Outline of “*Guidelines for Seismic Performance Evaluation of Dams During Large Earthquakes (Draft)*”

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ABSTRACT

On March 2005, the River Bureau of the Ministry of Land, Infrastructure and Transport issued “Guidelines for Seismic Performance Evaluation of Dams during Large Earthquakes (Draft).” The Draft Guidelines describe the methods for systematically evaluating the seismic safety of dams subjected to large earthquake motions, including establishment of scenario earthquakes and required seismic performance of dam bodies and appurtenant structures. Before practical application of the Guidelines, we require further study for verification with existing dams. Therefore, the Guidelines are used as “Draft” during trial implementation for verification.
The Draft Guidelines are composed of four chapters,” Basic matters”,” Required seismic performance”,” Methods for evaluating dam bodies” and ” Methods for evaluating appurtenant structures.” The chapter of “Basic matters” describes the definitions of technical terms, the seismic safety to be evaluated, etc. The chapter of “Required seismic performance” describes the procedure for setting scenario earthquake for seismic performance evaluation. Especially, it also shows “Earthquake motions with lower-limit acceleration response spectrum for evaluation.” The chapter of ” Methods for evaluating dam bodies” describes that the seismic performance of the dam body is evaluated basically by dynamic analysis and additionally by cumulative pertinent damage processes analysis . The chapter of ” Methods for evaluating appurtenant structures” shows the basic concept for evaluating gates, pier, intake facility, control devices and so on.

Keyword: Earthquake-proof design ,Large earthquakes, Seismic performance evaluation, Technical guideline.

1. INTRODUCTION

On March 2005, the “*Guidelines for Seismic Performance Evaluation of Dams during Large Earthquakes*” [1] (hereinafter referred to as the “Guidelines”) was announced by the River Bureau of the Ministry of Land, Infrastructure and Transport (MLIT).
The guidelines show three important matters to evaluate the seismic performance of dams against large earthquakes.

i) The definition of earthquake motions that should be taken into consideration in evaluations

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ii) The concepts of the required seismic performance of dams.

iii) The methods of seismic performance evaluation of dam bodies and appurtenant structures

The Guidelines were applied as a "trial implementation" to verify the applicability in the technical viewpoint. Verification was conducted at several existing dams to find out various problems in working-level and solve them.

In the following section, the Guidelines are introduced as shown in Table 1.

2. BASIC MATTERS IN SEISMIC PERFORMANCE EVALUATION

Chapter 1 of the guidelines shows basic thoughts of the seismic performance evaluation.

Those are intent and purpose of the guidelines, the definition of terms, scope of application, a definition of the seismic performance required and evaluation conditions.

At first, we mainly describe the intent and purpose of guidelines, the definition of terms, a definition of the seismic performance required and so on.

2.1 The Intent and Purpose of the Guidelines

In the beginning of the guidelines, it shows that "the guidelines showed a standard way of thinking to evaluate of the seismic performance of dams for *level 2 earthquake motions.*"

The purpose of evaluation is to confirm the seismic performance safety for the large earthquakes of dams designed in a current design standard.

The Guidelines are based on the knowledge available at present, and do not prevent the use of new and more rational evaluation methods when new knowledge about the earthquake motion prediction and dynamic response analysis is acquired.

2.2 Definitions of Terms

The definitions of terms used in the Guidelines are as follows:

1) Earthquake motions

Ground vibration generated when seismic waves are transmitted through the ground during an earthquake

2) *Level 2 earthquake motions*

Motions having the maximum-scale level of intensity conceivable at the dam site, at the present and in the future

(The level of earthquake motion was proposed by Japan Society of Civil Engineering [2]. "*Level 1 condition*" demands a structure to suffer no damage even if *level 1 earthquake motion* acts. "*Level 2 condition*" demands to consider the damage process and evaluation of the seismic performance of the structure when it rarely suffers the damage by very strong earthquake motion. Level 2 condition is approximately corresponding to the concept of Maximum Credible Earthquake (MCE).)

