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TRIAL IMPLEMENTATION OF NEW JAPANESE GUIDELINES FOR SEISMIC PERFORMANCE EVALUATION OF DAMS DURING LARGE EARTHQUAKES

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SUMMARY

As one of the most earthquake-prone countries in the world, Japan has frequently experienced large-scale earthquakes. Public demand for the safety of civil engineering structures during large earthquakes has increased since the *Hyogo-ken Nanbu (Kobe) Earthquake* in January 1995. In the meantime, the basic seismic design of dams in Japan is conducted using traditional pseudo-static analysis in compliance with the existing technical standards. Fortunately, dams in Japan designed in accordance with the standards have not suffered any earthquake damage so severe as to affect people's lives and property in the lower reaches.

However, recently improved monitoring systems in Japan have detected a lot of earthquake motions at several dam sites exceeding the level stipulated in the existing standard. In addition, there has been quite progress in various studies including a method of predicting earthquake motions at each site based on researches of active faults and a method to simulate the dynamic behavior of civil engineering structures including dams. These developments require a new methodology to evaluate the seismic performance of dams in Japan considering maximum-class earthquake motions.

This report outlines the new Japanese guidelines for seismic performance evaluation of dams, which was announced in 2005 and is now in trial implementation. Several problems that were revealed through the trial implementation are also discussed.

BACKGROUND

In March 2005, the "*Guidelines for Seismic Performance Evaluation of Dams during Large Earthquakes*" (hereinafter referred to as the "Guidelines") was announced by the River Bureau of the Ministry of Land, Infrastructure and Transport (MLIT), and subsequently implemented on a trial basis for dams under the bureau's jurisdiction. The Guidelines were compiled after four years of deliberations in the committee organized within the Japan Dam Engineering Center (JDEC) and comprising experts and administrative representatives, and the Guidelines were based on a draft jointly prepared and submitted to the committee by the National Institute for Land and Infrastructure Management (NILIM) of MLIT and the

Independent Administrative Organization of Public Works Research Institute (PWRI). The main points of the Guidelines are as follows:

i) The definition of earthquake motions that should be taken into consideration in evaluating the seismic performance of dams against large earthquakes

ii) The concepts of the required seismic performance of dams against large earthquakes as a criterion for evaluating their seismic safety

iii) The methods of seismic performance evaluation of dams and appurtenant structures

The major background for establishing the Guidelines was public demand for the safety of civil engineering structures during large earthquakes. In Japan, the demand has increased, especially since the *Hyogo-ken Nanbu (Kobe) Earthquake* in January 1995 (more than 6,000 people died), and various existing standards for seismic design (e.g. road bridges, railroad structures, etc.) were promptly reviewed and revised from then on.

Fortunately, dams in Japan have not suffered any damage so severe as to affect people's lives and property in the lower reaches during past large earthquakes including the Kobe earthquake (1995), and the design standards for dams have not been revised for several decades.

At present, Japanese dams should be basically designed so as to meet the technical standards of the "Cabinet Order Concerning Structural Standards for River Administration Facilities" (hereinafter referred to as the "Standards"). In the Standards, seismic load is considered to be the horizontal inertia force obtained by multiplying the dead weight of the dam and the design seismic intensity (e.g., 0.1–0.12 in the case of gravity dams), which is empirically determined for each of three seismic-activity regions. "*Report of the Committee on Evaluation of Earthquake Resistance of Dams*" (1995) published after the *Kobe Earthquake* (1995) showed that dams in Japan designed based on the Standards have sufficient seismic resistance.

However, recently improved monitoring systems in Japan have detected earthquake motions at several dam sites considerably exceeding the level stipulated in the Standard, as shown in Table 1.

Moreover, enough knowledge has been accumulated to rationally evaluate seismic performance of dams considering specific earthquake motions at each dam site based on information about nearby active faults and plate boundaries, and by using numerical simulation such as earthquake response analyses.

Taking this situation into consideration, the Guidelines were prepared to enable rational evaluation of the safety of dams designed based on the Standards from the viewpoint of securing the required seismic performance against the largest-class earthquake motion that could conceivably occur at each site in the future. Initially, the Guidelines were applied as a "trial implementation" to verify their applicability in view of anticipated technical problems. Studies were conducted at several MLIT dams to thresh out various working-level problems and find the means to solve them.

In the following section, the essential points of the Guidelines including the process through which the Guidelines were adopted are introduced along the composition of the Guideline indicated in Table 2.

