STUDY ON EARTHQUAKE DAMAGE MECHANIZM AND MEASURES OF SPILLWAY COMPOSED OF CONCRETE PIERS WITH DIFFERENT SHAPES AND DYNAMIC RESPONSE PROPERTIES

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ABSTRACT :

A spillway is an important facility, whose function is discharge. Spillway is composed of various structural elements such as piers, shafts, hoisting equipments, gates, and so forth. So, in order to evaluate seismic safety of spillway accurately, it is necessary to evaluate the mutual dynamic effects among these structural components of spillway. At the 1993 Kushiro-oki Earthquake (M7.8), earthquake damage occurred at the existing spillway. Taking the opportunity, the seismometers were installed at the dam and spillway after the 1993 Kushiro-oki Earthquake. Soon after that, the earthquake motions of maximum acceleration 709.52 gal at the top of concrete piers and 81.69 gal at the dam base were recorded during the 1994 Hokkaido-touhou-oki Earthquake (M8.2). Then, I made the 3-D dynamic analysis in regard to the actual earthquake behaviors of concrete piers of the spillway, and made clear the mechanism of earthquake damage of spillway.

KEYWORDS: spillway, earthquake damage, relative displacement, 3-D dynamic analysis

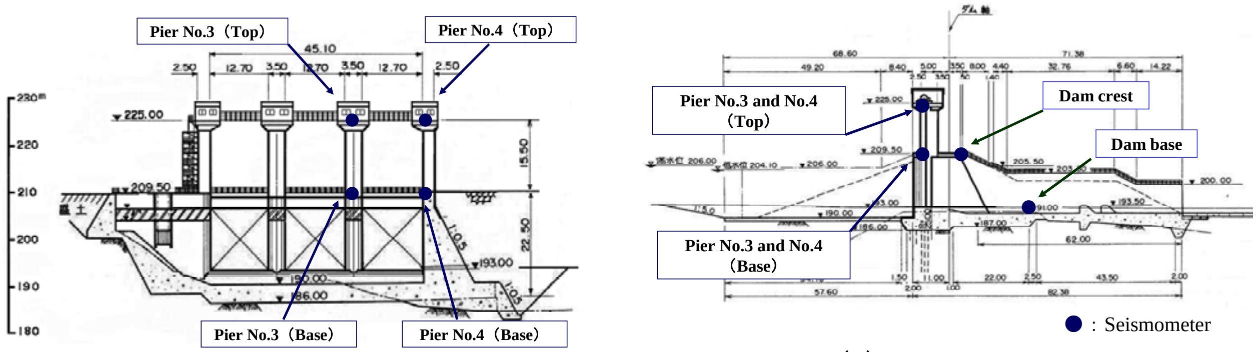
1. PURPOSE

The fundamental function of dam is water storage. And, the discharge function is also required to be preserved in connection with the water storage function. A spillway is an important facility which shoulder the function of discharge, therefore the loss of discharge function is not allowable. Spillway is a hybrid structure which is composed of various structural members and equipments. So, the spillway will be apt to be affected by earthquakes because of its complex structure. According to the literature, some earthquake damages of spillway were reported thus far, (ICOLD, 2001). The earthquake resistant design of spillway has been made based generally based on the seismic coefficient method in the past. The seismic coefficient method is compatible and useful for the massive and rigid structure, but it is difficult to evaluate the complex earthquake behaviors of spillway by the seismic coefficient method. In order to evaluate the complex earthquake behaviors of spillway accurately, it is considered that the dynamic analysis is necessary. In regard to the existing structures, the necessity for the seismic safety evaluation and the seismic countermeasures will increase more and more with the passage of time after construction. Taking these matters into account, I made 3-D dynamic analysis for actual earthquake behavior of existing spillway in order to improve the accuracy of seismic safety evaluation based on the actual earthquake phenomena, and considered about the mechanism of earthquake damage of the spillway and the rational seismic countermeasures.

2. DYNAMIC SIMULATION ANALYSIS FOR ACTUAL EARTHQUAKE BEHAVIOR

2.1 Existing spillway analyzed

3-D dynamic analysis was made in regard to the existing spillway of the Kuttari Dam constructed in 1987. The dam is rock-fill dam, whose height and crest length is 27.5m and 220.1m, respectively. The spillway is located at the left abutment of the dam, and composed of 4 concrete piers. The hoisting equipments, or the winches, are 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 13.5m, width 12.7m) are made with steel. The geology at the dam site is the riverbed sediment of sand, and the terrace is developed around the site. The shape of the spillway analyzed and the location of the seismometers are shown in Figure 1.



