Ninth Canadian Conference on
Earthquake Engineering
Ottawa, Ontario, Canada
26-29 June 2007

3-D REPRODUCTION ANALYSES FOR ACTUAL EARTHQUAKE BEHAVIORS AND QUANTITATIVE EVALUATION OF DYNAMIC PROPERTY VALUES OF EXISTING CONCRETE DAMS

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ABSTRACT

Dynamic property values of dam and foundation will have significant effects on the results calculated by dynamic analysis. Therefore, the dynamic property values of dam and foundation should be quantitatively evaluated based on the actual earthquake phenomena. A 3-D nonlinear dynamic analysis method has been developed for a coupled dam-joints-foundation-reservoir system for the purpose of realizing an accurate evaluation for seismic safety of existing dams. And, in order to verify the validity of the method developed, the 3-D reproduction analyses has been made for the actual earthquake behaviors of the Nukabira Dam, the Ikehara Dam, the Shintoyone Dam, and the Tagokura Dam. By these 3-D reproduction analyses, the values of the dynamic shear modulus and the damping factor of the dam have been evaluated quantitatively. Furthermore, the efficiency of the method developed has been proved. The 3-D reproduction analysis for actual earthquake behavior of existing dam is necessary to verify the efficiency of the seismic safety evaluation method. An effective utilization of observed earthquake motions is important for realizing an accurate and reliable evaluation for seismic safety of existing dams.

Purpose of 3-D Reproduction Analysis

Confirmation and securing of dam safety against large earthquakes is a very important subject in earthquake prone countries. As for the dams, a seismic design has been made generally based on a static analysis method, which is the seismic coefficient method up to now in Japan. With the rapid improvement of performance of computers and the higher development of numerical analysis techniques in recent years, a 3-D dynamic analysis method has come to be applied for seismic safety evaluation of existing dams. The dynamic stresses and strains calculated by the dynamic analysis will be greatly changed according to the dynamic property values of dam and foundation. Among the dynamic properties, the dynamic shear modulus (or shear wave velocity) and the damping factor are the most influential. Therefore, the dynamic shear modulus and the damping factor of dam and foundation should be evaluated quantitatively based on the actual earthquake motions in order to realize an accurate and reliable evaluation for seismic safety. The purpose of the 3-D reproduction analyses for the actual earthquake behaviours of existing dams is as follows:

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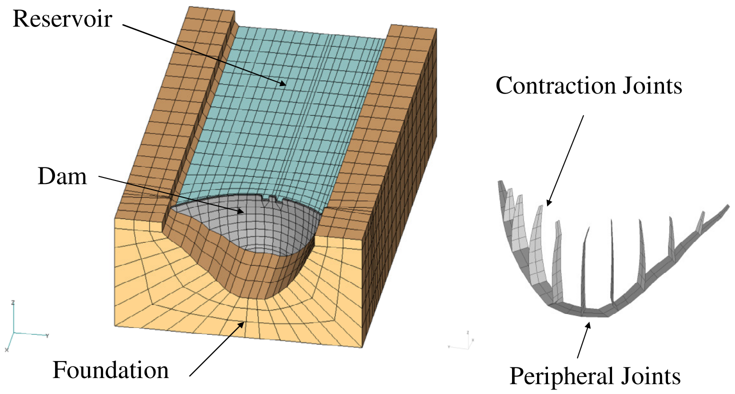
- Quantitative evaluation of dynamic property values
- Identification of 3-D analytical model
- Verification of 3-D dynamic analysis method

In this study, the dynamic shear modulus and the damping factor of dam and foundation were evaluated quantitatively, and the validity of the 3-D dynamic analysis method proposed was verified based on the reproduction analyses for actual behavior of existing concrete dams.

Development of 3-D Nonlinear Dynamic Analysis Method

A dynamic interaction between dam and foundation, a dynamic interaction between dam and reservoir, a dynamic reduction effect by reservoir water, a radiation of wave energy from the boundary of foundation to the free field, a dissipation of wave energy from the boundary of reservoir, a non-linear effect of dam material against strong earthquake motions, a discontinuous behaviors of contraction joints and peripheral joints, and so forth should be considered quantitatively and properly in order to realize an accurate and reliable evaluation for seismic safety of existing dams.