Table 1 Recent examples of strong earthquake motions observed at dams in Japan

Name of earthquake	Magnitude[1)] / Type of earthquake[2)]	Name of dam (dam type[3)])	Distance from epicenter (km)	Maximum acceleration[5)] [cm/sec^2]
Hyogo-ken Nanbu (1995)	M7.3 /Af	Hitokura (PG)	47(10) [4)]	183
		Minohgawa (ER)	48(11) [4)]	135
Tottori-ken Seibu (2000)	M7.3 /Af	Kasho(PG)	12(1) [4)]	569
Miyagi-ken Oki (2003)	M7.1 / ItP	Tase (PG)	73	232
		Hinata (PG)	55	228
Tokachi-Oki (2003)	M8.0 / InP	Urakawa (PG)	115	103
Niigata-ken Chuetsu (2004)	M6.8 /Af	Kawanishi (TE)	17	558
		Shirokawa (PG)	14	162

1) Japan Meteorological Agency (JMA) magnitude 2) Af: Active fault, ItP: Intra-plate, InP: Inter-plate
3) PG: Gravity, ER: Rockfill, TE: Earthfill 4) ( ): Distance from earthquake source fault
5) Horizontal–direction component

Table 2 Composition of the Guidelines

Chapter	Section
1. Basic matters	1.1 Intent of Guidelines 1.2 Definition of terms 1.3 Scope of application 1.4 Basic concepts of evaluation 1.5 Seismic performance required 1.6 Water level condition for evaluation
2. Earthquake motion for seismic performance evaluation	2.1 Selection of *Scenario earthquakes* 2.2 Setting of *Level 2 earthquake motion*s for evaluation
3. Methods for evaluating dam bodies	3.1 Policy for evaluation of dam bodies 3.2 Evaluation of concrete dams 3.3 Evaluation of embankment dams
4. Methods for evaluating appurtenant structures	4.1 Selection of structures to be evaluated 4.2 Evaluation of appurtenant structures

BASIC MATTERS IN SEISMIC PERFORMANCE EVALUATION

The basic concepts of the seismic performance evaluation of dams are stated in Chapter 1 of the Guidelines.

Required Seismic Performance

The definition of required seismic performance of dams against *Level 2 earthquake motions* (defined in the Guidelines as the "largest-class earthquake motion that could conceivably occur at each dam site now and in the future", approximately corresponding to the concept of Maximum Credible Earthquake (MCE)) is the most fundamental concept of seismic performance evaluation of dams.

With regard to the question of how to define required seismic performance against *Level 2 earthquake motions,* diligent discussion ensued during the process of establishing the Guidelines. In the end, the required seismic performance of dams against *Level 2 earthquake motions* was defined as follows:

i) Dam's function to store water should be maintained even after suffering damage; and

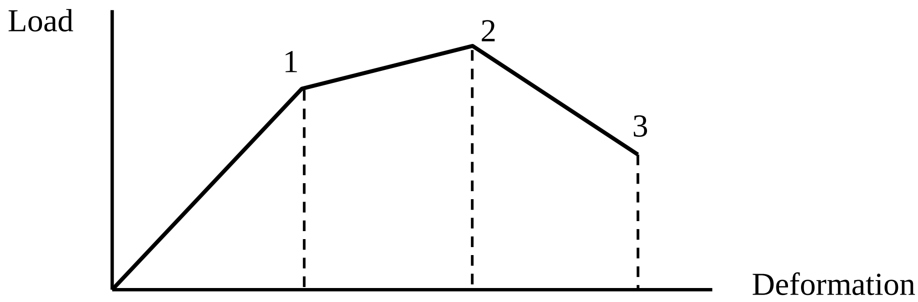
ii) Any damage suffered should be limited to the repairable extent.

The first definition means that there would be no uncontrollable release of stored water. This provision was stipulated due to concerns that if a dam were damaged so severely by an earthquake that an uncontrollable discharge of stored water were to occur, the damage to the people in the lower reaches of the river could be socially unacceptable. On this point, the guidelines of the International Commission on Large Dams (ICOLD) (1989) were also referenced.

The second definition is based on the concept of the so-called limit state design. The "*Basis of Structural Design for Buildings and Public Works*", announced by MLIT in 2002, provides the concepts of three limit states, as shown in Fig. 1, and requires that any design criteria be revised to set the goal of seismic design to limit the damage suffered during an assumed earthquake to within one of the three limit states.

