INTERNATIONAL SYMPOSIUM ON
DAMS FOR A CHANGING WORLD
-Need for Knowledge Transfer across the Generations & the World
Kyoto, Japan June 5, 2012

Efficient Confirmation Method for Seismic Safety of Dam and Spillway by combining Earthquake Early Warning and 3D Dynamic Analysis

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ABSTRACT
We studied on the efficient method for confirming the seismic safety of dam and spillway by combining the Earthquake Early Warning (EEW), the earthquake observation at the site, and 3D dynamic analysis in order to rationalize the emergency inspection just after large earthquake. The method proposed is mainly composed of 3 stages. The first stage is an advance evaluation at ordinary time, the second is an immediate evaluation just before the arrival of earthquake motion, and the third is a proof evaluation just after the earthquake. In the first stage, the earthquake damage of structure is evaluated by the 3D dynamic analyses. In the second stage, the earthquake motion is estimated immediately based on EEW, and the most suitable analytical results are automatically selected and displayed. In the third stage, the verification analyses are made by using the actual earthquake motions recorded at the site. The applicability of the method proposed was examined by the case study. By applying the method proposed, the workers at the site, who are not familiar with the earthquake engineering, can easily recognize the important parts which should be inspected quickly. Consequently, the rational emergency inspection and the efficient confirmation for seismic safety of hydraulic structures can be realized.

Keywords: hydraulic structure, emergency inspection, seismic safety, Earthquake Early Warning, 3D dynamic analysis

1. INTRODUCTION

Seismological observation networks such as the Hi-net/ KiK-net, the K-NET by the National Research Institute for Earth Science and Disaster Prevention (NIED), and the seismological observation network by the Japan Meteorological Agency (JMA) have been densely arranged in Japan. Magnitude of earthquake and the location of epicenter have come to be estimated in a few seconds based on the observed data of P-waves. And, arrival time and seismic intensity of main shock can be estimated and informed before the attack of S-wave. This earthquake information before the arrival of main shock is defined as the Earthquake Early Warning (EEW).

On the other hand, 3D dynamic analysis method for coupled dam-foundation-reservoir system has been developed (Ariga, 2001). And it has become possible to evaluate the earthquake safety of structures with high accuracy.

With these points as background, we have developed a method for evaluating the earthquake damage of existing dam and spillway immediately by combining 3D dynamic analysis, EEW and strong earthquake motions observed at the site in order to rationalize the emergency inspection for hydraulic structures just after large earthquake.

2. PURPOSE

Confirmation and securing of seismic safety of existing infra-structure is very important subject in earthquake countries. In regard to the structures of great importance, such as dam, spillway, hydroelectric power facilities, and so forth, it is necessary to grasp the earthquake damages accurately, and to confirm the seismic safety smoothly. Especially at the time of severe earthquake, a quick and efficient inspection will be strongly required. Furthermore, the reliable information regarding safety and security should be dispatch to the parties concerned and the public as soon as possible.

The following problems can be pointed out from the earthquake experiences thus far.

・It takes a lot of time to recognize what happens, or what earthquake occurs.
・It takes a lot of time to grasp the actual state of earthquake damage, the quality and the quantity of

damage.
・Usually, there is not an engineer who is familiar with the seismology or the earthquake engineering at the site.
・Decision making becomes more difficult as the earthquake damage becomes extensive.
・A flood of inquiries for safety and security of dam facilities rushes to the site and the parties concerned.

Taking such necessity into account, we studied on the efficient method for confirming the seismic safety of hydraulic structures by combining 3D dynamic analysis, EEW, and the earthquake observation data at the site in order to rationalize the emergency inspection just after large earthquake.

3. EFFICIENT CONFIRMATION METHOD FOR SEISMIC SAFETY

3.1. Outline of the Method

The outline of efficient confirmation method for earthquake damage of dam and spillway is shown in Fig. 1. And the fundamental flow of earthquake disaster prevention information in ordinary and earthquake time is shown in Fig. 2. Main feature of this study is a combination between 3D dynamic analysis and earthquake observation data, such as EEW and actual strong earthquake motions. As shown in Fig. 1, the method is mainly composed of three stages.

