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Prediction Method for Reservoir Collapse During Earthquakes

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ABSTRACT

This paper compares the detailed stability analysis by seismic response analysis (Watanabe-Baba method) with the seismic coefficient method in the stability of a reservoir for Level 1 earthquake motion. While the results from the seismic coefficient method require countermeasures to overcome the unsatisfied stability factors, the minimum factors of safety on the slip surfaces are greater than 1.0 in the Watanabe-Baba method. Therefore, the detailed analysis should provide reasonable results in terms of countermeasures against the reservoir collapse. The residual deformation analysis (by using ALID), the effective stress analysis (by using FLIP) and the Watanabe-Baba method are used for Level 2 earthquake motion. The ALID and FLIP have a difficulty in detecting a local slope collapse while they are able to demonstrate the deformation of the whole of an embankment. The Watanabe-Baba method should predict such a local collapse on an upstream slope as reservoir collapses caused by the 2011 Tohoku earthquake in Japan.

Introduction

Japan has reservoirs at approximately 200,000 locations, and 70% of these are presumed to be constructed more than 150 years ago. This means that the dam bodies were compacted by human effort, and as such, many dams have insufficient degree of compaction. There are also cases where sandy soil, which is vulnerable to seismic ground motions, was used to build dam bodies. Because stored water remains at high levels in reservoirs for prolonged periods of time, phreatic surfaces develop and reservoirs are highly likely to be subjected to seismic external forces in such conditions. In addition, earthquake-resistant design has naturally not been implemented because of the time of construction of these reservoirs. This has led to many reservoirs sustaining damage from earthquakes in the past. Reservoirs have collapsed, and settlements located downstream have sustained extensive damage due to earthquakes, particularly during the Great East Japan Earthquake that occurred on March 11, 2011. Because large-scale earthquakes are expected in the future in Japan, evaluation of reservoir safety in the event of an earthquake has become an important subject.

The seismic design of a reservoir was conducted based on two kinds of earthquakes. For reservoirs where the embankment height is small, and only limited damage would occur in the case of a dyke failure, the seismic resistance was designed for a “level 1” earthquake which has a return period of 50-100 years. For reservoirs where significant damage would occur in the case of a dyke failure, the seismic design was carried out for a “level 2” earthquake where the return period is up to several thousand years. Safety evaluations related to the collapse of reservoirs during earthquakes are generally performed by a sliding stability calculation using the seismic coefficient method for level 1 earthquakes and an evaluation of deformations through dynamic analysis for level 2 earthquakes. Application of the seismic coefficient method to existing reservoirs, however, tends to require an excessive degree of safety.

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This study therefore considered the safety of reservoirs during a level 1 earthquake by comparing sliding slip calculation using the seismic response analysis (Watanabe-Baba method) with the seismic coefficient method. Furthermore, various analysis methods (effective stress analysis, residual deformation analysis, seismic response analysis for performing sliding slip calculation) were used to predict the collapse pattern of a reservoir during an earthquake. The applicability of the prediction methods to level 2 earthquake motions was examined.

Reservoir Cross-section and Stratum Composition

Figure 1 shows the cross-section of the reservoir considered in this study and Figure 2 shows the liquefaction curve used for analysis and lists the soil properties

The stratum of the considered ground was composed primarily of gravel soil, and it contained the dam body (B1) and loose alluvial gravel stone layer (Asg), which was distributed in the foundation ground immediately below the dam body. Below this layer, cohesive soil layers and sandy gravel layers were distributed essentially uniformly, forming alternating strata. The lowest layer, which was a diluvial sandy layer (Dg), indicated an N-value of 50 or more, which can be considered as the engineering base surface for the location.

The layer subject to liquefaction was the alluvial gravel stone layer (Asg); the dam body (B1) was also subject to liquefaction in layers that were deeper than the ground water. The reservoir water level considered for the analysis was the full reservoir level, at which the phreatic surface was at the highest level. The phreatic line in the dam body was obtained by a seepage flow analysis (steady analysis) based on the finite element method.

