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3-D DYNAMIC ANALYSIS OF EARTHQUAKE DAMAGE TO AN EXISTING SPILLWAY COMPOSED OF CONCRETE PIERS WITH DIFFERENT DYNAMIC RESPONSE PROPERTIES

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INTRODUCTION

For a dam, a spillway is an important facility, serving to discharge stored water. A spillway is composed of various structural elements including piers, shafts, hoisting equipment, and gates. Accurate evaluation of the seismic safety of a spillway thus requires evaluation of the mutual dynamic interactions of these structural components.

The 1993 Kushiro-oki earthquake (M7.5) damaged an existing spillway at the Kuttari Dam, which led to the installation of seismometers at that dam. Soon after, during the 1994 Hokkaido-touhou-oki earthquake (M8.2), recordings showed a maximum acceleration of 709.52 gal at the top of the spillway's concrete piers and 81.69 gal at the dam base. We then performed a 3-D dynamic analysis of the actual earthquake behavior of the concrete piers of the spillway, and made clear the mechanism of earthquake damage to the spillway.

3-D DYNAMIC ANALYSIS OF ACTUAL EARTHQUAKE BEHAVIOR OF EXISTING SPILLWAY

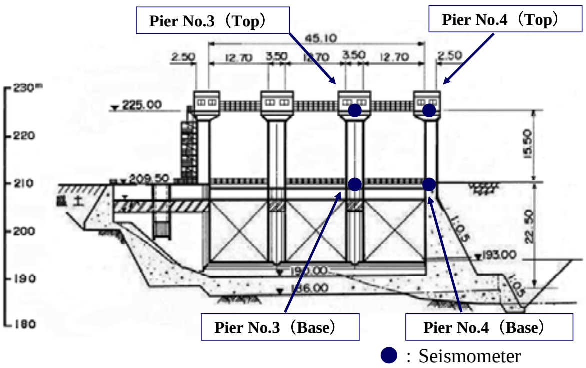
Purpose of the dynamic analysis

A fundamental function of dams is to store water and to discharge it in a safe manner. The spillway is thus a vital facility, and its discharge capability must never be compromised. A spillway is a hybrid structure composed of a variety of equipment and structural members, so it will show complex behavior during earthquakes, possibly increasing its vulnerability. Reports of earthquake damage to spillways have appeared in the published literature (ICOLD, 2001). Earthquake-resistant design of spillways has generally been based on the seismic coefficient method, which is appropriate and useful for a massive and rigid structure, but is not well suited to accurately evaluate the complex earthquake behavior of a spillway. For this purpose, a dynamic analysis is necessary. For existing structures, the necessity for seismic safety evaluation and seismic countermeasures will continue to increase as they age. Taking all this into account, we performed a 3-D dynamic analysis of the actual earthquake behavior of an existing spillway in order to improve the accuracy of seismic safety evaluation based on actual earthquake phenomena, and considered the mechanism of earthquake damage to the spillway, as well as rational seismic countermeasures.

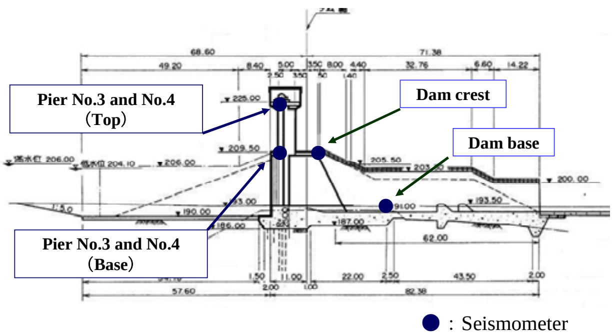
Existing spillway analyzed

3-D dynamic analysis was performed for the existing spillway of the Kuttari Dam, owned by Electric Power Development Co., Ltd. completed in 1987. The dam is a rock-fill structure with a height and crest length of 27.5 m and 220.1 m, respectively. The spillway of the dam is shown in Fig.1. The spillway is located at the left abutment of the dam, and includes 4 concrete piers. The hoisting equipment, or the winches, is placed at the top of the concrete piers. The piers and the training walls are made with reinforced concrete, and the fixed-wheel gates (height 13.5 m and width 12.7 m) are made of steel. The geology at the dam site is sandy riverbed sediment, and the terrace is developed around the site. The shape of the analyzed spillway and the location of the seismometers are shown in Fig.2.