（1）Front Elevation（Upstream-side）　（2）Vertical Section

Figure 1 Shape of the spillway analyzed and location of seismometers

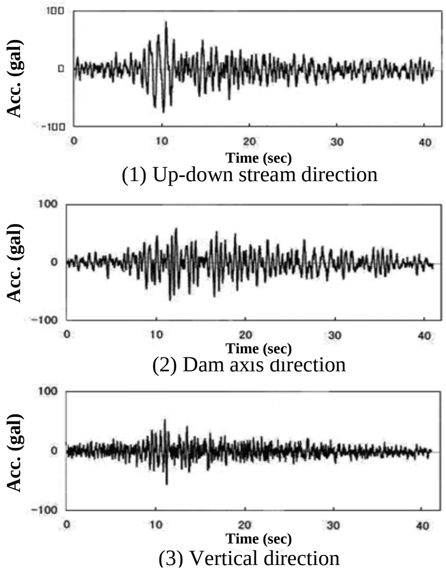
2.2 Earthquake event analyzed

Earthquake damage occurred at the spillway during the 1993 Kushiro-oki Earthquake (15, January, M7.8). The winches for winding up the gates are placed at the top of 4 concrete piers of the spillway. The fixed bolts of winches were broken and the steal shafts of winches were deformed by this earthquake. After the 1993 Kushiro-oki Earthquake, the seismometers were installed at the dam and spillway. Soon after that, the 1994 Hokkaido-touhou-oki Earthquake (4, October, M8.2) occurred, and the earthquake motions of maximum acceleration 709.52 gal at the top of concrete piers and 81.69 gal at the dam base were recorded during this earthquake. Then, I made the 3-D dynamic reproduction analysis regarding the actual earthquake behaviors of the concrete piers of the spillway, and made clear the mechanism of earthquake damage of the hoisting equipments. Maximum acceleration and predominant frequency of earthquake motions recorded at the Kuttari Dam and Spillway is shown in Table 1.

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

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

The predominant frequencies were evaluated based on the Fourier spectra of motions. The predominant frequencies at the dam crest are 1.22Hz (stream direction), 1.86Hz (dam-axis direction) and 2.06Hz (vertical direction). The predominant frequencies at the top of Pier No.3 are 4.63Hz (stream direction) and 1.87Hz (dam-axis direction). Similarly, the predominant frequencies at the top of Pier No.4 are 4.24Hz (stream direction) and 1.64Hz (dam-axis direction). According to Table 1, it is considered that the dam tends to response in the up-down stream direction, but the spillway tends to response in the dam-axis direction. Acceleration time histories recorded at the bottom of the dam are shown in Figure 2, which are used as input motions for 3-D reproduction analysis. In order to make an accurate reproduction analysis, it is necessary to confine the frequency band, so the components higher that 5 Hz were cut before input. Three components of motions are input simultaneously in the 3-D reproduction analysis. Incidentally, no earthquake damages were reported about the dam and spillway at the 1994 Hokkaido-touhou-oki Earthquake. Incidentally, no earthquake damages were reported about the dam and spillway at the 1994 Hokkaido-touhou-oki Earthquake.



Hokkaido-touhou-oki Earthquake
4 October 1994
Magnitude 8.1
Epicenter Distance388km
Observed acceleration
Pier Top : Max709gal
Pier Base : Max177gal
Dam Base : Max 81gal

Figure 2 Acceleration time histories recorded at the bottom of dam in the 1994 Hokkaido-touhou-oki Earthquake, which are used as input motions for the 3-D reproduction analysis

2.3 Dynamic analysis model

The dynamic analysis model used for the reproduction analysis is shown in Figure 3. The spillway is composed of 4 concrete piers and 3 steel fixed-wheel gates. The fixed-wheel gates were omitted in the model, because the fixed-wheel gates are separated from the piers. The reservoir water was also omitted in the model, because the reservoir water will not have any influence on the response of spillway especially in the dam-axis direction. The spillway and the foundation were meshed with the finite elements. As for the boundary conditions, the rigid boundary is applied for the bottom boundary, and the viscous boundary for the lateral boundaries. The shape of the spillway was modeled as faithful as possible.