3) Dam body

The dam body and the adjacent foundation ground

4) Appurtenant structures

Various structures and facilities that are located on or near the dam body serve as portion of the dam functionally but are not included in the main body physically

5) Dynamic response analysis

The general analyses used in estimating and assessing the responses of structures and the ground during an earthquake

2.3 Required Seismic Performance

The required seismic performance of dams against *Level 2 earthquake motions* was defined as follows:

i) Dam's function to store reservoir 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 reservoir water. This definition was stipulated due to concerns that if a dam were damaged so severely by an earthquake and 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.

In 2002, Ministry of Land, Infrastructure and Transport announced "*Basis of Structural Design for Buildings and Public Works*."[3] It showed a basic direction of development and revision of the technical standard to affect the structure design.

The second definition is based on the concept of the so-called limit state design. "*Basis of Structural Design for Buildings and Public Works*" provides the concepts of three limit states. They are "*Serviceability limit*", "*Restorability limit*", "*Ultimate limit*." Furthermore, the Basis requires that any design criteria should be revised to set the goal of seismic design so as to restrict the damage suffered during an assumed earthquake to one state among the above-mentioned three limit.

For the *level 2 earthquake motions*, it is not realistic to the use *Serviceability limit* to make a demand.

However, dams are very important for flood control and water use in river basins. 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 for replacement of the dam functions would be extremely difficult to find or reconstruct without delay.

Therefore, it is necessary for the damage of dams by the earthquake to be confined to the restorable range.

The application of guidelines doesn't depend on reservoir capacity and scale of dams. In Japan dams are usually constructed in precipitous river basins where a large number of people and properties are concentrated. If, by chance, the dam should break, the consequences would be devastating to the people in the lower reaches.

2.4 Water Level Condition

In evaluating the seismic performance of dams, an important factor is the stored water level, which determines the load conditions including hydrodynamic 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.

The Guidelines also state that the dam should also be evaluated for seismic performance using the other water level (e.g., lowest water level in arch dams) in which dam is structurally susceptible to effects of earthquakes.

The guidelines may not take into consideration about water levels which temporarily occur during floods, such as the Surcharge Water Level, because the possibility of *Level 2 earthquake motions* occurring during floods is very low.

3. EARTHQUAKE MOTIONS FOR SEISMIC PERFORMANCE EVALUATION

The guideline shows that the seismic performance evaluation of dams for the large earthquake uses "*Level 2 earthquake motions*" defined as "earthquake motion having maximum-scale level of intensity conceivable at the dam site at the present and in the future."

Chapter 2 of the Guidelines explains how to set *Level 2 earthquake motions* for evaluation.

3.1 How to Set *Level 2 Earthquake Motions*

Under the Guidelines, *Level 2 earthquake* *motions* 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*). In other words, *level 2 earthquake motions* to use for evaluation are earthquake motions occurring in dam site by "*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 suggest to the occurrence of future earthquakes, should be gathered from reports provided by various earthquake research organs. The results of the Quaternary fault survey, which is to be carried out in determining the sites for dam construction in Japan, should also be checked.

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 site. 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 [4], which is a set of empirical equations derived from 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 have 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.

The Guidelines state 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. However, 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 and there is a limited number of faults for which such data is available. Therefore, there are still problems to use these methods, and the further studies are necessary. Thus, Guidelines state that earthquake motions for evaluation should be estimated basically by using an empirical method such as the *Distance attenuation formula of acceleration response spectra for dams.*

3.2 *Lower-limit Acceleration Response Spectrum for evaluation*

The Guidelines provide "*Lower-limit acceleration response spectrum for evaluation*" shown in Table.2 and Fig. 1 that should be considered as the mandatory minimum *Level 2 earthquake motions*. The reason for stipulating this minimum spectrum is that 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 in an earthquake-prone country such as Japan. This spectrum has been estimated from 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.

