3-D reproduction analyses for actual earthquake behaviors of existing dams

Y. Ariga
Chigasaki Research Institute, Electric Power Development Co., Japan

Abstract

Results evaluated by dynamic analysis method will be significantly affected by the values of dynamic property. Therefore, the dynamic property values should be quantitatively evaluated based on actual earthquake phenomena in order to realize reliable dynamic analysis. I have developed 3-D nonlinear dynamic analysis method for coupled dam-joints-foundation-reservoir system and in order to verify the validity of the method developed, I have made 3-D reproduction analyses for actual earthquake behaviors of existing dams. By these reproduction analyses, the dynamic property values of dam and foundation have been evaluated quantitatively. Furthermore, the efficiency of the analytical method developed has been proved. The 3-D reproduction analysis for the actual earthquake behavior of an existing dam is necessary to verify the efficiency of the dynamic analysis method. Effective utilization of the earthquake motions observed is important for realizing accurate and reliable evaluation for seismic safety of structures.
Keywords: earthquake safety, 3-D dynamic analysis, verification, earthquake observation, dynamic property.

1 Introduction

Confirmation and securing of dam safety against large earthquakes is very important subject in earthquake countries. With the rapid improvement of numerical analysis techniques, a 3-D dynamic analysis method has come to be applied for earthquake safety evaluation of existing dams. The stresses and strains calculated by the dynamic analysis procedure will be largely changed according to the dynamic property values. Among the dynamic properties, the dynamic shear modulus (or shear wave velocity) and the damping factor are the

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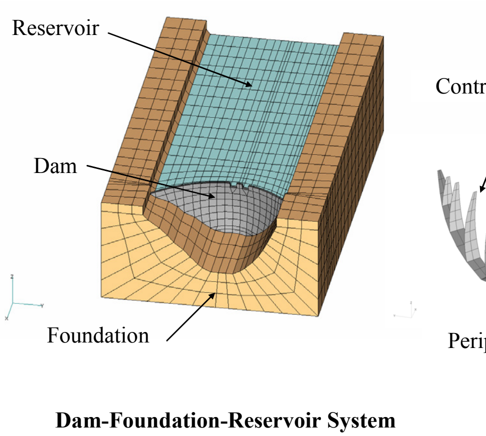
most influential. Therefore, the dynamic shear modulus and the damping factor should be evaluated carefully and quantitatively based on the actual earthquake phenomena. In this study, the dynamic shear modulus and the damping factor of dam and foundation were evaluated quantitatively, and the validity of the 3-D dynamic analysis method proposed was verified based on the reproduction analyses for actual earthquake behaviors of existing dams. The purpose of 3-D reproduction analysis for the actual earthquake behaviour of existing dam is as follows:

- quantitative evaluation of dynamic property values;
- identification of 3-D analytical model;
- verification of reliability of 3-D dynamic analysis method.

2 Development of 3-D nonlinear dynamic analysis method

A dynamic interaction between dam and foundation (Miura, [2]), a dynamic reduction effect on dam by reservoir water, a radiation of wave energy from the boundary of foundation, a dissipation of wave energy from the boundary of reservoir, a non-linear effect of dam material against strong earthquake motions (Hatano [3]), a discontinuous behaviors of joints, and so forth should be considered quantitatively and properly in order to realize an accurate evaluation for earthquake safety of dams. Taking these matters into account, I have developed a 3-D nonlinear dynamic analysis method for a coupled dam–joints–foundation–reservoir system (Ariga [4]). One of the typical examples of 3-D analytical model for a coupled dam-joints-foundation-reservoir system is shown in fig. 1.



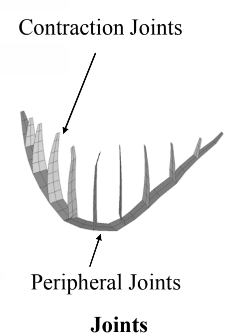


Figure 1: Typical 3-D model for dam–joints–foundation–reservoir system.

The contraction and peripheral joints are generally arranged for preventing the cracks due to the change of temperature, etc. So, it is considered that the discontinuous behaviors of joints will have significant effects on the dynamic response of dam against very strong earthquake motion. A 3-D joint element is applied for modeling the joints or cracks. As for the reservoir, the wave equation is dispersed by the finite difference method.