As a result of discussions referring to this basic framework, with regard to dams, the committee concluded that it is unrealistic to demand "serviceability limit states" for *Level 2 earthquake motions*. However, dams are very important for flood control and water use in river basins, and when a dam suffers earthquake damage to such an extent that it cannot be repaired using available technologies at a reasonable cost and within a reasonable period of time, facilities to replace the functions of the dam would be extremely difficult to find or reconstruct without delay. Thus, it was agreed that damage from *Level 2 earthquake motions* should be repaired so that the functions of the dam would be recovered as stated in the second definition.

In addition, in the debate over the definition of required seismic performance of dams, whether or not the importance of dams should be taken into consideration was also discussed. However, dams in Japan are usually constructed in precipitous river basins where a large number of people and assets are concentrated and if, by chance, the dam should break, the consequences would be devastating to the people in the lower reaches. Thus, it was decided that the dams should not be classified in terms of their importance.



1. *Serviceability limit state*: Limit state in which the required serviceability of a structure is retained and its intended functions are ensured.
2. *Restorability limit state*: Limit state in which continued use of a damaged structure is possible by repair with technologies available within reasonable cost and time.
3. *Ultimate limit state*: Limit state in which the stability of a structure is barely retained under structural failure or large deformation expected to result from foreseeable actions, and the safety of human life in and around the structure is ensured.

Fig. 1 Concepts of three limit states by MLIT (2002)

Water Level Condition

In evaluating the seismic performance of dams, an important factor is the stored water level, which is used to determine the load conditions including hydrodynamic water pressure. The Guidelines state that the reservoir water level to be considered in seismic performance evaluation for *Level 2 earthquake motions* is basically the normal water level (NWL), which is the highest water level in non-flood season although the Standard (Cabinet Order) requires that the 1/2 seismic forces be considered even for the surcharge water level (SWL). This is because extremely strong earthquake motions like *Level 2 earthquake motions* are extremely rarely expected for each dam and therefore are not likely to occur during a flood in which the water level rises to the SWL. The Guidelines also state that in the case of a dam when a dam is structurally susceptible to effects of earthquakes at water levels other than NWL, and if such water levels could continue for an extended period of time, the dam should also be evaluated for seismic performance using these water levels (e.g., lowest water level in arch dams).

EARTHQUAKE MOTIONS FOR SEISMIC PERFORMANCE EVALUATION

Chapter 2 of the Guidelines explains how to set *Level 2 earthquake motions* used for evaluating the seismic performance of dams.

Selection of *Scenario Earthquakes*

Under the Guidelines, *Level 2 earthquake motions* used for evaluating the seismic performance of dams should be determined by thoroughly investigating and collecting information about past earthquakes, active faults and plate boundaries near the dam site. *Level 2 earthquake motions* for each dam are determined as the estimated earthquake motions at each dam site and caused by selected earthquakes that could have the largest impact on the dam (*Scenario earthquakes*).

For determination of the *Scenario earthquakes* for each dam, information such as location and magnitude of past earthquakes, active faults and plate boundaries that might point to the occurrence of future earthquakes, should be gathered from reports provided by the Central Disaster Prevention Council, the Earthquake Research Committee of the Headquarters for Earthquake Research Promotion and other governmental organizations. The results of the Quaternary faults survey, which is to be carried out in determining the sites for dam construction in Japan, should also be checked. Moreover, to secure consistency with the policies of the disaster prevention administration system, consideration should also be given to the earthquakes assumed in the national and regional level disaster prevention plans.

The *Scenario earthquakes* for each dam should be selected by comparing the estimated earthquake motions at the site caused by potential earthquakes that might occur near the dam. The effects of individual potential earthquakes is basically estimated by comparison of acceleration response spectrum evaluated using the *Distance attenuation formula for dams* on acceleration response spectrum (Matsumoto et al. (2001)), which is a set of empirical equations derived based on earthquake motions observed at locations corresponding to rock foundation ground at numerous dams in Japan.

However, if the damage process by extremely strong earthquake is taken into account, for example, earthquakes at plate boundaries, which are of much longer duration than those at active faults, may have a greater final impact on dams compared to earthquakes at active faults even if the acceleration response spectrum for an active fault earthquake is larger than that of a plate boundary earthquake. Thus, there is a situation in which two or more S*cenario earthquakes* should be selected.