Fig.1 Spillway analyzed in this study



1）Front Elevation （Upstream-side）



2）Vertical Section

Fig.2 Shape of spillway analyzed and location of seismometers

Earthquake event analyzed

The spillway was damaged during the 1993 Kushiro-oki earthquake (15, January, M7.5). Winches to wind up the gates are mounted on top of the four concrete piers of the spillway. The winches' attaching bolts were broken and the winches' steel shafts deformed by this earthquake. After the 1993 Kushiro-oki earthquake, seismometers were installed at the dam. Soon after that, the 1994 Hokkaido-touhou-oki earthquake (4 October, M8.2) occurred, causing motions with a maximum acceleration of 709.52 gal at the top of concrete piers and 81.69 gal at the dam base. Then we performed a 3-D dynamic reproduction analysis of the actual earthquake behavior of the concrete piers of the spillway, and ascertained the mechanism of the earthquake damage to the hoisting equipment.

Maximum accelerations and predominant frequencies of the earthquake motion recorded at the Kuttari Dam are shown in Table 1. The predominant frequencies were evaluated based on the Fourier spectra of the motion. The predominant frequencies at the dam crest were 1.22 Hz (stream direction), 1.86 Hz (dam-axis direction) and 2.06 Hz (vertical direction), with predominant frequencies at the top of Pier No.3 of 4.63 Hz (stream direction) and 1.87 Hz (dam-axis direction). Similarly, the predominant frequencies at the top of Pier No.4 were 4.24 Hz (stream direction) and 1.64 Hz (dam-axis direction). From the data in Table 1, it is considered that the dam body tends to respond in the stream direction, and the spillway responds more in the dam-axis direction. Incidentally, no earthquake damage was reported for the dam in the 1994 Hokkaido-touhou-oki earthquake.

Table 1 Maximum acceleration and predominant frequency of earthquake motions recorded at the Kuttari Dam

Position		Direction of motion	Maximum Acceleration (gal)	Predominant Frequency (Hz)
Dam Crest		Up-down stream	122.29	1.22
		Dam axis	115.78	1.86
		Vertical	80.82	2.06
Dam Base (Measuring chamber)		Up-down stream	81.69	1.22
		Dam axis	64.31	1.86
		Vertical	55.96	2.05
Pier No.3	Top	Up-down stream	187.29	4.63
		Dam axis	333.83	1.87
	Base	Dam axis	177.65	1.88
Pier No.4	Top	Up-down stream	243.96	4.24
		Dam axis	709.52	1.64
	Base	Dam axis	128.06	2.28

Acceleration time histories recorded at the bottom of the dam are shown in Fig.3, and were used as input motions for 3-D reproduction analysis. For accurate reproduction analysis, it is necessary to confine the frequency band, so components higher than 5 Hz were cut before input. Three motion components were input simultaneously in the 3-D reproduction analysis.

