Effect of Ground Motion Level and Dam Shape on Cracking Damage in Concrete Gravity Dams

by

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ABSTRACT

It is predicted that several strong earthquakes such as Tokai Earthquake, Miyagi-oki Earthquake will occur in Japan in the near future. So, it is increasingly becoming important to evaluate seismic performance of dams against Level-2 Earthquake motions that is the largest of ground motions estimated to occur in the future at each dam site. The Ministry of Land, Infrastructure and Transport is considering the method of evaluating the seismic performance of dam against Level-2 Earthquake motions in cooperation with PWRI and is now summarizing its findings to propose the guidelines.

The seismic performance that the dam must keep against Level-2 Earthquake motions is to maintain the function that the dam stores water at least. It is necessary to judge whether or not a dam will be able to keep the function of storing water through the numerical analysis considering the damage to the dam. In the case of a concrete dam, it is necessary to consider the damage by the tensile crack generated in the dam body.

Many researches concerning the methods of evaluating the tensile crack generated in a concrete dam body have been carried out. It is difficult to estimate the locations of the crack occurrence in the concrete gravity dam body in advance during large earthquakes. So we have conducted research on the method of evaluating seismic performance of concrete gravity dams using the smeared crack model that does not require the set of the locations of the crack occurrence in advance.

In this report, the crack progress analysis for a concrete gravity dam using the smeared crack model was performed and the effect of the dam shape and the ground motion strength on the degree of crack damage to the concrete gravity dam was studied.

KEYWORDS: Concrete Gravity Dam, Crack Propagation, Smeared Crack Model, Ligament Residual Ratio, Ground Motion Level

1. INTRODUCTION

Japan, that is one of the world's most earthquake-prone countries, has suffered severe damage by many past large earthquakes. With the Kobe Earthquake in 1995 particularly as a turning point, the demand for the preservation of the safety of public structures during large earthquake has increased, and research organizations are now vigorously conducting surveys and researches to develop methods of evaluating the degree of risk of large earthquakes that could occur in the future and methods of evaluating the safety of various structures against extremely strong ground motion.

The present seismic design of dams in Japan is based on the seismic coefficient method with considerably large safety factor. No dam in Japan designed by this method has ever suffered earthquake damage that caused human harm even during previous large earthquakes, including the Kobe Earthquake in 1995. Therefore, it is assumed that existing dams designed based on the seismic coefficient method are adequately safe against large earthquakes such as the Kobe Earthquake in 1995.

But in order to satisfy the public demand mentioned above, it is necessary to concretely estimate "Level-2 Earthquake motions", the maximum ground motion that is estimated to occur in the future at each dam site, and to rationally explain the safety of the dam against such extremely strong ground motion. Therefore,

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it is essential to evaluate the seismic performance of dam by considering the dynamic response characteristics of dam against the ground motion that is actually predicted at the dam location and accurately estimating the behavior of the dam. The Ministry of Land, Infrastructure and Transport is investigating the method of evaluating the seismic performance of dam against Level-2 Earthquake motions in cooperation with PWRI and is now summarizing its findings to propose the guidelines.

2. BASIC CONCEPT OF METHOD OF EVALUATING SEISMIC PERFORMANCE OF DAM AGAINST LEVEL-2 EARTHQUAKE MOTIONS

2.1 Level-2 Earthquake Motions

Because dams are extremely important structures, Level-2 Earthquake motions that are used to evaluate the seismic performance of dam must be considered to be the largest of ground motions that is estimated to occur at each dam location in the future. To estimate Level-2 Earthquake motions, it is necessary to completely survey earthquakes that occurred around the dam location in the past, and the faults and plate boundaries existing in the surrounding region of dam in order to select the scenario earthquake that could have the most severe impact on the dam. And the earthquake motion that will be caused at the dam location by the selected earthquake is estimated by the appropriate method.

2.2 Seismic Performance to Be Secured

As the seismic performance of dam against Level-2 Earthquake motions, even when damage to dam has occurred during earthquakes, the function of storing water must be kept at least. And a dam is a structure that has extremely important functions, such as protecting the drainage basin from floods and providing it with water. It is thought that even if dam has been damaged, the damage must be within the range that permits its restoration.

