Advanced Research Activities on Dynamic Analysis for Concrete Dams in Japan and an Study on Seismic Performance of Concrete Gravity Dams by Smeared Crack Model

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ABSTRACT

Several research activities about dynamic analysis to evaluate the seismic performances of dams have been conducted by the research institutes and agencies in Japan, and the effects of analytical conditions on the results by numerical analyses have been studied. The activities have speeded up since Hyogo-ken Nanbu Earthquake (the Kobe Earthquake). On the other hand, recent large earthquakes gave us the important acceleration data. Using these data, the efficiencies of developed numerical analysis methods have been verified.
In this report, we summary the recent research activities about dynamic analyses of concrete gravity dams in Japan, and introduce the examples of non-linear analysis results using the smeared crack model, one of advanced methods, by the PWRI.

KEYWORDS: Concrete Gravity Dam, Crack Development Analysis, Large Earthquake, Smeared Crack Model

1. INTRODUCTION

More than 2,600 dams with the height of 15m or higher have been constructed in Japan [1]. In Japan the earthquake-resistant design of dams is basically made by the seismic coefficient method [2] according to the Cabinet Order [3, 4], even though the more sophisticated methods can also be used. A lot of existing dams in Japan have experienced strong earthquake ground motions. However, no serious damage on these dams has been observed at large earthquake including the Kobe Earthquake [5]. The review of the earthquake-resistant design method, therefore, has not become an urgent issue. This situation is not similar to that for other public structures, e.g. bridges, levees. However, due to the recent rapid progress of computer's capabilities and numerical analysis techniques, it is possible to evaluate the dynamic performances of dams during an earthquake using the dynamic analysis method. Further, from a social viewpoint, accountability to general public about the safety of dams is quite important and necessary. Thus, to rationally evaluate the safety of dams during earthquakes is required by simulating dynamic behaviors of dams more realistically.
In this report, we introduce the recent research activities in Japan about the evaluation of dams with referring the report [6] prepared by the Subcommittee on Seismic Safety of Dams of the Technical Committee, Japan Commission on Large Dams, and present the results of non-linear dynamic analysis for concrete gravity dams using the smeared crack model by the PWRI.

2. ORIENTATION OF EVALUATION METHOD AND RESEACH ACTIVITIES ON DYNAMIC ANALYSIS

2.1 Proposal and Guideline for Seismic Design by the Japan Society of Civil Engineers

In view of the tremendous damage of public and private structures by the Kobe Earthquake, the Japan Society of Civil Engineer (JSCE) issued the Proposal on the earthquake-resistance design and criteria for civil engineering structures (the First Proposal) [7] in May 1995, the Second Proposal in January 1996 [8], and the Third Proposal in June 2000 [9]. The Subcommittee on Earthquake Resistant Design Standard of the

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Earthquake Engineering Committee, the JSCE submitted a draft of Guideline for Earthquake-Resistant Design of Civil Engineering Structures [10] in 2001, based on these proposals.

The Guideline classified the strong ground motions to be used for structural design into the Level 1 earthquake motion and Level 2 earthquake motion as shown in Table 1. In addition, the lowest limit of the level 2 earthquake motions should be set as the earthquake ground motions caused by a magnitude 6.5 earthquake because of possibility of earthquakes by lurking faults.

The Guideline proposes the following 2 types of earthquake resistance performances from the viewpoint of the dam's basic function, that is, the water storage function.

Earthquake Resistance Performance I:
A concerned structure must not receive any structural damage.

Earthquake Resistance Performance II:
Even if a concerned structure is damaged structurally, the damage should be a repairable degree. A dam's water storage function must be maintained all the time.

The Guideline says that dams must have the Earthquake Resistance Performance I against Level 1 earthquake motions and the Earthquake Resistance Performance II against Level 2 earthquake motions. The evaluation of the Earthquake Resistance Performance II needs the consideration of the progress of structural damage to dam bodies and foundation rock during earthquakes. The practical Earthquake Resistance Performance II in the Guideline is shown in Table 2. That permits cracks in bodies of concrete dams and deformation of embankment dams that may be caused by Level 2 earthquake motions as long as the water storage function of dams is not affected. To confirm the Earthquake Resistant Performance II, the dynamic analysis method that can accurately evaluate the occurrence and progress of cracks in concrete dams is absolutely required. As for embankment dams, the dynamic analysis method that can accurately evaluate the plastic deformation and residual deformation is necessary.

