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Three-dimensional dynamic simulation analysis of existing arch dam

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ABSTRUCT: The dynamic simulation analyses based on the three-dimensional finite element method have been carried out to reappear the dynamic behaviour of existing arch dam during actual earthquake. Through the analyses, the varidity and reliability of three-dimensional finite element analysis technique for arch dam has been investigated by comparing the numerical analysis results with the seismological observation results.
In this paper, the Ikehara Dam (Nonsymmetric dome-shape arch dam, Dam hight:111m, Dam crest length:460m) is selected as the subject of analyses. Many cases of analyses have been executed assuming various analysis conditions. As the results of analyses, the numerical analysis values agreed comperatively well with the seismological observation values when the dynamic modulus of elasticity for arch dam was assumed to be 450,000kgf/cm² ,and the damping factor to be 5%.

1 INTRODUCTION

The arch dam is generally designed by the Trial Load Method. However, with the rapid improvement of calculation ability and memory capacity of computer and the higher development of numerical analysis program in recent years, the three-dimensional finite element analyses are come to be executed for the purpose of confirming the stability of arch dam. It has been expected that the optimum design of arch dam based on the three-dimensional finite element method will be put into practice in the near future. In order to realize it, it is considered that the accuracy and reliability of three-dimensional finite element analysis technique should be verified.

In this study, the dynamic simulation analyses based on the three-dimensional finite element method have been carried out for the purpose of reproducing the dynamic behaviour of existing arch dam during actual earthquake, and the appropriateness of three-dimensional finite element analyses for arch dam has been investigated.

2 OUTLINE OF IKEHARA DAM

In this paper, the Ikehara Dam is selected as an example of application to the three-dimensional dynamic simulation analyses.

The Ikehara Dam is a nonsymmetric domeshape arch dam constructed in 1964, which is located in Nara Prefecrure in the central part of Japan. The height of the Ikehara Dam is 111m. The crest length and the dam volume are 460m and 640,000m3 , respectively.

The foundation rock at the dam site is composed of the alternation of sandstone and slate which belongs to the Mesozoic formation. The acidid rock (Quarz Prophyry) has intruded into the foundation rock around the dam site. Consequently, the foundation rock is significantly influenced by the intrusive rock and comes to be very hard. The shear wave velocity of foundation rock at the dam site is considered to be around 2,000 ～2,500km/s.

3 SEISMOLOGICAL OBSERVATION AT THE IKEHARA DAM

The seismological observation at the Ikehara Dam has been made since 1964 for the purpose of grasping and making clear the seismicity around the site, the characteristics of earthquake motion at the site, the dynamic behavior of arch dam during earthquakes, and so forth.

The seismometers are installed at seven points in the Ikehara Dam as shown in Fig.-1.

As for the dam foudation , three measuring components of horizontal radial direction , horizontal tangential direction, and vertical direction are observed at three points, namely at the dam foundation, the left bank abutment, and the rigth bank abutment. And as for the dam body, one measuringnt component of horizontal radial direction is obserbed at four points on the dam body. (see Figure 1.)