2.3 Evaluating Method for Concrete Dam Body

The following is the basic method of evaluating the seismic performance of a concrete dam body. Linear analysis is firstly performed using the Level-2 Earthquake motions estimated for each dam site. In the case where damage to the dam body might occur, a nonlinear analysis considering the damages including the occurrence of tensile crack has to be made to evaluate seismic performance.

As the results of the nonlinear analysis considering the occurrence of tensile crack, even if the tensile crack penetrates from the upstream side to downstream side through the dam body, if the overall dam body block above the crack does not become destabilized, an uncontrolled release of reservoir water will not occur and the function of storing water of dam will be kept. But there are specific limits to the precision of analytical estimations of the tensile crack progress. From the view point of the safe and conservative side, it is thought that if the tensile crack does not split the body of concrete gravity dam from the upstream face to the downstream face, the function of storing water of dam can be kept.

3. CRACK PROGRESS ANALYSIS OF CONCRETE GRAVITY DAM USING SMEARED CRACK MODEL

3.1 Introduction

The tensile crack in concrete dam body is considered as one major type of damage modes to concrete gravity dams during large earthquakes. The discrete model and the smeared crack model are major methods in order to reproduce the tensile fracture in concrete by the numerical analysis. The analysis using the discrete model is necessary to beforehand set elements considering cracks at the locations where cracks may occur. On the other hand, the analysis using the smeared crack model does not need to set the locations where the crack may occur in advance. And the behavior of a crack is expressed as the change of the material properties of the elements, therefore, it can pursuit the crack progress without modifying the initially set geometrical conditions. Because it is difficult to estimate in advance the locations of cracks in the body of the concrete gravity dam during large earthquakes, many researches on the crack propagation in concrete gravity dams have been performed using the smeared crack model [1, 2, 3].

The damping property is one of important factors in dynamic analysis using the smeared crack model. In early researches, the damping properties after the occurrence of crack were set without considering the change of stiffness in the elements. But it has been reported that if the damping property after the crack occurrence is set using the initial stiffness, the damping force works as the false force connecting the elements passing a crack surface and the tensile stress is not adequately released and re-distributed. So, the method of varying the damping properties continually based on the change of stiffness as the crack progresses is also adopted recently [4, 5].

We have conducted researches on the method of evaluating the earthquake-resistant of the concrete gravity dam using the smeared crack model during large earthquakes. And we have clarified the locations of cracks generated in the body of concrete gravity dam during earthquakes and the effect of the tension-softening properties of the concrete, such as stress at beginning of tension-softening and fracture energy on the occurrence and progress of cracks in the dam body [6].

In the nonlinear analysis of concrete structure, the curve approximated in two straight lines is often used as the tension-softening curve that shows the relationship between the stress and displacement after the occurrence of tensile crack. But because dams are much larger than common reinforced concrete structures, the scale of elements are also necessarily larger. And after the tensile crack occurs, a phenomenon known as snapback in which the displacement also decreases with the reduction of tensile stress occurs, and the calculation is destabilized. Therefore, the analysis of dams is often carried out using the single straight line shown in Figure 1 as the tension-softening curve.

In this study, the tensile crack was considered using the smeared crack model, and the tension-softening curve was represented by the single straight line as shown in Figure 1. And the analysis was carried out considering the constant damping properties before and after the crack occurrence.

To perform qualitative study on the effects of the dam shape and ground motion level on the safety of dam, the tension-softening curve and damping properties were simply modeled, here. Therefore, we cannot quantitatively evaluate the earthquake-resistant of concrete gravity dams using only analysis results in this paper.

3.2 Analysis Models and Analysis Conditions

The analysis models are concrete gravity dam with nine shapes: combinations of three dam heights (50m, 100m and 150m) for each of three upstream slope configurations shown in Figure 2 (no fillet, small fillet and large fillet). The material properties of concrete used for the analysis are summarized in Table 1. About the tensile fracture properties of the concrete, the single straight line shown in Figure 1 was used as the tension-softening curve.

