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Seismic Performance Evaluation of Concrete Dams Considering Ultimate Stability of Detached Upper Block

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ABSTRACT:
Japanese guidelines for evaluating the seismic performance of dams against large earthquakes (draft) define the seismic performance required against extremely large earthquake motions. The most important requirement is that the storage function of a dam is maintained, which means that an uncontrolled release of stored water does not occur. A dynamic analysis considering the critical damage process by the generation of tensile cracks is conducted to evaluate the seismic performance of a concrete gravity dam under the guidelines. If the estimated cracks do not penetrate completely between the upstream and downstream faces of the dam body, the storage function is judged to be maintained. However, no method has been established to evaluate the seismic performance of a concrete dam taking into consideration the stability of the upper block after the dam body is divided due to penetrated tensile cracks. This paper discusses a method for evaluating the ultimate stability of concrete gravity dams in this situation, based on findings from shaking table tests and numerical analyses. A fundamental study on the effect of uplift pressure that might be generated along the detached interface is also introduced.

Keywords: concrete gravity dam, seismic performance, penetrated crack, detached block, uplift pressure

1. INTRODUCTION

In Japan, draft guidelines for evaluating the seismic performance of dams against large earthquakes have already been published (River Bureau of *the Ministry of Land, Infrastructure, Transport and Tourism*, 2005). These draft guidelines define the seismic performance of dams required against “Level 2 earthquake motion,” which is equivalent to the earthquake motion caused by the maximum credible earthquake. The most important requirement is that the storage function of the dam is maintained, which means that an uncontrolled release of stored water does not occur. The seismic performance of gravity concrete dams, which is one of the major types of concrete dam, is usually evaluated by nonlinear dynamic analysis considering the growth and progress of tensile cracking of concrete, which is one of the major failure modes of this type of dam. It is judged that the storage function of this type of dam will be maintained if the analysis result shows that the estimated tensile cracking does not penetrate the dam body between the upstream and downstream faces. Strictly speaking, however, this condition does not mean that the storage function is maintained. This is because no uncontrolled release of stored water is considered to occur unless penetrated cracks completely separate the dam body, and the upper block above the detached interface eventually loses stability by overturning or greatly sliding in the downstream direction. In other words, the seismic performance of concrete gravity dams based on the commonly used analysis at present is judged based on not the real ultimate limit state but one step before that state. This suggests that the current analysis method is appropriately on the safe side considering various uncertainties in the evaluation analysis. However, it is also important to clarify how a severely damaged dam body with detached interface behaves in case of prolonged large earthquake motion and how the dam ultimately loses its storage function. During *the 2011 Off the Pacific Coast of Tohoku Earthquake* (M_w 9.0), earthquake motions with much longer duration than ever observed at dam foundations occurred (Yamaguchi et al., 2012). Fortunately, no concrete dams suffered severe damage that affected their safety, but such motion indicates the importance of clarifying the ultimate stability of dams against very strong and long earthquake motions.

This paper firstly reviews the behavior of a detached upper block of a concrete gravity dam based on the results of prior shaking table tests (Iwashita et al., 2011). Secondly, the behavior of the detached upper block of an actual-scale dam is simulated by numerical analysis using the distinct element method (DEM). Reproduction analysis of an actual damaged spillway structure is also reported. Lastly, a fundamental study to establish a method of evaluating the ultimate stability of concrete gravity dams considering the effect of uplift pressure that might be generated due to water infiltration into the detached interface is introduced.

2. BEHAVIOR OF DETACHED UPPER BLOCK

2.1. Shaking Table Test and Reproduction Analysis

The Public Works Research Institute (PWRI) has conducted a series of shaking table tests to clarify the behavior of the detached upper block of a concrete gravity dam (Iwashita et al., 2011). Fig. 1 outlines the test equipment. The dam model used in the test was constructed of low-strength mortar considering the similarity rule, and horizontally split into upper and lower blocks in advance. The amplitude of horizontal acceleration with sine waveform acting on the lower block fixed on the shaking table was increased step by step.