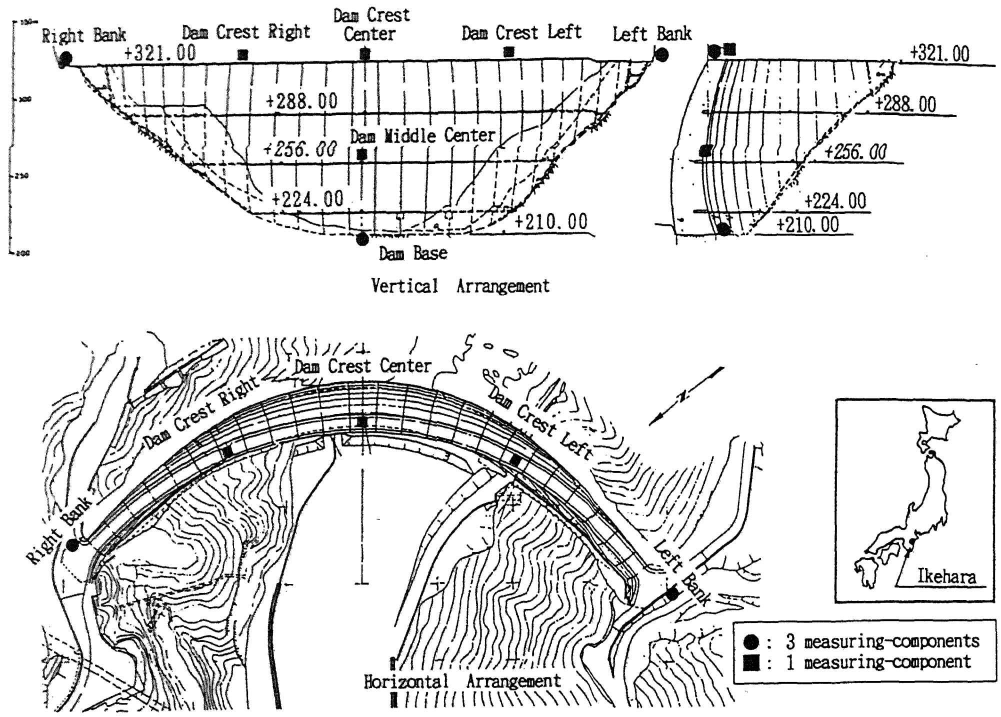


Figure 1. Location of seismological observation points at the Ikehara Dam

The seismometers have been renewed in 1986, and the diagram of seismological observation system at present is as shown in Fig.-2.

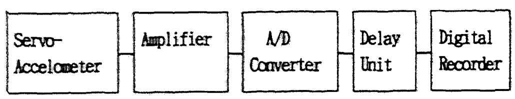


Figure 2. Seismological observation system at the Ikehara Dam

The outline of overall performance of the seismological observation system is shown in Table-1.

Table 1. Overall performance of seismological observation system at the Ikehara Dam

ITEM	PERFORMANCE
Measuring Range	0.1 ~ 1000 (gal)
Frequency Range	0.02 ~ 30 (Hz)
Delay Time	10.24 (sec)
Sampling Time	0.01 (sec)

At the Ikehara Dam, 33 earthquakes have been recorded during the period from 1964 to 1991. The relationship between hypocentral distance and magnitude of earthquakes oserbed at the Ikehara Dam is shown in Fig.-3. As is evident from the figure, the magnitudes of observed earthqaukes are rather small, which is roughly distributed from 3 to 6. The tendency that

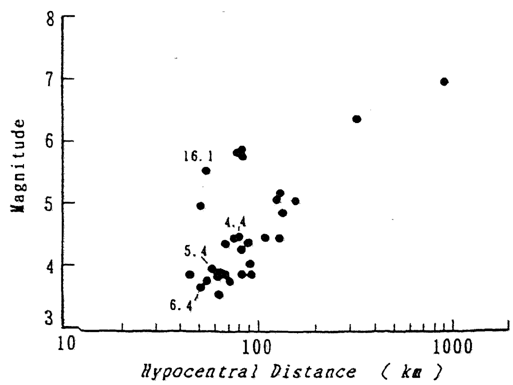


Figure 3. Relationship between magnitude and hypocentral distance concerning earthquakes observed at the Ikehara Dam. Numeral in the figure means the acceleration response ratio (Max.Acc at Dam crest / Max.Acc at Dam base)

the acceleration response magnifications of the dam change according to the magnitude and hypocentral distance can be recognized. The acceleration response of arch dam is considered to be largely influenced by the frequency characteristics of earthquake motion.

4 EARTHQUAKE EVENT FOR ANALYSIS

The earthquake event which occurred on 12 April 1987 was chosen as the object for the three-dimensional dynamic simulation analyses in this paper. The epicenter of the earthquake is 33.83°N, 136.38°E. The magnitude and the focal depth are 4.0 and 39 km, respectively.

Main features of the earthquake, and the maximum amplitudes of acceleration recorded at the Ikehara Dam are listed in Table-2. The maximum amplitude of acceleration in the horizontal radial direction recorded at the dam base is 2.4gal, and 12.8gal at the dam crest center.