This spectrum is earthquake motion equivalency to occur when an inland earthquake of magnitude 6.5 (Japan Meteorological Agency magnitude, *Mj*.) just under the dam site of the dam. This spectrum considers a cover rate of 84% that increased normal deviation value to the mean including unevenness of occurring earthquake motion. When it thought at 50% cover rate equivalent to the mean, it is *Mj*=7.3 equivalency. This spectrum was calculated, using the above-mentioned *the Distance attenuation formula of acceleration response spectra for dams*, and assumed various fault planes right under the site of the dam.

When the spectrum of earthquake motion calculated by the above-mentioned earthquake motion setting method is compared with Lower-limit Acceleration Response Spectrum for evaluation,, the calculated spectrum is used for evaluation. Therefore, we perform evaluation of all dams with larger earthquake motion than Lower limit spectrum, evaluating of dams based on this guidelines.

4. METHODS FOR EVALUATING DAM BODIES

Chapter 3 of the Guidelines shows how to evaluate the seismic performance of concrete dams and embankment dams, against *Level 2 earthquake motions as follows*.

Dynamic response analyses appropriate for the structural properties of the dam shall be conducted to evaluate the seismic performance of the dam main body. It shall be confirmed that the dam will continue to store reservoir water even when the main body suffers damage, and that the damage is limited to a repairable extent.

When the damage of the dam body is expected by dynamic analysis using *Level 2 earthquake motions*, we should estimate the state and degree of damage, identify available repair methods, and estimate the cost and time needed to restore the required seismic performance. When the repair method, cost and period are judged to be reasonable, the damage suffered can be regarded as repairable.

4.1 Concrete Dams

Concerning the seismic performance evaluation of concrete dams, the Guideline states, "As a result of linear dynamic analysis, when the estimated stress in the dam is smaller than the strength of the concrete materials, the dam will not suffer damage and preserve the required seismic performance." The Guideline also states, "If some damage would be expected in the dam body, dynamic 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.

This way of thinking, whereby consideration is given to the damage extent of dams during earthquakes, is a stance never taken before in technical standards or guidelines for dams in Japan.

Fig.2 shows the flow chart of the seismic performance evaluation for concrete gravity dams based on the Guidelines.

In the case of concrete gravity dam, the two-dimensional dynamic response analysis is carried out for the maximum cross section of the dam.

Therefore, we would regard that the dam's function of water storage will be maintained in case that "limited damage" is the following states.

1) The dam body is not divided by continuous tensile cracks between the upstream and downstream surfaces.

2) Stress that may cause compressive or shearing fracture of the main body is not generated or is generated only locally.

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 of water storage 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. The time-history response analysis such as a smeared crack model is available and a kind of nonlinear dynamic analysis for simulating tensile cracks.

Fig.3 shows the flow chart of the seismic performance evaluation for concrete arch dams based on the Guidelines.

The basic points for analysis of the arch dam are common to that for a gravity dam in many respects, except several points.

In the evaluation of the arch dam, three-dimensional analysis is required structurally and simulates the transmission of arch thrust between adjacent monoliths and to the abutments considering the behavior of transverse and perimeter joints.

So, the nonlinear dynamic analysis is available for arch dams.

Conclusively, we would regard that the dam's function of water storage will be maintained in case that "limited damage" is the following states.

1) The dam body is not divided due to the opening of joints or continuous tensile cracks generated between the upstream and downstream surfaces.

2) Stress that may cause compressive or shearing fracture of the main body is not generated or is generated only locally.

In nonlinear dynamic analysis considering the behavior of joints, the estimated opening of the joints must also be confirmed not to exceed a range obtained from the structure of keys and water stops.

