An immediate evaluation method of earthquake damage of dams by utilizing real-time earthquake information

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Abstract

Recently, the magnitude of earthquakes and the location of epicenters have come to be estimated urgently in 3–4 seconds based on the observed data of a P-wave. Urgently estimated earthquake information is termed the real-time earthquake information. Furthermore, an arrival time and an intensity of the S-wave can be estimated and people informed before the arrival of the main shock. Such earthquake information before the arrival of the main shock is defined as the early earthquake warning. In this study, we have developed an immediate evaluation method for earthquake damage of dams by combining the early earthquake warning and a 3-D dynamic analysis. As a result, the earthquake damage of dams can be evaluated by the method proposed within one second. This method is useful to mitigate not only human disaster but also physical damage by earthquakes.
Keywords: dam safety, earthquake damage, real-time, 3D dynamic analysis, immediate evaluation, the early earthquake warning.

1 Introduction

Verification of seismic safety of dams against very large earthquake is very important theme. In Japan, the seismological observation networks such as the Hi-net(High sensitivity seismograph network), the KiK-net(Kiban kyoshin Network), the K-NET(Kyoshin network), the seismic intensity observation network, and so forth have been densely arranged by the Ministry of Education and Science, the National Research Institute for Earth Science and Disaster Prevention (NIED), the Japan Meteorological Agency (JMA), and so forth. And a magnitude of earthquake and a location of epicenter can be estimated in 3~4 seconds based on the observed data of P-waves by NIED and JMA respectively. Furthermore, an arrival time and a seismic intensity of S-wave have come to be estimated and informed before the attack of main shock. The earthquake information before the arrival of main shock is defined as the early earthquake warning.

On the other hand, a 3-D dynamic analysis method for a coupled dam-foundation-reservoir system has been developed [1], and it becomes possible to evaluate the earthquake safety of dams with high accuracy.

With these points as background, we have developed a method for evaluating the earthquake damage of existing dams immediately by combining the early earthquake warning and a 3-D dynamic analysis. The basic procedure of the immediate evaluation method developed in this study is composed of two steps. The first step is a preparatory evaluation at ordinary time and the second step is an immediate evaluation at the time of earthquake. The first step consists of an analysis of earthquake damages of existing dams in the world [2], a 3-D dynamic analysis, and a preparation of chart concerning the earthquake damage of dams. The second step consists of estimation of earthquake motion at the dam site by utilizing the early earthquake warning, the immediate evaluation of earthquake damage based on the chart, and a dispatch of information to the dam site. As a result, the earthquake damage of dams can be evaluated immediately by the method proposed within one second. This method is useful to mitigate a human disaster, a physical damage and an economical loss by earthquakes.

2 Purpose

We have been studied the immediate evaluation method for earthquake damage of existing dams by utilizing the early earthquake warning. The purpose of this study is to confirm dam safety just before or just after large earthquake, to rationalize an extraordinary inspection after large earthquake, to improve the performance of earthquake disaster prevention of dams, to make good use for training and education regarding the earthquake disaster prevention, and so forth.

3 Early earthquake warning

The earthquake observation networks have been densely and highly realized in Japan. The K-NET is made up of 1031 observation points, and the Hi-net / the KiK-net is made up of 669 observation points by NIED. The magnitude of earthquake and the location of epicenter, that is latitude and longitude, have come to be estimated urgently based on the earthquake observation data by the Hi-net, at present time. In the near future, other earthquake networks will be utilized. The arrival time of main shock and the seismic intensity at the site can be estimated based on the epicenter information estimated urgently. And, the estimated arrival time and the seismic intensity can be dispatched to the site