Determining the *Level 2 Earthquake Motions* for Seismic Performance Evaluation

The Guidelines mention several methods for estimating earthquake motions at dam sites other than the empirical method mentioned above, such as the quasi-empirical method (e.g., methods using Green’s function) and the theoretical method. Appropriate modeling of the fault rupture process or the transmission process of seismic motions from the fault to the site becomes necessary when applying these methods to estimate earthquake motions at a dam site. However, there is a limited number of faults for which such data is available. Thus, the Guidelines state that earthquake motions used for seismic performance evaluation should be estimated firstly by using an empirical method such as the *Distance attenuation formula of acceleration response spectra for dams*, and when possible, the results from other methods can be compared to determine the earthquake motion through comprehensive judgment.

The Guidelines provide the “*Lower-limit acceleration response spectrum*” shown in Fig. 2 that should be considered as the mandatory minimum *Level 2 earthquake motions*. The reason for stipulating this minimum spectrum is that in an earthquake-prone country such as Japan, the earthquake motion used for seismic performance evaluation should be determined taking into consideration the possibility of an earthquake occurring directly at an active fault under the dam site even when no active faults are found by the observation of the ground surface. This spectrum has been estimated based on the response spectrum of earthquake motions generated at the ground surface of rock foundation by an earthquake that could occur just under the dam site. Modifications on the spectrum have been provided to consider the dynamic response of dams and observed response of existing dams during severe earthquakes.

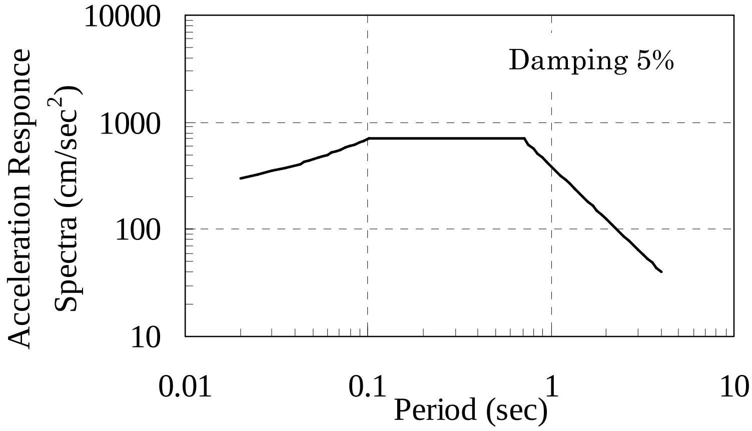


Fig. 2 *Lower-limit acceleration response spectrum* for evaluating seismic performance

Seismic performance evaluation of dams based on the Guidelines is usually carried out by time-history response analyses as mentioned later. Therefore, *Level 2 earthquake motions* are finally determined as time-history acceleration by adjusting the amplitude of the original accelerations such as strong motions observed at the dam site so as to correspond to the acceleration response spectrum of the *Level 2 earthquake motions* selected through comparison with the spectra of the *scenario earthquakes* and the *lower-limit spectrum*.

METHODS FOR EVALUATING DAM BODIES

Chapter 3 of the Guidelines explains how to evaluate the seismic performance of dam bodies and judge the safety against *Level 2 earthquake motions*.

Concrete Dams

Regarding the seismic performance evaluation of concrete dams, the Guideline states, “As a result of linear dynamic analysis, when the estimated stress generated in the dam is smaller than the strength of the concrete, the dam will not suffer damage, and the dam will maintain the required seismic performance.” The Guideline also states, “If some damage would be expected in the dam body, seismic response analysis in which the damage process during the earthquake can be simulated should be carried out, and if only limited damage is expected, the dam could be evaluated as maintaining the required seismic performance. In this context, "limited damage" means tensile cracks that do not divide the dam body between upstream and downstream surfaces and local compressive or shearing fractures. This way of thinking, whereby consideration is given to the damage extent of dams during earthquakes, is a stance never before taken in technical standards or guidelines for dams in Japan. Figure 3 shows the flow of the seismic performance evaluation for concrete gravity dams based on the Guidelines.