Table 2. Main features of earthquake occurred on 12 April 1987, and seismological observation records at the Ikehara Dam

Date	1987 4 12 03:47:47	
Epicenter	33.83°N , 136.38°E	
Magnitude	4.0	
Focal Depth	39 (km)	
Hypocentral Distance	58.2 (km)	
Maximum Acceleration at the Ikehara Dam		
CH. (Location)	(Direction)	(gal)
1 Dam Base	Radial	2.4
2 Dam Base	Tangential	1.9
3 Dam Base	Vertical	1.6
4 Right Bank	Radial	3.3
5 Right Bank	Tangential	2.1
6 Right Bank	Vertical	1.3
7 Left Bank	Radial	2.0
8 Left Bank	Tangential	2.0
9 Left Bank	Vertical	1.8
10 Dam Crest (Right)	Radial	9.1
11 Dam Crest Center	Radial	12.8
12 Dam Crest (Left)	Radial	10.3
13 Dam Middle Center	Radial	3.5

The earthquake motions (acceleration time-history) in regard to the horizontal radial direction recorded at the Ikehara dam on 12 April 1987 are shown in Fig-4.

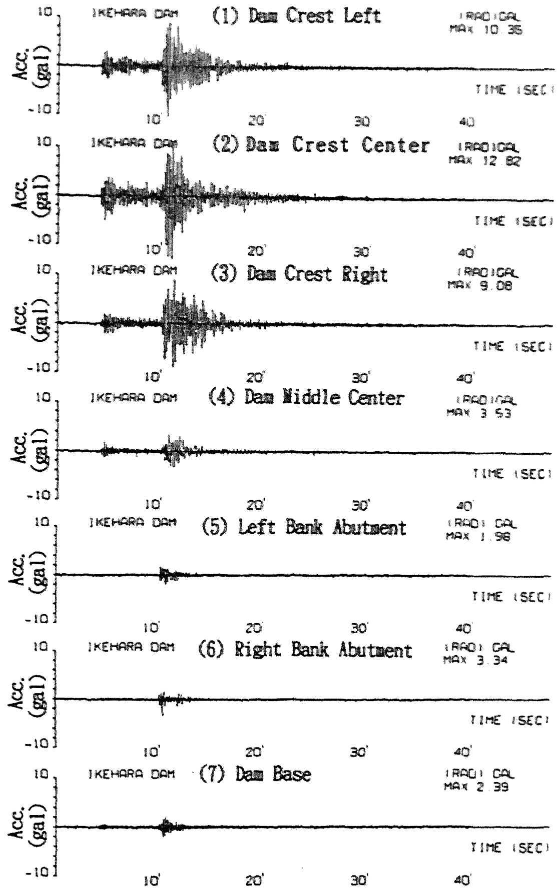


Figure 4. Earthquake motions in horizontal radial direction recorded at the Ikehara Dam on 12 April, 1987

5 DYNAMIC SIMULATION ANALYSES BASED ON THREE-DIMENSIONAL FINITE ELEMENT METHOD

5.1 OUTLINE OF ANALYSIS

The stability of arch dam is greatly affected by the discontinuities or weak zones within the foundation rock. Accordingly, it can be considered to be necessary to model not only the dam body but also the foundation rock in the practical design of arch dams. By Taking this point into account, the three-dimensional finite element models including dam body and foundation rock were made.

The actual earthquake motion recorded at the dam base of the Ikehara Dam was used as input earthquak motion for the three-dimensional dynamic simulation analyses.

The comparison of seismological observation results with numerical analysis results were made regarding the natural frequency of dam, the acceleration response, the power spectrum ratio , and the wave form of acceleration time-history.

Since the amplitudes of acceleration of recorded earthquake motions were very small, the linear dynamic analyses were carried out without considering the dynamic nonlinearity in regard to dynamic shear modulus and damping factor. The computrer program "SAP-6" was used , and the mode superposition method was applied. The first 30th mode were selected for the analyses.

5.2 THREE-DIMENSIONAL FINITE ELEMENT MODELS

The three-dimensional finite element meshes were made for not only the arch dam body but also the foundation rock in order to analyse the arch dam-foudation rock system.