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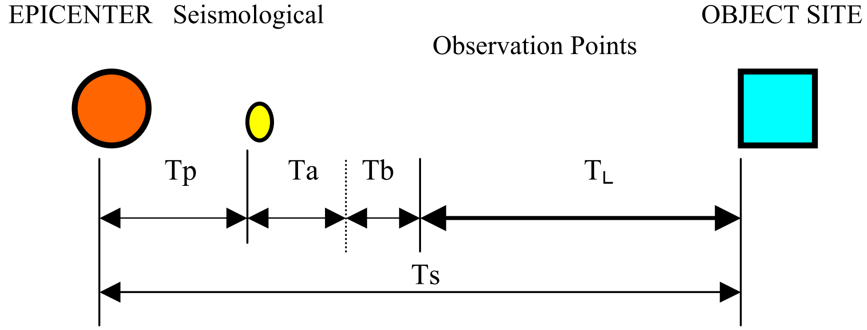
before the attack of S-wave, or main shock of large earthquake. The leeway time before the attack of main shock can be effectively utilized for disaster prevention and mitigation. The leeway time, which is expressed by equation (1), will be short in the case of near field earthquake, however, it will become longer in the case of far field earthquake of large magnitude. The leeway time will be several seconds—several tens of seconds in the case of far field earthquake.

$$\mathbf{T_L = Ts - (Ta + Tb) - Tp} \quad (1)$$



Here,
T_L : Leeway time before arrival of S-wave (main shock).
Tp : Propagating time of P-wave from epicenter to observation point
Ts : Propagating time of S-wave from epicenter to object site
Ta : Time required for estimating early earthquake warning (3～4sec.)
Tb : Time required for sending information (1～2sec.)

Figure 1: Relation between propagating time of earthquake motions and leeway time.

4 Immediate evaluation method of earthquake damage of dams

4.1 Outline

The outline of immediate evaluation method for earthquake damage of dams is shown in Figure 2 and Figure 3. The method is composed of two steps. The first step is the preparatory evaluation at ordinary time. The second step is the immediate evaluation at earthquake time. The preparatory evaluation consists of the arrangement of earthquake damages of existing dams in the world, the 3-D dynamic analyses under various conditions, and the arrangement of charts concerning the earthquake damage. The immediate evaluation consists of the estimation of earthquake motion at the object dam site based on the early earthquake warning, the immediate evaluation of earthquake damage based on the charts, and the information transmission to the dam site.

As the preparatory evaluation at ordinary time, the 3-D dynamic analyses are made to evaluate the stress and strain distribution within the dam body under various conditions in regard to the input motions, the dynamic properties of foundation rock, the depth of reservoir water, etc. By combining the results of the 3-D dynamic analyses and the world case histories of earthquake damages of dams, the earthquake damage of dam against large earthquake can be evaluated. The procedure from the receipt of early earthquake warning to the transmission of information will be completed within 1 second.

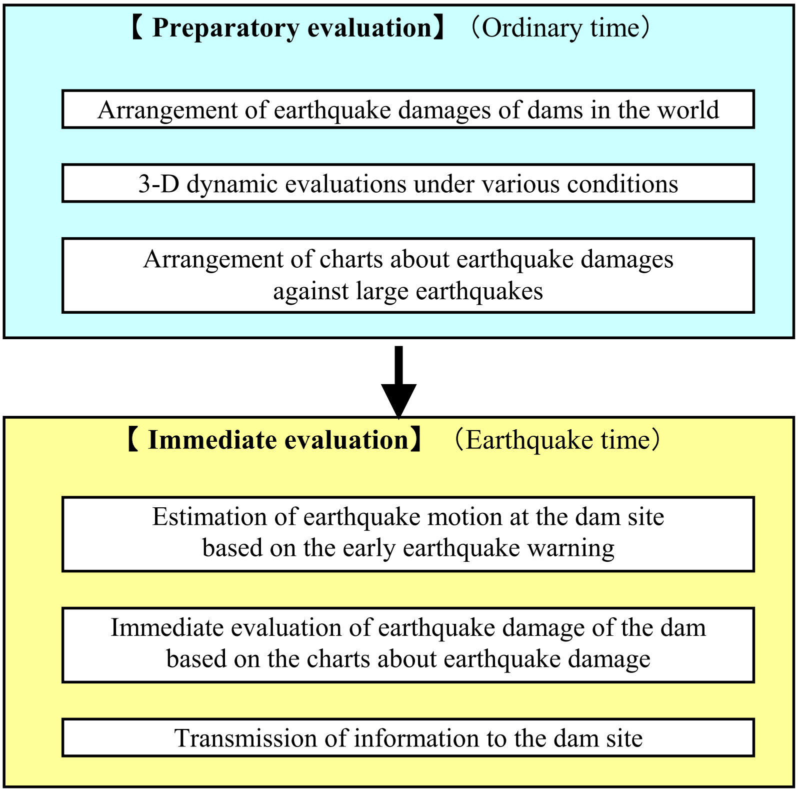


Figure 2: Outline of preparatory evaluation and immediate evaluation.