2.2 Research Activities on Numerical Analysis for Evaluation of Earthquake Resistance of Concrete Gravity Dams

Because any existing concrete dams in Japan have never been damaged severely during large earthquakes, it can be said that concrete dams have strong earthquake resistance performance. Generally speaking, the behavior of a concrete gravity dam body can be sufficiently simulated by the linear elastic analysis as long as the earthquake motion is relatively small and the may not cause cracks in the body.

There are several elastic analysis methods. The analysis using two-dimensional model of the dam body can sufficiently simulate the overall behavior of a dam during an earthquake. In addition, it may be possible to more accurately simulate the behavior of a dam during an earthquake by conducting an analysis combined with comprehensive foundation and reservoir model or by using the three-dimensional analysis method.

Besides, there are a few actual examples of crack occurrence into concrete dam body when the dam suffers strong earthquake motions [11].

In order to examine the earthquake resistance of a concrete dam against severe earthquake motions, it is necessary to conduct the non-linear analysis that takes into account its fracture mechanism. To conduct the non-linear analysis, it is necessary to determine whether or not the cracking of the dam body may occur, that is, to set up the dynamic physical characteristics of dam concrete. This is also important for the evaluation of linear analysis result. Studies on this aspect are being conducted mainly by experiments. As for the numerical analysis of a dam body, researchers have developed various numerical analysis codes to express its damage. They are gradually put in use.

The researches on linear analyses of concrete gravity dams, needless to say, have been conducted by many researchers. Recently, the accuracy evaluation of the results of numerical analysis has actively been conducted because the large acceleration records obtained at big earthquakes in Japan. Earthquake motions due to the Kobe Earthquake were observed at Hitokura Dam site, and its maximum acceleration value is the largest one among the acceleration records obtained at dam sites during the earthquake. Taguchi et al. [12] conducted the two-dimensional analysis of Hitokura Dam model using a dam model without the foundation and the reservoir, simulated its behavior and, as a result, confirmed the earthquake resistance of the dam. Shiojiri et al. [13] conducted the two-dimensional response analysis of the model of Hitokura Dam with the foundation and reservoir. By this analysis, the effects of the damping ratios of the dam body and foundation rock and the modulus of elasticity of the rock were examined. In addition to the above-mentioned two-dimensional analysis, Shiojiri et al. [14] conducted the three-dimensional model analysis of the dam body, foundation rock and reservoir water of the dam. A good result was obtained as compared with the actual dam's behavior by the three-dimensional analysis, and they concluded that the dam can be assumed to be behaved as a linear elastic body to simulate the dam behavior against the Kobe Earthquake. Ariga et al [15] conducted the two- and three-dimensional analyses of Tohira Dam model using the record of the 1993 Kushiro-oki Earthquake observed at the dam site. From these analyses, they estimated the damping ratios by separating material damping and added damping. As a result, it was concluded that larger damping ratios is needed for two-dimensional analysis in order to simulate the three-dimensional phenomena of a dam. At present, the three-dimensional analyses and the analysis with interaction model of a dam, a foundation and a reservoir are still in the process of development and there are various issues. It is considered that advanced skills of users are needed for these analysis methods.