The bottom of dam body was assumed to contact with a rigid foundation, and the self-weight and hydrostatic pressure were considered as static loads. The effect of the reservoir during an earthquake was considered by a consistent added mass matrix obtained assuming that water was incompressible fluid.

As the input waves, we used the adjusted waves based on the acceleration data (maximum acceleration of 183gal) observed at the lower inspection gallery of Hitokura Dam during the Kobe Earthquake in 1995, so that its acceleration response spectrum shape conforms to the shape shown in Figure 4 in which the response acceleration is 300gal at the period of 0.02 sec. The time history wave created by such method is shown in Figure 3. The input waves were set up by changing only the amplitude of the time history wave shown in Figure 3. They were inputted in the horizontal direction from the bottom of the dam body with the downstream side as positive.

The general-purpose finite element method analysis code [7] that can perform structural analysis using the smeared crack model was used for the analysis in this study.

3.3 Locations of Crack Occurrence

Table 2 shows the locations of the crack occurrence as the results of the crack progress analysis in the case of the maximum acceleration of 500gal for each of the nine models. This shows the locations of all cracks that occurred throughout the analysis, and cracks occurred on the black colored elements.

Cracks occur from the bottom of dam body and the upstream-slope changing point for low accelerations. When the acceleration rises, cracks also occur from the upstream and downstream side above the upstream-slope changing point. Cracks that occur from the upstream side and the downstream side each progress as the acceleration rises.

Here, the ligament residual ratio in the crack occurrence part [=1.0 - (the crack length / the thickness of dam body measured along the direction of the crack progress)] is considered as one index that shows the safety degree of the dam, and calculated. For the calculation of the ligament residual ratio, the crack length is calculated by dropping a perpendicular line from the tip of the crack from the upstream side and the downstream side to the ligament part as shown in Figure 5 and considering both cracks.

After this, we examine the tendency of the crack progress focusing on three locations: the bottom of dam body, the upstream-slope changing point and the upper part of dam body.

And because the foundation was not included in this analysis model, the stress concentration occurred at the bottom of the body and the progress of the crack in such part is more conspicuous than that in the case that the foundation was included.

3.4 Relationship between Earthquake Motion Strength and Crack Progress

The degree of damage that occurs in the concrete gravity dam by the parametric analysis is considered focusing on the locations of crack occurrence and the dam height.

3.4.1 Relationship between Location of Crack Occurrence and Crack Progress

The relationship between an increase of the earthquake motion strength and the crack progress in each location of crack occurrence is considered using the ligament residual ratio.

Table 3 shows the ligament residual ratio for each location of crack occurrence in each model. First, the results of models with dam height of 150m are focused on.

From Table 3 (7), (8) and (9), the strength of acceleration when the crack start to occur in the upstream-slope changing point and the upper part of dam body tends to be higher than that in the bottom of dam body. And the crack in the upstream-slope changing point and the upper part of dam body tends to progress more rapidly as the acceleration strength rises than the crack in the bottom of dam body. From this, it is found that the crack in the upstream-slope changing point and the upper part of dam body is sensitive to the effect of the maximum acceleration.

Similar tendencies are found in the results for models with dam heights of 50m and 100m, although those are not as conspicuous as the tendency in model with dam height of 150m.

Based on this fact, it is seemed that the penetration through the dam body would be caused by the crack progress generated from the upstream-slope changing point or the upper part of dam body if the crack passes through the dam body when the earthquake motion is very strong.

Next, tendencies in the crack progress according to differences of the location of the upstream-slope changing point are considered. Table 4 shows the ligament residual ratio of the crack at the upstream-slope changing point for each dam height.

From this table, it is found that the ligament residual ratio in Model-3 with dam height of 100m and 150m with a high location of upstream-slope changing point tends to be lower than that in Model-2 with a low location of upstream-slope changing point. It is considered that this is affected by that the ligament in Model-3 with a high location of upstream-slope changing point is shorter than that in Model-2 with a low location of upstream-slope changing point. Consequently, it is assumed that among dams with fillets, the safety degree of dam with a low location of upstream-slope changing point is higher than that of dam with a high location of upstream-slope changing point.