4.2 Utilization of early earthquake warning

One of peculiarity of this study is utilization of the early earthquake warning which can be informed before the attack of main shock. The maximum acceleration at the dam site can be estimated by using the empirical equation between maximum acceleration and epicenter distance. As for the dam site where the seismological observation has been made, not only the maximum acceleration but also the frequency characteristics can be evaluated by using the actual observation data.

4.3 Three dimensional dynamic analysis

The earthquake damage of dam is evaluated by the 3-D dynamic analysis of dam - foundation rock - reservoir system. The leeway time before the attack of main

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shock will be expected to be several～several ten seconds. It is impossible to execute 3-D dynamic analysis within several ten 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 the early earthquake warning. The flow of the immediate evaluation method is shown in Figure 3.

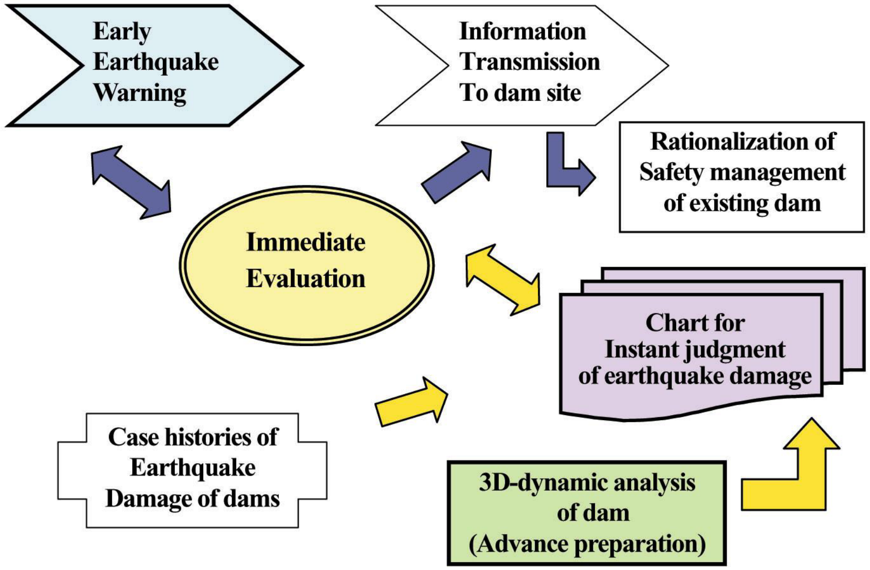


Figure 3: Flow of immediate evaluation method of earthquake damage of dams.

4.4 Chart for urgent judgment of earthquake damage of dams

The charts for urgent judgment of earthquake damage of dams are made based on the results of the 3-D dynamic analyses. The charts are arranged as the function of maximum acceleration and predominant frequency of input earthquake motions. The 3-D 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 rock, and so forth, as shown .in Figure 4.

5 Evaluation of earthquake damage by 3-D dynamic analyses

The damage of dam by strong earthquake motion will be affected by the shape and the dynamic property of dam and foundation, the reservoir condition, the amplitude and frequency characteristics of motion. So these affects are examined by the 3-D dynamic analyses. The dam analyzed in this study is the Shintoyone

Dam, which is a parabolic arch dam built in 1972. Figure 5 shows the panoramic view of the Shintoyone Dam, and Figure 6 shows the 3-D analysis model of coupled dam - foundation - reservoir system. The depth of reservoir water is supposed to be 75m, 90m, and 104m. The lateral boundary of the 3-D model is set to be the viscous boundary, and the bottom boundary is set to be the rigid boundary. The analysis program named UNIVERSE [1] is used. The dynamic property values of dam and foundation are supposed as shown in Table 1, which were identified by the 3-D reproduction analysis of actual earthquake behavior observed at the dam analyzed [3, 4].