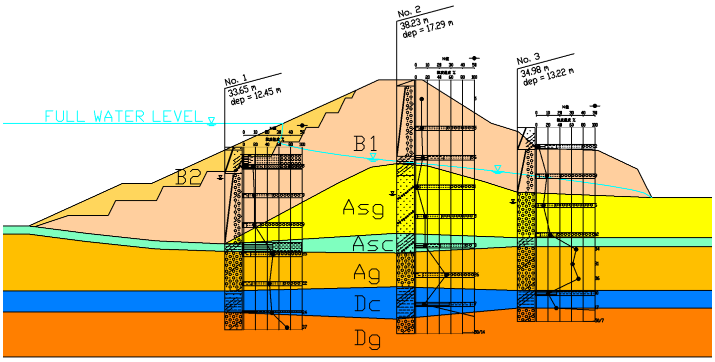
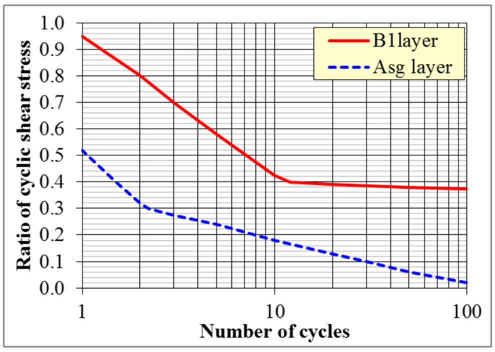


Figure 1. Cross-section of reservoir for analysis



layer	N value	Fc (%)	D50 (mm)	Specific weight (kN/m^3)	C (kN/m^2)	ϕ (°)
B1	6	20.1	2.339	18	0	33
B2	8	35.2	0.280	20	12	37
Asg	9	5.8	2.927	19	0	26
Asc	7	54.5	0.757	19	2	34
Ag	24	18.1	1.481	21	0	35
Dc	11	67.2	0.096	20	2	34
Dg	58	–	–	21	0	40

Figure 2. Liquefaction strength curve used in analysis and soil properties

Applied Seismic Ground Motions

The Tonankai Earthquake and Nankai Earthquake, which were assumed to have caused extensive damage to the considered site, were adopted for the level 2 seismic motions, and the seismic waveforms published by the Central Disaster Prevention Council were used (Figure 3). To prepare the ground input waveform for the level 1 seismic motions, the amplitude of the seismic waveforms for the level 2 seismic motions was adjusted so that the maximum acceleration in the proximity of the center of the dam body reached 150 Gal. This was done because the site is located in a moderate earthquake zone and the design horizontal seismic coefficient kh is 0.15 (Figure 3).

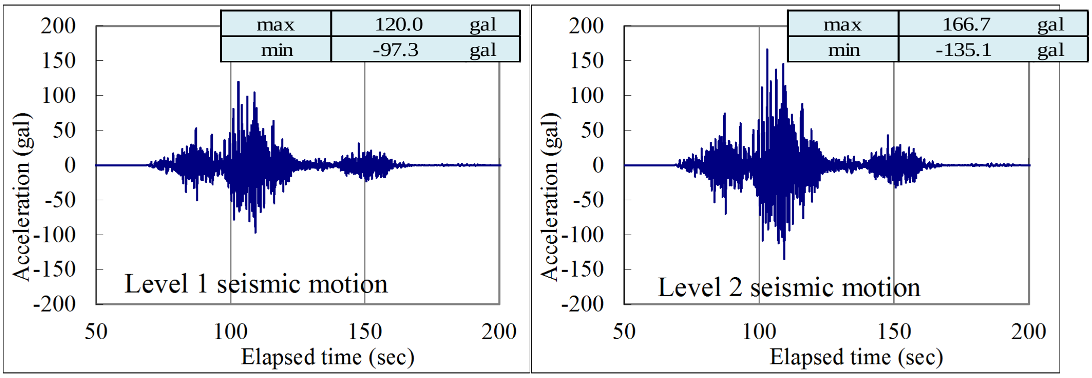


Figure 3. Seismic motion waveform used in analysis

Analysis Methods

Level 1 Seismic Motions

The following two methods were used for the analysis of level 1 seismic motions to calculate the stability and the amount of displacement during earthquakes:

(1) Arc sliding method (seismic coefficient method)
(2) Stability calculation according to the Watanabe-Baba method[1)] to derive the time history of sliding surface stress obtained from total stress seismic response analysis

Watanabe-Baba method calculates the time history of a slip safety factor by comparing the driving moment with the resistance moment on an arc. These moments are calculated based on the stress and the stiffness of each element obtained from seismic response analysis which adopts the equivalent linear model.