As for the foundation rock , the range of 1135m in the up-downstream direction and 855m in the left-rigth bank direction was set up for the analysis region and 8-node solid elements were used. The three-dimensional finite element mesh used in this study is shown in Fig.-5.

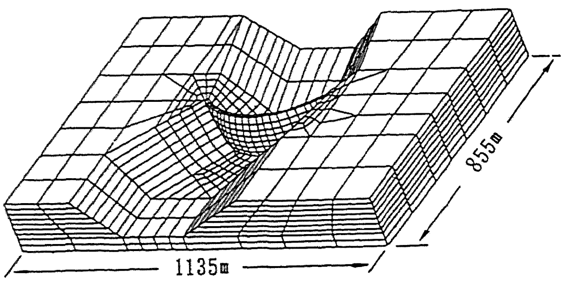
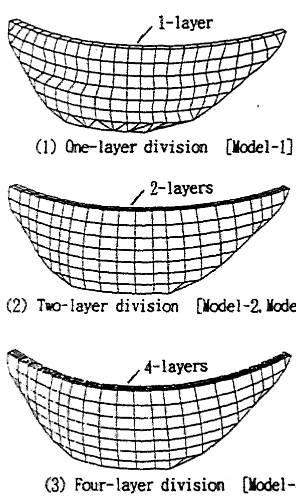


Figure 5. Three dimensional finite element mesh used in the analyses



(1) One-layer division [Model-1]

(2) Two-layer division [Model-2, Model-3]

(3) Four-layer division [Model-4]

Figure 6. Mesh division for dam body

As for the dam body , four kinds of finite element mesfes were made as shown in Fig.-6 in order to check and examine the appropriatness of division of finite element mesh. The dam body was modeled by using 8-node solid or 20-node isoparametric element.

Outline of four kinds of analysis models is shown in Table-3.

The horizontal up-downstream direction was assumed as the vibration direction. The rigid boundary was assumed for the bottom boundary, and the horizontal roller-support in the vibration direction was assumed for the side boundaries.

Table 3. Three dimensional finite element mesh used in the analyses (Whole Model)

Analysis MODEL	Mesh Division of Dam Body *1	Element Type	Elements		Nodes	
			Dam	Total	Dam	Total
Model-1	1 layer	8-Node Solid	129	393	274	719
Model-2	2 layer	8-Node Solid	224	1221	378	1730
Model-3	2 layer	20-Node Isoparametric	224	1221	1244	2596
Model-4	4 layer	8-Node Solid	448	1676	635	2248

[NOTE] *1: Dvision in the upstream-downstream direction

5.3 DYNAMIC PROPERTIES

The property values for analyses concerning dam body and foundatioin rock were assumed as shown in Table-4.

The dynamic modulus of elasticity of dam was assumed to be 450,000kgf/ cm^2, and the damping factor to be 5%.

Table 4. Property values assumed for analyses

Property	Dam	Rock
Unit Weight (tf/m3)	2.3	2.6
Dynamic Elastic Modulus(kgf/cm2)	450000	450000
Dynamic Poisson's Ratio	0.2	0.3
Damping Factor (%)	5	5
P-Wave Vlocity (m/s)	3500	4100
S-Wave Vlocity (m/s)	2100	2150

5.4 HYDRODYNAMIC EFFECT

The hydro-dynamic effect by reservoir water was estimated as the added mass evaluated by Westergaard's equation. The reseroir level when the earthquake occurred on 12 April 1987 was EL+292.00m.

5.5 INPUT EARTHQUAKE MOTION

The actual earthquake motion of first 20(sec) recorded at the Ikehara dam was used as input eaerthquake motion. The earthquake motion is deconvoluted from the dam base to the bottom of analysis model , and then the deconvoluted earthquake motion was propagated from the bottom boundary.

5.6 ITEMS FOR COMPARISON

The comparison of the numerical analysis results with the seismological observation results was made by concentration on the items mentioned below.