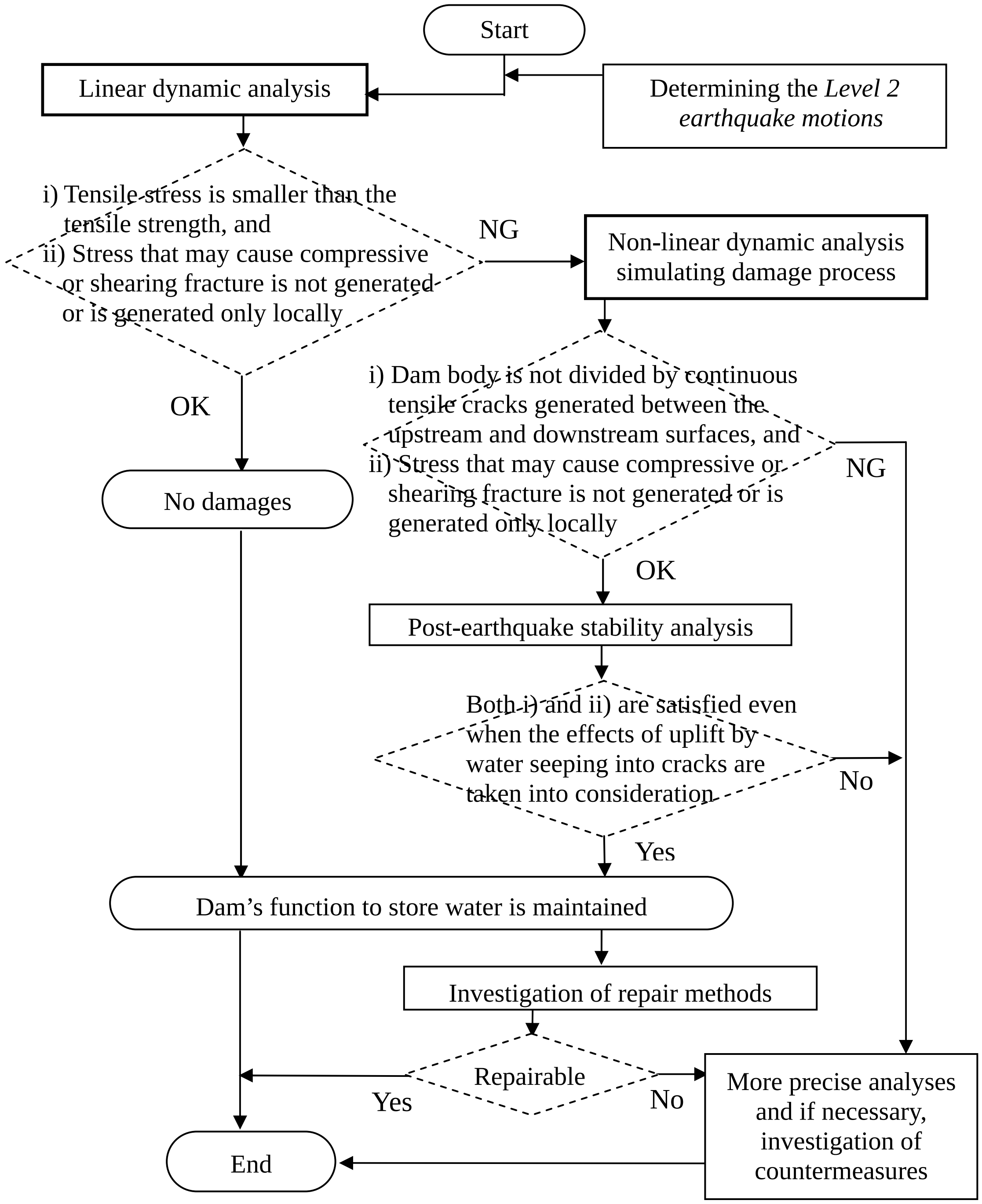


Fig. 3 Flow of seismic performance evaluation for concrete gravity dams

The condition for tensile failure, which requires that dam body is not divided by continuous tensile cracks generated between the upstream and downstream surfaces, was established as the condition including the margin for safety. This is because the dam's function to store water will be maintained even when continuous tensile cracks are generated, unless the entire upper block of the dam body destabilizes. Therefore, when continuous tensile cracks between the upstream and downstream surfaces are expected, further investigation should be conducted including analyses to confirm the stability of the upper block of the dam body. Among the methods of non-linear dynamic analysis for simulating tensile cracks, time-history response analysis that employs a smeared crack model such as illustrated in Fig. 4 (Sasaki et al. (2005)) is effective.