The displacement of the sliding mass above the failure surface is calculated by the time integral of the part of equivalent instantaneous seismic intensity which exceeds yielding seismic intensity, whereby the yielding seismic intensity is the seismic intensity when the safety factor equals 1.0. The equivalent instantaneous seismic intensity is the averaged seismic intensity which works against overall sliding mass during an earthquake.

The analysis conducted according to the Watanabe-Baba method involved deriving the time history of sliding safety factor based on the time history of shear stress obtained from the total stress seismic response analysis. The amount of sliding slip was then obtained by integrating the excessive acceleration that satisfies $Fs > 1.0$.

An arc that represents the minimum safety factor according to the seismic coefficient method for the level 1 seismic motions was selected as the sliding arc under consideration.

Level 2 Seismic Motions

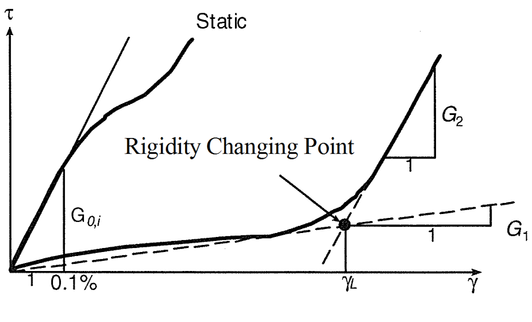
The following three methods were used for the analysis of level 2 seismic motions to calculate the amount of displacement inducing a collapse during an earthquake:

(1)Residual deformation analysis using ALID(Analysis for Liquefaction-Induced Deformation) [2)]
(2)Effective stress analysis using FLIP(Finite element analysis of Liquefaction Program)[3)]
(3)Stability calculation according to the Watanabe-Baba method to derive time history of sliding surface stress obtained from total stress seismic response analysis

ALID calculates the ground deformation induced by self-weight during and after liquefaction. During calculation, the degree of liquefaction is evaluated by the FL (Safety factor of liquefaction) and depending on FL, rigidity of each element reduced accordingly. ALID conducts static analysis by FEM, therefore it can't consider inertial force during an earthquake.

The shear stress-strain relationship of the soil after liquefaction was represented by a convex curve as shows in Figure 4. Note that the strength of the soil recovered exponentially after the shear strain exceeded a boundary value. ALID assumed that the ground deformation during the liquefaction was caused by the stiffness reduction and the self-weight of the soil. In ALID program, the stress - strain relationship during the liquefaction was approximated by a bilinear curve the deformation of an element was calculated by loading the dead weight onto the element which had both the shear modulus G1 during the reduction in the strength and the shear modulus G2 after the strength recovered. The relationship among the reduced shear modulus G1 during the liquefaction, the initial shear modulus G0 before the liquefaction and FL was shown in Figure 4. ALID calculated the reduction in the shear modulus during the liquefaction from the FL based on the relationship.

The FL value, which is a liquefaction element, must be determined for the residual deformation analysis using ALID. However, setting the ground surface acceleration is difficult when the dam body soil liquefies. Two cases were therefore implemented and compared: a simplified method for determining liquefaction using the maximum acceleration (250 Gal) at the crown derived from the total stress seismic response analysis and a method for setting the FL value for each element by using the maximum shear stress distribution derived from the seismic response analysis,.



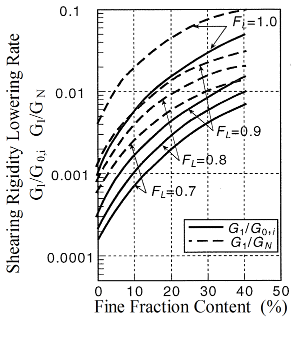


Figure 4. Shear stress-strain relationship after liquefaction and Shearing rigidity lowering rate

FLIP is a sequential nonlinear analysis that calculates stress and strain at minute differential time steps using the rigidity matrix which includes tangent rigidity of soil stress-strain relationship.

Flip can consider the decrease of the effective stress and changing of the rigidity during the liquefaction and make it possible to calculate deformation caused by gravity and inertial force. The liquefaction parameters are required to perform the effective stress seismic response analysis using FLIP, and these were determined by a simplified method based on the N value, effective earth covering pressure, and the fine-grained soil content Fc.

In the analysis conducted according to the Watanabe-Baba method, the time history of the excess pore water pressure was derived by a cumulative damage method based on the time history of shear stress derived from the total stress seismic response analysis. The time history of the sliding safety factor was derived based on the time history of the sliding surface stress by using a similar method, and the excessive acceleration that satisfies Fs > 1.0 was integrated to derive the amount of sliding slip. An arc that represents the minimum safety factor according to the seismic coefficient method for the level 1 seismic motions as well as an arc that passes through the region with large excess pore water pressure ratio were selected as the sliding arcs under consideration.

