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REPRODUCTION ANALYSIS OF REAL BEHAVIOR OF EXISTING ARCH DAM DURING THE 1995 HYOGOKEN-NANBU EARTHQUAKE

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SUMMARY

During the 1995 Hyogoken-Nanbu Earthquake, the earthquake motion of maximum acceleration of 82.3gal(cm/s^2) was observed at the Ikehara Arch Dam, which is located in the Kii Peninsular in the western part of Japan. The Ikehara Dam is a non-symmetric dome-shape arch dam, whose height and crest length are 111m and 460m, respectively.

In regard to the dynamic analysis, the values of dynamic deformation properties of dam and foundation will have significant effects upon the dynamic stresses and strains calculated by the analysis. For this reason, in order to improve the accuracy and reliability of evaluation about the earthquake safety of dams, the dynamic deformation property values of dam and foundation should be qualitatively evaluated based on the real phenomena.

Therefore, we made 3-D reproduction analysis in regard to the real earthquake behavior of the Ikehara Dam during the 1995 Hyogoken-Nanbu Earthquake by using the 3-D coupled dam-foundation-reservoir system model. And we evaluated the dynamic deformation property values of dam and foundation quantitatively.

As the results, the dynamic shear modulus and the damping factor of the dam were evaluated to be 13,500N/mm^2 and 2%, respectively. Similarly, the dynamic shear modulus and the damping factor of the foundation were evaluated to be 11,700N/mm^2 and 3%, respectively.

In this case, as the level of earthquake motions is not so large, the real behavior can be well reproduced by the linear analysis, not by the nonlinear dynamic analysis. In case of very strong earthquake motions, it is considered that the nonlinear dynamic analysis taking not only the non-linearity of dam material but also the discontinuous behavior of joints should be taken into account.

INTRODUCTION

One of the most important structures of civil engineering facilities in the electric power industry is dams, whose earthquake stability is vital to downstream urban areas and the relevant economic activities. As for the concrete arch dams, the dam was generally designed by the trial load method and constructed in the past. With the rapid improvement of calculation ability of computer and the higher development of numerical analysis techniques in recent years, a 3-D dynamic analyses have come to be applied to the earthquake safety evaluation of existing dams. However, the dynamic stresses and strains calculated by the dynamic analysis

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will be greatly changed according to the values of dynamic properties of dam and foundation. Among the dynamic properties, the dynamic shear modulus and the damping factor are most important. So, the dynamic property values of dam and foundation, especially the dynamic shear modulus and the damping factor, should be qualitatively evaluated based on the real earthquake behavior, in order to realize the accurate and reliable evaluation for the earthquake safety of dams. Many studies have been carried out on the earthquake stability and the dynamic analysis method for arch dam thus far. In the field of numerical analysis, some analysis methods have being developed, Clough[1],Watanabe[2]. However, a 3-D dynamic analysis method which can qualitatively treat the interaction among dam and reservoir and foundation, the energy dissipation and inflow between foundation and semi-infinite free field, the discontinuous effects of joints and the nonlinear effects of dam materials has not been well realized. Furthermore, a study based on the actual earthquake observation at the actual dam is few. From these necessities, a 3-D nonlinear dynamic analysis method (program "UNIVERSE") for a coupled dam-joints-reservoir-foundation system has been developed, Ariga[3].
We made a 3-D reproduction analysis in regard to the actual earthquake behavior of the Ikehara Arch Dam during the 1995 Hyogoken-Nanbu Earthquake by using a 3-D coupled dam-foundation-reservoir system model. And we evaluated the dynamic deformation property values of dam and foundation quantitatively. The results of the reproduction dynamic analysis of the existing Ikehara Arch Dam during the 1995 Hyogoken-Nanbu Earthquake are described in this paper,.