The first stage is an advance evaluation in ordinary time. The advance evaluation consists of the arrangement of earthquake damages of existing dams and spillways, the 3D dynamic analyses under various conditions, and the arrangement of the analyzed results concerning earthquake damage. The 3D dynamic analyses are made in order to evaluate the dynamic stress and strain within the structures under various conditions, such as input earthquake motions, dynamic properties of structures and foundation, depth of reservoir water, and so forth.

The second stage is an immediate evaluation just before the arrival of earthquake motion. The immediate evaluation consists of the receipt of EEW, the estimation of earthquake motion at the object site based on EEW, the immediate evaluation of earthquake damage, search of the most adequate results about earthquake damage, the transmission of selected information to the site, and so forth. The procedure from the receipt of EEW to the transmission of information can be executed within 1 second.

And the third stage is a proof evaluation just after the earthquake. The verification analyses by using the actual earthquake motions are made in the third stage.

3.2. Immediate Evaluation Method

The earthquake damage of dam and spillway is evaluated by the 3D dynamic analysis. The leeway time before the attack of main shock will be expected to be several to several ten seconds. At present time, it is difficult to execute 3D dynamic analysis within several seconds. And the engineer who is familiar with the earthquake engineering is not necessarily working at the dam site. Taking these matters into consideration, we devised the information transmission system which works automatically at the same time of receipt of EEW. The fundamental flow of the immediate evaluation before earthquake and verification analysis after earthquake is shown in Fig. 3.

The damage of structure by strong earthquake motion will be affected by the shape and the size of structure, the dynamic property of structure and foundation, the condition of reservoir water, the amplitude and frequency characteristics of input motion. These affects should be examined by the 3D dynamic analyses.

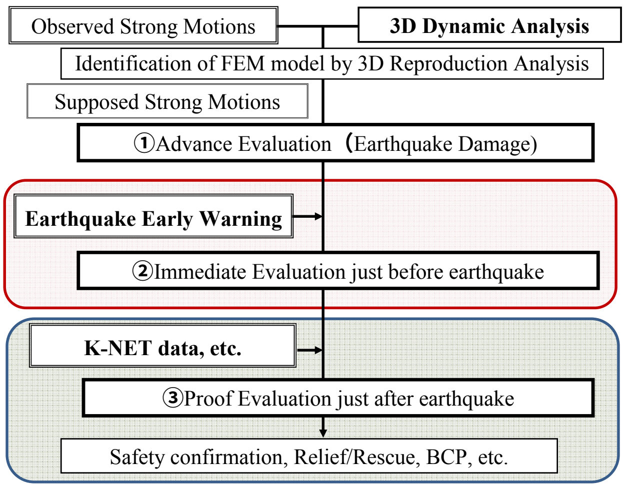


Figure 1. Procedure of immediate evaluation and efficient confirmation method

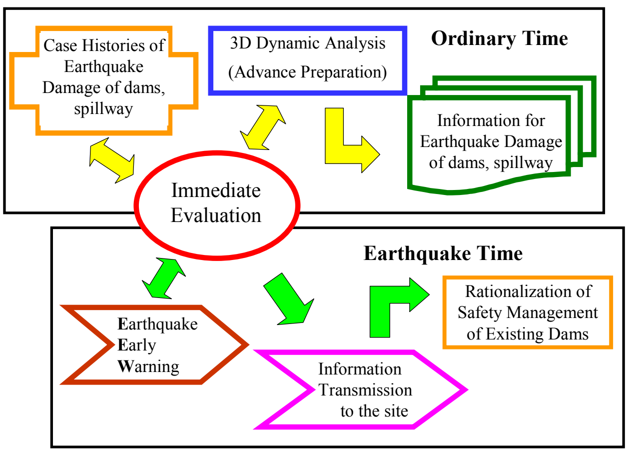


Figure 2. Fundamental flow of earthquake disaster prevention information in ordinary time and earthquake time

The 3D dynamic analyses are made by assuming various conditions in regard to the maximum acceleration of input motions, the water level of reservoir, the dynamic property values of foundation.