2.4 Dynamic property values used

The 3-D reproduction analyses for the actual earthquake behaviours of existing dam and its ancillary facilities were made as a combination between the earthquake observation data and the 3-D dynamic analysis. The values of the dynamic shear modulus and the damping factor were identified by reproducing the actual earthquake behaviors of existing dam. The dynamic shear modulus and the damping factor of dam and spillway were evaluated by adjusting until the analysis results approximate the earthquake observation results based on the assumption of linear properties.

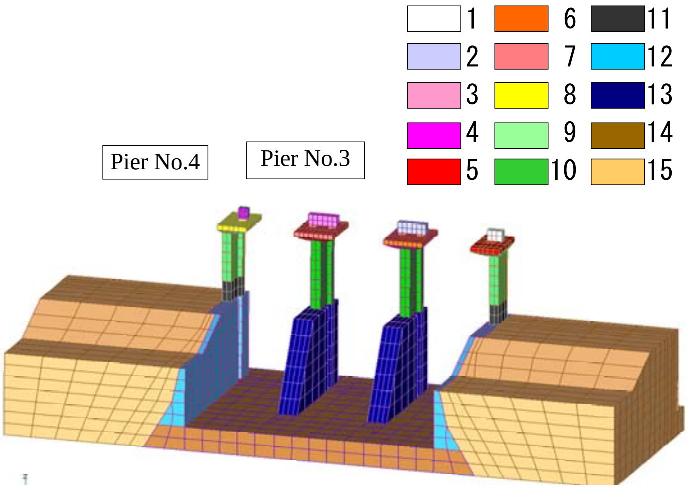


Figure 3 3-D dynamic analysis model (from down-stream side)

The dynamic shear modulus was evaluated by reproducing the predominant frequencies of transfer function between top and bottom. The damping factor was evaluated by reproducing the maximum amplitude of motions. The dynamic property values are shown in Table 2. The dynamic shear modulus and damping factor were identified by the 3-D reproduction analysis for actual earthquake behavior during the 1994 Hokkaido-touhou-oki Earthquake, as explained above. The hoisting equipments such as winches, shafts, house and bridges were converted to the unit weight and modeled by using solid elements.

Table 2 Dynamic property values identified by the reproduction analysis

(No. corresponds to the zoning number shown in Figure 3.)

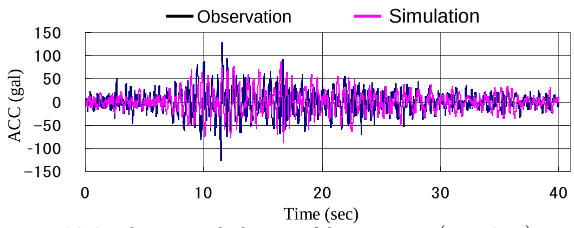
Zone		Dynamic shear modulus N/mm^2	Unit weight kN/m^3	Poisson's ratio	Damping factor
No.	Place				
1	No.1 Winch	50000	34.9	0.20	0.02
2,3	No.2・3 Winch	50000	29.6	0.20	0.02
4	No.4 Winch	22500	36.9	0.20	0.02
5-8	Basement of winch	22500	23.5	0.20	0.02
9	Pier No.1, 4	22500	23.5	0.20	0.04
10	Pier No.2, 3	22500	23.5	0.20	0.09
11	No1, 4 Pier base	22500	23.5	0.20	0.03
12	No.1,4 Training wall	22500	23.5	0.20	0.03
13	No.2,3 Training wall	22500	23.5	0.20	0.03
14	Foundation	22500	23.5	0.20	0.02
15	Fill dam	310	16.7	0.30	0.08

2.5 Analysis method

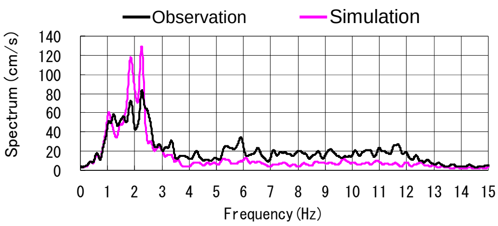
In order to realize an accurate and reliable evaluation for seismic safety of existing dams, a dynamic interaction between dam and foundation, a reduction effect on a dynamic response of dam by reservoir water, a radiation of wave energy from the boundary of foundation to the free field, a non-linear 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 was developed, (Ariga,2001). This dynamic analysis method was applied for the 3-D dynamic analysis in this study.