4.2 Embankment Dams

Once reservoir, water should overflow from the crest of an embankment dam, a catastrophe such as dam failure might occur. The Guidelines states that the seismic performance evaluation of embankment dams should be conducted by confirming that the settlement of crest embankment during an earthquake is small, the overflow of reservoir water is not caused. Moreover no risk of seepage failure after the earthquake must be verified. The flow chart of seismic performance evaluation for embankment dams is shown in Fig. 4.

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

Furthermore, the liquefaction potential should also be examined, although this investigation is required only in exceptional cases such as rock-fill dams on un-solidified sedimentary stratum, or earth-fill dams with insufficiently consolidated body or on foundation of liquefiable sandy soil.

5. METHODS FOR EVALUATING APPURTENANT STRUCTURES

Chapter 4 of the Guidelines shows how to evaluate the various appurtenant structures 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 by earthquake damage, should be evaluated. Moreover, the structures needed to ensure the safety of the dam by urgently lowering the water level and restricting rises of lowered water level are required for evaluation.

The main gates of principal outlet with a large capacity below NWL should be evaluated whether there is a risk of buckling or plastic deformation, leading to a defect. Additionally, the facilities equivalent to the main gates for lowering the water level must also be evaluated. Crest piers that support the gates or bridges above the gate should also be evaluated whether or not to collapse or fall.

Evaluation of appurtenant structures is carried out by the dynamic response analysis method, or the other suitable methods.

6. 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-scale 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 appurtenant structures.

During three or four years of trial implementation for evaluation, we apply the guidelines to several existing dams and verify the applicability in the technical viewpoint. Studies were conducted at several MLIT dams to find out various problems in working-level and find the means to solve them, and after then, guidelines become formal.

Further efforts should be made to strengthen and consolidate the applicability of the present guidelines through evaluating existing dams.

7. ACKNOWLEDGEMENT

This paper revised a paper of *the 75th Annual Meeting of ICOLD* (2007). The title of the original paper is “Trial Implementation of New Japanese Guidelines for Seismic Performance Evaluation of Dams during Large Earthquakes.” [5]

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8. REFERENCE

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Table 1 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

Table 2 *Lower-limit acceleration response spectrum for evaluation* (attenuation constant = 5%)

Range of natural period T (sec)	Acceleration response spectrum S_A (gal)
$0.02 \leq T < 0.1$	$\boldsymbol{S_A} = 400/0.08 \times (T-0.02) + 300$
$0.1 \leq T \leq 0.7$	$\boldsymbol{S_A} = 700$
$0.7 < T \leq 4$	$\boldsymbol{S_A} = 700 \times (T/0.7)^{-1.642}$

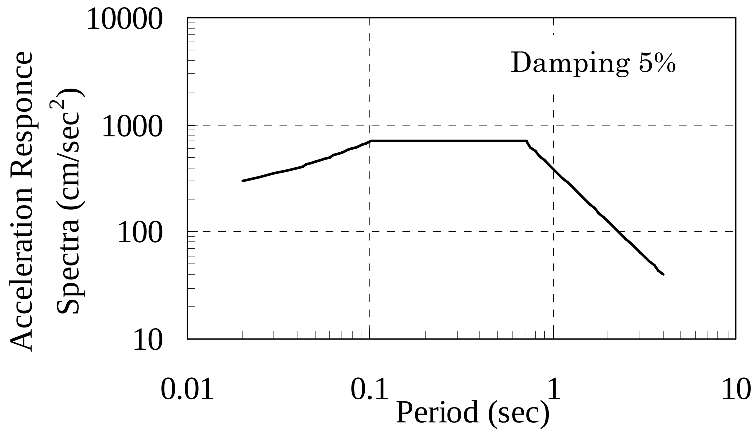

Fig. 1 *Lower-limit acceleration response spectrum for evaluating seismic performance*