Analysis of Results

Level 1 Seismic Motions

Arc Sliding Method (Seismic Coefficient Method)

The safety calculation performed using the design horizontal seismic coefficient kh of 0.15 resulted in a standard safety factor Fs under 1.2 for both the upstream and downstream (Figure 6). This result indicated that sliding occurred from upstream to downstream. Therefore, some type of countermeasure was deemed necessary because the safety factor was insufficient.

Stability Calculation According to Watanabe-Baba Method

Figure 5 and 6 show the analysis results. The stability calculation performed according to the Watanabe-Baba method resulted in a safety factor higher than the results obtained using the seismic coefficient method. Therefore, the seismic coefficient method, which calculates shear stress by assuming a constant horizontal acceleration across all regions, gives an excessively low sliding safety factor. Furthermore, reducing the scale of countermeasures that must be implemented is presumed possible by using the Watanabe-Baba method to analyze methods that were used to obtain the countermeasures and raise the safety factor to the required level (Fs > 1.2). Therefore, according to detailed analyses, existing reservoirs that have been determined to require countermeasures may not actually need any countermeasures or may only require such countermeasures at a reduced scale.

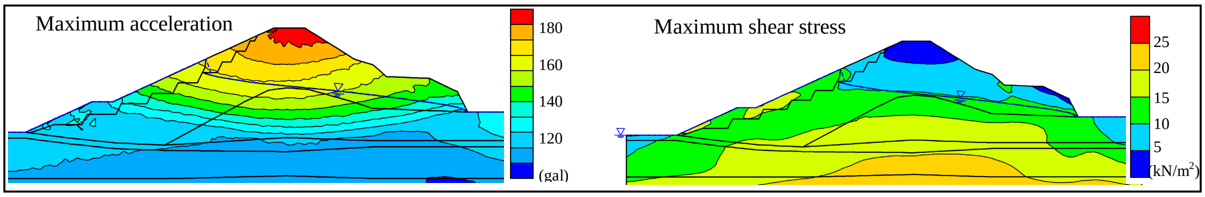


Figure 5. Maximum acceleration distribution according to total stress seismic response analysis and maximum shear stress (level 1 seismic motions)

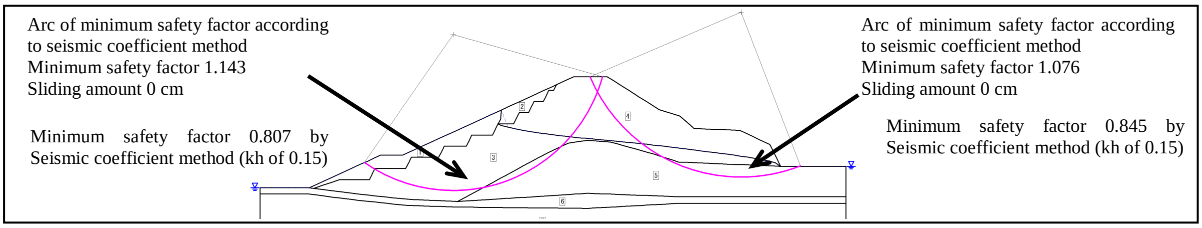


Figure 6. Watanabe-Baba method (level 1 seismic motions)

Level 2 Seismic Motions

Residual Deformation Analysis

Figure 7 shows the distribution of FL which is calculated by the cyclic stress ratio based on Eq. (1) and (2); assuming that the acceleration on the ground surface at the top of the embankment is 250gal.

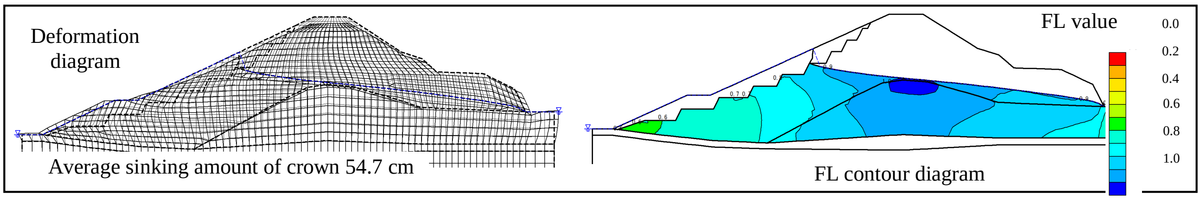


Figure 7. Residual deformation analysis (case where maximum acceleration at crown was set to 250 Gal)

$$\mathrm{CSR} = 0.65 \cdot r_d \cdot \frac{\alpha}{g} \cdot \frac{\sigma_v}{\sigma_v{}'} \tag{1}$$

$$r_d = 1.0 - 0.015Z \tag{2}$$

Where;