The contraction joints and the peripheral joints are generally arranged in the dam for preventing the cracks due to temperature variation or contraction in regard to the concrete dam. So, it is considered that the discontinuous behaviors of joints will have significant effects upon the dynamic responses of dam against very strong earthquake motions. Taking these points into account, a 3-D nonlinear dynamic analysis method for a coupled dam-joints-foundation-reservoir system has been developed (Ariga, 2000, 2001). A 3-D interface element is applied for modeling the joints or cracks. The discontinuous behaviors such as the opening and sliding of joints can be simulated with this method. Concerning the modeling of reservoir, the wave equation is dispersed by the finite difference method. One of the typical examples of the 3-D analytical model for dam-joints-foundation-reservoir system is shown in Fig. 1.



Joints

Dam-Foundation-Reservoir System

Figure 1. Representative 3-D analytical model for dam-joints-foundation-reservoir system

Procedure for 3-D Reproduction Analysis of Existing Dams

The 3-D reproduction analyses for the actual earthquake behaviours of existing dams can be made as a combination between the earthquake observation data and the 3-D dynamic analysis procedure. The basic flow of the 3-D reproduction analysis is shown in Fig. 2.

The dynamic property values of the dynamic shear modulus and the damping factor can be identified by reproducing the actual earthquake behaviors of existing dams. The dynamic shear modulus and the damping factor of dam and foundation can be evaluated by adjusting until the analysis results approximate the earthquake observation results based on the assumption of linear properties. The dynamic shear modulus can be evaluated by reproducing the predominant frequencies of transfer function between dam base and dam crest. The damping factor can be evaluated by reproducing the maximum amplitude of motions at dam crest.

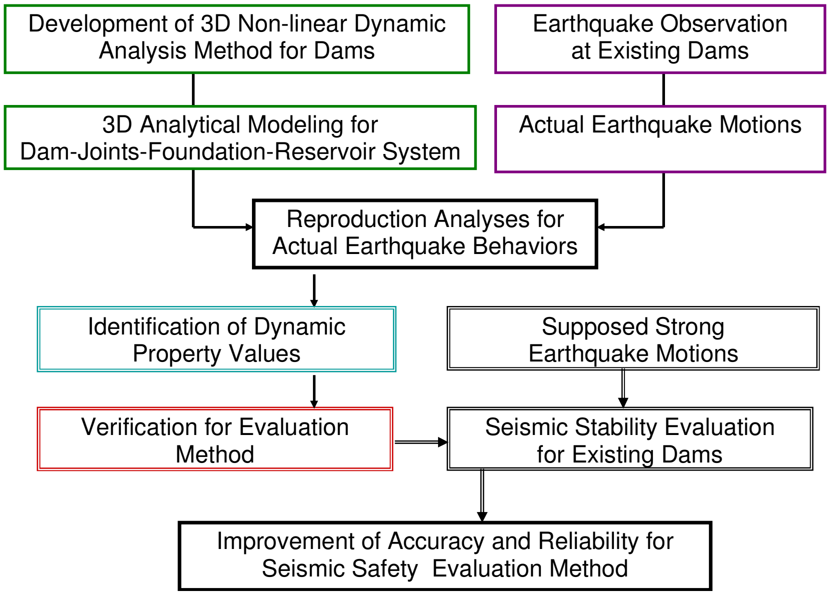


Figure 2. Organic combination between earthquake observation and 3-D dynamic analysis.