3.4.2 Relationship between Dam Height and Crack Progress

Next, the relationship between the dam height and the crack progress is considered using the ligament residual ratio.

From Table-5 (1), (2) and (3), up to 500gal, the ligament residual ratio in the bottom of dam body in low dam is larger than that in high dam. But at the strength of higher acceleration, the ligament residual ratio in the bottom of dam body in low dam is smaller than that in high dam. It is considered that this is affected by that the stress concentration occurred at the bottom of the body and that when the dam height is low, the ligament is small as an absolute value.
From Table-5 (4) and (5), it is found that the crack in the upstream-slope changing point do not occur easily in the model with dam height of 50m, and that the higher the dam is, the larger the rate of the crack progress as an increase of the maximum acceleration becomes.
From Table-5 (6), (7) and (8), the crack in the upper part of dam body does not occur in the model with dam height of 50m. The greater the dam height is, the greater the rate of crack progress as an increase of the maximum acceleration becomes.
Table 6 shows the values of the smallest ligament residual ratio for the cracks generated in the dam body in nine models, regardless of the three locations of crack occurrence, such as the bottom of dam body, the upstream-slope changing point and the upper part of dam body. It can be considered that this minimum ligament residual ratio indicates the safety degree of the whole of dam against crack penetrations through the dam body.
As mentioned above, looking at the results separately for each location of crack occurrence, there are parts where the ligament residual ratio in low dam may be is smaller than that in high dam. But the higher the dam is, the lower the minimum value of the ligament residual ratio becomes. This means that at the same acceleration strength, the higher the dam is, the safety degree of dam would become smaller.
Consequently, it is considered that regardless of shape of dam, the safety degree in low dam is relatively higher than that in high dam.

4. CONCLUSIONS

The followings are summaries of the results of the qualitative study on the earthquake-resistant of concrete gravity dam by numerical analysis using the smeared crack model.

1) Crack in the concrete gravity dam tends to occur in the bottom of dam body and the upstream-slope changing point.
2) At the low acceleration, crack tends to occur in the bottom of dam body.
3) The acceleration strength that cracks in the upstream-slope changing point and the upper part of dam body start to occur is higher than that in the bottom of dam body, but it is sensitive to the maximum acceleration.
4) Among dams with fillets, the safety degree of dam with low location of upstream-slope changing point is higher than that of dam with high location of upstream-slope changing point.
5) The safety degree of a low dam is relatively higher than that of a high dam.

The method of non-linear dynamic analysis of the concrete gravity dam considering the damage to concrete is still at the researching and developing stage, and it is necessary to study material properties about failure and the damping properties and to increase the precision of the analysis in the future.

5. REFERENCES

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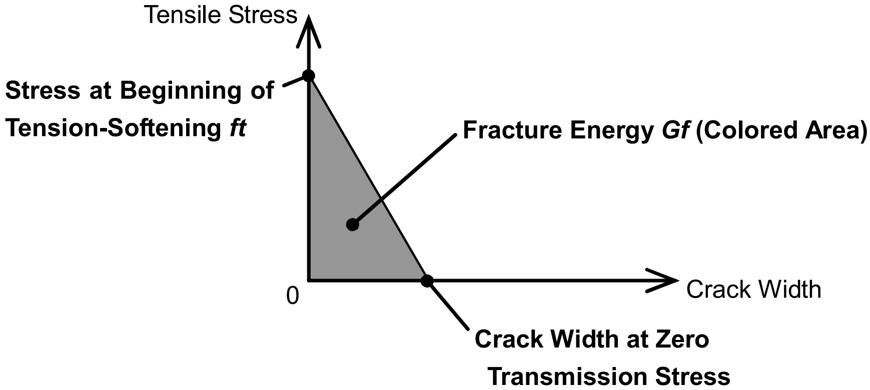


Figure 1. Tension-Softening Curve (Single Straight Line Approximation Model)