CSR : Cyclic Stress Ratio,
r_d : reduction coefficient,
α : acceleration on the ground surface,
g : gravitational acceleration,
σ_v : total vertical stress,
σ_v’ : effective vertical stress and
Z : depth from the top of the embankment.

Figure 8 shows FL calculated by the distribution of the maximum shear stress on each element. The maximum shear stress was obtained from seismic response analysis based on the equivalent linear method.

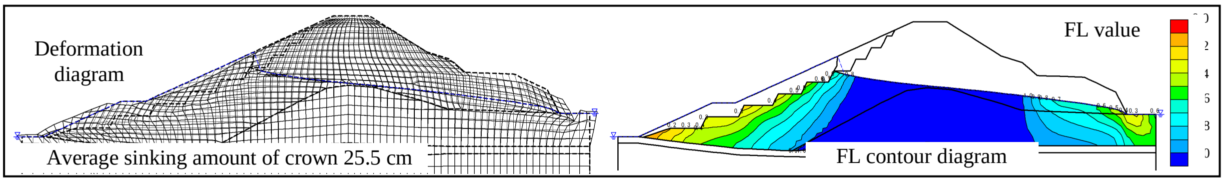


Figure 8. Residual deformation analysis (case where FL value was set for each element)

The FL value had a tendency to increase at locations where the effective earth covering thickness was small, in the case where the maximum acceleration of the dam body crown was set to 250 Gal (Figure 7). In the case where the FL value was set for each element, the degree of liquefaction of the dam body on the upstream side was severe (Figure 8). Liquefaction on the upstream slopes such as this can also be verified based on the distribution of excess pore water pressure ratio derived from the total stress seismic response analysis and cumulative damage method and can be observed using the effective stress seismic response analysis. Therefore, an appropriate FL value distribution must be set when the dam body undergoes liquefaction. Furthermore, the deformation behavior in both cases involved the stretching of the overall dam body, which resulted in the sinking of the crown.

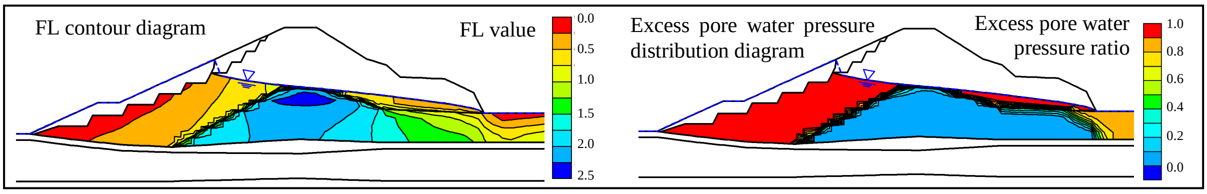


Figure 9. Final FL value and excess pore water pressure ratio distribution derived from total stress seismic response analysis and cumulative damage method

Effective Stress Seismic Response Analysis

The excess pore water pressure ratios of the layers subject to liquefaction increased to nearly 0.9 in all regions, indicating a practically complete liquefaction. The deformation behavior was the sinking action of the crown associated with the stretching of the dam body, similar to the behavior obtained from the residual deformation analysis.

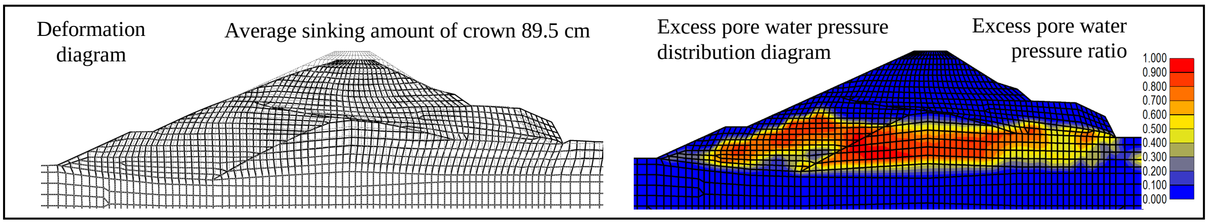


Figure 10. Effective stress analysis

Stability Calculation According to Watanabe-Baba Method

The sliding amount of the arc that passed through the entire dam body was small, suggesting an occurrence of crack in the crown. Arcs that passed through the upstream slopes with a large excess pore water pressure ratio in all instances showed an excessive sliding amount, and slope failure in the upstream direction during the earthquake was evident. This result was quite similar to the collapse phenomenon of reservoirs observed during the Great East Japan Earthquake.