3 Procedure for 3-D reproduction analysis of existing dams

The basic flow of 3-D reproduction analysis is shown in fig. 2. The dynamic property values can be identified by reproducing the actual earthquake behaviors of existing dams. The dynamic shear modulus and the damping factor can be evaluated by adjusting the analytical results to the earthquake observation results. The dynamic shear modulus can be evaluated by fitting the predominant frequencies of transfer function between dam base and dam crest. The damping factor can be evaluated by fitting the maximum amplitude of motions.

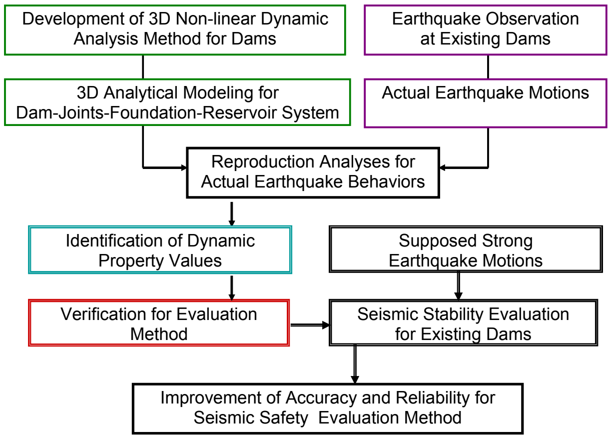


Figure 2: Verification and improvement for 3-D dynamic analysis method.

4 Reproduction analyses for existing concrete dams

4.1 Existing dams analyzed

The 3-D reproduction analyses were made about the Nukabira Dam [4] (hereafter the NK Dam) during the 1993 Kushiro-oki Earthquake, the Shin-toyone Dam [5] (hereafter the ST Dam) during the 1997 near-field earthquake, the Ikehara Dam [6] (hereafter the IK Dam) during the 1995 Hyogoken-nanbu Earthquake, and the Tagokura Dam (hereafter the TG Dam) during the 2004 Niigataken-chuetsu Earthquake. By these reproduction analyses, the dynamic shear modulus and the damping factor were evaluated quantitatively, and the efficiency and validity of the 3-D dynamic analysis method proposed was proved finally.

4.2 Transformation of motions from the observed point to the input boundary

In regard to 3-D reproduction analysis, it is necessary to transform the motions observed at the dam into the input motions at the bottom boundary of the 3-D analytical model. I have devised the procedure for transforming the observed motions into the input motions. The input motions at the bottom boundary can be regenerated by utilizing the transfer function between the earthquake observation point and the bottom boundary of the model, as shown in fig. 3. In the de-convolution, each component of motions is converted one by one. And, in the 3-D reproduction analysis, three components of motions are input simultaneously.

4.3 Reproduction analysis for the TG Dam

The shape of the TG Dam and the arrangement of the seismometers are shown in fig. 4. 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 foundation is 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 is applied for the lateral boundaries. The water depth of the reservoir was set to be the same condition when the earthquake occurred.

The dynamic property values of the TG Dam identified by the 3-D reproduction analysis for actual earthquake behavior are shown in table 1.

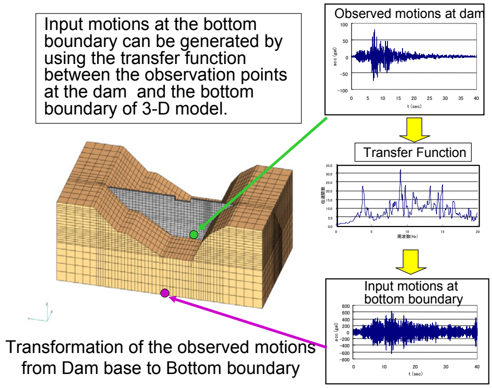
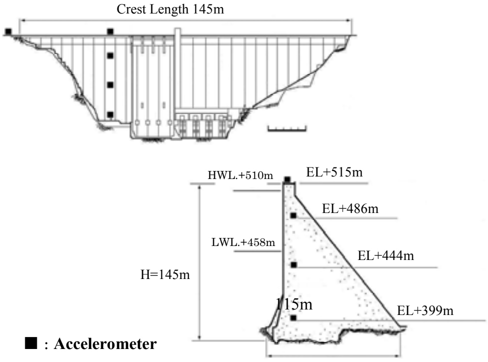


Figure 3: Transform of motions from the observed point to the input boundary.