① Maximum Ampliude of acceleration
(Dam base~Dam crest center)

② Wave form of accelerarion time-history
(Dam base~Dam crest center)

③ Power spectrum ratio : R(f)
(Dam crest center/Dam base)

④ Natural frequency of dam

The natural frequency of dam was estimated based on the power spectrum ratio. The power spectrum ratio is defined as described below

$$R(f) = PA(f) / PB(f)$$

RR(f) : Power spectrum ratio
f : Frequency
PA(f) : Power spectrum of earthquake motion at the dam crest center
PB(f) : Power spectrum of earthquake motion at the dam base

5.7 ANALYSIS RESULTS

The natural frequency of the Ikehara Dam is evaluated to be 3.10Hz according to the earthquake event occurred on 12 April 1987.

On the other hand, the results of eigenvalue analyses are as shown in Table-5.

Table 5. Natural frequency evaluated by eigenvalue analyses

FEM Model	Natural Frequency (Hz)					
	1st	2nd	3rd	4th	5th	30th
Model-1	2.64	2.73	3.65	3.70	3.80	5.63
Model-2	2.56	2.70	2.82	2.89	3.54	6.12
Model-3	2.56	2.72	2.82	2.89	3.54	6.10
Model-4	2.53	2.69	2.82	2.89	3.56	6.18

The calcurated earthquake motions and power spectrum ratio correspond to the analysis model-1, -2, -3, -4 are shouwn in Fig.-7, -8, -9, -10, respectively. In the same way, the

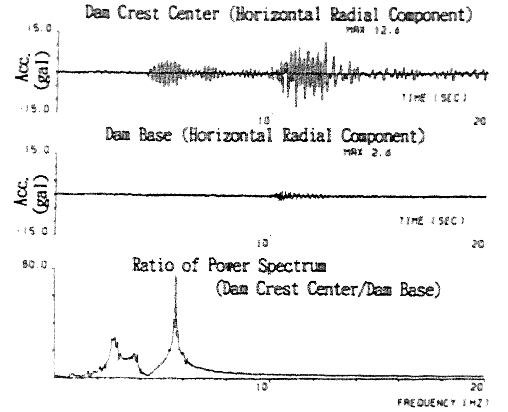


Figure 7. Anslysis result regarding the case of Model-1 (1-layer division, 8-node solid element)

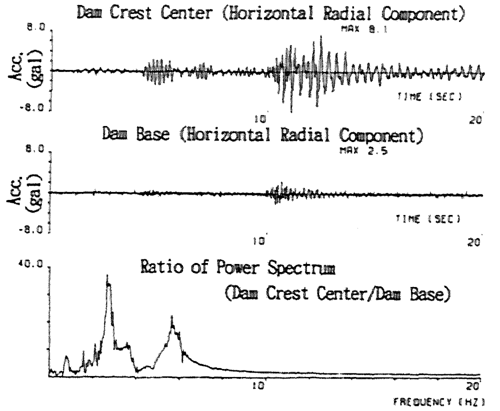


Figure 8. Anslysis result regarding the case of Model-2 (2-layer division, 8-node solid element)

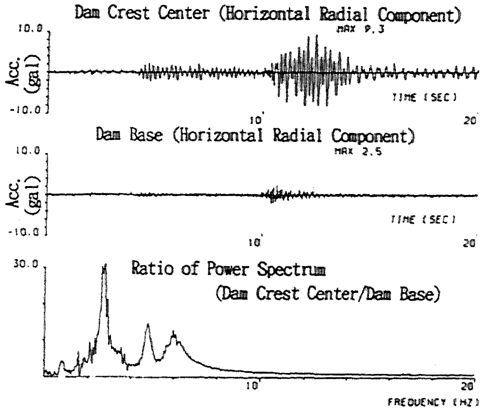


Figure 9. Anslysis result regarding the case of Model-3 (2-layer division, 20-node iso-parametric element)