Reproduction Analyses for Existing Concrete Dams

Existing Dams analyzed

The 3-D reproduction analyses has been made for actual earthquake behaviors of the Shin-toyone Dam (hereafter the ST Dam) during the 1997 near-field earthquake, the Nukabira Dam (hereafter the NK Dam) during the 1993 Kushiro-oki Earthquake, the Ikehara Dam (hereafter the IK Dam) during the 1995 Hyogoken-nanbu Earthquake, and the Tagokura Dam (hereafter the TG Dam) during the 2004 Niigataken-chuetsu Earthquake, in order to verify the validity of the 3-D dynamic analysis method developed in this study. By these 3-D reproduction analyses, the reproducivility for not only the earthquake behaviors of dam but also the dynamic analysis method were examined. As a result, the dynamic property values of dynamic shear modulus and the damping factor of dams and foundations were evaluated quantitatively, and the efficiency and validity of the 3-D dynamic analysis method proposed were proved.

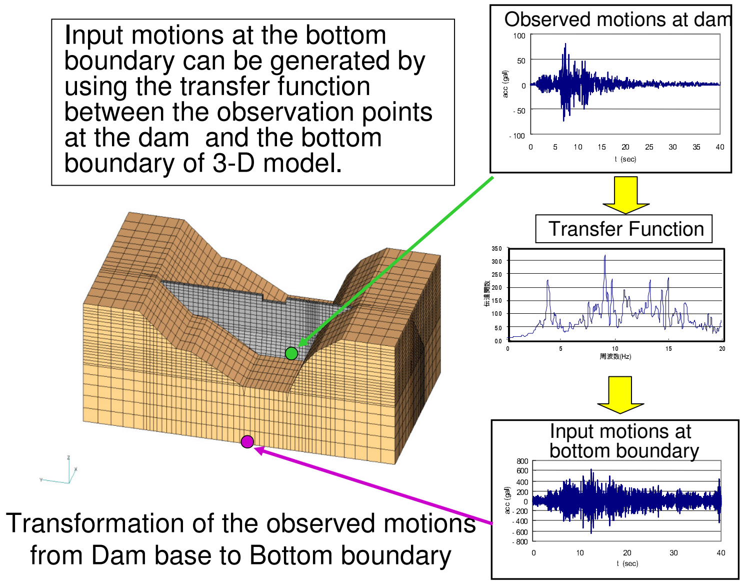
Transformation of the motions from the observed point to the bottom boundary

In order to execute a 3-D reproduction analysis, it is necessary to transform the observed earthquake motions at the dam site into the input motions at the bottom boundary of 3-D analytical model. The procedure for transforming the observed earthquake motions into the input motions has been devised. The input motions at the bottom boundary of the 3-D model for the reproduction analysis can be regenerated based on the earthquake motions recorded at the dam by utilizing the transfer function between the earthquake observation point at the dam and the bottom boundary of the model, as shown in Fig. 3. Each component of earthquake motion is converted one by one in the case of de-convolution. And three components of motions are input simultaneously in the 3-D reproduction analysis.

Reproduction Analysis for the TG Dam

The shape of the TG Dam and the arrangement of the seismometers are shown in Fig. 4. And, the 3-D analytical model for the TG Dam is shown in Fig. 5. The model was made as the 3-D coupled dam-foundation-reservoir system. The dam and the foundation are meshed with the finite elements, and the reservoir is meshed with the finite difference grids. As for the boundary conditions, the rigid boundary is applied for the bottom boundary, and the viscous boundary for the lateral boundaries. The water depths of the reservoirs were set to be the same condition when the earthquakes occurred.

The dynamic property values of the TG Dam identified by the 3-D reproduction analysis for actual earthquake behavior are shown in Table 2.


Input motions at the bottom boundary can be generated by using the transfer function between the observation points at the dam and the bottom boundary of 3-D model.

Transformation of the observed motions from Dam base to Bottom boundary

Figure 3. De-convolution of actual earthquake motions observed at the TG Dam.