When the vibration of a dam becomes large and the strain and the stress is beyond the range of linear elastic range, the non-linearity of dynamic characteristics of concrete, the effects of the occurrence and progress of cracks should be considered in the numerical analyses. Nagayama et al. [16] conducted studies on the dynamic tensile strength of concrete by conducting tensile tests under high speed loading. As a result, the relationships between the tensile strength and loading speed and that between the static tensile strength and the compression strength were found. To estimate not only the occurrence of cracks but also their progress, it is necessary to establish the stress-strain softening constitutive relation of concrete for dams. The Agency for Natural Resources and Energy and the Japan Electric Power Civil Engineering Association [17] conducted wedge inserting-type splitting tests of large specimens by setting the crack-opening speed and the maximum size of coarse aggregate as parameters. As a result, it was confirmed that the crack progress speed related to the amount of fracture energy and the bilinear strain-softening relations of concrete for dams were proposed. Ariga et al. [15] conducted the non-linear analyses of dam body and foundation by using the three-dimensional analysis. These analyses were made by the equivalent linearity method. The maximum tensile stress in dam body was $2.06 N/mm^2$ for the PGA (Peak Ground Acceleration) 500gal earthquake and the dam's earthquake resistance was judged to be sufficient. The Agency for Natural Resources and Energy and the Japan Electric Power Civil Engineering Association [16, 18] analyzed the seismic cracking process of a 150m height model dam during a large earthquake. The seismic cracking process was analyzed based on the concept of the smeared crack model (crack-band model) using the above-mentioned strain-softening relation. As a result, they proposed the index to evaluate the stability of the earthquake resistance of a dam based on crack length ratio to the width of dam along the crack propagating plane. Ohmachi et al. [19] conducted the analysis of the seismic cracking of a dam body under intensive shaking by using a smeared crack model. This analysis was conducted by using a 100m height model dam by taking into account the interaction of the dam body, foundation and reservoir. In this analysis a bilinear failure criterion based on the combination of the 1st principal stress and 3rd principal stress and the linear type of strain-softening relation was used. In the analysis, cracks were generated along the dam base and from the point where the upstream slope changes. From the results, the installation of local reinforcement with steel bars and the selection of dam body's cross sectional shape was considered to be one of effective possible measures to increase the earthquake resistance of dams.

In accordance with the development of comprehensive and complicated numerical analysis methods, many factors, such as the selection of physical characteristics of construction materials and foundation rock and the selection of boundary conditions will be involved in these analyses, and these factors often are unknown and to set proper values is difficult. It is, therefore, necessary to carefully recognize the purpose of an analysis to be conducted when selecting an appropriate analysis method for a concerned dam whether it should be simplified or complicated method. In the case of a non-linear analysis and seismic cracking analysis, more unknown factors will be involved than the case of a linear analysis. For these reasons, the effect of analytical conditions including concrete material properties and the modeling method of a reservoir and foundation should be carefully examined by the sensitivity analysis, and further studies on improvement of analysis techniques are necessary.

3. A STUDY ON DYNAMIC ANALYSIS CONSIDERING CRACK DEVELOPMENT IN CONCRETE GRAVITY DAM

3.1 Outline

The discrete model and the smeared crack model are major methods to consider the tensile fracture of concrete in the numerical analysis. The discrete model is necessary to beforehand set the elements that can describe cracks in proper locations where cracks may occur. But the smeared crack model doesn't need to determine the locations where the crack may occur in advance. Because it is difficult to estimate such locations in the dam body, we, the PWRI, have conducted researches on the crack development analysis of the concrete gravity dam using the smeared crack model and the safety evaluation method during the earthquake. The fracture progress of concrete material is decided by the characteristics of the fracture material characteristics of concrete material such as tensile strength, fracture energy and the tension-softening curve. Here, we report results of study on effects of the fracture material characteristics of concrete on the occurrence and the development of cracks in concrete gravity dam.

3.2 Analytical Condition

Figure 1 shows the FEM model of a concrete gravity dam with a height of 100m. Dead weight and hydrostatic pressure were considered as static loads. As physical properties of material are shown in Table 3, the tensile strength was set a value between 2.0 and 4.0MPa and the fracture energy was set a value between 100 and 500N/m in an analysis case. The damping coefficient was set as the Rayleigh type damping using the first and third natural frequency for the linear model without considering crack occurrence. The analyses were carried out using a tension-softening curve expressed by a simple straight line shown in Figure 2. The boundary condition of a bottom of a dam body was set as rigid and an effect of a reservoir was considered by added mass matrix obtained assuming water is incompressible fluid. The uplift pressure was not considered. As an input wave, we used the acceleration data observed at the lower inspection gallery of Hitokura Dam during the Kobe Earthquake. Only the amplitude of the acceleration data was enlarged, and it was inputted in the horizontal direction from the bottom of the dam body. Figure 3 shows the original time history data whose PGA is 183gal.