EARTHQUAKE OBSERVATION AT THE IKEHARA ARCH DAM

Outline of the Ikehara Dam

The Ikehara Dam is a non-symmetric dome-shape arch dam constructed in 1964, which is located in the Nara Prefecture in the western part of Japan. The height of the dam is 111m, and the crest length and the volume are 460m and 640,000m^3, respectively. The location and the panorama view of the Ikehara Dam are shown in Figure 1 and Figure 2, respectively. Figure 3 shows the shape of the Ikehara dam and the arrangement of seismometers. The foundation rock at the dam site is composed of the alternation of sandstone and slate which belongs to the Mesozoic formation. The acidified rock, or the quartz porphyry, has intruded into the foundation rock around the dam site. Consequently, the foundation rock at the dam site is significantly influenced by the intrusive rock and becomes to be very hard. The shear wave velocity of foundation rock was estimated to be about 2000～2500m/s according to the field tests executed before construction.

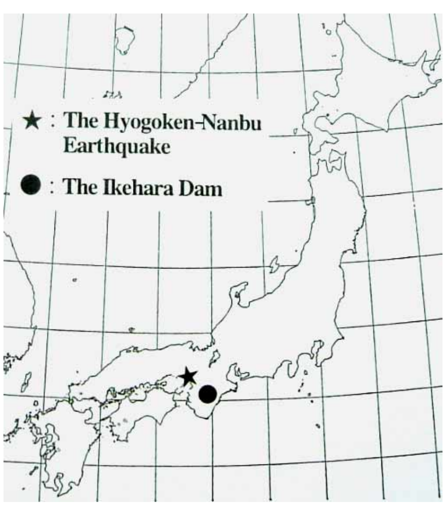
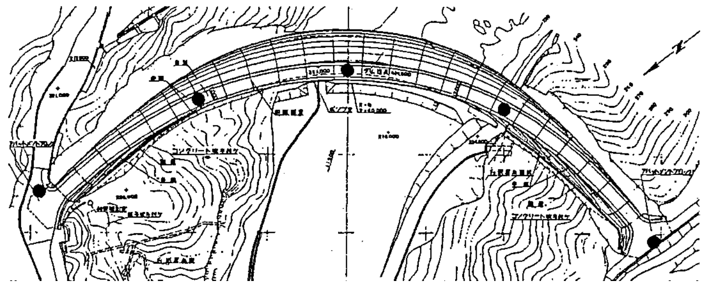
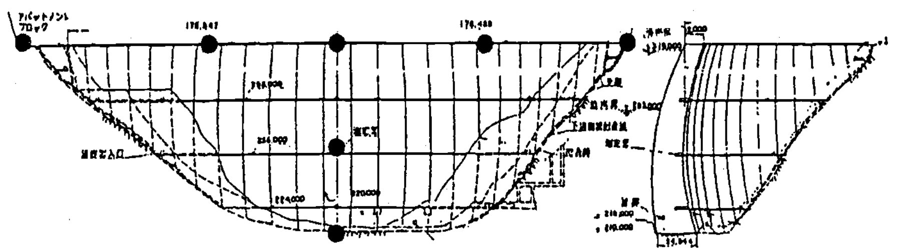


Figure 1 Location of the Ikehara Dam

Figure 2 The Ikehara Arch Dam



(1) Horizontal arrangement



(2) Vertical arrangement ● : Accelerometers

Figure 3 Shape of the Ikehara Dam and arrangement of seismometers

Earthquake Observation at the Ikehara Arch Dam

The seismological observation at the Ikehara Dam has been made since 1964 in order to make clear the dynamic behavior of the dam during earthquake and to evaluate the dynamic property values quantitatively. 13 seismometers have been installed at 7 points, as shown in Figure 3. Three components, that is a horizontal radial direction, a horizontal tangential direction and a vertical direction, have been observed at the dam base gallery, the left and the right abutment. One component in the horizontal radial direction has been observed at 4 points on the dam.

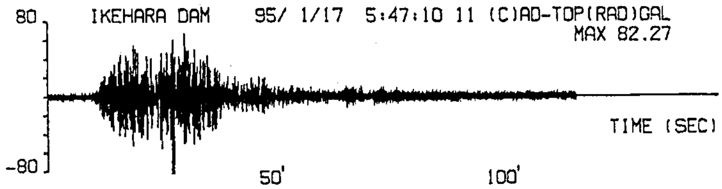
Recorded Motions during the 1995 Hyogoken-Nanbu Earthquake

On 17th January 1995, the Hyogoken-Nanbu Earthquake (Magnitude 7.2) occurred.