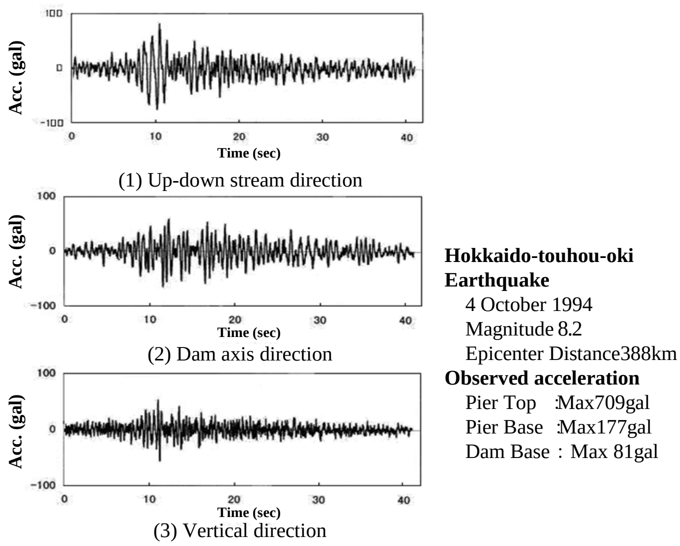


Fig.3 Acceleration time histories recorded at the bottom of the dam, which are used as input motions for 3-D reproduction analysis

3-D dynamic analysis model

The dynamic analysis model used for the reproduction analysis is shown in Fig.4. The spillway is composed of 4 concrete piers and 3 steel fixed-wheel gates. However, because they are separate from the piers, the fixed-wheel gates were not involved in the analysis model. The reservoir water was not involved in the analysis model because the reservoir water will not affect the response of the spillway, especially in the dam-axis direction. The spillway and the foundation were modeled with finite elements. The boundaries used were rigid for the bottom and viscous for the lateral boundaries. The shape of the spillway was modeled as faithfully as possible.

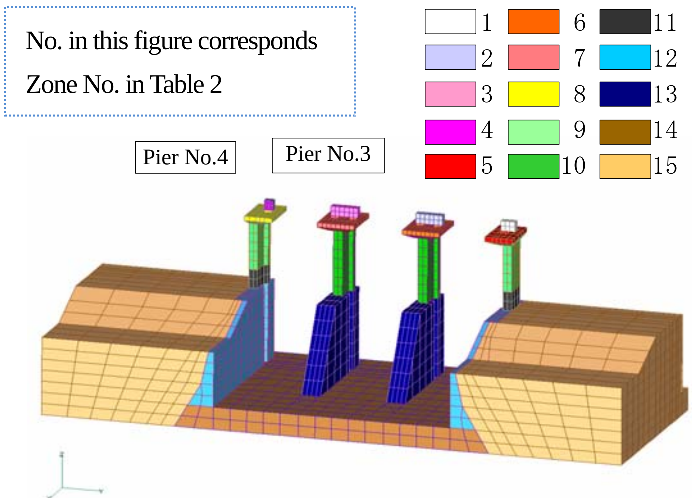


Fig.4 3-D dynamic analysis model (downstream view)

Dynamic property values used

A 3-D reproduction analysis of the actual earthquake behavior of the existing dam and its appurtenant structures can be performed by combining observed earthquake data with 3-D dynamic analysis. The basic flow of the 3-D reproduction analysis is shown in Fig. 5 .The values of the dynamic shear modulus and the damping factor can be determined by reproducing the actual earthquake behavior of the existing dam (Watanabe, et al. 2002, Ariga, et al. 2003). The dynamic shear modulus and the damping factor of the dam can be evaluated by adjusting until the analysis results approximate the actual earthquake observations based on the assumption of linear properties. The dynamic shear modulus can be evaluated by reproducing the predominant frequencies of the transfer function between the top and the bottom of a pier. The damping factor can be evaluated by reproducing the maximum motion amplitudes.