The charts for urgent judgment of earthquake damage of dams are made based on the results of the 3D dynamic analyses which are made under the plenty of analytical conditions. The charts are arranged as the function of maximum acceleration and predominant frequency of input earthquake motions.

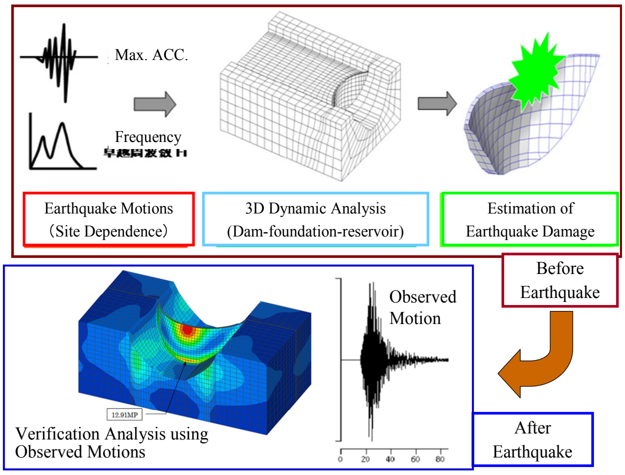


Figure 3. Flow of immediate evaluation before earthquake and verification evaluation after earthquake

4. FUNDAMENTAL CASE STUDIES

The method proposed in this study is contrived as the organic fusion of 3D dynamic analysis and EEW and seismological observation. This method is devised based on the idea that the organic fusion of earthquake observation data and 3-D dynamic analysis enables to produce new information necessary for the earthquake disaster prevention and mitigation.

The case study was made in order to examine the applicability of the method. An arch dam and a spillway were selected as the objects for the case study. The strong earthquake motions observed during the Mid Niigata Prefecture Earthquake in 2004 (M6.8) and the Iwate-Miyagi Nairiku Earthquake in 2008 (M7.2) were applied for the case studies. 3D analysis program UNIVERSE (Ariga, 2001) is used.

4.1. Case Study for Arch Dam

3D FEM model of arch dam is shown in Fig. 4. The height of the dam is set to be 100m. The dam and foundation were meshed by using the solid elements. The rigid boundary is applied for the bottom boundary, and the viscous boundary for the lateral boundaries. The dynamic property values of dam and foundation are supposed as shown in Table 1.

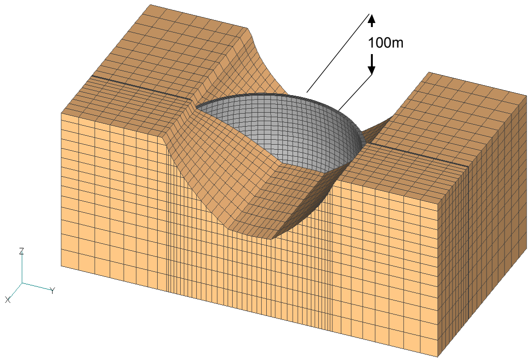


Figure 4. 3D model of arch dam

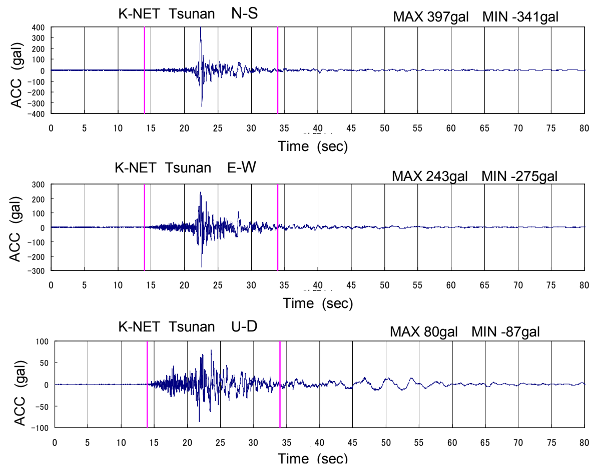


Figure 5. Acceleration time histories recorded at Tsunan Point during the Mid Niigata Prefecture Earthquake in 2004