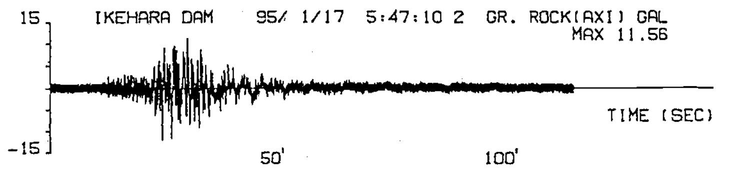
Table 1 Maximum acceleration recorded at the Ikehara Dam during the 1995 Hyogoken-Nanbu Earthquake

No.	Location	Direction	Max. Acc. (gal)
1	Dam base gallery	Radial	11.98 (cm/s^2)
2		Tangential	11.56
3		Vertical	9.78
4	Right abutment	Radial	13.98
5		Tangential	13.85
6		Vertical	9.98
7	Left abutment	Radial	12.60
8		Tangential	13.98
9		Vertical	8.40
10	Crest right side	Radial	56.62
11	Dam Crest center	Radial	82.27
12	Crest left side	Radial	70.78
13	Dam middle center	Radial	28.20

During this earthquake, the motion of maximum acceleration 82gal(cm/s^2) was recorded at the Ikehara Dam. The epicenter distance was 106km. The maximum values of recorded acceleration time history are shown in Table 1. The earthquake motions recorded at the dam crest center and the dam base gallery are shown in Figure 4.



(1) Dam crest center



(2) Dam base gallery

Figure 4 Motions recorded at the Ikehara Dam during the 1995 Hyogoken-Nanbu Earthquake

3-D REPRODUCTION ANALYSIS REGARDING ACTUAL EARTHQUAKE BAHAVIOR OF THE IKEHARA DAM

Purpose of reproduction analysis

The calculated dynamic stresses and strains are strongly influenced by the deformation property values of dam and foundation in regard to the dynamic analysis. Consequently, in order to execute the accurate and reliable evaluation for the earthquake safety of dam, the dynamic deformation property values of dam and foundation should be qualitatively evaluated based on the real earthquake phenomena. For this reason, the reproduction analyses of real earthquake behaviors of existing dams have been carried out in order to evaluate the dynamic property values of dam and foundation quantitatively, and to examine the validity and availability of the 3-D dynamic analysis method developed, Ariga[3].

Namely, the 3-D reproduction analysis regarding the actual earthquake behavior of the Ikehara Dam during the 1995 Hyogoken-Nanbu Earthquake has been made by using the 3-D coupled dam-foundation-reservoir system model in order to evaluate the dynamic property values of dam and foundation quantitatively.

Principles of 3-D Analysis Method for Coupled Dam - Reservoir - Foundation System

In the earthquake safety analysis of dams, the various influential factors, such as the interaction between dam and reservoir and that between dam and foundation, the energy dissipation and inflow between foundation and semi-infinite free fields, and so forth should be considered. In this study, these problems are treated in the following way. The coupled dam – reservoir – foundation system is expressed in the following equations.

$$\left\{\begin{array}{ll}
\begin{bmatrix} M_d & M_{df} \\ M_{fd} & M_f \end{bmatrix}\begin{Bmatrix} \ddot{u}_d \\ \ddot{u}_f \end{Bmatrix} + \begin{bmatrix} C_d & C_{df} \\ C_{fd} & C_f^* \end{bmatrix}\begin{Bmatrix} \dot{u}_d \\ \dot{u}_f \end{Bmatrix} + & \\
\qquad \begin{bmatrix} K_d & K_{df} \\ K_{fd} & K_f \end{bmatrix}\begin{Bmatrix} u_d \\ u_f \end{Bmatrix} = \begin{Bmatrix} F_w \\ Te + T_f \end{Bmatrix} & (1.1) \\
\dfrac{\partial^2 \Phi}{C_0^2 \partial t^2} = \dfrac{\partial^2 \Phi}{\partial x^2} + \dfrac{\partial^2 \Phi}{\partial y^2} + \dfrac{\partial^2 \Phi}{\partial z^2} & (1.2) \\
[M_g]\{\ddot{u}_g\} + [C_g]\{\dot{u}_g\} + [K_g]\{u_g\} = \{T_b\} & (1.3)
\end{array}\right.$$