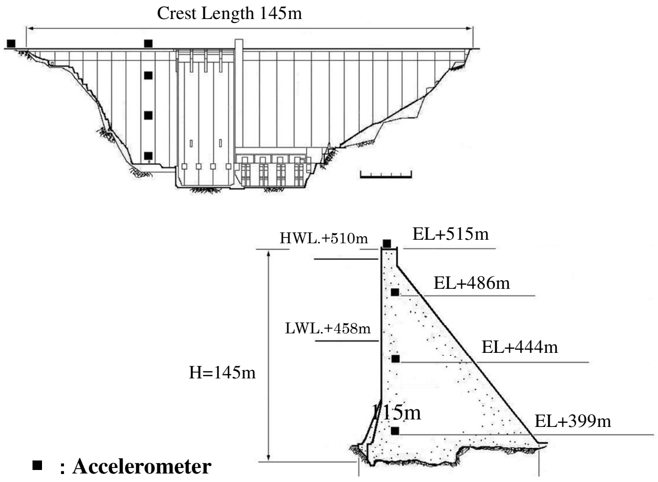


Figure 4. Location of seismometers at the TG Dam.

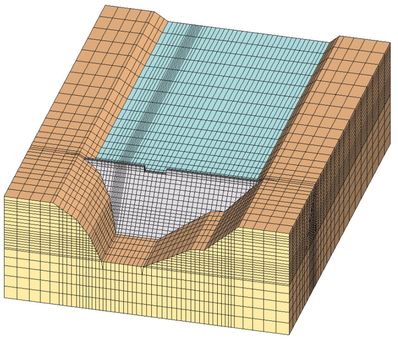
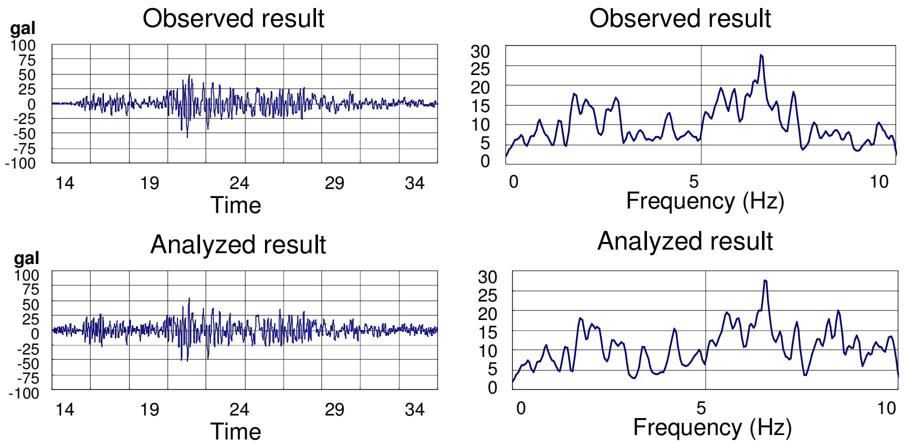

Concrete Gravity Dam
Dam height: 145m, Crest length: 462m
Dam volume: 1950000m^3

Figure 5. 3-D analytical model for the TG Dam.

Table 2. Dynamic property values for the TG Dam.

Item	Density	Poisson's ratio	Dynamic shear modulus	Shear wave Velocity	Damping Factor
Dam	2.4 g/cm^3	0.20	9600 N/mm^2	1980 m/s	5.0%
Rock	2.6 g/cm^3	0.25	8000 N/mm^2	1740 m/s	5.0%

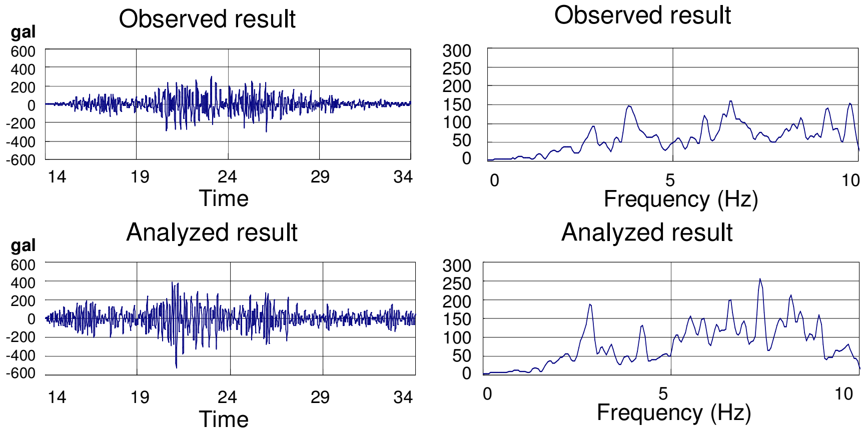
Fig. 6 shows the comparison between the earthquake observation results and the 3-D reproduction analysis results in regard to the acceleration time history and the Fourier spectrum ratio, that is the transfer function between the dam crest and the dam base), at the dam base (EL.+399m) of the TG Dam during the 2004 Niigataken-chuetsu Earthquake. Similarly, the comparison between the earthquake observation results and the 3-D reproduction analysis results in regard to the dam crest is shown in Fig. 7. As for the dam base (EL.+399m), the reproduction analysis results agree with the observation results well. As for the dam crest, the reproduction analysis results became slightly larger than the observation results.