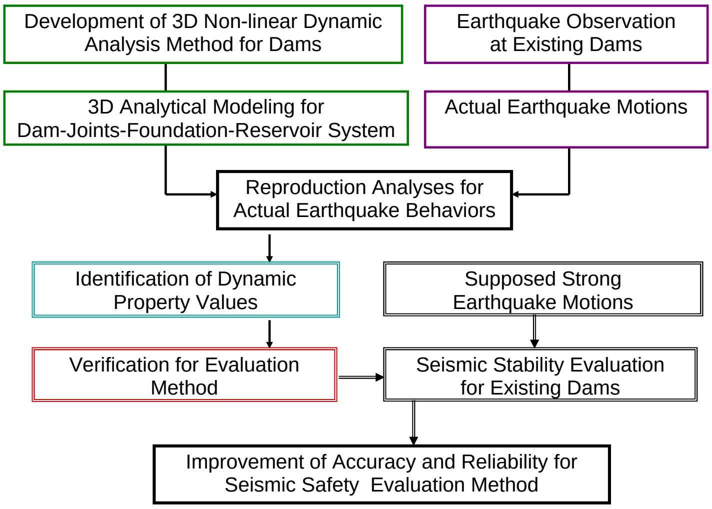


Fig.5 Basic flow of reproduction analysis

Values of the dynamic properties are shown in Table 2. The dynamic shear modulus and damping factor were determined from the 3-D reproduction analysis of actual earthquake behavior during the 1994 Hokkaido-touhou-oki earthquake, as explained above. Hoisting equipment such as winches, shafts, house and bridges were converted to the solid elements with actual weight.

Table2 Dynamic property values

(No. corresponds to the zoning numbers shown in Fig.4)

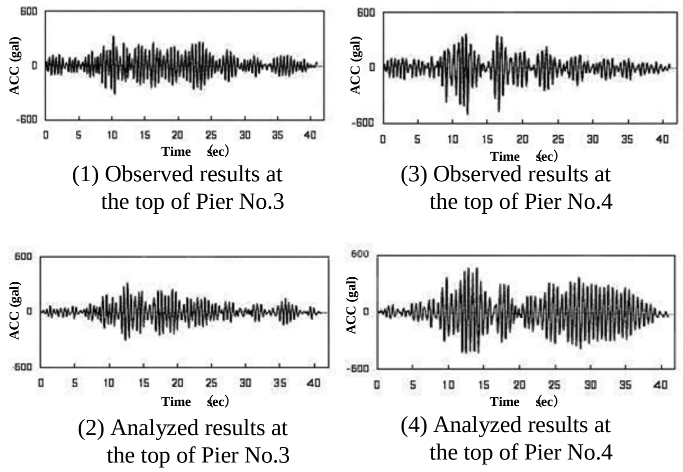
Zone		Dynamic shear modulus N/mm^2	Unit weight kN/m^3	Poisson's ratio	Damping factor
No.	Place				
1	No.1 Winch	50,000	34.9	0.20	0.02
2,3	No.2･3 Winch	50,000	29.6	0.20	0.02
4	No.4 Winch	22,500	36.9	0.20	0.02
5-8	Basement of winch	22,500	23.5	0.20	0.02
9	Pier No.1, 4	22,500	23.5	0.20	0.04
10	Pier No.2, 3	22,500	23.5	0.20	0.09
11	No1, 4 Pier base	22,500	23.5	0.20	0.03
12	No.1,4 Training wall	22,500	23.5	0.20	0.03
13	No.2,3 Training wall	22,500	23.5	0.20	0.03
14	Foundation	22,500	23.5	0.20	0.02
15	Fill dam	310	16.7	0.30	0.08

3-D dynamic analysis method

In order to produce an accurate and reliable evaluation of the seismic safety of an existing dam, several factors should be considered quantitatively and appropriately, including the dynamic interaction between the dam and its foundation, the damping of the dam's dynamic response by reservoir water, the radiation of wave energy from the boundary of the foundation to the free field, the non-linear effect of fill material, and the discontinuous behaviors of contraction joints and peripheral joints subjected to very strong earthquake motions. Taking these factors into account, a 3-D nonlinear dynamic analysis method for a coupled dam-joints-foundation-reservoir system was developed (Ariga, 2001), and this method was used excluding the interaction effect of the reservoir in the present study.