Where Equation (1.1) is concerning the motion of dam and foundation, Equation (1.3) is for the motion of free field. And Equation (1.2) deals with the wave propagation of reservoir water. The matrices M, C, and K indicate mass, damping, and stiffness matrix respectively. The subscripts d, df (fd), f, g mean, in turn, that these matrices are relevant to the dam, the conjunct part of dam and foundation, the foundation, and the free field respectively. The variables $u, \dot{u}, \ddot{u}$ are the vectors of displacement, velocity, and acceleration. Vector F_w is hydrodynamic pressure load acting on the dam. Vectors T_e and T_f are earthquake load acting on rock surface and traction acting on the lateral boundaries of the foundation result from the difference between the foundation vibration and the free field motion. T_b indicates the earthquake load acting on the rock surface (input surface) of the free field. Φ is the velocity potential function of water particles. Variables x, y, z are the components of Descartes coordinates, and t indicates time. C_0 is the sonic velocity in water. C_f^* is the dissipation matrix including the component of foundation material C_f and that of the viscous boundaries C_b ($C_f^* = C_f + C_b$). Here, the viscous boundary matrix C_b is derived from the principle of virtual work. Its function for energy dissipating has been verified to be much better than that of the traditional viscous boundary, Lysmer [4]. For details of the matrix C_b, please refer to relevant paper, Miura[5].

Between dam and reservoir, the following continuous condition is applied. That is to say, on the interface between dam and reservoir the velocity of water particle $\partial\Phi/\partial n$ equals to the vibrating velocity of the dam, and the hydrodynamic pressure P_w is treated as the surface load of the dam.

$$\begin{cases} \dfrac{\partial \Phi}{\partial n} = V_d \\ F_w = P_w \end{cases} \qquad (2)$$

The coupling between dam and foundation has been naturally considered in Equation (1). As for the traction T_f, it is calculated according to the following equation.

$$\{T_f\} = [K_b]\{u_g\} + [C_b]\{\dot{u}_g\} \qquad (3)$$

Where, $[K_b]$ is the stiffness matrix of the lateral boundaries of the foundation, and is used for evaluating the effects of free field motion. $[C_b]$ is the viscous boundary matrix, and has been mentioned above.

As mentioned above, since the free field around the foundation is taken into the analytic model, only the boundaries of the reservoir should be treated here.

On the bottom and the valley of the reservoir, the following viscous boundary condition is applied.

$$\frac{\partial \Phi}{\partial t} - C_0 \beta \frac{\partial \Phi}{\partial n_r} = 0 \qquad (4)$$

Where, β is the impedance ratio between reservoir bottom sediment and reservoir water. Variable n_r indicates the normal direction of the boundary surface.

On the free surface of the reservoir, the condition of surface wave is applied. And at the upstream boundary of the reservoir, the following viscous boundary condition is applied.

$$\frac{\partial \Phi}{\partial t} = -C_0 \Big/ \sqrt{1 - \frac{1}{\beta^2}} \, \frac{\partial \Phi}{\partial x} \qquad (5)$$

Numerical model

Figure 5 shows the 3-D numerical model generated for the coupled dam - reservoir - foundation system. The foundation has a depth (from dam base downward) of 120 meters, and a width of 700 meters (120 meters extends from abutments to both lateral sides respectively). Additionally, a free field is modeled with layer elements around the foundation. The dam, the foundation and the free field are meshed with finite elements, and the reservoir is meshed with finite difference grids. As for the boundary conditions of the 3-D model, the rigid boundary is applied for the bottom boundary , and the viscous boundary for the lateral boundary. The water depth of the reservoir is set to be 93.77m according to the actual data on 17th January 1995. The input motions for the reproduction analysis were regenerated based on the earthquake motions recorded at the dam base gallery by applying the transfer function between the dam base gallery and the bottom input base of the 3-D model. Three components of motions were input simultaneously.