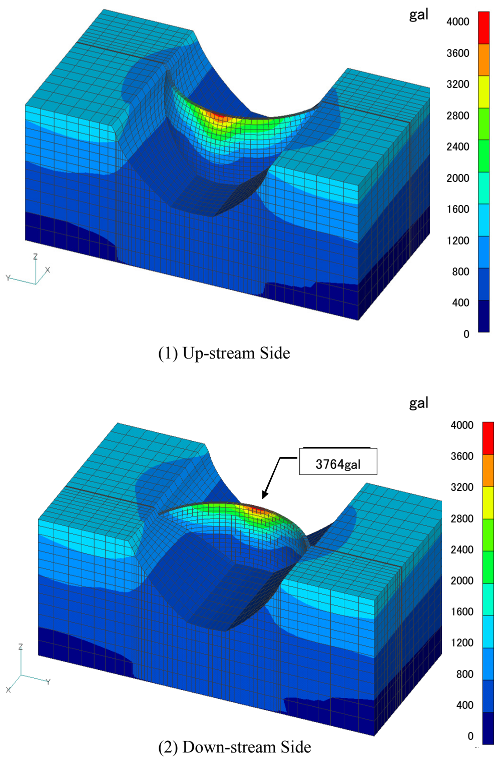


Figure 6. Distribution of calculated maximum acceleration

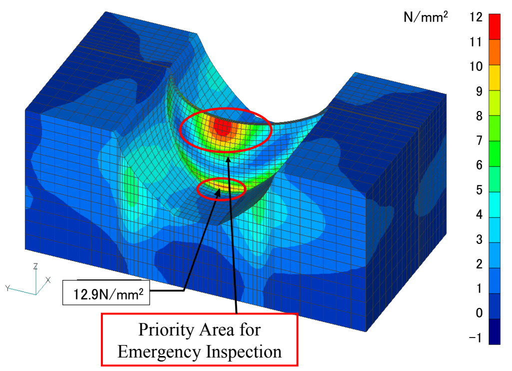
The values of the dynamic shear modulus and the damping factor were supposed by taking the 3D dynamic reproduction analysis for actual earthquake behavior of the existing arch dam into consideration (Ariga, 2007).

Table 1. Dynamic property values of arch dam

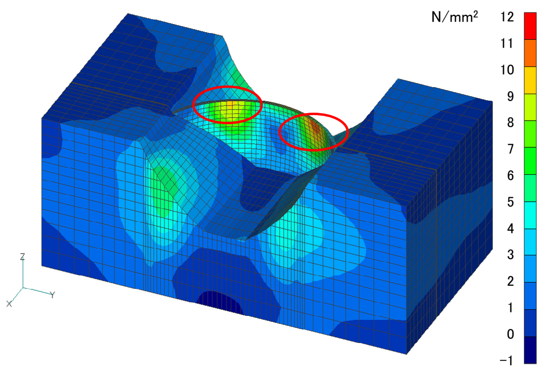
Item	Dynamic shear modulus (N/mm^2)	Density (g/cm^3)	Poison's ratio	Damping factor (%)
Concrete dam	10500	2.40	0.20	5
Rock	9600	2.60	0.25	5

Fig. 5 shows the acceleration time histories recorded at the Tsunan Point (Epicentral distance 36km) of K-NET during the Mid Niigata Prefecture Earthquake (M6.8), which are used for input motions. Three components of motions are input simultaneously in the analyses.

Fig. 6 shows the distribution of calculated maximum acceleration. The maximum acceleration at the crest of dam was 3764gal in this case. Fig. 7 shows the distribution of calculated maximum tensile stress through all the time. The maximum tensile stress was 12.91N/mm^2. In general, the dynamic tensile strength of dam concrete is supposed to be around 3~5N/mm^2. Therefore, in such a case, it will be necessary to suppose some possibility of earthquake damage and to make emergency inspection quickly and smoothly at the site.