Acceleration time history
at the dam base (EL.+399m)

Fourier spectral ratio
at the dam base (EL.+399m)

Figure 6. Comparison of acceleration time history and transfer function at the dam base of the TG Dam.



Acceleration time history
at the dam crest (EL.+515m)

Fourier spectral ratio
at the dam crest (EL.+515m)

Figure 7. Comparison of acceleration time history and transfer function at the crest of the TG Dam.

Reproduction Analysis for the IK Dam

The shape of the IK Dam and the arrangement of the seismometers are shown in Fig. 8 and the 3-D analytical model for the IK Dam is shown in Fig. 9. The model was made as the 3-D coupled dam-joints-foundation-reservoir system. The dynamic property values of the IK Dam identified by the 3-D reproduction analysis for actual earthquake behavior are shown in Table 3.

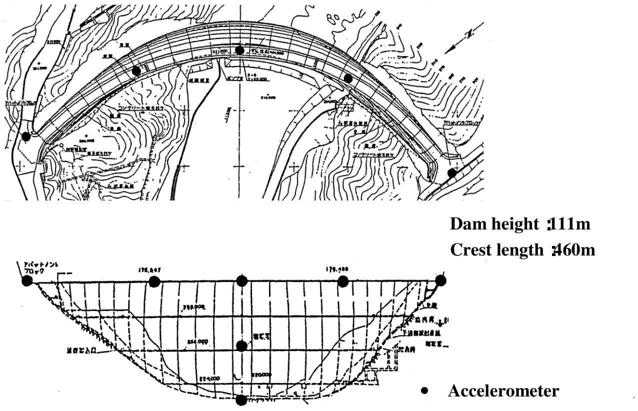
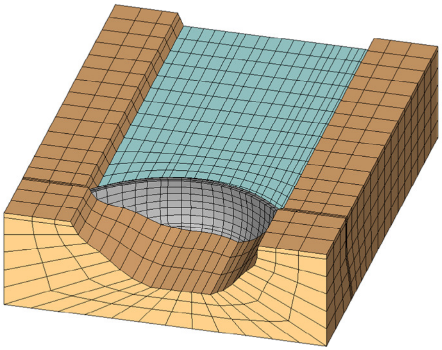


Figure 8. Location of seismometers at the IK Dam.



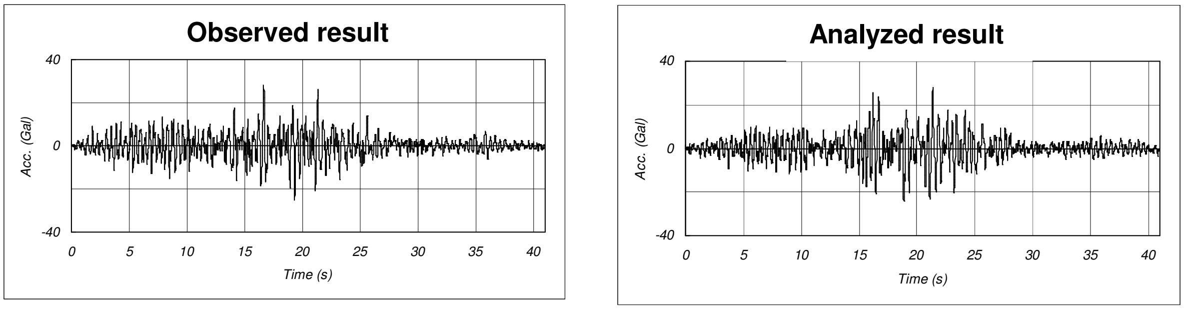
Concrete Arch Dam
Dam height: 111m, Crest length: 460m
Dam volume: 640000m^3

Figure 9. Location of seismometers at the IK

Table 3. Dynamic property values for the IK Dam.