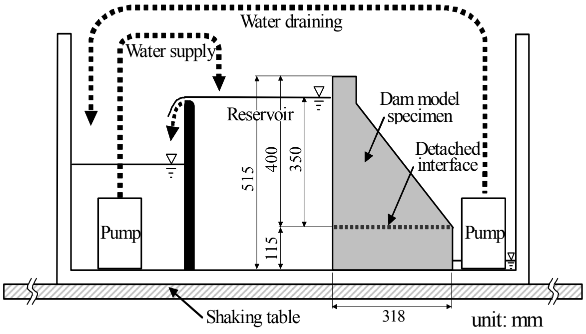
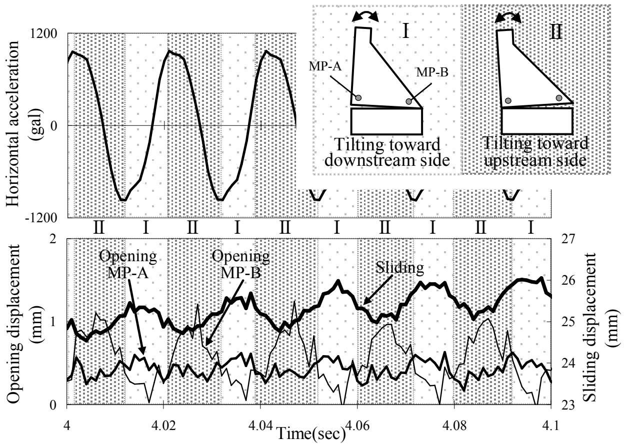
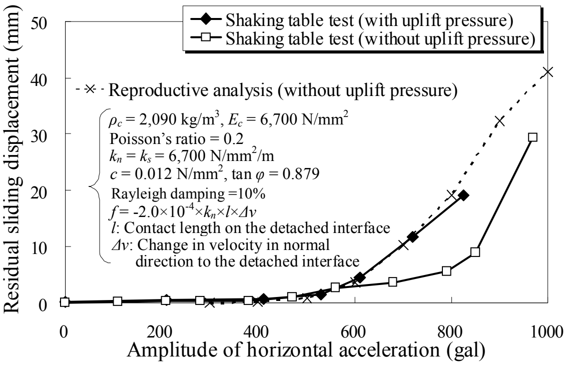


Figure 1. Shaking table test (Iwashita et al., 2011)

As a result, rocking motion and horizontal displacement (sliding) of the upper block were observed. Fig. 2(a) indicates the observed vertical opening displacement of detached interface due to rocking motion and sliding displacement of upper block with the horizontal acceleration of input motion (1 gal=1x10^{-2} m/sec^2). Fig 2(b) shows the relationship between the amplitude of horizontal acceleration and the residual sliding displacement with the result of reproduction analysis using DEM code UDEC (Itasca, 2004). In this analysis, the shear friction along the detached interface was considered by defining stiffness in the tangential direction (k_s) and shear strength determined by cohesion (c) and angle of internal friction (φ). The damping force (f), which is proportional to stiffness in the normal direction (k_n) at the detached interface, was also considered in order to take account of the damping effect associated with rocking motion of the upper block. The values of c and φ were set based on the results of a direct shear test using a previously split concrete specimen. The values of k_n and k_s were assumed with reference to the elastic modulus of dam concrete (E_c). The effect of uplift pressure that might be generated by infiltration of stored water into the detached interface was not considered because an adequate method of assessing the effect has yet to be established.