Analytical results

Fig.6 shows a comparison between the earthquake observations and the 3-D reproduction analysis for the acceleration time history at the top of Pier No.3 and Pier No.4. For Pier No.3, the analysis agreed well with the observed results. For Pier No.4, the analysis produced values larger than actual observations, especially for the time domain from 20 to 40 seconds. From the viewpoint of dynamic analysis, it might be concluded that the value of the damping factor is small, but from the viewpoint of the dynamic response of the structure, it is thought that Pier No.4 might be damaged, or some cracks might have reduced the response of Pier No.4.



(1) Observed results at the top of Pier No.3

(3) Observed results at the top of Pier No.4

(2) Analyzed results at the top of Pier No.3

(4) Analyzed results at the top of Pier No.4

Fig.6 Comparison between earthquake observation results and 3-D reproduction analysis results in regard to the acceleration time history at the top of Pier No.3 and Pier No.4

Similarly, the observed results and the analysis of the Fourier spectrum are compared in Fig.7. A representative comparison between the observed results and the analyzed results is summarized in Table 3. Natural frequencies shown in Table 3 were evaluated based on the transfer function between the top and the bottom of the pier. As a whole, the reproduction analysis results agreed well with observations.

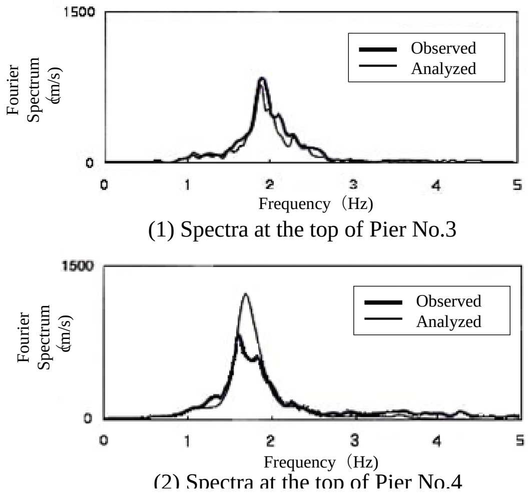


Fig.7 Comparison between the observed results and the analyzed results in regard to Fourier spectrum at the top of Pier No.3 and Pier No.4

Table 3 Representative comparison between the observed results and the analyzed results

Position of Pier		Earthquake observation results		3-D Dynamic analysis results	
		Maximum Acceleration (Gal)	Natural Frequency (Hz)	Maximum Acceleration (Gal)	Natural Frequency (Hz)
No.3	Top	321.3	1.89	318.5	1.94
	Base	81.2		89.6	
No.4	Top	507.5	1.64	487.9	1.72
	Base	92.1		91.9	

Fig.8 shows the distribution of maximum acceleration, and Fig.9 shows the distribution of maximum stress during the earthquake. The maximum tensile stress was 4.01 N/mm^2 at the base of Pier No.4. In general, the dynamic tensile strength of concrete is taken to be 3~5 N/mm^2, so it seems reasonable that slight cracks occurred in the pier due to the observed responses.