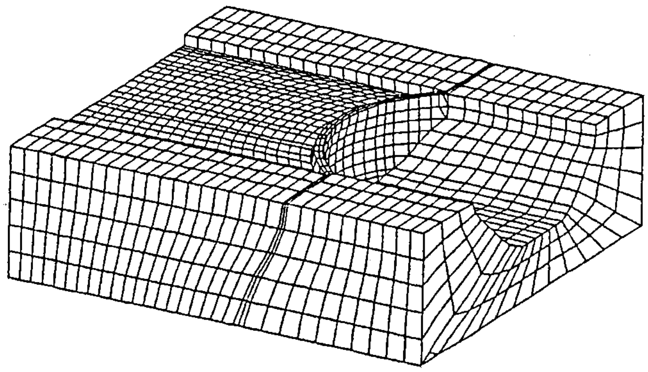


Figure 5 3-D dyamic analysis model of the Ikehara Dam as a coupled dam-reservoir-foundation system

Technique for Reproduction

The values of the dynamic shear modulus and the damping factor were identified to reproduce the earthquake motions at the Ikehara Dam. Based on the assumption of linear properties, the dynamic shear modulus and the damping factor of dam concrete and foundation rock were adjusted until the analysis results approximate the earthquake observation results.

Analysis results

Table 2 shows the dynamic property values of the Ikehara Dam identified by the 3-D reproduction analysis of actual earthquake behavior during the 1995 Hyogoken-Nanbu Earthquake. As the results, the dynamic shear modulus and the damping factor of dam concrete were evaluated to be 13,500N/mm^2 and 2%, respectively. Similarly, the dynamic shear modulus and the damping factor of the foundation rock were evaluated to be 11,700N/mm^2 and 3%, respectively. In this case, as the amplitude of motions is not so large, the real behavior can be well reproduced by the linear analysis. In case of very strong earthquake motions, it is considered that the nonlinear dynamic analysis taking the non-linearity of dam material or the non-linear behavior of joints into account will be needed.

Table 2 Dynamic Property Values of the Ikehara Dam identified by the 3-D reproduction analysis of actual earthquake behavior during the 1995 Hyogoken-Nanbu Earthquake

Item	Dynamic Property Values		
	Dam	Foundation rock	Free field
Density (g/cm^3)	2.3	2.55	2.55
Dynamic Poisson's ratio	0.2	0.3	0.3
Dynamic shear modulus(N/mm^2)	13,500	11,700	11,700
S wave velocity (m/s)	2420	2140	2140
Damping factor (%)	2	3	3

The comparison of maximum acceleration values between the observation results and the analysis results for the Ikehara Dam is shown is Table 3. As for the maximum acceleration, the observed value at the dam crest center is 82.3gal(cm/s^2), and the analyzed value is 77.5gal(cm/s^2).

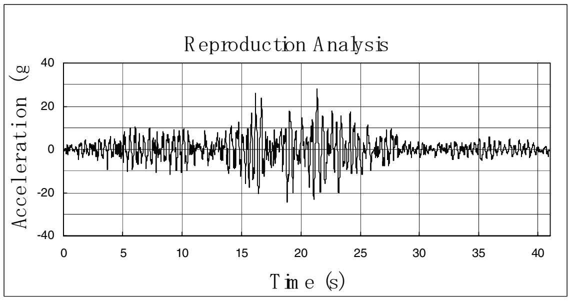
Table 3 Comparison of maximum acceleration between earthquake observation results and 3-D reproduction analysis results for the Ikehara Dam

No. of Channel	Location of seismometer	Direction of Motion	Maximum acceleration of motion	
			Earthquake Observation (gal)	Reproduction Analysis (gal)
1	Dam base gallery	Radial	11.98 (cm/s^2)	10.91 (cm/s^2)
2		Tangential	11.56	11.77
3		Vertical	9.78	11.29
4	Right abutment	Radial	13.98	14.83
5		Tangential	13.85	21.38
6		Vertical	9.98	12.56
7	Left abutment	Radial	12.60	13.11
8		Tangential	13.98	20.29
9		Vertical	8.40	16.44
10	Crest right side	Radial	56.62	49.81
11	Dam Crest center	Radial	82.27	77.22
12	Crest left side	Radial	70.78	67.90
13	Dam middle center	Radial	28.20	28.02