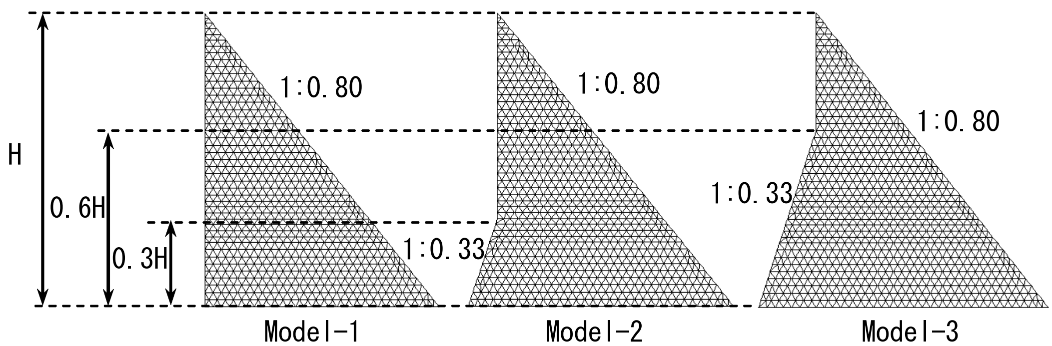


Figure 2. Analysis Models

Table 1. Material Properties of Concrete

Young's Modulus of Elasticity E (MPa)	2.70E+04
Poisson's Ratio v	0.2
Stress at Beginning of Tension-Softening ft (MPa)	2.5
Fracture Energy Gf (N/m)	300
Unit Mass ρ (kg/m3)	2,300
Damping Ratio h (%)	15 (Rayleigh damping, the first and third frequency)