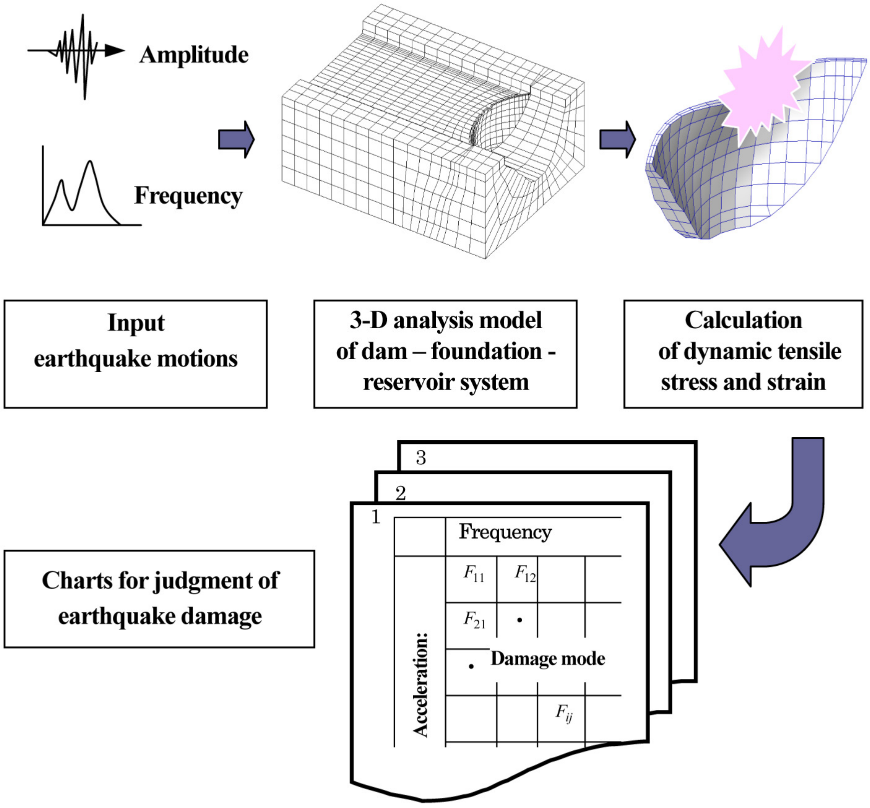


Figure 4: Preparatory evaluation of earthquake damage by 3-D dynamic analyses.

The observed earthquake motions recorded at the Hitokura Dam during the 1995 Hyogoken-nanbu earthquake shown in Figure 7 were applied for the input motions in this analysis. The maximum amplitudes of input motions are modified according to the magnitude and the epicenter distance as shown in Table 2. The maximum amplitudes of input motions are ranged from 100gal to 1000gal.

Figure 5: The Shintoyone Arch Dam.

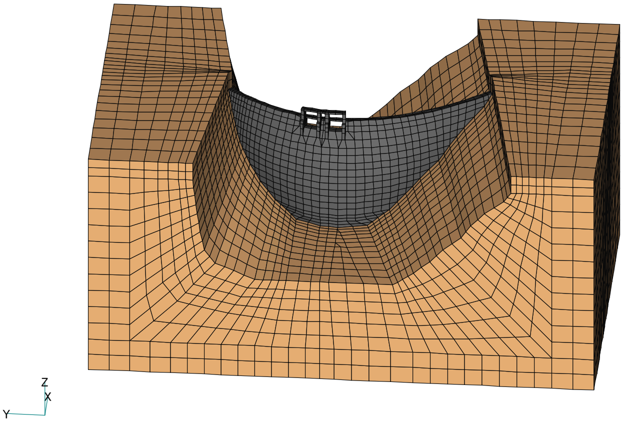


Figure 6: 3-D FEM model of the Shintoyone Dam - foundation - reservoir system.