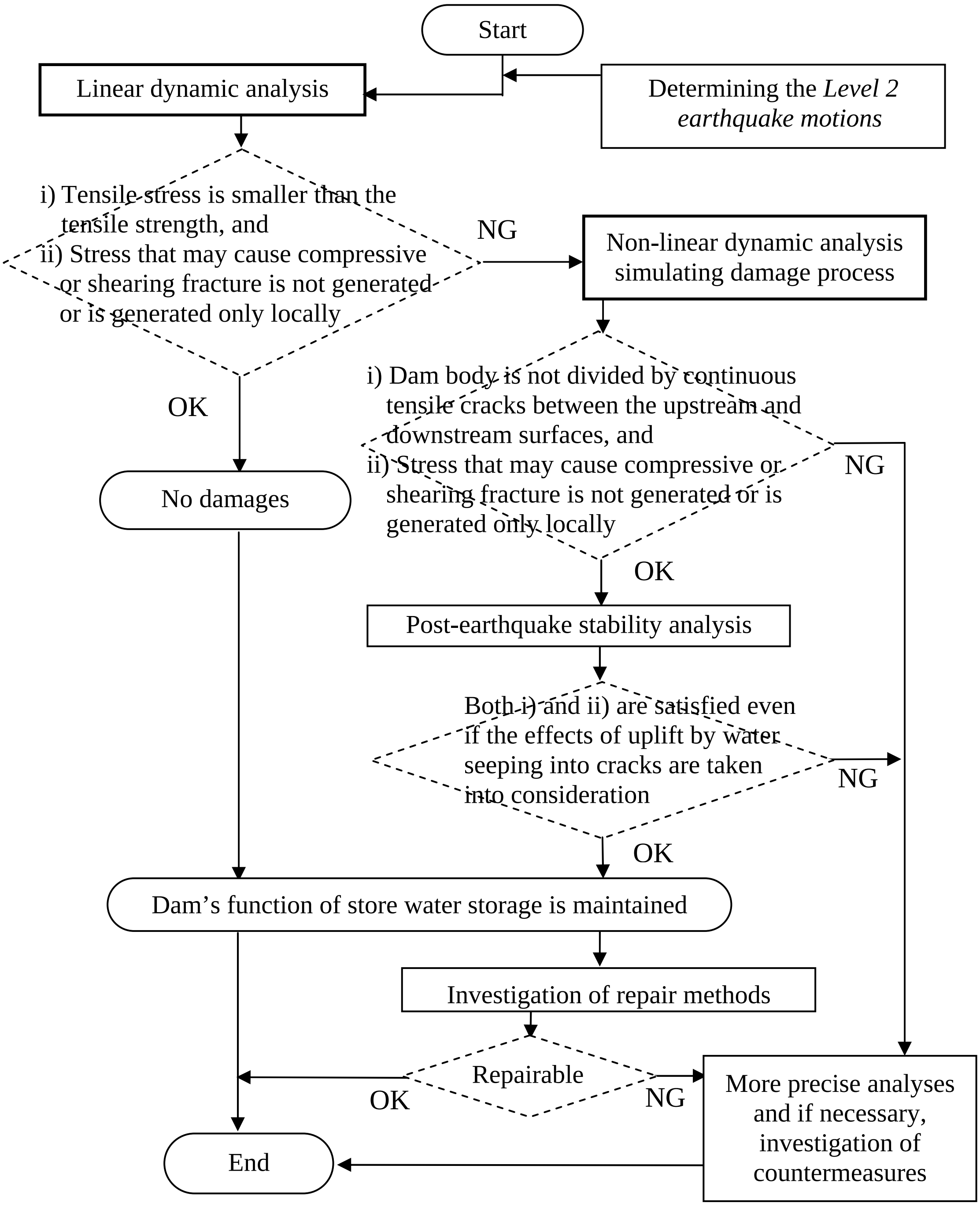

Fig. 2 Flow chart of seismic performance evaluation for concrete gravity dams