(a) Input motion and time series responses of upper block



(b) Acceleration level and residual sliding displacement

Figure 2. Examples of test result and reproduction analysis

2.2. Discussion on Results of Shaking Table Test

The shaking table test and its reproduction analysis revealed that the sliding displacement of the upper block increases with an increase in the acceleration level. The test also revealed that the sliding displacement increases with infiltration of stored water into the detached interface. It is speculated that this phenomenon is related to the reduction of shear resistance along the detached interface associated with rocking of the upper block which might cause stored water to infiltrate the detached interface and generate uplift pressure. When considering this phenomenon, the conditions that cause rocking of the upper block are important in order to predict the stability of the detached upper block. By assuming the upper block as a rigid body, the conditions are given by Eq. 1, equilibrium of moment around the pivot points, namely Points A and B in Fig. 3, during rocking.

$$M_I + M_S + M_D + M_G + M_U > 0 \tag{1}$$

where M_I, M_S, M_D, M_G and M_U are respectively the moment of inertial force (F_I), hydrostatic force (F_S), hydrodynamic force (F_D), weight of the dam body (F_G), and uplift force (U) generated by stored water infiltrated into the detached interface. Assuming that the sectional shape of the upper block is a right-angled triangle, the detached interface is horizontal, the hydrodynamic pressure distribution along the upstream face is given by Westergaard's formula and that no stored water exists at the downstream side, the conditions for rocking motion to occur are obtained as:

$$a < a_1 = -\frac{n^2 + \frac{\rho}{\rho_c}\left(\frac{h}{H}\right)^3 - n^2 U_p \frac{\rho}{\rho_c}\left(\frac{h}{H}\right)}{n + \frac{7}{5}\left(\frac{\rho}{\rho_c}\right)\left(\frac{h}{H}\right)^3} g \tag{2.1}$$

$$a > a_2 = \frac{2n^2 - \frac{\rho}{\rho_c}\left(\frac{h}{H}\right)^3 - 2n^2 U_p \frac{\rho}{\rho_c}\left(\frac{h}{H}\right)}{n + \frac{7}{5}\left(\frac{\rho}{\rho_c}\right)\left(\frac{h}{H}\right)^3} g \tag{2.2}$$

where, a: horizontal acceleration acting on upper block; a_1 and a_2: critical accelerations for occurrence of rocking around Point A at the upstream end and Point B at the downstream end, respectively; ρ and ρ_c: density of water and dam body, respectively; h and H: depth of stored water and dam height above the detached interface, respectively; n: downstream slope of dam body (1:n); U_p: ratio of uplift pressure to hydrostatic pressure at the upstream end of the detached interface; and g: acceleration due to gravity.

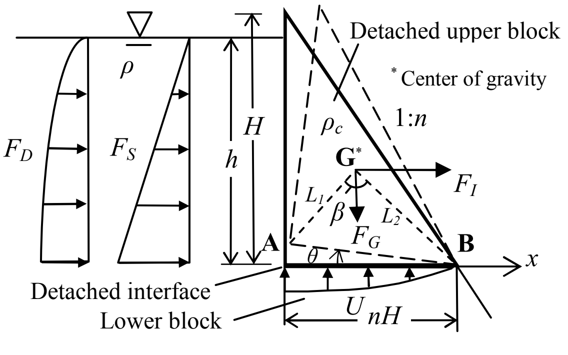


Figure 3. Forces acting on a detached upper block (Rigid body model; case of downstream end as pivot point)

Fig. 4 shows the changes in limit accelerations for occurrence of rocking to the value of h/H assuming typical design values for ρ_c, n and U_p. The values of both a_1 and a_2 are calculated to be approximately 600 gal when the water level condition is the same as that of the shaking table test (h/H = 0.875). This value is slightly larger than the acceleration level, approximately 500 gal, where rocking motion of the upper block began in the shaking table test, but is still closer to the value calculated above. When the acceleration level exceeds that level, the residual sliding displacement shown in Fig. 2(b) obviously increases. It is therefore considered that these critical accelerations are important indicators for evaluating the stability of the detached upper block of concrete gravity dams.