Item	Density	Poisson's ratio	Dynamic shear modulus	Shear wave Velocity	Damping Factor
Dam	2.3 g/cm^3	0.20	13500 N/mm^2	2400 m/s	2.9%
Rock	2.55 g/cm^3	0.25	11700 N/mm^2	2120 m/s	4.0%

As the representative results of reproduction analyses, the comparison between the earthquake observation result and the 3-D reproduction analysis result in regard to the acceleration time history at the crest center of the IK Dam is shown in Fig. 10. The acceleration time history at the dam can be reproduced well. In this case, the damping factor of the IK Dam are supposed according to the time domain of the motion, namely the damping factor for the time domain from 0 to 13 (sec) is set to be 2.6%, 2.9% for the time domain from 13 to 20 (sec), and 3.1% for the time domain from 20 to 41 (sec). It is considered that the reproducibility can be improved by taking the non-linearity for damping factor into account. As for the waveform of the time history, a peculiar difference between the observed results and the analyzed results was not recognized.



(1) Observed time-history

(2) Analyzed time-history

Figure 10. Comparison of acceleration time-history at the crest center of the IK Dam.

The comparison in regard to the spectral function (the ratio of Fourier spectrum between the crest center and the dam base of the IK Dam) is show in Fig. 11. In regard to the frequency domain lower than 4Hz, especially as for the natural frequency (2.8Hz) of the IK Dam, the reproduction analysis result agreed with the observation result very well.

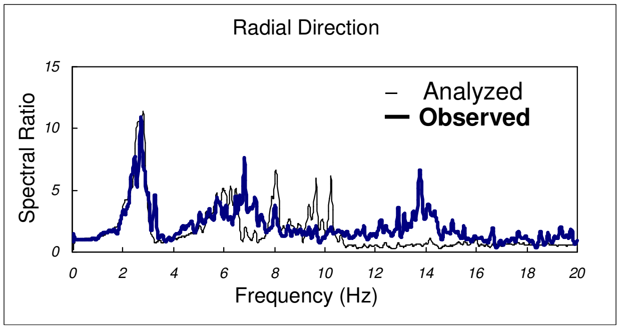


Figure 11. Comparison of transfer function in the radial direction between the dam center and the dam base of the IK Dam.

Dynamic Property Values evaluated quantitatively by Reproduction Analyses

Table 4 shows the dynamic property values identified by the 3-D reproduction analyses of actual earthquake behaviors. As the results, the S-wave velocity of the TG Dam, the IK Dam, the NK Dam (Ariga, 2003) and the ST Dam (Ariga, 2004) were evaluated to be 1980 m/s, 2400 m/s, 2120 m/s and 2110 m/s, respectively. Similarly, the damping factor of the TG Dam, the IK Dam, the NK Dam and the ST Dam were evaluated to be 5%, 2.9%, 5%, and 5%, respectively.

Table 4. Dynamic property values of the dams identified by the 3-D reproduction analyses.