3.3 Result of Analysis

3.3.1 Location of Crack Occurrence

Figure 4 shows the location where cracks finally occurred as the analytical result on condition that the PGA of the input wave was 300gal, the tensile strength was 2.5MPa, and the fracture energy was 300N/m. This shows all locations where the cracks were generated throughout analysis. Because the foundation was not modeled in this analysis and the stress concentration occurred at the bottom of the body, the development of the crack in such part stood out. The cracks are apt to occur in the bottom and near the slope changing point during the earthquake. According to the earthquake acceleration, the type of the seismic wave or the tensile strength of the concrete, the cracks may also occur on the downstream of the dam body like Figure 5.

3.3.2 Effect of PGA

Figure 6 shows the relationship between the PGA and the crack length (the distance from the dam surface to the crack's tip) for cracks at the slope changing point and the bottom of the dam body. The tensile strength is 2.5MPa, and the fracture energy is 300N/m. as seen in the figure, the larger the PGA is, the longer the crack length is, and the relationship between the crack length and the PGA is almost linear.

3.3.3 Effect of Tensile Strength

Figure 7 shows the relationship between the tensile strength and the crack length for the crack at the slope changing point and the bottom of the dam body. The PGA of the input wave is 300gal, and the fracture energy is 300N/m. From this figure, it is found that with the increase of the tensile strength, the crack length is shorter, and the relationship between the crack length and the tensile strength is almost linear.

3.3.4 Effect of Fracture Energy

Figure 8 shows the relationship between the fracture energy and the crack length about the slope changing point and the bottom of the dam body. The PGA of the input wave is 300gal, and the tensile strength is 2.5MPa. From the figure, it is found that with the increase of the fracture energy, the crack length decreases a little, but there is hardly any change for the crack at the bottom of the dam body.

3.3.5 Comparison of Effects of Tensile Strength and Fracture Energy

Figure 9 shows the relationship between ratio of crack and ratio of the tensile strength or the fracture energy. The ratio of crack was obtained from a crack length divided by the crack length on condition of the tensile strength 2.5MPa and the fracture energy 300N/m, and standards of the tensile strength and the fracture energy are, respectively, 2.5MPa and 300N/m. The PGA of the input wave is 300gal. As seen in this figure, it is found that the slope of the curve for the tensile strength is sharper than the fracture energy. From this result, the tensile strength must be set more appropriately set than the fracture energy when the material property is set.

3.4 Conclusions

The followings were found by this examination.

- The cracks tend to occur in the bottom of the dam body and near the slope changing point of the upstream face of the concrete gravity dam during the earthquake.
- The relationship between the crack length and the PGA of the input wave is almost linear.
- Because the tensile strength has larger effect on the crack development than the fracture energy, the definition of tensile strength is important for the crack propagation analysis of concrete gravity dam.

4. CONCLUSIONS

As mentioned at the beginning of this paper, the safety criteria for designing of dams in Japan are legislated, and the earthquake-resistant design using the seismic coefficient method is used in Japan. However, it is consider that not only the evaluation method of the earthquake resistance performances of existing dams but also the earthquake-resistant design method of the new dams should be improved to a more rational and accountable one from the engineering view point in the future. It is, therefore, necessary to continue the researches on the dynamic analysis method and evaluation ways of dam safety. On the other hand, advancing of further studies on the expectation method of large earthquake motion for dynamic analysis is indispensable.

5. REFERENCES

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Table 1 Definition of Level 1 and Level 2 Earthquake Motions [10]

Classification	Definition
Level 1 Earthquake Motions	Level 1 earthquake motions are those that are to be used for conventional design method, such as the allowable stress design method and so on.
Level 2 Earthquake Motions	Level 2 earthquake motions are those that are to be used for examining the safety of structures with taking account of damaging process if necessary. That motion should be the motion of the largest possible grade which may occur at a concerned site from the present to the future.