2.6 Analytical results

Figure 4 shows the comparison between the earthquake observation results and the 3-D reproduction analysis results in regard to the acceleration time history at the top of Pier No.4. The analyzed results agreed with the observed results comparatively well, but the analyzed results became larger than the observed results, especially for the time domain from 20 to 40 (sec). From the viewpoint of dynamic analysis, it can be thought that the value of damping factor might be small, however from the viewpoint of dynamic response of structure, it can be supposed that the Pier No.4 might be damaged, or some cracks might occurred, and the response of the Pier No.4 might reduce.
The comparison between the observed results and the analyzed results about the Fourier spectrum is also shown in Figure 4. The representative comparison between the observed results and the analyzed results are summarized in Table 3. Natural frequencies shown in Table 3 were evaluated based on the transfer function between the top and the bottom of pier. As a whole, the reproduction analysis results agreed with the observation results well.



(1) Acceleration at the bottom of the No.4 Pier（Dam Axis）



(2) Spectra at the bottom of the No.4 Pier（Dam Axis）

Figure 4 Comparison between earthquake observation results and 3-D reproduction analysis results in regard to the acceleration time history and Fourier spectrum at the top of 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	

Figure 5 shows the distribution of maximum acceleration, and Figure 6 shows the distribution of maximum stress through all the time. The maximum tensile stress was 4.01N/mm^2 at the base of the Pier No.4. In general, the dynamic tensile strength of concrete is thought to be 3~5N/mm^2. So, it can be thought that some slight cracks may occur.

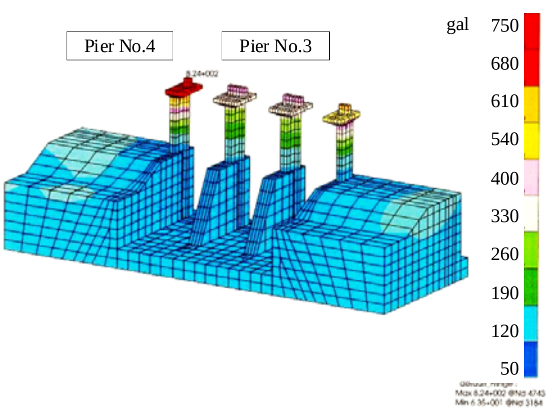


Figure 5 Distribution of maximum acceleration

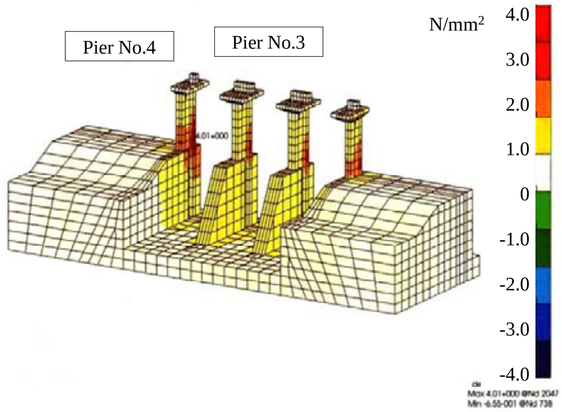
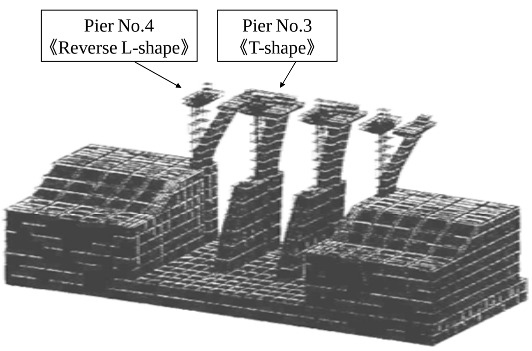