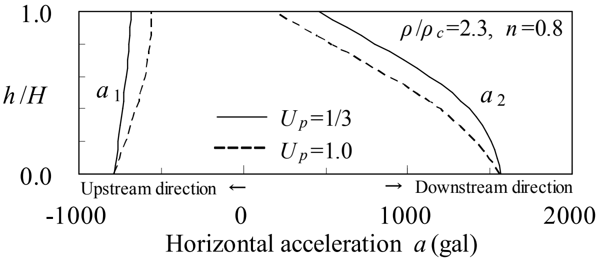


Figure 4. Critical accelerations for occurrence of rocking

3. BEHAVIOR ESTIMATION OF DETACHED UPPER BLOCK BY NUMERICAL ANALYSES

3.1. Analysis of Actual-scale Dam

To estimate the behavior of a detached upper block of an actual-scale dam, 2-D numerical simulations using DEM, which can deal with the behavior of discontinuous bodies, were conducted. The analysis model is shown in Fig. 5 with the values of analytical parameters. Cohesion (c) was assumed to be zero in this analysis. One of the input seismic motions to the bottom of the dam is shown in Fig. 6; this is the largest horizontal acceleration waveform ever observed at the foundation of a concrete dam in Japan, with a maximum acceleration ($a_{\max}$) of 494 gal. Another case assuming a waveform with twice the amplitude and a maximum acceleration of 987 gal was also conducted.

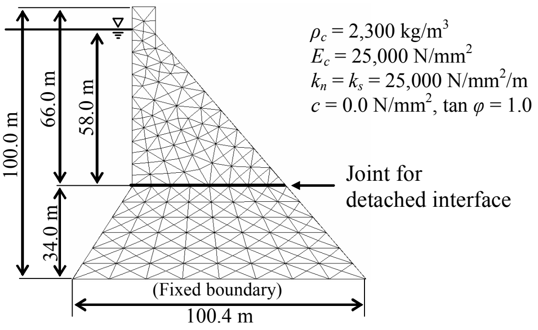


Figure 5. Analysis model of actual-scale dam

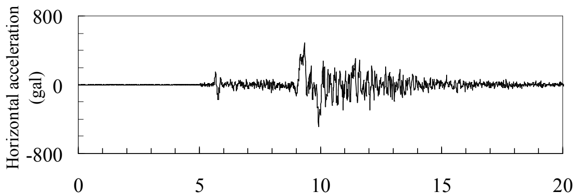


Figure 6. An example of input seismic motion for analysis of actual-scale dam ($a_{\max}$ = 494gal)

The analysis results are shown in Fig. 7. In both cases, slight rocking and sliding displacement occurred after the point in time when the acceleration amplitude reached a major peak. The opening displacement of the detached interface and sliding displacement of the upper block, however, turned out to be so small in both cases that no loss of water storage function would occur. Note that the effect of uplift pressure that might be generated due to infiltration of stored water into a detached interface is not taken into consideration, because an appropriate method of dealing with it has yet to be established. Referring to the shaking table test result indicated in Fig. 2(b), a calculation considering this effect is likely to produce a larger sliding displacement.

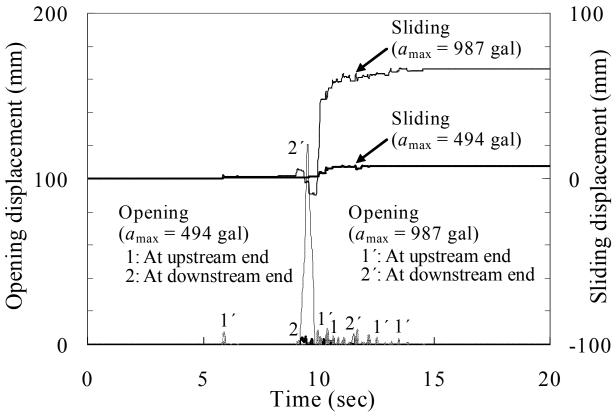


Figure 7. DEM analysis results for actual-scale dam

3.2. Reproduction Analysis of Actual Damaged Spillway Structure

In Japan, there has been no report of a concrete dam where penetrating cracking occurred and caused complete separation of the main body. However, after the Iwate-Miyagi Nairiku (Inland) Earthquake in 2008 (M_w 7.0), a dividing wall that formed the spillway of a rockfill dam under construction suffered penetrating cracking (Sasaki et al., 2009). It was not directly confirmed whether the cracks caused complete separation of the structure, but a water filling test indicated penetration of the cracks. A survey on this damaged structure conducted after the earthquake revealed that these penetrated cracks were generated mainly along the horizontal construction joints, but no residual displacement of the upper part was found. Repair works to integrate the upper and lower sections by anchoring have already been completed.