Table 2 Earthquake Resistance Performance II of Dams
in order to secure Water Storage Functions [10]

Type of Dam	Requirement
Concrete Dam	・ No falling down nor sliding ・ No through cracks in dam body nor foundation ・ No dam-body collapse
Embankment Dam	・ No through cracks in impervious core zone ・ No overflowing of reservoir water ・ No dam-body collapse

Table 3 Physical Properties of Material

Elastic Modulus (MPa)	3.00E+04
Poisson Ratio	0.2
Tensile Strength (MPa)	2.0, 2.5, 3.0, 4.0
Fracture Energy (N/m)	100, 200, 300, 400, 500
Compressive Strength (MPa)	25
Unit Weight (kg/m^3)	2,300
Damping Coefficient (%)	10（Rayleigh）

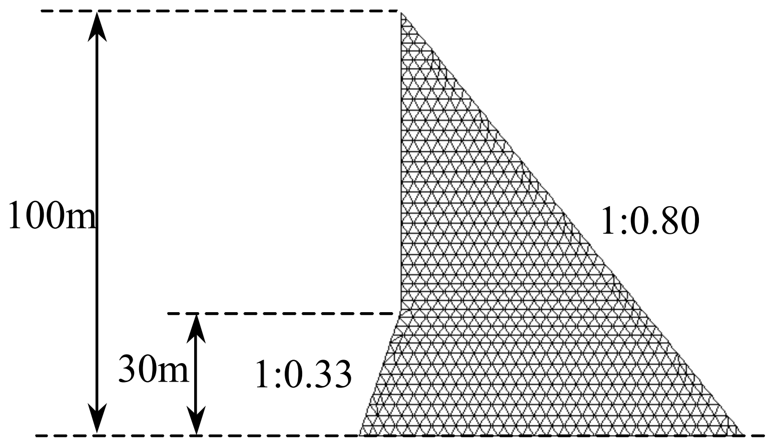


Figure 1 FEM Model

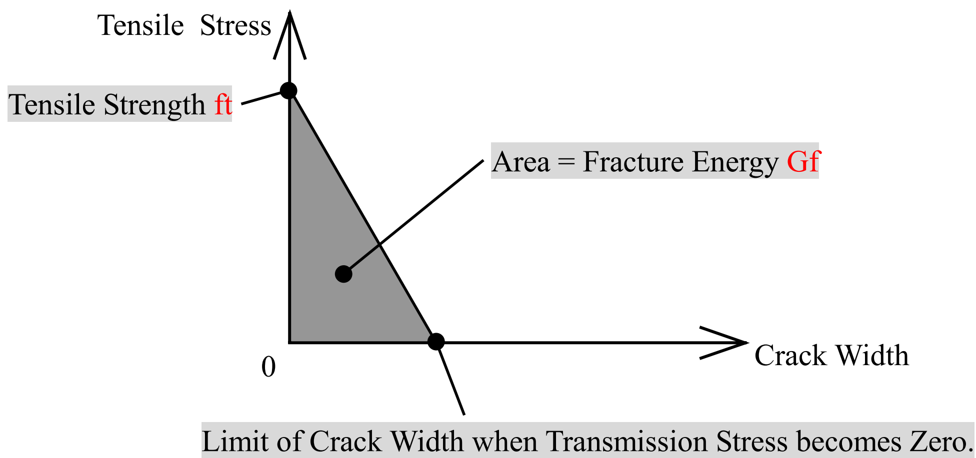


Figure 2 Tension-Softening Curve（Simple Straight Line Model）

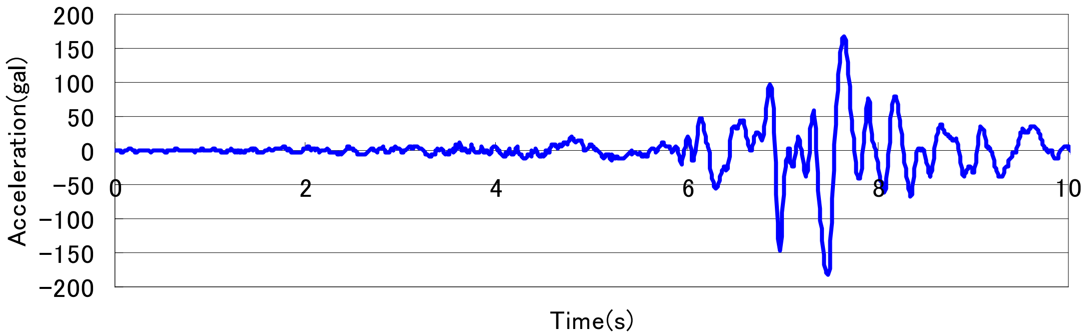


Figure 3 Input Wave (Original Wave was observed at Hitokura Dam.)