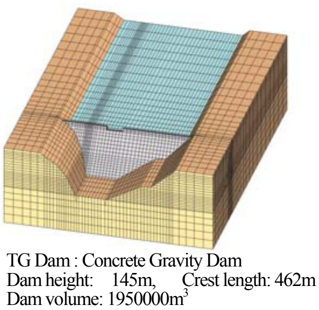


Figure 4: Location of seismometers at the TG Dam.

Figure 5: 3-D analytical model.

Table 1: Dynamic property values identified 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%

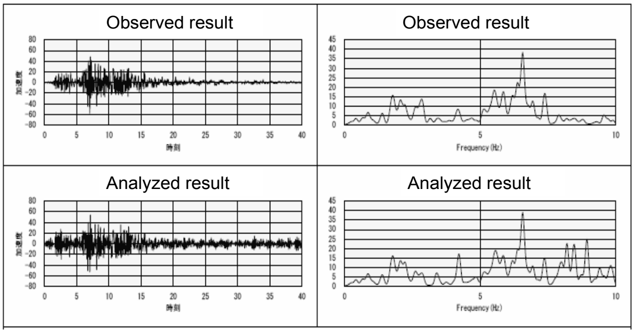
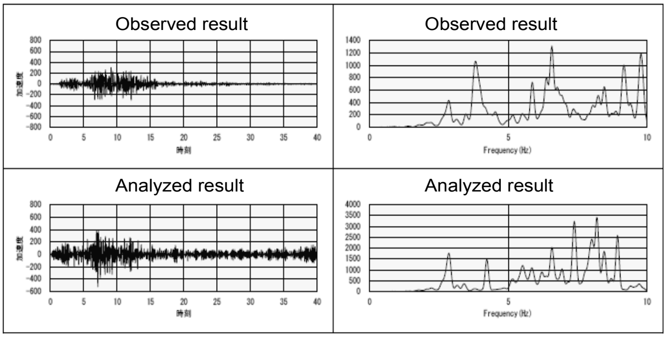


Figure 6: Comparison of acceleration time history at the dam base of the TG Dam.

The comparison between the observed results and the reproduction analysis results regarding the acceleration time history and the Fourier spectra at the dam base (EL.+399m) of the TG Dam is shown in fig. 6. Similarly, the comparison about the acceleration time history at 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 rest (EL.+515m)

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

Figure 7: Comparison of acceleration time history at the crest of the TG Dam.

4.4 Reproduction analysis for the IK Dam

The shape of the IK Dam and the arrangement of the seismometers are shown in fig. 8. The 3-D analytical model for the IK Dam is shown in fig. 9. The dynamic property values of the IK Dam identified by the 3-D reproduction analysis are shown in table 2.

As the representative results, the comparison between the observed result and the analyzed result about the acceleration time history at the crest center is shown in fig. 10.

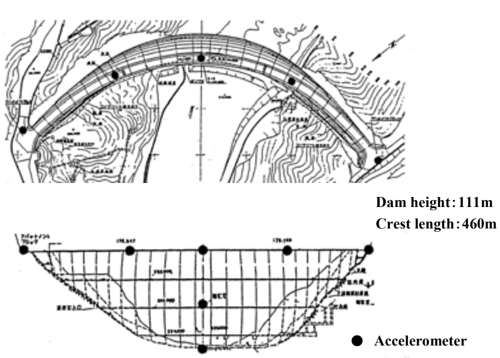
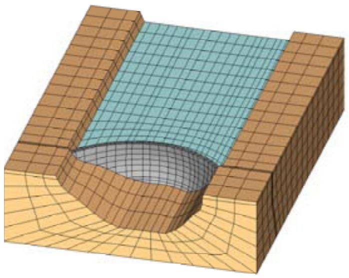


Figure 8: Location of seismometers at the IK Dam.



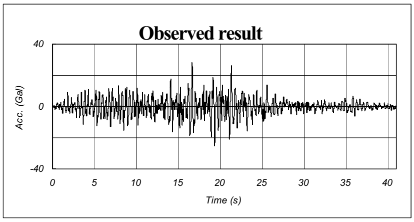
Concrete Arch Dam
Dam height: 111m, Crest length: 460m
Dam volume: 640000m^3

Figure 9: 3-D analytical model.