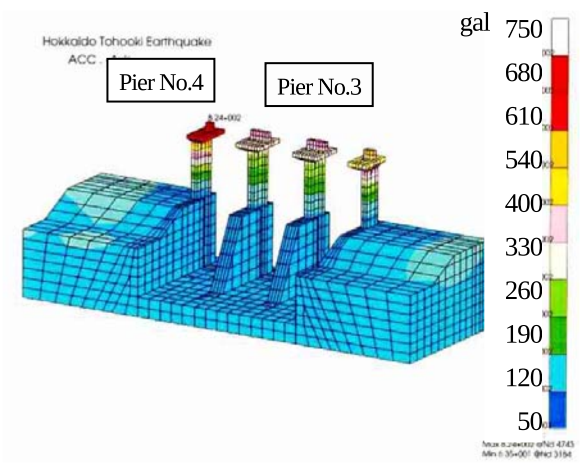


Fig.8 Distribution of maximum acceleration

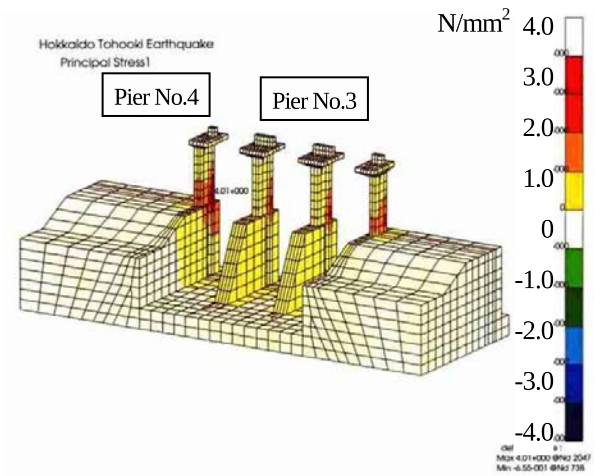
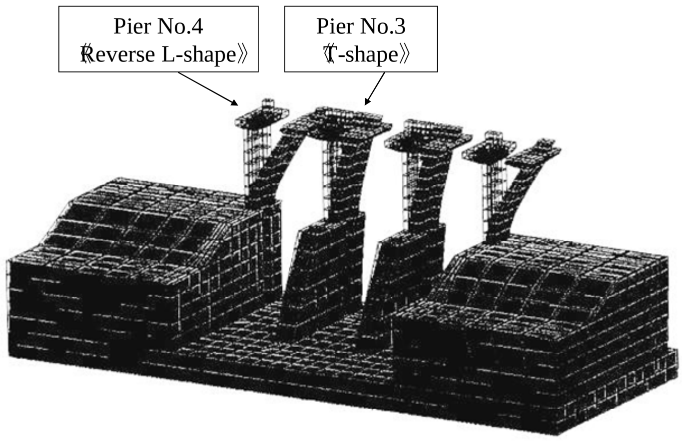


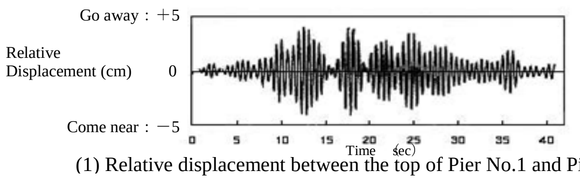
Fig.9 Distribution of maximum stress

Fig.10 shows the maximum displacement during the earthquake. In this case, the displacements of Piers No.1 and 4 were larger than those of Piers No.2 and 3. The maximum displacement at the top of Pier No.4 in the 1994 Hokkaido-touhou-oki earthquake was estimated to be 4.9 cm. Fig.11 shows the time history of relative displacement of the pier tops. The relative displacement between Piers No.2 and 3 was estimated to be very small, because their shapes and dynamic response characteristics were almost the same. The relative displacement between Piers No.1 and 2, and the relative displacement between Piers No.3 and 4 were estimated to be 4.5 cm and 4.9 cm, respectively. It is considered that the significantly different dynamic response characteristics of the piers derives from their shape differences. While Pier No.1 and Pier No4 are a reverse L-shape and thin, Pier No.2 and Pier No.3 are T-shaped and thick.

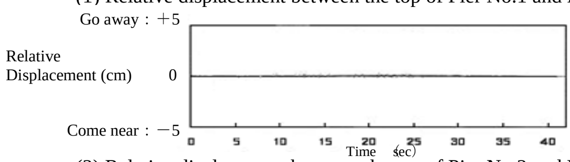


The Pier No.4 is the reverse L-shape and thin, and the Pier No.3 is the T-shape and thick. Therefore, the earthquake behaviors of these piers will become different from each other, and the relative displacement will appear by the earthquake motions. Maximum relative displacement between the top of Pier No.3 and Pier No.4 during the 1994 Hokkaido-touhou-oki Earthquake was estimated to be 4.9cm.