This section describes a reproduction analysis on this damaged dividing wall. This analysis provides a useful reference for estimating the behavior of a detached upper block of a concrete gravity dam, because the sectional shape and the structural design concept of this kind of structure are similar to those of the main body of a concrete gravity dam except for the loaded condition with stored water.

The analysis was conducted using 2-D DEM of the two sections shown in Fig. 8. In Section A, the damaged horizontal construction joint is located near the base, while it is located in the upper position in Section B. The values of analytical parameters other than those shown in Fig. 8 were set to the same values as used for the actual-scale dam analysis. The input seismic motion from the model bottom is shown in Fig. 9. This waveform was estimated as the motion at the foundation of an existing dam located very close to the rockfill dam with the damaged dividing wall. The peak acceleration of this input seismic motion is approximately 630 gal.

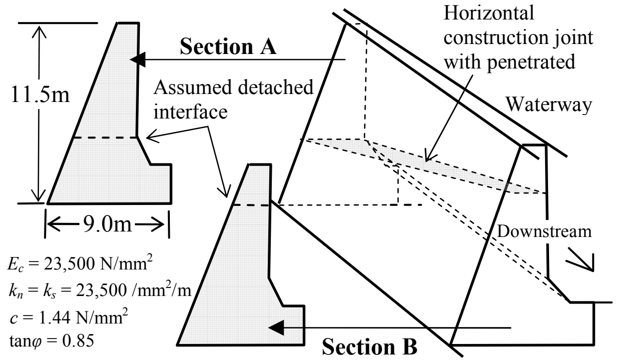


Figure 8. Damaged dividing wall and sections for 2-D analysis

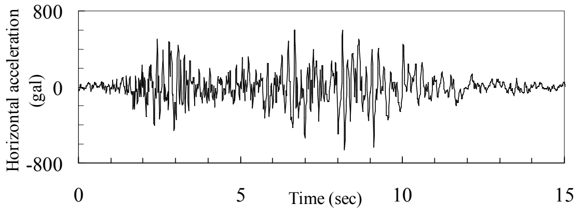
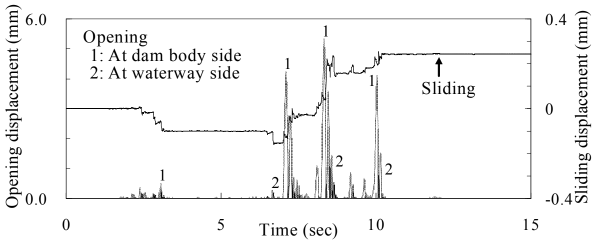
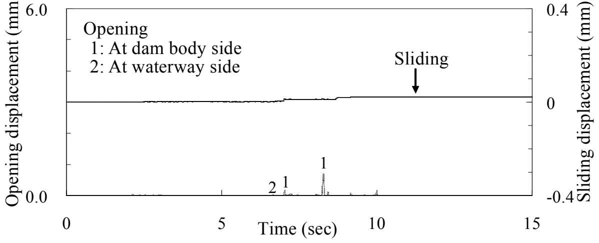


Figure 9. Input seismic motion for reproduction analysis of damaged dividing wall ($a_{\max}$ = 630gal)



(a) Section A



(b) Section B

Figure 10. Analysis result of damaged dividing wall

The analysis results are shown in Fig. 10. Although slight opening and sliding displacements were calculated for Section A, the value of residual horizontal displacement of the upper block for this section was very small, less than 0.3 mm. For Section B, almost no opening and sliding displacements were calculated. The maximum response acceleration at the elevation of the penetrated crack is calculated to be 670 gal for Section A and 740 gal for Section B, while the critical acceleration for rocking of the upper part as a rigid body is calculated to be 640 gal for Section A and 940 gal for Section B from Eq. 1. These simply calculated values are roughly consistent with the results of DEM analysis. Considering these points and the fact that the dividing wall has a three-dimensional shape, the results of this reproduction analysis do not contradict the fact that no residual displacement was confirmed along the horizontal cracking.