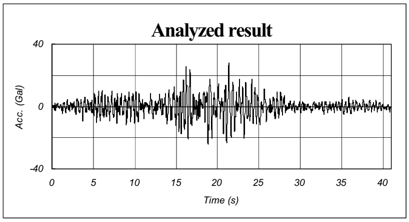
Table 2: Dynamic property values identified for the IK Dam.

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%

The acceleration time history at the dam can be reproduced well. The damping factor of the IK Dam was supposed according to the time of the motion, namely the damping factor for the time of 0 - 13 (sec) was set to be 2.6%, 2.9% for 13 - 20 (sec), and 3.1% for 20 - 41 (sec). It is considered that the reproducibility can be improved by applying this procedure. 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. (a) Observed history, (b) analyzed time-history.

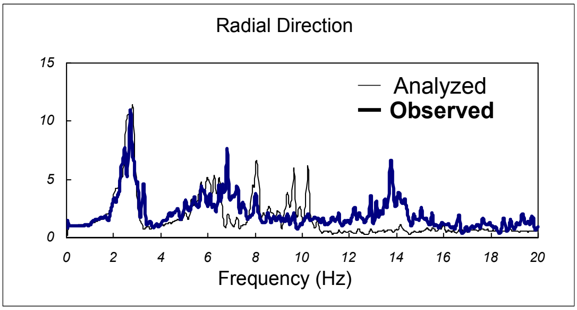


Figure 11: Comparison of transfer function in the radial direction between the dam center and the dam base of the IK Dam.

The comparison in regard to the spectral function, or the ratio of Fourier spectrum between the crest center and the dam base) is show in fig. 11. In regard to the frequency domain lower than 4 Hz, especially as for the natural frequency

(2.8 Hz) of the IK Dam, the analyzed result agreed with the observed result comparatively well.

4.5 Dynamic property values identified by the reproduction analyses

Table 3 shows the dynamic property values identified by the 3-D reproduction analyses. As the results, the S-wave velocity of the TG Dam, the IK Dam, the NK Dam and the ST Dam 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. In these cases, as the amplitude of earthquake motions are not so large, the actual earthquake behaviors can be reproduced by the linear analysis. In case of very strong earthquake motions, the nonlinear dynamic analysis taking the non-linearity of material will be required.

Table 3: Dynamic property values identified by the 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 %

The damping factor described here means a material damping factor, that is 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. If the radiation damping from the foundation to the free field is not considered, an additional damping factor should be taken into account.

It is considered that the values of the S-wave velocity and the damping factor were slightly changed according to the dam, because of the differences about the shape and size of dam, the acceleration level of earthquake motion, the dynamic interaction between dam and foundation.

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.

5 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 matters into account, I have developed a 3-D nonlinear dynamic analysis method for a coupled dam – joints – foundation – reservoir system.

The dynamic deformation property values 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.

An efficiency and validity of the dynamic analysis procedure be verified based on the actual earthquake phenomena.

I have made the 3-D reproduction analyses for actual earthquake behaviors of the NK Dam, the IK Dam, the ST Dam and the TG Dam, and evaluated the values of dynamic shear modulus and the damping factor of these dams quantitatively and practically.

And I have verified the efficiency and validity of the 3-D non-linear dynamic analysis method which I have developed in this study based on these reproduction analyses.

When the acceleration level of earthquake motion is not so large, the earthquake behavior can be reproduced by the linear dynamic analysis. But, 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 [7].

The 3-D dynamic analysis method is necessary to evaluate the earthquake safety quantitatively. If the earthquake observation data are obtained, the 3-D reproduction analysis for the actual earthquake behavior is effective to verify the validity of the dynamic analysis method [8].

In order to improve the disaster prevention performance of existing dams, the feedback of seismic safety evaluation to the earthquake countermeasures is necessary. A smooth and quick confirmation of dam safety will be strongly required after very large earthquake. The organic fusion of the earthquake observation data and the 3-D dynamic analysis enables to produce new information which is useful for the earthquake disaster prevention and mitigation [9].

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