(1) Up-stream Side



(2) Down-stream Side

Figure 7. Distribution of calculated maximum tensile stress

These figures can be sent to the site through the internet before the arrival of main shock when EEW is received. By referring these figures, the worker at the site who is unfamiliar with structural engineering or earthquake engineering can easily recognize the priority parts for emergency inspection. Consequently, the worker at the site can make emergency inspection smoothly and efficiently.

4.2. Case Study for Spillway

3D FEM model of spillway is shown in Fig. 8. The spillway is composed of four concrete piers and 3 steel fixed-wheel gates. The total height of spillway is 34m. The piers and the training walls are made with reinforced concrete. The fixed-wheel gates were missing in this model, because the fixed-wheel gates are structurally separated from the piers. The reservoir water was also missing in this model, because the reservoir water will not have significant influence on the displacement behaviour of spillway especially in the dam-axis direction. The spillway and the embankment were meshed with the solid elements. As for the boundary conditions, the rigid boundary is applied for the bottom boundary, and the viscous boundary for the right and left lateral boundaries.

The dynamic property values of concrete piers and embankment are set as shown in Table 2. The values of dynamic shear modulus and damping factor were supposed according to the 3-D reproduction analysis for actual earthquake behaviour of existing spillway (Ariga, 2008).

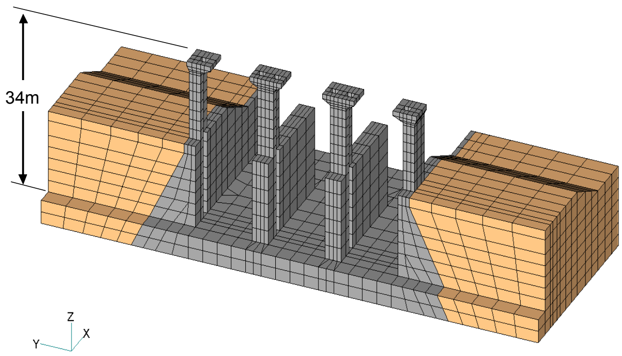


Figure 8. 3D model of spillway

Table 2. Dynamic property values of spillway

Item	Dynamic shear modulus (N/mm^2)	Density (g/cm^3)	Poison's ratio	Damping Factor (%)
Concrete Pier	9375	2.40	0.20	3
Embank-ment	119	1.76	0.30	8

Fig. 9 shows the acceleration time histories recorded at the Ichinoseki Point (Epicentral distance 23km) of K-NET during the Iwate-Miyagi Nairiku Earthquake (M7.2), which are used for input motions. Three components of motions are input simultaneously in the analyses.

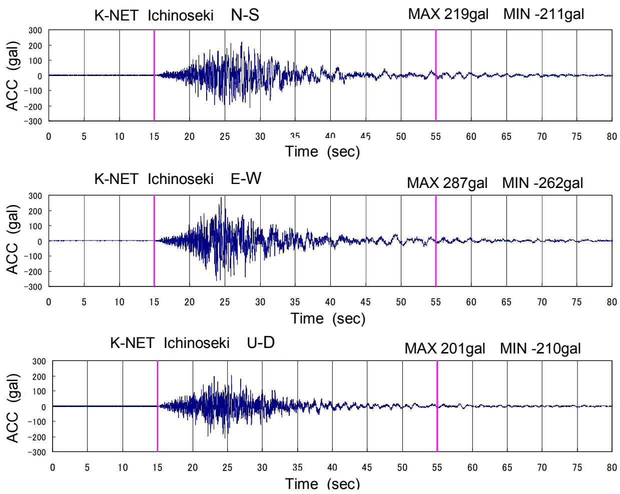


Figure 9. Acceleration time histories recorded at Ichinoseki point during the Iwate-Miyagi Nairiku Earthquake in 2008