4. EFFECT OF UPLIFT PRESSURE DUE TO WATER INFILTRATION INTO DETACHED INTERFACE

The shaking table tests indicated that water infiltration into the detached interface affects the behavior of the upper block of a concrete gravity dam (Fig. 2(b)). This effect, however, is not considered in all the numerical analyses introduced above. To estimate the behavior of a detached upper block more accurately, it is necessary to appropriately deal with this issue. Although several experimental and theoretical researches have been conducted, such as Javanmardi et al. (2005), few studies have considered penetrating cracks that completely separate a dam body. One such study by Pekau et al. (2008) proposed a method that considers the pressure of infiltrating water into the detached interface by applying the resistance law of flow between parallel plates. This approach seems to be a powerful method for theoretically dealing with the variable uplift pressure occurring from opening/closing of the detached interface.

When considering the resistance law for laminar flow between parallel flat plates (Louis, 1966), the pressure gradient of infiltrated water along the detached interface can be expressed as (Pakau et al., 2008):

$$\frac{dp(x,t)}{dt} = 12\rho\nu\{1+8.8(\kappa/D)^{1.5}\}\frac{q(x,t)}{\delta(x,t)^3} \tag{3}$$

where, $p(x,t)$: pressure of water infiltrated into the detached inter face at position x on the detached interface at time t; v: dynamic viscosity of water; κ: roughness of detached interface; D: hydraulic opening of detached interface; and $q(x,t)$ and $\delta(x,t)$: water flow rate per unit width due to opening/closing of the detached interface and opening of the detached interface at position x at time t, respectively.

If the spatial distribution of p is obtained by integrating Eq. 3, the opening/closing state of the detached interface can be related to the load acting on the detached upper block. When considering the upper block as a rigid body, the rocking behavior of the upper block can be calculated by numerically integrating the following equation, which is a motion equation including the uplift moment (M_U) by the variable uplift pressure ($= p$):

$$J \cdot \ddot{\theta} = M_I + M_S + M_D + M_G + M_U \tag{4}$$

where, J: polar moment of inertia around the pivot point of rocking; and $\ddot{\theta}$: opening angular acceleration of the detached interface.

It should be noted that the movement of the pivot point during rocking motion needs to be considered in the numerical integration of Eq. 4. This problem can be solved by considering Eq. 5; this equation is derived from the principle of conservation of angular momentum of the upper block before and after collision between the lower block and a corner point of the upper block, namely Point A or B shown in Fig. 3, which alternately become a pivot of rocking motion:

$$\frac{\dot{\theta}_{j\ t+}}{\dot{\theta}_{i\ t-}} = -\frac{mL_iL_j\cos\beta + J_G}{mL_j^{\ 2} + J_G} \tag{5}$$

where, left-side term: ratio of the opening angular velocity ($\dot{\theta}$) between just before (t-) and just after (t+) the rocking pivot shifting from point i to j; m: mass of upper block; J_G: polar moment of inertia around the center of gravity of the upper block; L_i, and L_j: length of the line segment connecting the center of gravity of the upper block to the pivot point of rocking motion (i or j) as shown in Fig. 3; and β: angle formed by those line segments.

Furthermore, the sliding displacement of the upper block can be calculated by the following equation, which is a motion equation in the horizontal direction which includes the effect of uplift force (U) obtained by integrating the distribution of uplift pressure (p) along the detached interface:

$$m \cdot \ddot{x} = F_I + F_S + F_D - \mu\ (mg - U) \tag{6}$$

where, $\ddot{x}$: relative horizontal acceleration of sliding upper block, and μ: friction coefficient between upper and lower blocks.