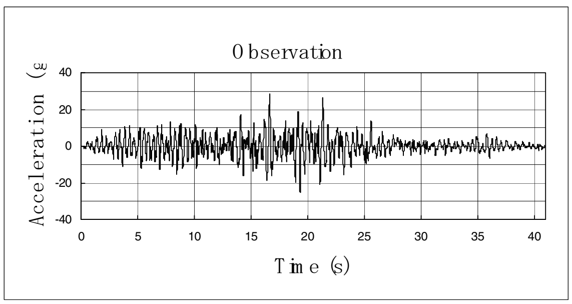
The comparison between the earthquake observation results and the 3-D reproduction analysis results in regard to the acceleration time history at the dam middle center (middle height of the dam) is shown in Figure 6. Similarly, the comparison in regard to the dam crest center is shown in Figure 7. The acceleration time history at the dam middle center can be reproduced well. As for the dam crest center, the analysis result is rather smaller than that of observed in the former period (approximately from 0sec to 15sec), as shown in Figure 7. To the contrary, the analysis result is rather larger than that of observed results the latter period (approximately from 15sec to 40sec). In the reproduction analysis described here, the value of damping factor is set to be constant, or 2%. Therefore, it is considered that if the value of damping factor is set to be slightly smaller than 2% for the former period, and slightly larger than 2% for the latter period, the agreement between the observation results and the analyzed results will be improved. In other words, it can be considered that the reproducibility may be improved by taking the non-linearity of dynamic properties, especially in regard to the damping factor, into account. As for the waveform of the time history, a peculiar component of vibration was not recognized.

The comparison in regard to the spectral function (spectral ratio between dam middle center and dam base gallery) is show in Figure 8. Similarly, the comparison in regard to the spectral function between dam crest center and dam base is shown Figure 9. The reproduction analysis result does not completely agree with the observation results in the frequency domain higher than 4Hz. However, in regard to the frequency domain lower than 4Hz, especially at the natural frequency (2.8Hz) of the dam, the reproduction analysis results agree with the observation results very well.

The distributions of dynamic tensile stress in the vertical section of dam body are shown in Figure 10 (tensile stress in the horizontal tangential direction) and Figure 11 (tensile stress in the vertical direction), respectively. And, the distributions of dynamic tensile stress on the upstream face of the dam are shown in Figure 12 (tensile stress in the horizontal tangential direction) and Figure 13 (tensile stress in the vertical direction). The acceleration level of the motions recorded at the Ikehara Dam during the 1995 Hyogoken-Nanbu Earthquake was 83.2gal(cm/s^2), and not so strong, the dynamic tensile stresses estimated by the 3-D dynamic analysis was 0.25N/mm^2 at most. The dynamic tensile strength of dam concrete is generally considered to be 3～5N/mm^2 , Hatano[6]. So, the Ikehara Dam was quite safe during the 1995 Hogoken-Nanbu Earthquake.

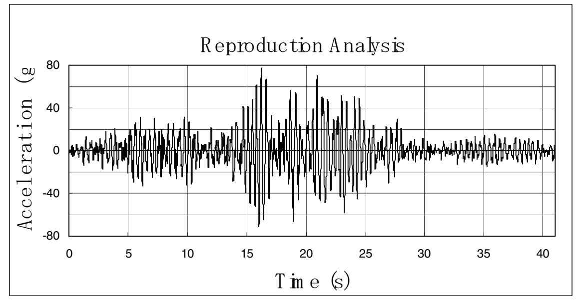


Dam Middle Center (EL.+260).
(1) Analysis result

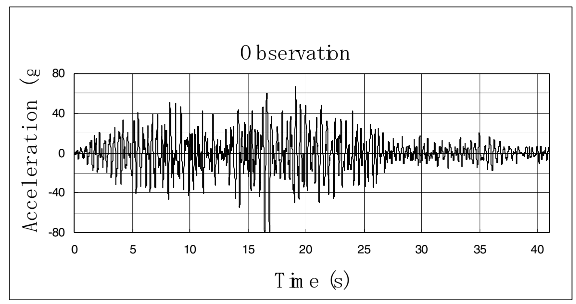


Dam Middle Center (EL.+260).
(2) Observation result

Figure 6 Comparison of acceleration time history at dam middle center (EL.+260).



Dam Crest Center (EL.+321).
(1) Analysis result



Dam Crest Center（EL.+321).
(2) Observation result

Figure 7 Comparison of acceleration time history at dam crest center (EL.+321).