Dam Type		Concrete Gravity Dam		Concrete Arch Dam	
Dam Name		Tagokura	Numabira	Ikehara	Shintoyone
Earthquake	Date	2004.10.23	1993.1.15	1995.1.17	1997.3.16
	Name	Niigataken-Chuetsu	Kushiro-oki	Hyogoken-nanbu	Near Toyohashi
	Magnitude	M6.8	M7.8	M7.2	M5.8
	Epicenter Distance	37 km	110 km	106 km	35 km
DAM	Density	2.4 g/cm^3	2.4 g/cm^3	2.3 g/cm^3	2.35 g/cm^3
	Dynamic Shear Modulus	9,600 N/mm^2	11,032 N/mm^2	13,500 N/mm^2	10,700 N/mm^2
	S-wave Velocity	1980 m/s	2120m/s	2400 m/s	2110 m/s
	Damping Factor	5 %	5 %	2.9 %	5 %
	Max. Acc. at Dam Crest	454.9 gal	77.4 gal	82.3 gal	709 gal
	Max. Acc. at Dam Base	102.5 gal	27.5 gal	11.6 gal	68.5 gal
	Natural Frequency	3.9 Hz	5.2 Hz	2.8 Hz	5.2 Hz
	Dam Height	145 m	76 m	111 m	116.5 m
	Crest Length	462 m	293 m	460 m	311 m
BASE	Density	2.6 g/cm^3	2.6 g/cm^3	2.55 g/cm^3	2.60 g/cm^3
	Dynamic Shear Modulus	8,000 N/mm^2	9,380 N/mm^2	11,700 N/mm^2	9,600 N/mm^2
	S-wave Velocity	1740 m/s	1880 m/s	2120 m/s	1900 m/s
	Damping Factor	5 %	5 %	4.0 %	5 %

For the reference, the shape of the NK Dam and the arrangement of the seismometers are shown in Fig. 12, and the 3-D analytical model for the NK Dam is shown in Fig. 13. Similarly, the shape of the ST Dam and the arrangement of the seismometers are shown in Fig. 14, and the 3-D analytical model for the ST Dam is shown in Fig. 15. In these cases, as the amplitude of earthquake motions are not so large, the actual earthquake behaviors can be reproduced well 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 will be required.

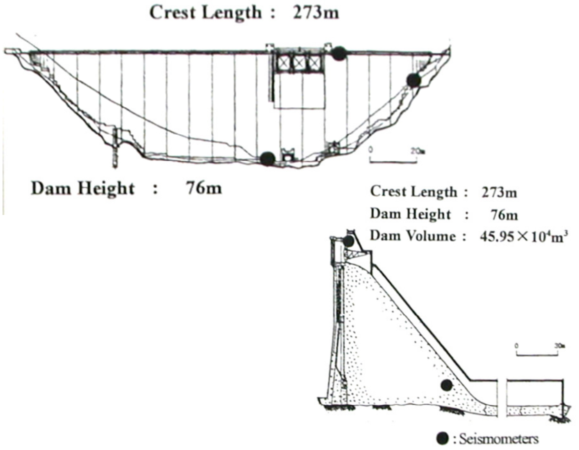
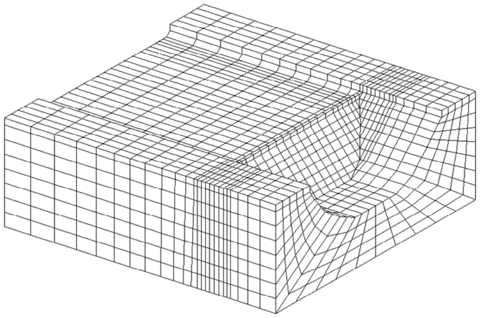


Figure 12. Location of seismometers at the NK Dam.



Concrete Gravity Dam
Dam height: 76m, Crest length: 293m
Dam volume: 460000m^3

Figure 13. 3-D analytical model for the NK Dam.

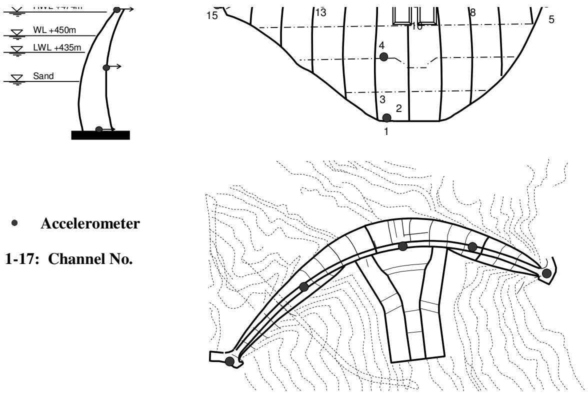
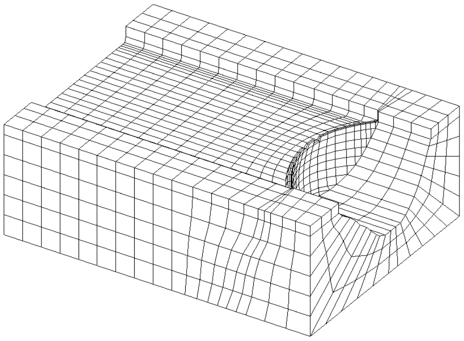