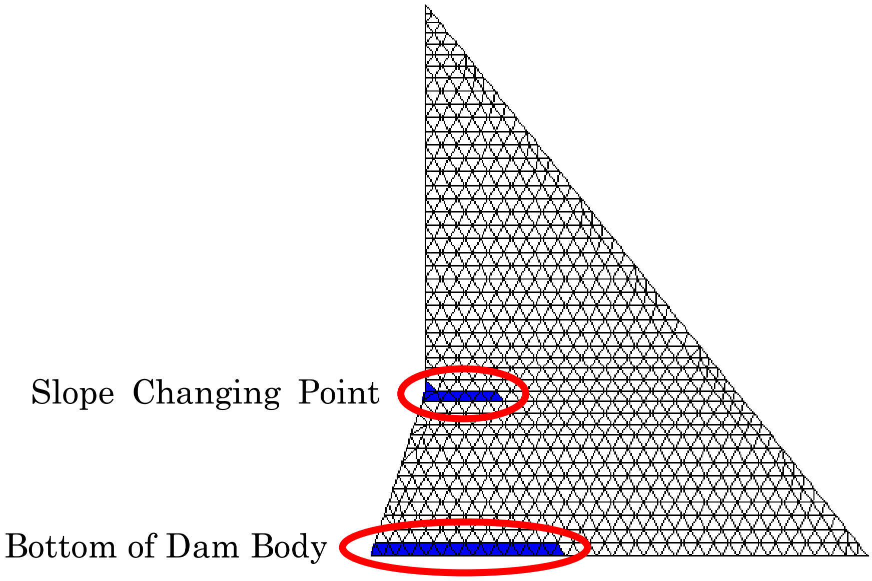


Figure 4 Position of Crack Generation （ft=2.5MPa, Gf=300N/m, PGA=300gal）

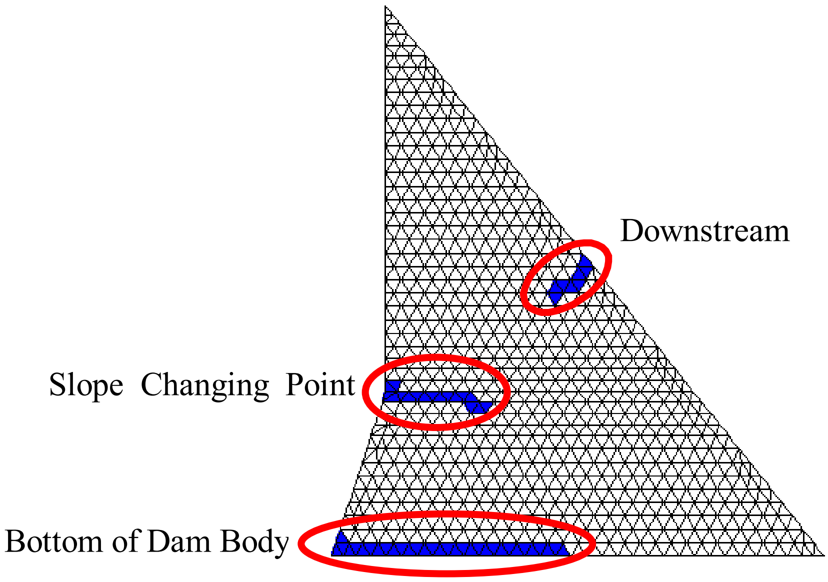


Figure 5 Position of Crack Generation（ft=2.5MPa, Gf=300N/m, PGA=400gal）