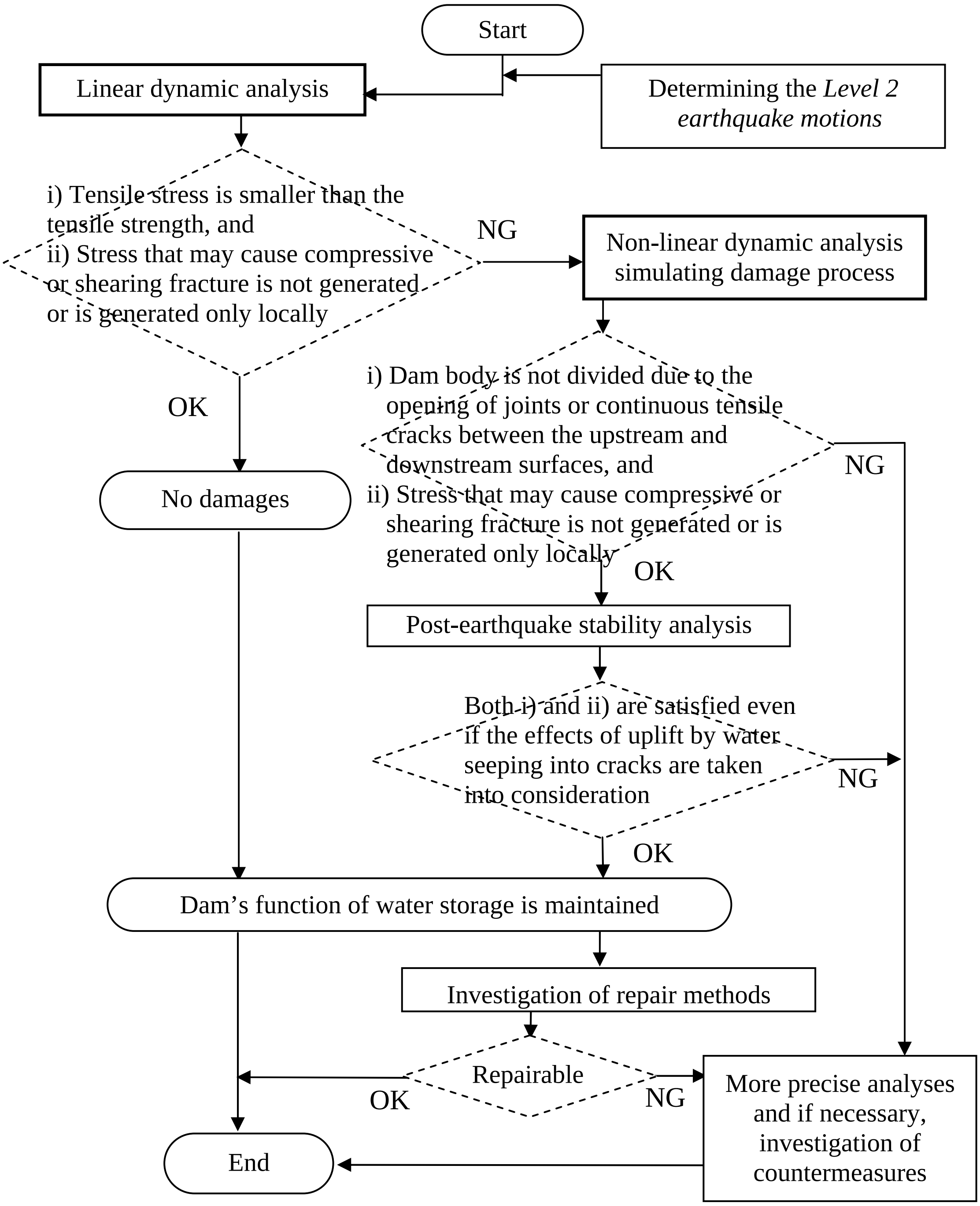

Fig. 3 Flow chart of seismic performance evaluation for concrete arch dams