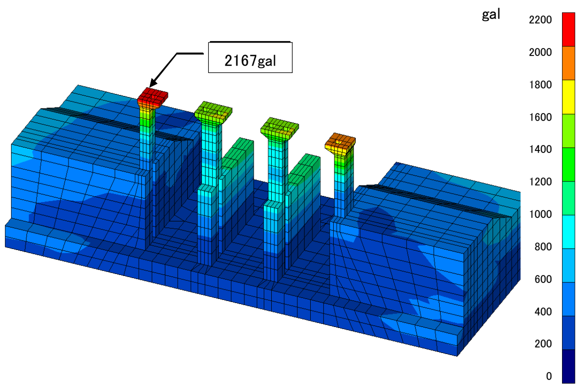


Figure 10. Distribution of calculated maximum acceleration

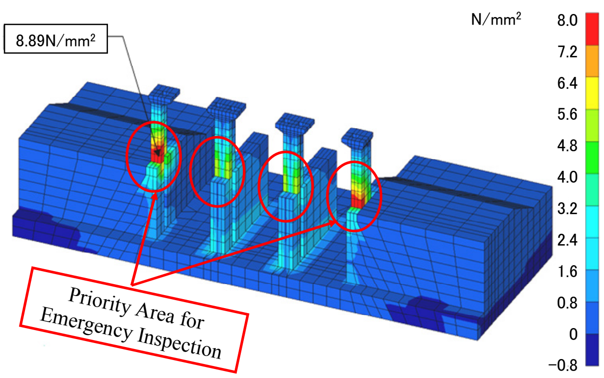


Figure 11. Distribution of calculated maximum tensile stress

Fig.10 shows the distribution of calculated maximum acceleration. The maximum acceleration at the top of pier was 2167gal in this case. Fig.11 shows the distribution of calculated maximum tensile stress through all the time. The maximum tensile stress was 8.89N/mm^2 at the lower part of pier. In such a case, it will be necessary to suppose some earthquake damage and to make emergency inspection quickly and smoothly.

5. CONCLUSIONS

We studied on the efficient method for confirming the seismic safety of hydraulic structures by combining EEW, the earthquake observation at the site, and 3D dynamic analysis in order to rationalize the emergency inspection just after large earthquake.

By applying the method proposed, the rational emergency inspection and the efficient confirmation for seismic safety of hydraulic structures can be realized. This method will be useful for preventing and mitigating the human, physical and economical damage for the hydraulic structures by the large earthquakes.

There are approximately 2800 dams which are higher than 15m in Japan, and it is very important to verify the earthquake safety of existing dams and spillway. Especially at the time of very large earthquake, the smooth and quick confirmation of dam safety is strongly required. By making good use of EEW and 3D dynamic analysis, the rational confirmation of seismic safety can be realized. The process of immediate evaluation, which includes the receipt of EEW and the dispatch of information to the site, can be completed within a few seconds.

If the earthquake damage is not predicted, the safety and security information can be dispatched quickly after the earthquake to the site and the interested divisions. If the earthquake damage is predicted, the urgent inspection should be made by referring the 3D dynamic analysis results. According to need, the priority parts which should be inspected urgently can be referred on the computer screen. The immediate evaluation method for earthquake damage proposed in this study can be applied to the quantitative evaluation of earthquake safety of important social facilities.

This method can be broadly utilized for preventing not only the direct disaster but also the secondary disaster, and improving the earthquake disaster prevention performance. This method can be broadly applied to not only dam and spillway but also social infra-structures such as electric power station, highway, railway, high buildings, urban structures, and so forth.

The possibility for utilizing the information about the characteristics of earthquake motions, the improvement of reliability of earthquake damage evaluation, the development of supporting system for decision making at the time of emergency, the promotion of enlightening and education for earthquake disaster prevention, and so forth can be mentioned as the subjects for future study.

ACKNOWLEDGEMENT
We used the earthquake motions recorded by the K-NET of NIED in the case studies. We would like to express our thanks.

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