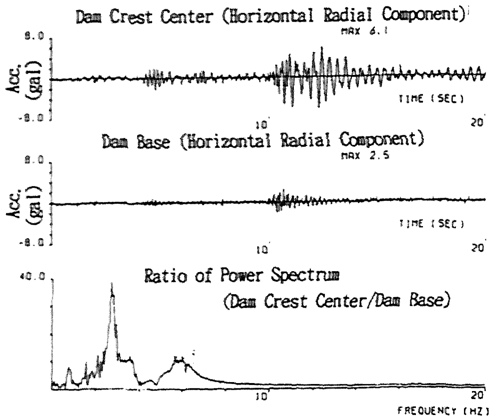


Figure 10. Anslysis result regarding the case of Model-4 (4-layer division, 8-node solid element)

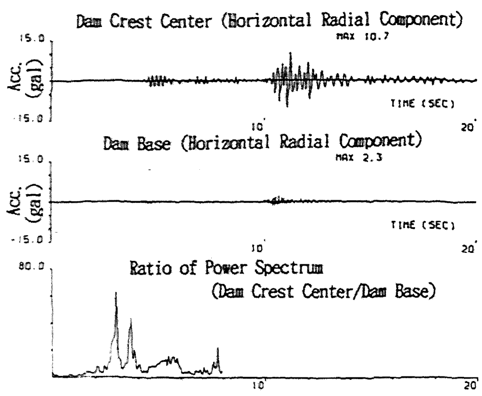


Figure 11. Seismologocal observation results. Frequency component higher than 8Hz was cut off to equalize frequency range as analyses.

Table 6. Comparison of seismological observation results and three-dimensional dynamic simulation analysis results

CASE	Natural *3 Frequency of Dam(Hz)	Max. Acceleration at Dam Crest Center (gal) *4	Acceleration Response *5 Magnification
Observed Value *1	3.10	12.8	5.3
Observed Value *2	3.10	10.8	4.3
Analysis Model-1	2.75	12.6	4.8
Analysis Model-2	2.65	8.1	3.2
Analysis Model-3	2.71	9.3	3.7
Analysis Model-4	2.69	6.1	2.4

[NOTE]
*1: Original observed result
*2: Modified observed result (Cut off frequency components higher than 8Hz to set up equivalent frequency range as analyses)
*3: estimated based on power spectrum response ratio : R(f)
*4: Horizontal radial component at dam crest center
*5: Ratio of maximum acceleration(Dam crest center / Dam base)

seismological observation result is shown in Fig.-11. The comparison of of seismological observation result and three-dimensional dynamic simulation analysis results are summarized in Table-6. Some differences are recognized concerning the acceleration response of dam according to the analysis models. However, the remarkable differences are not recognized concerning the natural frequency of dam.

The quantitative results obtained through the analyses are as follows.

The natural frequency of the arch dam is mainly controlled by the dynamic modulus of elasticity of dam and reservoir level. The acceleration response of the dam is mainly affected by the value of damping factor of dam. The acceleration of earthquke motion becomes large when the value of damping factor is assumed to be very small. But in this case, the vibration with a certain frequency comes to be conspicuous ,and the earthquake motion at dam crest tends to show harmonic wave form.

6 CONCLUSIONS

Three-dimensional dynamic simulation analyses for the existing Ikehara Dam were carried out in order to reproduce the behabiour of arch dam during actual earthquake by assuming various analysis conditions. The numerical analysis results agree comperatively well with the seismological observation results when the dynamic modulus of elasticity of the arch dam was assumed to be 450,000kgf/cm2 and the damping factor to be 5%.

However, it should be noiced that the analysis results introduced here are one of the po-ssible solution. It is considered that the appropriateness of the results should be invesitigated in more detail.

In verifying the the appropriateness of the results, two kinds of approaches are considered to be effective. One is the approach to examine the appropriateness of dynamic property values. The other is the approach to examine the appropriateness of analysis technique.

In general, the result of three-dimensional finite element analysis is greatly affected by the division of finite element mesh, boundary condition, dynamic modulus of elasticity (or shear wave velocity), damping factor, wave impedance ratio, analysis method(Step-by-step method, Mode superposition mthod, Complex fre- quency response method), analysis frequency, analysis mode, and so forth.

The investigation on the validity of dynamic modulus of elasticity, damping factor , nonlinear effect 、 analytical treatment of discontinueity will be continued in more etail.

Besides, the comperative analysis by using computer program "ABAQUS" will be carried out.