Figure 14. Location of seismometers at the ST Dam.



Concrete Arch Dam
Dam height: 116.5m, Crest length: 311m
Dam volume: 348000m^3

Figure 15. 3-D analytical model for the ST Dam.

The damping factor described here means a material damping factor, or a hysteretic damping, because the radiation of wave energy from the boundary of foundation to the free field can be naturally considered in the 3-D dynamic analysis based on the strict theory. If the radiation damping from the foundation to the free field is not considered in the dynamic analysis, some additional damping factor should be taken into account.

The values of the S-wave velocity and the damping factor were slightly changed according to the dams analyzed, because of the differences about the shape and size of dam, the level of earthquake motion, the mutual influence between foundation and dam, and so forth.

In executing the 3-D reproduction analyses, it was comparatively easy to reproduce in regard to the NK Dam, the ST Dam and the IK Dam. However, it was comparatively hard to reproduce for the TG Dam. It is considered that such difference may be caused by the appropriateness of the location and arrangement of seismometers.

Conclusions

In order to realize an accurate and reliable evaluation for seismic safety of existing dams, a dynamic interaction between dam and foundation, a reduction effect on a dynamic response of dam by reservoir water, a radiation of wave energy from the boundary of foundation to the free field, a non-linear effect of dam material, a discontinuous behaviors of contraction joints and peripheral joints against very strong earthquake motions, and so forth should be considered quantitatively and properly. Taking these points into account, a 3-D nonlinear dynamic analysis method for a coupled dam-joints-foundation-reservoir system has been developed.

The dynamic deformation property values of dam and foundation have significant effects on the dynamic stresses and strains calculated by the dynamic analysis, so the values of the dynamic shear modulus and the damping factor should be quantitatively evaluated based on the actual earthquake motions. In other words, an efficiency and validity of the seismic safety evaluation method should be verified based on actual earthquake phenomena, in order to realize an accurate and reliable evaluation for seismic safety of existing dams, the 3-D reproduction analyses has been made for actual earthquake behaviors of the NK Dam, the IK Dam, the ST Dam and the TG Dam, and the values of dynamic shear modulus and the damping factor of these dams have been evaluated quantitatively and practically. In addition, the efficiency and validity of the 3-D non-linear dynamic analysis method developed in this study based on these reproduction analyses has been verified. For such seismic safety analysis of dams, the 3-D dynamic analysis method for coupled dam-joints-reservoir-foundation system developed in this study is very effective.

A 3-D reproduction analysis in regard to the actual earthquake behaviour of existing dam is a combination between the earthquake observation data and the 3-D dynamic analysis technique. When the acceleration level of earthquake motion is small, the actual earthquake behavior can be successfully reproduced by the linear dynamic analysis. However, when the acceleration level is very large, the nonlinear dynamic analysis taking not only the non-linearity of dam material but also the discontinuous effects of joints will be required. The 3-D dynamic analysis method is useful to evaluate seismic performance quantitatively. If the earthquake observation data are obtained, the 3-D reproduction analysis for the actual earthquake behavior is necessary to prove the validity of the dynamic analysis method.

In order to improve the disaster prevention performance of existing dams, the feedback of seismic safety evaluation to the earthquake countermeasures is important. A smooth and quick confirmation of dam safety is strongly required at very large earthquake. The organic fusion of the earthquake observation data and the 3-D dynamic analysis and the information technology enables to produce new information which is necessary for earthquake disaster prevention and mitigation.

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