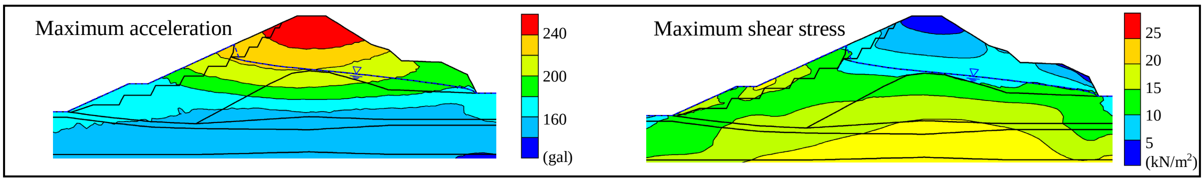


Figure 11. Maximum acceleration and maximum shear stress distributions according to total stress seismic response analysis (level 2 seismic motions)

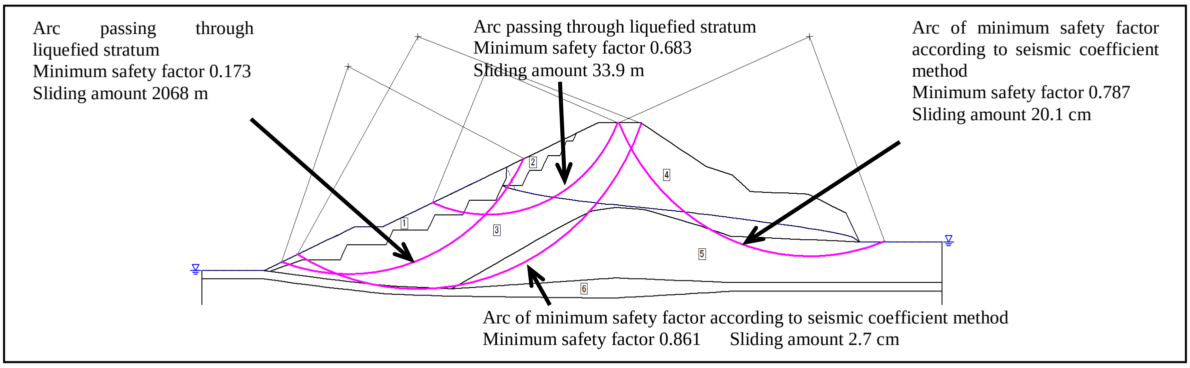


Figure 12. Watanabe-Baba method (level 2 seismic motions)

Conclusion

Level 1 Seismic Motions

(1) The seismic coefficient method was revealed to give an excessively low safety factor.
(2) A more detailed evaluation is possible by using the Watanabe-Baba method, which derives the time history of sliding surface stress by total stress seismic response analysis. Many inspections for level 1 earthquake resistance of reservoirs are being conducted currently, and several existing reservoirs are determined to have a safety factor below the standard safety factor set by the seismic coefficient method. Thus, these reservoirs are deemed to require an implementation of countermeasures. There is a potential for such countermeasures to be unnecessary or to be required at a reduced scale according to the findings from a more detailed analysis. Employing a detailed analysis method, such as the one described by this paper, is desirable from the perspective of cost reduction.

Level 2 Seismic Motions

(1) Setting an appropriate FL value distribution is essential when using the residual deformation analysis, and the total stress seismic response analysis is an effective means for that purpose.
(2) The overall stretching collapse of the dam body and the sinking of its crown can be expressed by the residual deformation analysis and effective stress seismic response analysis. It is, however, difficult to derive the details of localized slope failure.

(3) The Watanabe-Baba method, which derives the time history of sliding surface stress using the total stress seismic response analysis, can be used to estimate localized collapse of upstream slopes, such as those observed in the cases of damage sustained by reservoirs during the Great East Japan Earthquake.

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