Figure 6 Distribution of maximum stress

Figure 7 shows the maximum displacement through all the time. In this case, the displacements of Pier No.1 and No.4 became larger than those of Pier No.2 and No.3. The maximum displacement at the top of Pier No.4 against the 1994 Hokkaido-touhou-oki Earthquake was estimated to be 4.9cm.
Figure 8 shows the time history of relative displacement between the top of piers. The relative displacement between Pier No.2 and No.3 was estimated to be very small, because the shapes and the dynamic response characteristics were almost same. The relative displacement between Pier No.1 and No.2, and the relative displacement between Pier No.3 and No.4 were estimated to be 4.5cm and 4.9cm, respectively. In regard to this result, it is considered that the shapes and the dynamic response characteristics are much difference each other. While Pier No.1 and Pier No4 are the reverse L-shape and thin, Pier No.2 and Pier No.3 are the T-shape 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.

Figure 7 Maximum displacement

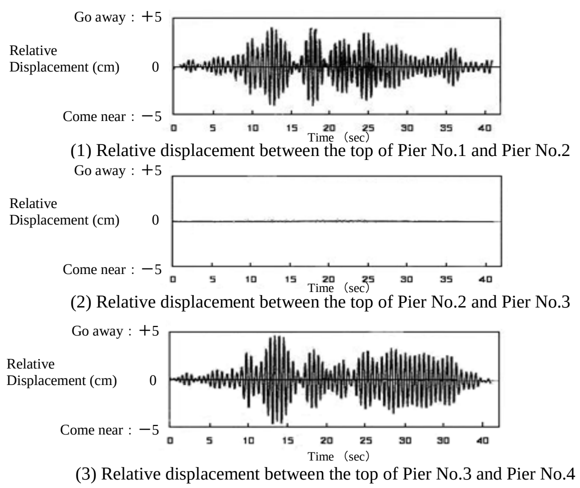
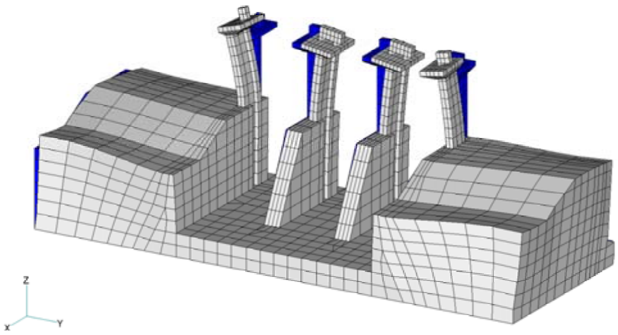
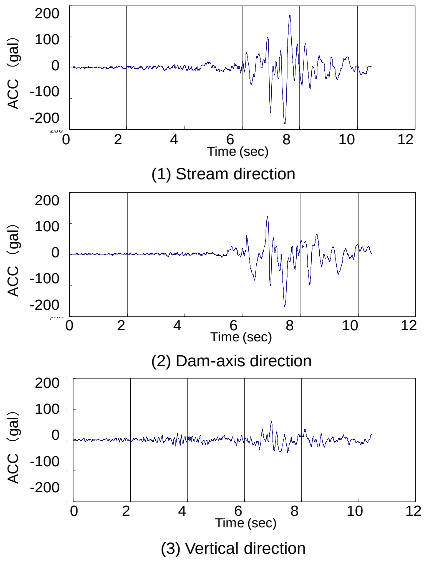


Figure 8 Relative displacement between the top of piers

For the reference, Figure 9 shows the earthquake behavior against the Hitokura motions, which are the actual motions observed at the Hitokura Dam in the 1995 Hyogoken-nanbu Earthquake.



Earthquake behavior against the Hitokura Motions
(The Hitokura motions are the actual earthquake motions observed at the Hitokura Dam during the 1995 Hyogoken-nanbu Earthquake)



Motions observed at the Hitokura Dam

Figure 9 Earthquake behavior against the Hitokura motions

3. CONSIDERATION ABOUT THE MECHANISM OF EARTHQUAKE DAMAGE OF SPILLWAY

Spillway is composed of various structural elements such as piers, shafts, hoisting equipments, gates, and so forth. So, in order to evaluate seismic safety of spillway accurately, it is necessary to evaluate the mutual dynamic effects between the structural components of spillway.

