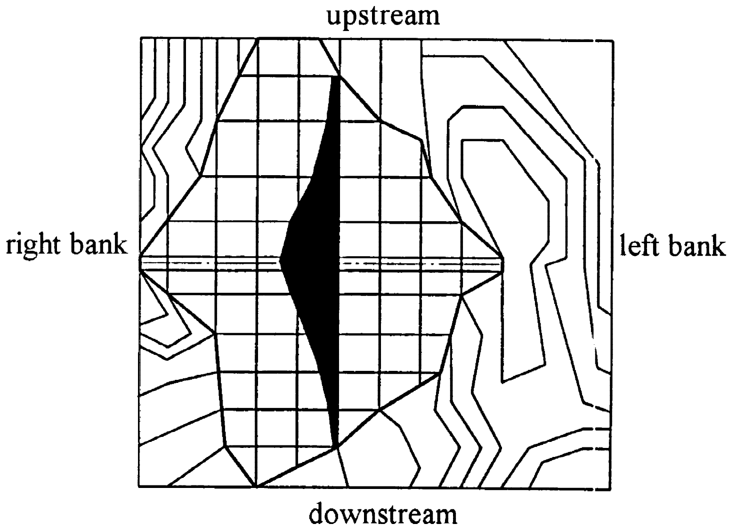


Fig.10 Secondary eigen value mode

The model of S wave velocity obtained at Ohgaki Dam were applied to another rock fill dam (Nishonai Dam: H = 86.0m) of the same size as Ohgaki Dam. Fig 12 shows the results of an analysis in the frequency zone (code name: FLASH). From this figure, it is believed that this model accurately represents the three dimensional dynamic modulus of elasticity of rock fill dams.

These results show that the analysis accurately expresses complex earthquake behavior. Consequently, three dimensional dynamic analysis that accounts for the three dimensional distribution of elastic properties in a dam body enable to predict the earthquake behavior of a dam including the vibration in the longitudinal direction.

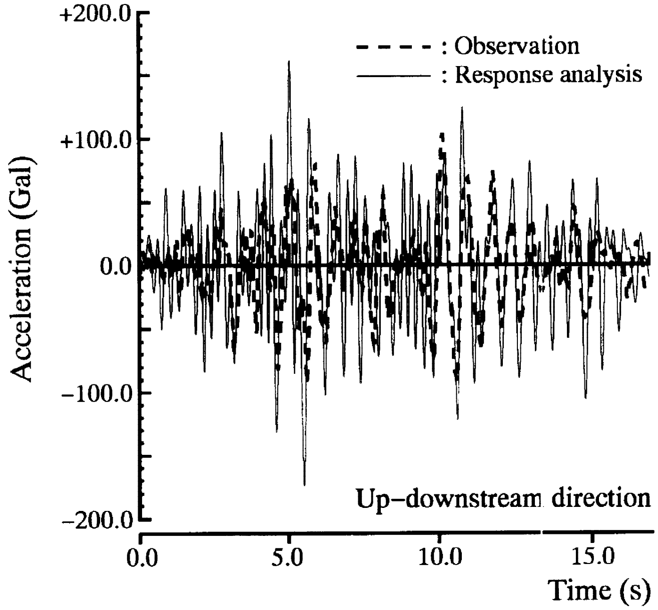


Fig.11 Response acceleration waves of Nishounai Dam

CONCLUSIONS

The authors have clarified that a fill dam constructed at a complex valley topography displays complex three dimensional earthquake behavior. The authors have prepared a model of the distribution of the elastic properties of the dam body. Furthermore, the results of three dimensional dynamic analysis that account for this model conform well with complex earthquake behaviors of a fill dam. For reasons mentioned above, the stability analysis for the maximum cross section can not be used to assess the stability of a fill dam during an earthquake. It must be performed by the three dimensional analysis taking account of the distribution of elastic properties at a dam body.

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