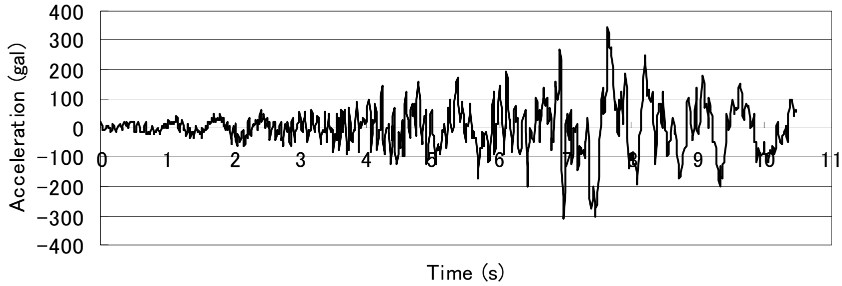


Figure 3. Input Wave

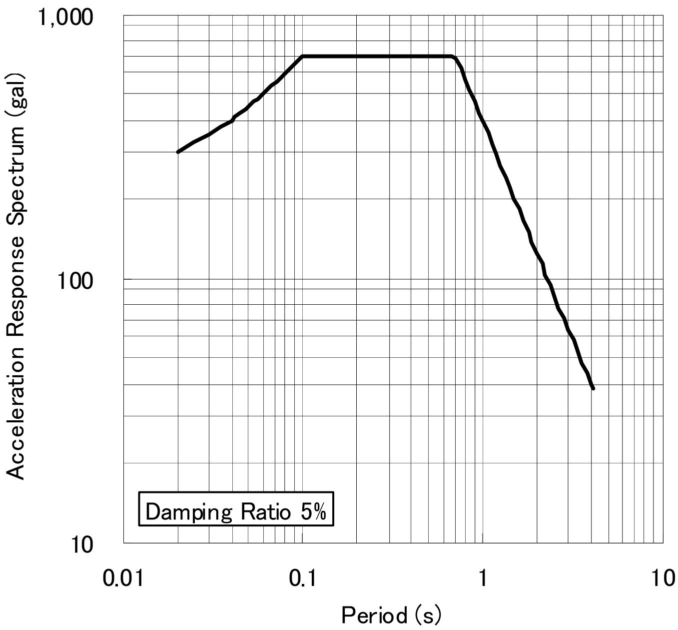
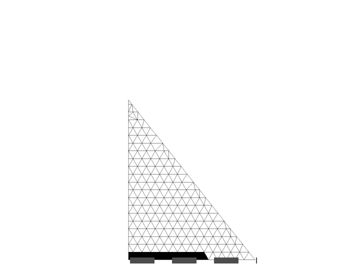
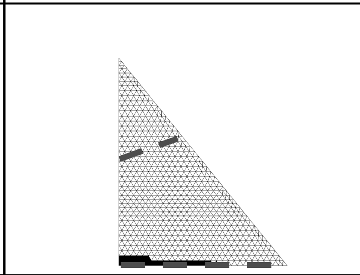
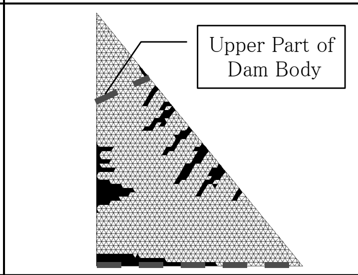
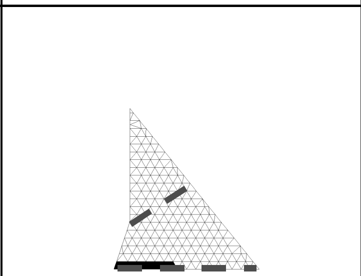
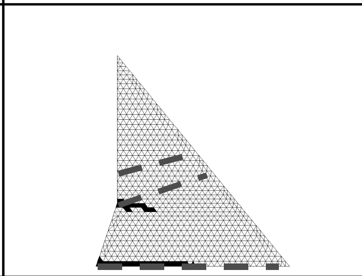
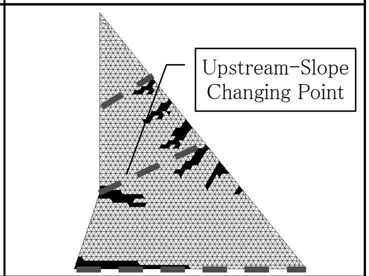
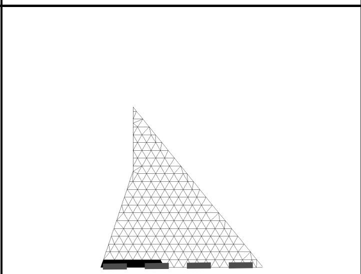
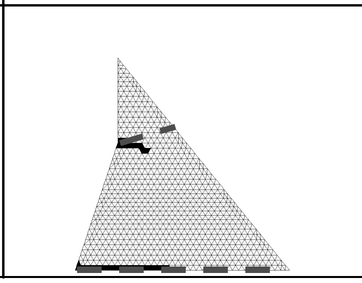
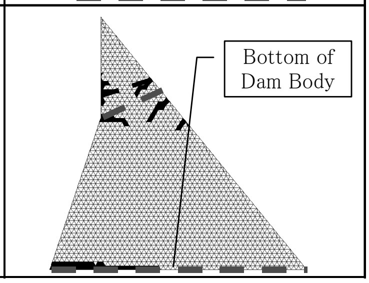


Figure 4. Acceleration Response Spectrum

Table 2. Location of Crack Occurrence

Maximum Acceleration of 500gal			
	H=50m	H=100m	H=150m
Model-1			
Model-2			
Model-3			

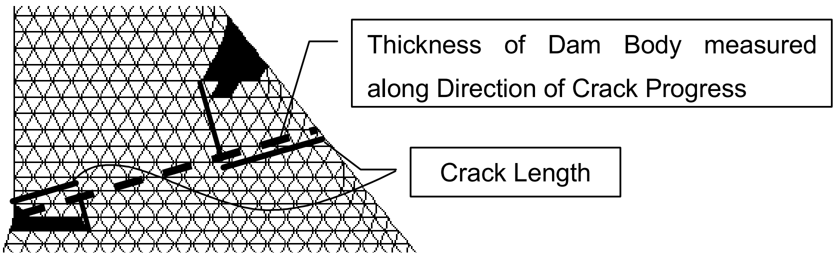


Figure 5. Definition of Ligament Residual Ratio

Table 3. Relationship between Crack Occurrence Location and Ligament Residual Ratio