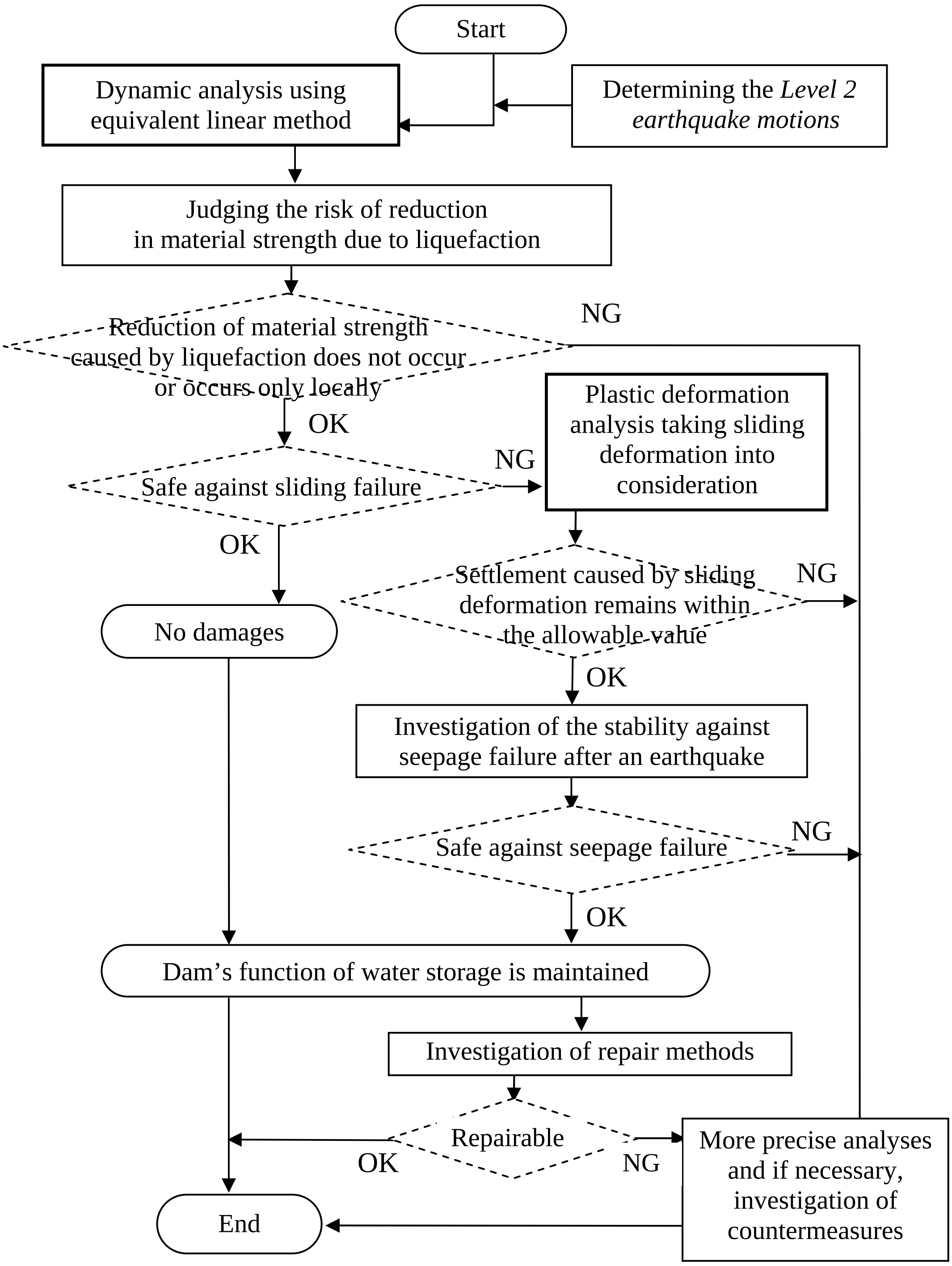

Fig. 4 Flow chart of seismic performance evaluation for embankment dams