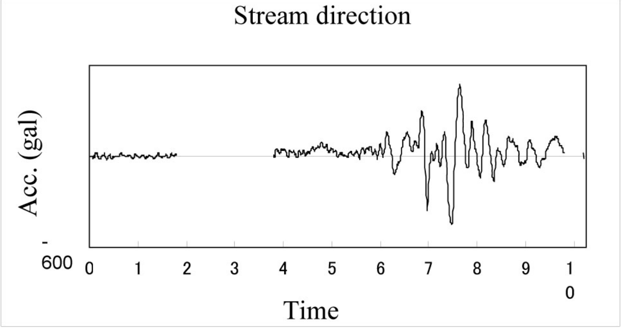


Figure 7: Input earthquake motion.

Table 1: Dynamic property values of the Shintoyone Dam identified by the reproduction analysis of actual earthquake behavior.

Item	Dynamic shear modulus（N/mm^2）	Density (g/cm^3)	Poison's ratio	Damping factor (%)
Dam	10500	2.4	0.20	0.05
Foundation Rock	9600	2.6	0.25	0.05
Free field	9600	2.6	0.25	0.05

Table 2: Combination of magnitude and epicenter distance (assumed conditions regarding input earthquake motions).

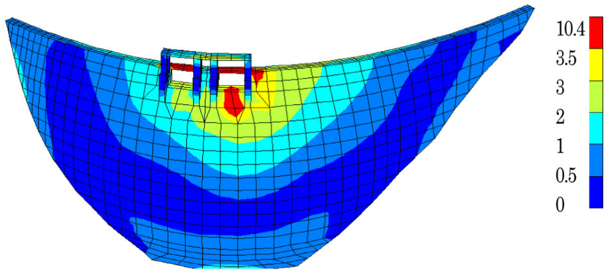
Item	Setting range	Division pitch	Pattern
Magnitude	3.0~8.6	Less than M6：0.3 More than M6：0.2	24 patterns
Epicenter distance	10~300km	Less than 200km：5km More than 200km：10km	49 patterns

As the example of the 3-D analysis results, the distribution of maximum tensile stress in the tangential direction when the earthquake motion whose maximum amplitude is set to be 306 gal is shown in Figure 8.

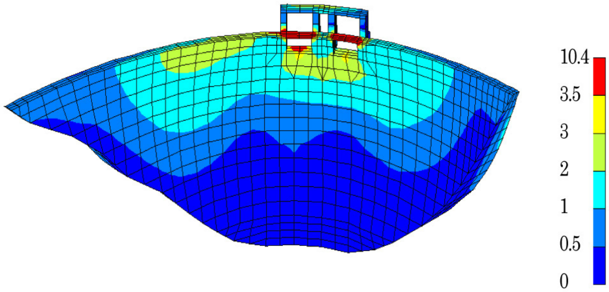
6 Results

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. Especially at the time of very large earthquake, the smooth and quick confirmation of dam safety is strongly required. By making good use of the early earthquake warning and the 3-D dynamic analysis, the rational confirmation of dam safety can be realized. As a result, it became clear that the process of immediate evaluation, which includes the receipt of early earthquake warning and the dispatch of information to the dam site, can be completed within 1 second. If the earthquake damage of dam is not predicted, the safety and security information can be dispatched quickly after the earthquake to the dam site and the interested divisions. If the earthquake damage of dam is predicted, the urgent inspection should be made by referring the 3D dynamic analysis results. According to need, the priority parts of dam body which should be inspected urgently can be referred on the computer screen. The practical information can be sent by the satellite communication to the dam site.

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 disaster prevention performance of social facilities.



(1) Maximum tensile stress in the upstream face (N/mm^2).



(2) Maximum tensile stress in the downstream face (N/mm^2).

Figure 8: Distribution of maximum tensile stresses in the tangential direction when the maximum amplitude of input motions is assumed to be 306 gal.

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, and so forth can be mentioned as the subjects for future study. The organic fusion of the early earthquake warning and 3-D dynamic analysis and communication technique enables to produce new information necessary for the earthquake disaster prevention and mitigation. Besides the dam, this method can be applied to the electric power facilities, the river facilities, the urban facilities, and so forth.

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