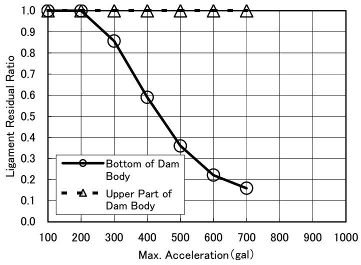
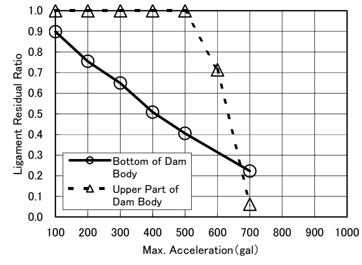
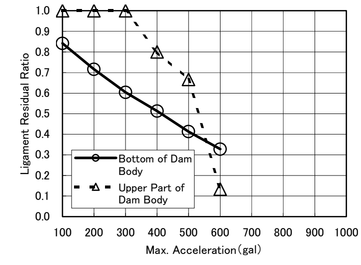
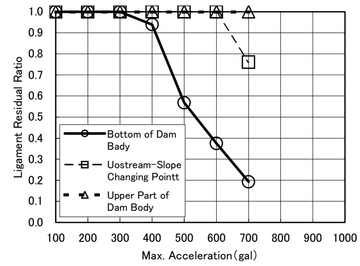
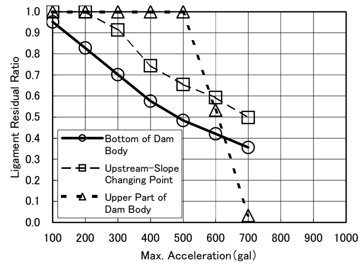
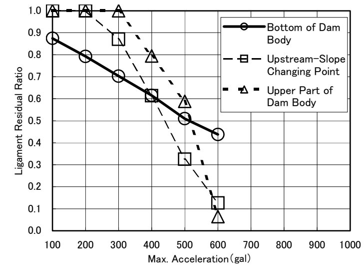
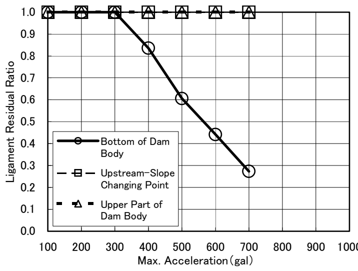
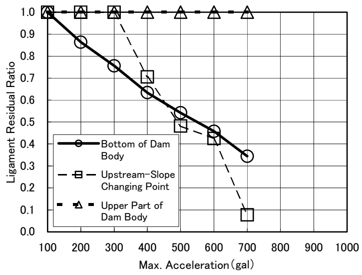
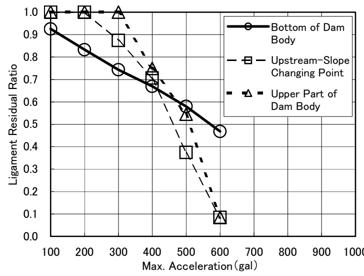
	H=50m	H=100m	H=150m
Model-1	 (1) H=50m Model-1	 (4) H=100m Model-1	 (7) H=150m Model-1
Model-2	 (2) H=50m Model-2	 (5) H=100m Model-2	 (8) H=150m Model-2
Model-3	 (3) H=50m Model-3	 (6) H=100m Model-3	 (9) H=150m Model-3

Table 4. Relationship between Crack at Upstream-Slope Changing Point and Ligament Residual Ratio

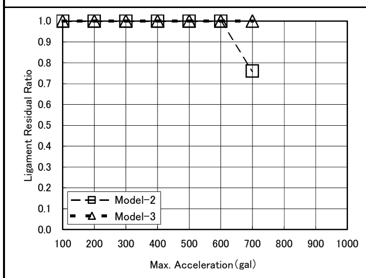
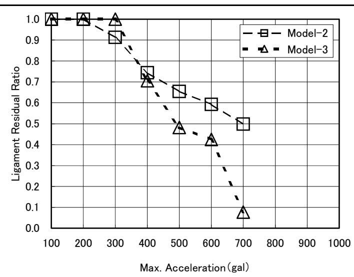
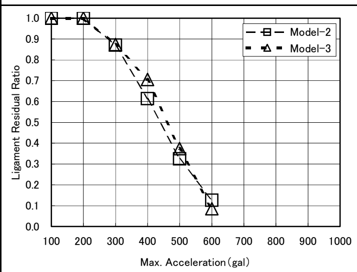
H=50m	H=100m	H=150m
		