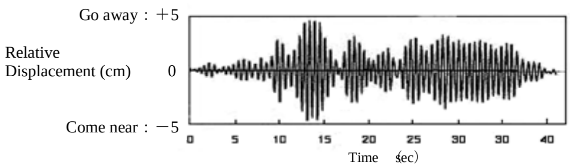
Fig.10 Distribution of maximum displacement



(1) Relative displacement between the top of Pier No.1 and Pier No.2



(2) Relative displacement between the top of Pier No.2 and Pier No.3

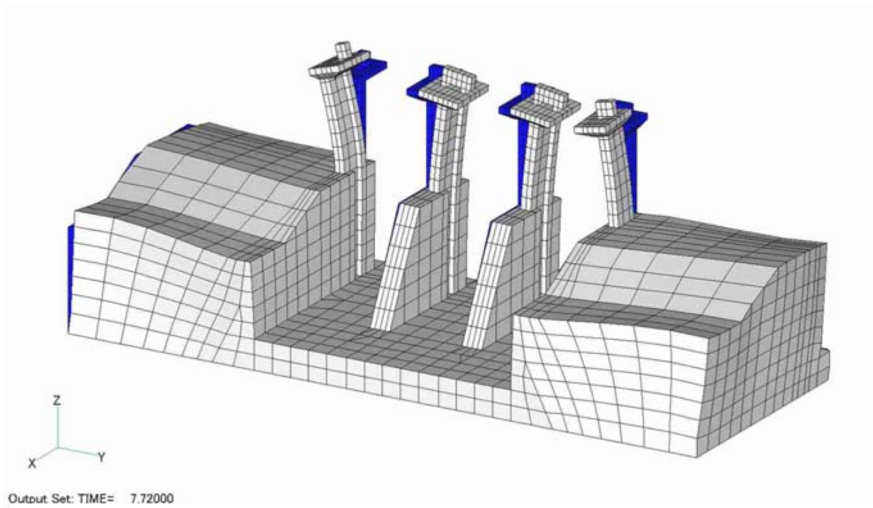


(3) Relative displacement between the top of Pier No.3 and Pier No.4

Fig.11 Relative displacement between the top of piers

CONSIDERATION OF THE MECHANISM PRODUCING SPILLWAY DAMAGE

The spillway analyzed in this study includes 4 concrete piers. Two piers on both sides are a reverse L-shape and thin, and two piers in the middle are T-shaped and thick. Because of their shape difference, their dynamic response, amplification and phase characteristics will differ. Consequently, the earthquake behavior of the piers differs, and the relative displacement of their tops due to earthquake motion will be larger. From the 3-D dynamic analysis results, it was concluded that the relative displacement between the piers was the main cause of earthquake damage to the hoisting equipment at the top of the piers. The dam’s motions in the stream direction were predominant and important. However, for the spillway, movement in the dam-axis direction was predominant and important. At many existing dams, the spillways have been constructed at the dam crest, where earthquake motion will be amplified and display a longer frequency and duration. Therefore, special attention should be paid to spillways located at the crest of a dam. Fig.12 shows a representative example of the different earthquake behavior of the piers.

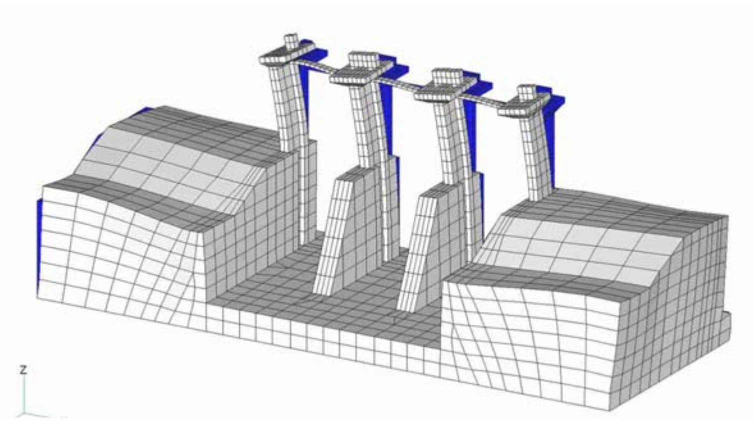


This figure shows the displacement behavior of concrete piers at the moment. 4 piers response individually against strong earthquake motion.
In this case, the Hitokura motions, that is the actual earthquake motions observed at the Hitokura Dam during the 1995 Hyogoken-nambu Earthquake, were used as the input motions.