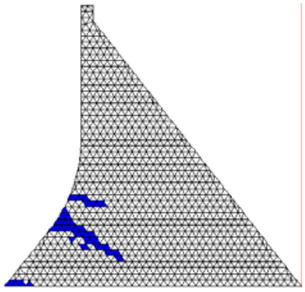


Fig. 4 Example of non-linear dynamic analysis of gravity dams using smeared crack model

Although not treated in detail in this report due to space limitations, the Guidelines also explain the methods for evaluating arch dam performance. In the earthquake response analyses of arch dams, 3-D analyses is required and it becomes more important to simulate the behavior of transverse and perimeter joints during an earthquake so as to simulate the transmission of arch thrust between adjacent monoliths and to the abutments.

Embankment Dams

If, by chance, water should overflow from an embankment dam, a catastrophe such as dam failure might occur. Keeping this point in mind, the Guidelines state that the seismic performance evaluation of embankment dams should be conducted by confirming that the value of settlement caused by embankment deformation during an earthquake is small and does not cause overflow of stored water, and that there is no risk of seepage failure after the earthquake. The flow of seismic performance evaluation for embankment dams is shown in Fig. 5.

As seen in the figure, dynamic analysis based on equivalent linear method can be used first to evaluate embankment dams. Static analysis simulating embanking and impounding processes to calculate the state of stress and deformation prior to the earthquake must be performed beforehand. If the results of abovementioned analysis show the possibility of failure caused by sliding, then plastic deformation analysis is required to estimate the amount of deformation or settlement caused by an earthquake. The allowable amount is basically within the freeboard height. Safety against seepage failure should be carefully investigated when possible sliding surfaces penetrating the core zone to the downstream are expected in earth core rock-fill dams, and when possible sliding surfaces starting at points lower than the water level and to the downstream are expected in earth-fill dams.

Furthermore, as shown in Fig. 5, the risk of liquefaction should also be examined, although this investigation is required only in exceptional cases such as rock-fill dams on unsolidified sedimentary stratum or earth-fill dams which bodies are insufficiently consolidated or which constructed on sandy soil and susceptible to liquefaction.