Table 5. Relationship between Dam Height and Ligament Residual Ratio

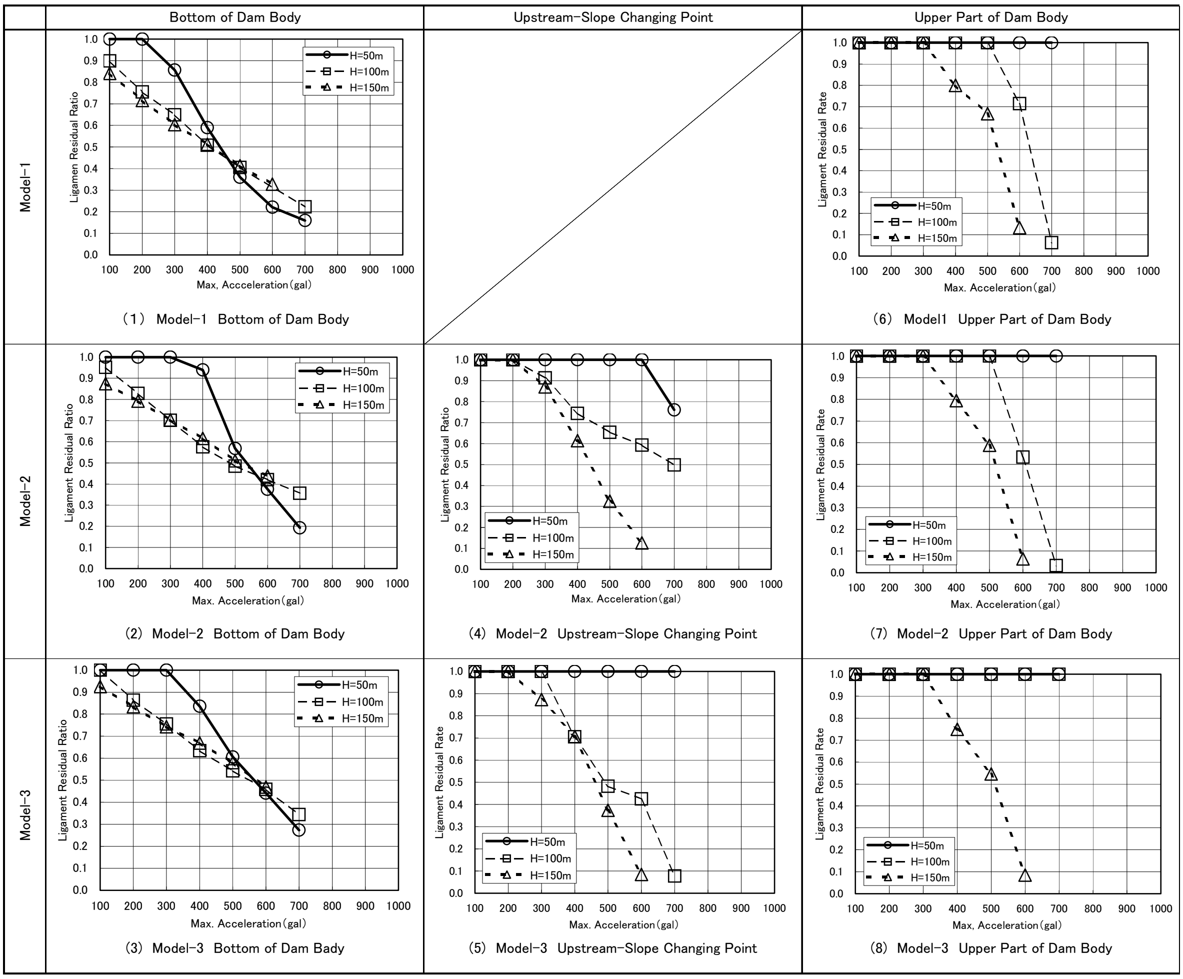


Table 6. Relationship between Maximum Acceleration and Ligament Residual Ratio (Minimum Values)