Fig.12 Representative example of complex earthquake behavior

COUNTERMEASURES TO REDUCE RELATIVE DISPLACEMENT

As mentioned above, relative displacement is one of the main causes of earthquake damage to a spillway. An easy and effective countermeasure to reduce the relative displacement is to connect the piers with reinforcing structures. Fig.13 shows an analysis on the assumption that the piers are connected with reinforcing structures as countermeasures. The structures connecting the crest of piers shown in Fig. 1 and 2 are footbridges, and not have provided reinforcing effect to the piers during the earthquake.



This figure shows the displacement behavior of connected concrete piers at the moment. 4 piers are connected by reinforcements. Relative displacement among the piers can be easily and effectively dissolved.

Fig.13 Countermeasures to reduce earthquake relative displacement

POSTSCRIPT

Risk management for important facilities requires that we plan for the worst and achieve the best. If a spillway is damaged severely by an earthquake, its discharge capability may be lost, and in the worst-case scenario an overflow may occur. With a concrete dam, overflow may not result in dam failure, but overflow may cause a fill dam to fail.

With rapid urbanization and the expansion of urban areas, many existing dams have come to be surrounded by urban residential areas, making the confirmation and ensuring of dam safety increasingly important. Dam safety should be considered not only from the viewpoint of the earthquake performance of an individual dam but also with respect to avoiding disasters in urban areas. Therefore, earthquake safety should be verified with care and accuracy. The 3-D dynamic analysis method is very useful in the quantitative evaluation of structural earthquake damage. If observational earthquake data are obtained at the structure, the 3-D reproduction analysis of the actual earthquake behavior of the structure can very effectively verify the reliability and accuracy of predictions of the behavior. In order to improve the disaster prevention performance of existing dams, feedback of evaluation results into actual seismic countermeasures is very important. Careful preparation and adequate training are important and necessary for preventing and mitigating human and physical disasters during earthquakes (Ariga, et al. 2006).

REFERENCES

International Commission on Large Dams, Historic performance of dams during earthquakes, Design features of dams to resist seismic ground motion (Guidelines and case studies), *ICOLD Bulletin* 120 (2001)

Ariga Y., Study on quantitative evaluation of dynamic properties of dams by 3-D reproduction analyses, *Thesis for doctorate of Saitama University* (2001)

Watanabe H., Y. Ariga, Z. Cao, Earthquake Resistance of a Concrete Gravity Dam Revaluated with 3-D Nonlinear Analysis, *Proc. of JSCE*, No.696/I-58, (2002) p.99-110

Ariga Y., Cao Z., Watanabe H., Seismic Stability Assessment of An Existing Arch Dam Considering the Effects of Joints, *Proceedings of the 21st International Commission on Large Dams,* Q.83-R.33, (2003) p.553-576.

Ariga Y., Z. Cao, H. Watanabe, Development of 3-D Dynamic Analysis Method for coupled Dam-Joints-Foundation-Reservoir System, *The 13th World Conference on Earthquake Engineering (13WCEE)*, No.412, (2004) p.1-13.

Ariga Y., Fujinawa, Y., Hori M. ：Development of Immediate Evaluation Method of Earthquake Safety of Existing Dams, *The 8th U.S. National Conference on Earthquake Engineering (The 100th Anniversary Earthquake Conference – commemorating the 1906 San Francisco Earthquake)*, 8NCEE-No.196, (2006), pp.1-11.

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