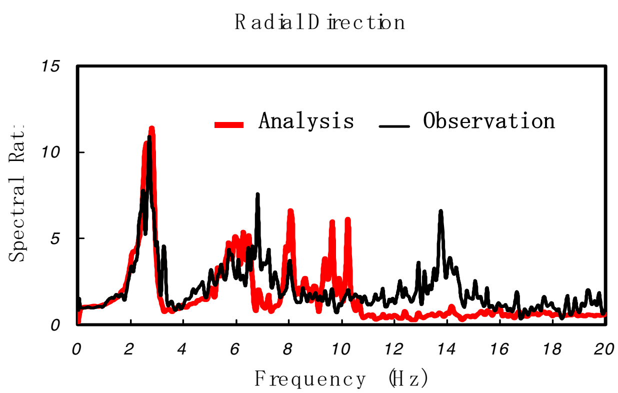


Figure 8 Comparison of spectral function between dam middle center and dam base (in the radial direction)

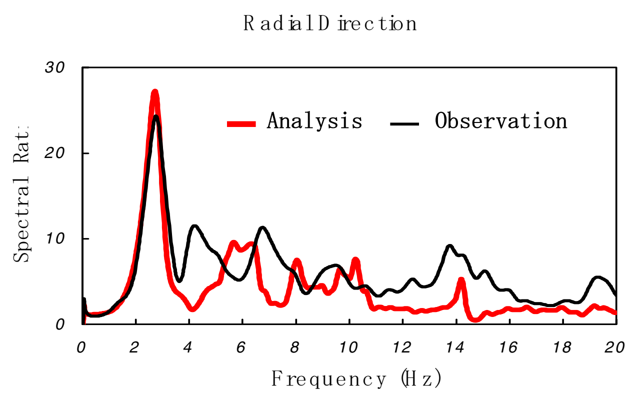


Figure 9 Comparison of spectral function between dam crest center and dam base (in the radial direction)

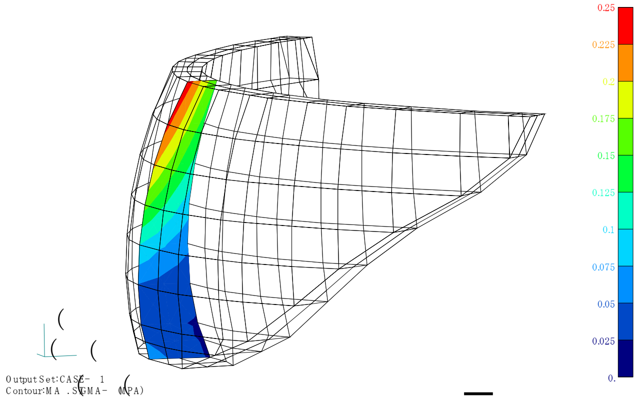


Figure 10 Distribution of dynamic tensile stress in tangential direction (N/mm^2)

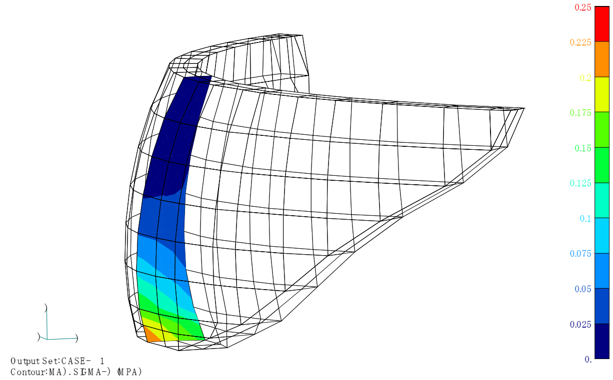


Figure 11 Distribution of dynamic tensile stress in vertical direction (N/mm^2)