Using these equations, the dynamic behavior of a detached upper block, namely rocking and sliding, can be calculated. Fig. 11 shows an example of the calculation result for the upper block with the same shape as shown in Fig. 5. The input seismic motion was an acceleration waveform with twice the amplitude of the waveform shown in Fig. 6 with a maximum acceleration of 987 gal. In the calculation, water was considered to be incompressible and the opening inside the detached interface was assumed to be filled with water. The occurrence of cavitation due to negative pressure is not considered. The value of friction coefficient (μ) was assumed to be 0.8 during sliding motion, and was set to be 1.0 before sliding.

Fig. 11 also shows the result without considering uplift pressure for comparison. The opening displacement in the case considering uplift pressure was calculated to be smaller than that in the case without considering uplift pressure. This may be related to the negative pressure that might occur when the detached interface begins to open. On the contrary, the sliding displacement of the upper block was calculated to be greater in the case when considering uplift pressure. This result shows the same tendency as that of the shaking table test shown in Fig. 2(b), and suggests that the uplift pressure due to infiltration of stored water into the detached interface affects the behavior of the upper block. Hereafter, the applicability of this method for evaluating the ultimate stability of severely damaged concrete gravity dams should be verified by further studies including a comparison with experimental data and other numerical analyses.

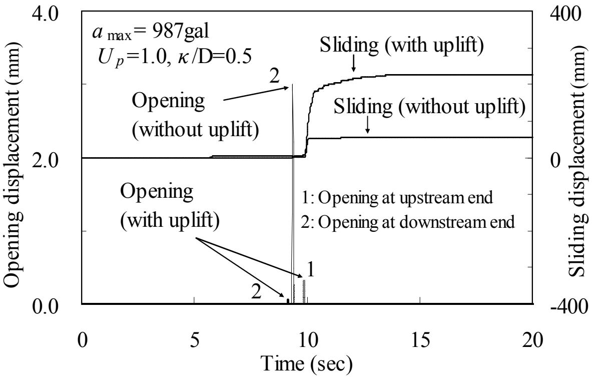


Figure 11. Calculated behavior of detached upper block (with and without considering uplift pressure)

5. CONCLUSIONS

To evaluate the ultimate stability of concrete gravity dams severely damaged by extremely strong earthquake motions, the behavior of a detached upper block and its estimation methods were studied. The following results and issues were identified:

1) To review the results of the shaking table test, the conditions for the occurrence of rocking motion were studied and limit accelerations for the phenomenon were obtained from the balance equations of a rigid body. These critical accelerations were calculated to be close to the acceleration at which rocking and pronounced sliding began to occur in the shaking table test. This fact indicates that the limit accelerations for occurrence of rocking may serve as indices for evaluating the ultimate stability of a severely damaged concrete gravity dam with a detached interface.

2) To estimate the behavior of an actual-scale dam with a detached interface, numerical analyses using DEM were conducted. An analysis of the main body of an actual-scale dam showed such small opening and sliding displacement that the storage function of the dam is unlikely to be lost. However, this analysis did not consider the effect of uplift pressure that might be generated by infiltration of stored water into the detached interface. A practical method for appropriately considering the effect needs to be established. A reproduction analysis for an actually damaged dividing wall, which is free of the effect of uplift force, was also conducted. The analysis resulted in almost no residual displacement along the cracked horizontal construction joint. This result does not contradict the actual situation reported.

3) To estimate the behavior of the detached upper block more accurately by considering the effect of uplift pressure that might be generated due to water infiltration into a detached upper block, a method for combining the resistance law of flow between parallel plates with the motion equations of a rigid body was tried. The results suggested that the uplift pressure generated in the detached interface may affect the stability of the upper block. More detailed studies should be done in the future.

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