The spillway analyzed in this study is composed of four concrete piers. Two piers on both sides are the reverse L-shape and thin, and two piers on middle sides are the T-shape and thick. Therefore, the earthquake behaviors of these piers became different from each other, and the relative displacements at the top of piers were increased by the earthquake motions. From the 3-D dynamic analysis results, it was concluded that the relative displacements between piers were main cause of earthquake damages about the hoisting equipment located at the top of piers. The countermeasures by connecting the piers with the reinforcement will be easy and effective to reduce the relative displacement between piers with different shapes and different dynamic response properties.

As for the dam, the motions in the stream direction are predominant and important. However, as for the spillway, the motions in the dam-axis direction are predominant and important. At many existing dams, the spillways have been constructed at the dam crest. So, special attention should be paid to the spillway located at the crest of dam.

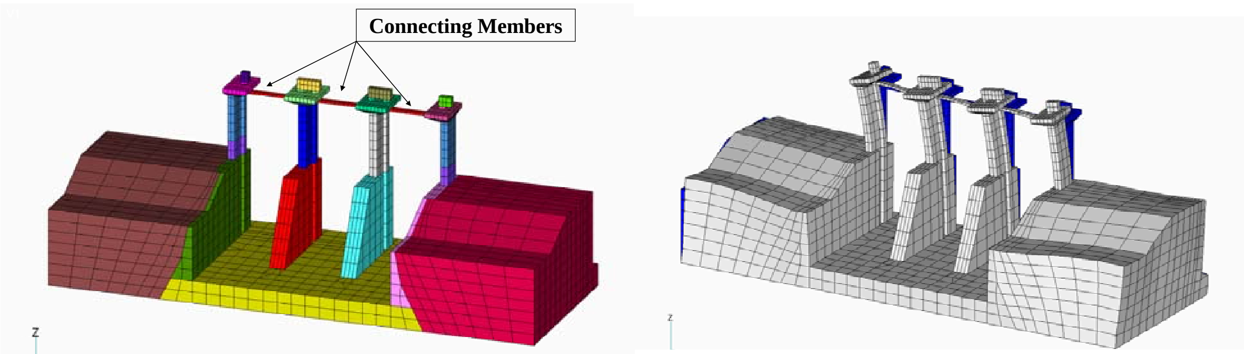
4. CONSIDERATION ABOUT COUNTERMEASURES TO REDUCE RELATIVE DISPLACEMENT

From the 3-D dynamic analysis results, it is concluded that the relative displacements between piers are the main cause of earthquake damages about the hoisting equipment located at the top of piers. The countermeasure by connecting the piers with the reinforcement is considered to be easy and effective to reduce the relative displacement between piers with different shapes and different dynamic response properties. One of the analytical results about the measures is shown Figure 10.

5. IMPROVEMENT OF DISASTER PREVENTION PERFORMANCE

From the viewpoint of the risk management of important facility, it will be necessary to suppose the worst, and realize the best. If the spillway is damaged by the earthquake and lose the discharge performance, the overflow may occur in the worst-case scenario. As for the concrete dam, the overflow may not result in the failure of dams. But as for the fill dam, the overflow may result in the failure of dams.

With the progress of urbanization and the expansion of urban area, many of existing dams have come to be surrounded by the urban residential area. Under such circumstances, the confirmation and securing of dam safety are becoming more important, because the dam safety should be considered from the viewpoint of not only the earthquake performance of individual dam but also the disaster prevention performance of urban area. Therefore, the verification of earthquake safety should be made more carefully and accurately. The 3-D dynamic analysis method is very useful to evaluate the earthquake damage of structures quantitatively. If the earthquake observation data are obtained at the structure, the 3-D reproduction analysis for the actual earthquake behavior of the structure is very effective in order to verify the reliability and accuracy of the evaluation. The preparatory evaluation at peace time, which is situated as the first step of the immediate evaluation method proposed in this study, can be effectively applied for the seismic diagnosis of existing structures. In order to improve the disaster prevention performance of existing structures, the feedback of the evaluation results to the seismic measures is very important. A careful preparation and an adequate training during peace time are important and necessary for preventing and mitigating human and physical disaster during earthquakes.



Analytical Model reinforced by the Connecting Members

Earthquake behavior against the Hitokura Motions
(The Hitokura motions are the actual earthquake motions observed at the Hitokura Dam during the 1995 Hyogoken-nanbu Earthquake)

Figure 10 Countermeasures to reduce earthquake relative displacement

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