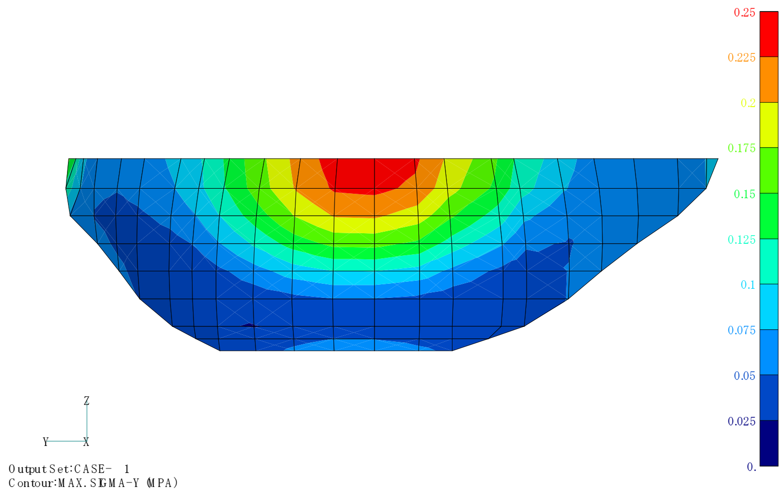


Figure 12 Distribution of dynamic tensile stress in horizontal tangential direction (N/mm^2)

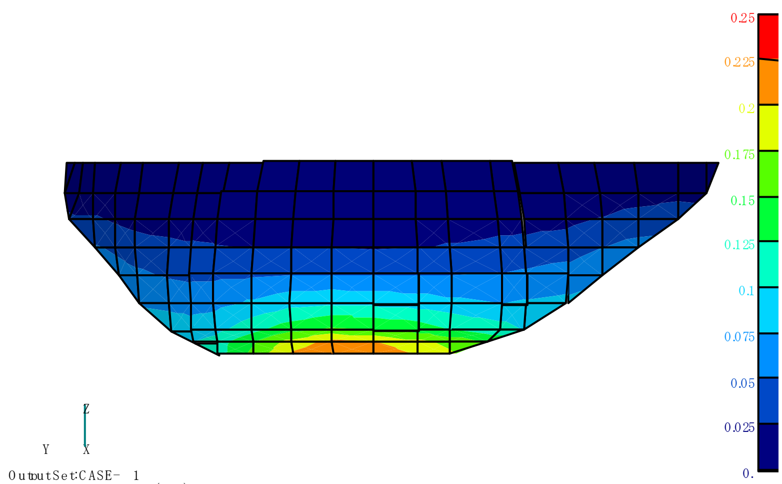


Figure 13 Distribution of dynamic tensile stress in vertical direction (N/mm^2)

CONCLUSIONS

1) The dynamic deformation property values of dam and foundation have significant effects upon the dynamic stresses and strains calculated by the dynamic analysis. For this reason, especially, the values of dynamic shear modulus and damping factor should be qualitatively evaluated based on the actual earthquake motions.
2) During the 1995 Hyogoken-Nanbu Earthquake (Magnichude7.2), the earthquake motion of maximum acceleration of 82.3cm/s^2 was observed at the Ikehara Arch Dam, whose height and crest length are 111m and 460m, respectively.
3) The 3-D reproduction analysis in regard to the actual earthquake behavior of the Ikehara Dam during the 1995 Hyogoken-Nanbu Earthquake by using the 3-D coupled dam-foundation-reservoir system model has been carried out, in order to evaluate the dynamic deformation property values of dam and foundation quantitatively .
4) As the results, the dynamic shear modulus and the damping factor of the dam were evaluated to be 13,500N/mm^2 and 2%, respectively. Similarly, the dynamic shear modulus and the damping factor of the foundation were evaluated to be 11,700N/mm^2 and 3%, respectively.
5) In this case, as the acceleration level of earthquake motions is not so large, the real earthquake behavior can be well reproduced by the linear analysis, not by the non-linear analysis. However, if the acceleration level is very large, the nonlinear dynamic analysis taking not only the non-linearity of dam material but also the discontinuous behavior of joints should be taken into consideration.
6) The interaction between dam and reservoir and between dam and foundation, the energy dissipation and inflow between foundation and free field, the discontinuous effects of joints, and the nonlinear effects of dam materials should be qualitatively treated in the earthquake safety analysis against very strong earthquake motions. For such an earthquake safety analysis of dams, the 3-D dynamic analysis method for coupled dam-joints-reservoir-foundation system, which is developed in this study, is very effective.

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