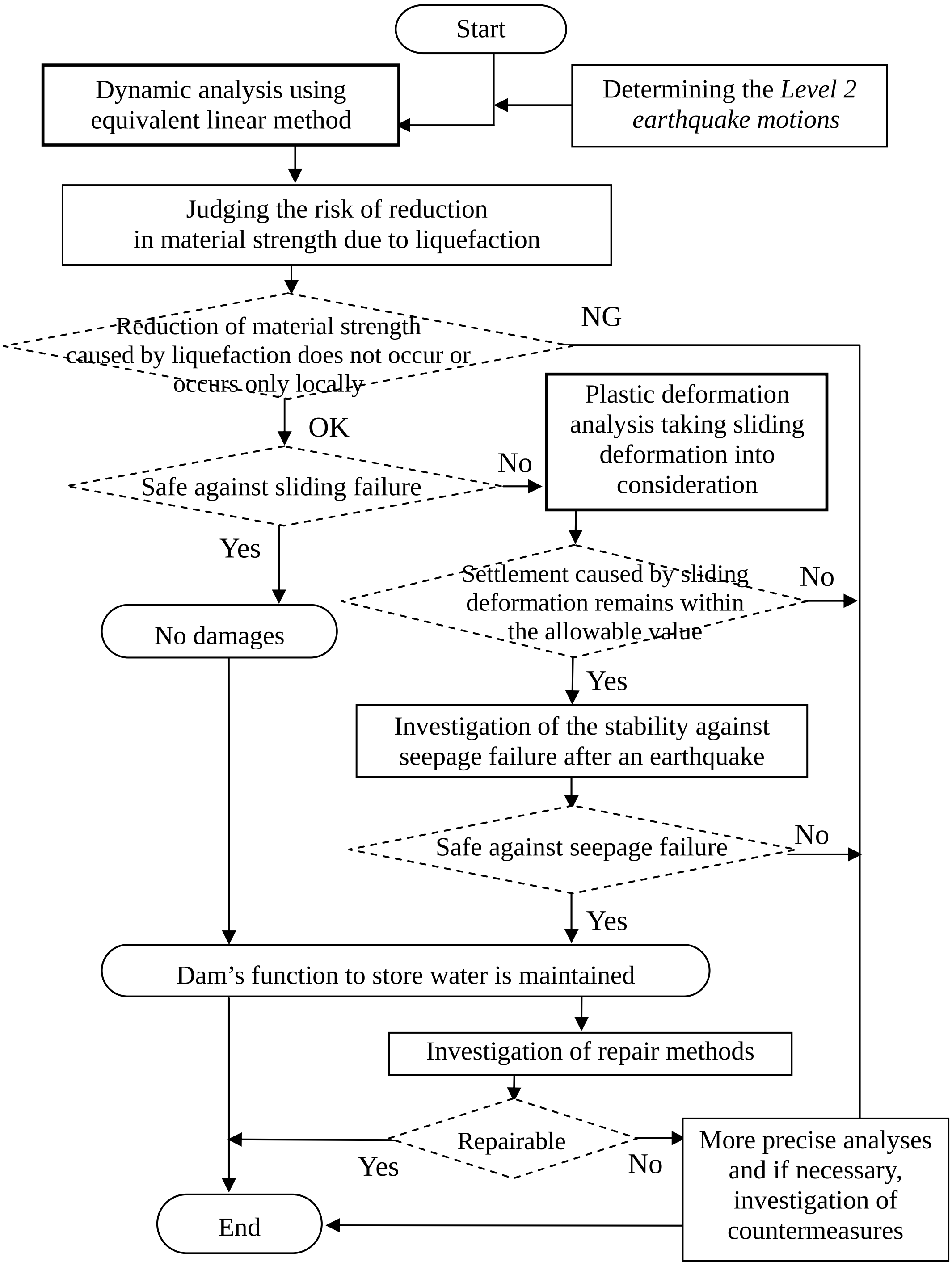


Fig. 5 Flow of seismic performance evaluation for embankment dams

METHODS FOR EVALUATING APPURTENANT STRUCTURES

Chapter 4 of the Guidelines explains how to evaluate the various structures appurtenant to dams including dam gates, crest piers and so on.

Not all of the structures require evaluation, but structures that are crucial for ensuring the seismic performance of dams, that is to say, structures that may cause the uncontrolled release of stored water if they should suffer damage, should be evaluated. For example, the main gates of principal discharge facilities having a large capacity and located below NWL should be evaluated whether there is a risk of buckling or becoming plastic, leading to a major deformation or defect. Crest piers which support the selected gates as critical structures, and the bridges on these gates should also be evaluated to confirm that they will not collapse or fall.

The seismic performance of the entire dam against *Level 2 earthquake motions* is finally judged by integrating the evaluation results for the dam body and for the selected appurtenant structures.

DISCUSSION

The Guidelines introduced above were announced as a trial implementation because a series of basic concepts and pragmatic means required for rationally evaluating seismic performance of dams against very strong earthquake motions including those exceeding the level provided in the existing Standards, were systematically organized to some extent.

However, through trial implementation focused on verifying the adaptability of the Guidelines targeting actual dams, several technical problems were identified.

For example, the validity of applying current empirical formula to estimate earthquake motions at dam sites very close to the epicenter was not clarified due to the lack of available data. Since Japan has a large number of active faults, some of which are located relatively close to dam sites, it is very important to develop or improve methods for estimating seismic motions in those areas.

Another important challenge is to appropriately reflect the dynamic properties of materials on seismic performance evaluations. For example, the compressive and tensile strength of concrete increases as the strain rate increases. However, these properties have not been taken into consideration in evaluating the seismic performance of concrete dams because dynamic properties under irregular load conditions such as during earthquakes have not yet been established. Therefore, it is very important to clarify the dynamic properties of materials under seismic load conditions.

Regarding seismic response analyses, a successive development of rational method is needed to simulate actual failure modes of dams besides tensile cracks in concrete dams and sliding failure in embankment dams. Accomplishing this requires sharing of information on actual examples of dams damaged due to earthquakes.

CONCLUSIONS

The outline of the new Japanese guidelines for seismic performance evaluation of dams was introduced. The Guidelines provide the method for determining the largest-class earthquake motions for each dam considering *scenario earthquakes*, define the required seismic performance against this earthquake motion and mention the methods used to evaluate the seismic performance of concrete dams, embankment dams and various structures appurtenant to dams including dam gates.

Several technical and practical issues that were revealed in the trial implementation of the Guidelines are also discussed. Further efforts should be made to strengthen and consolidate the applicability of the present guidelines through evaluating actual dams.

ACKNOWLEDGEMENT

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