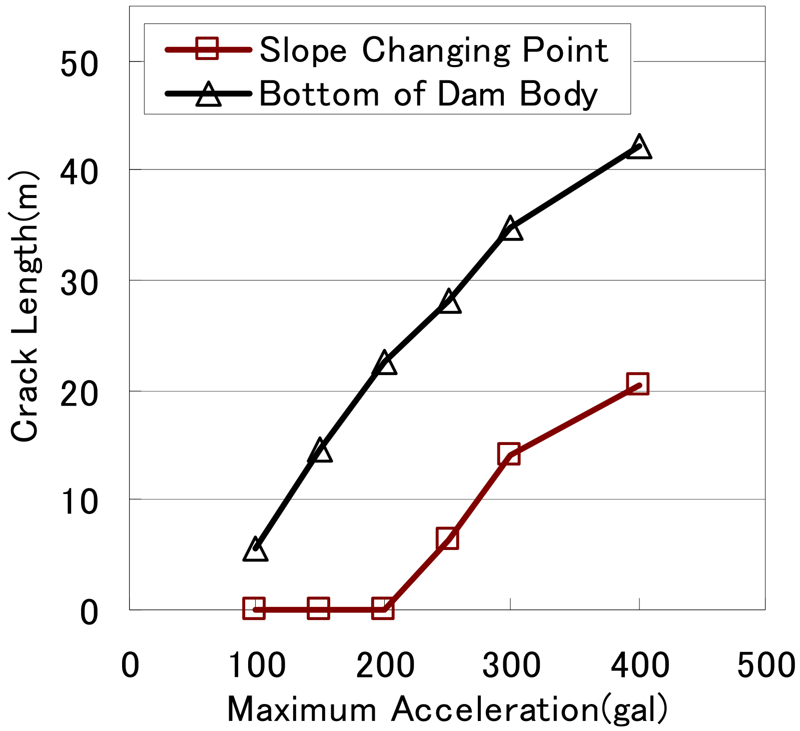


Figure 6 Relationship between Crack Length and PGA（ft=2.5MPa、Gf=300N/m）

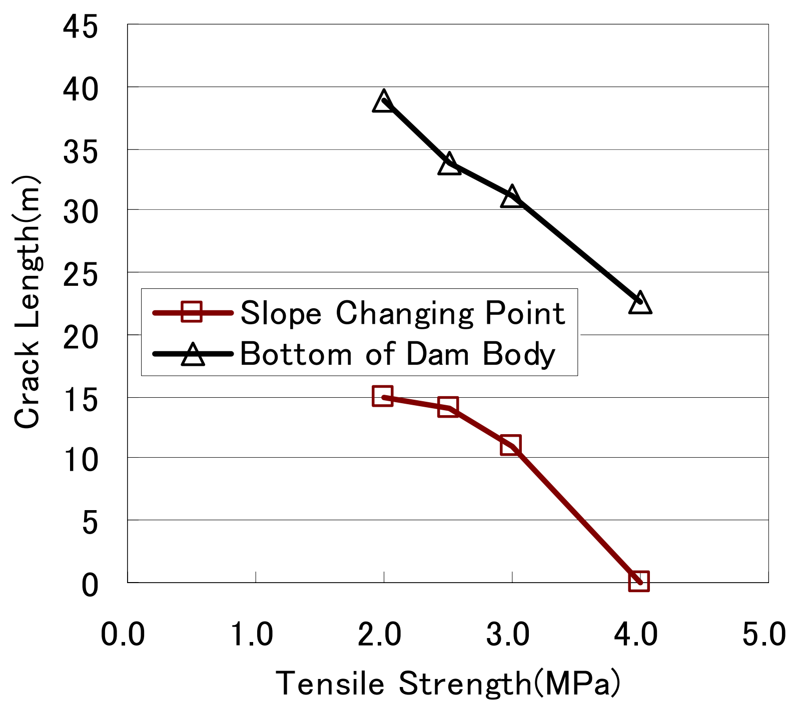


Figure 7 Relationship between Crack Length and Tensile Strength（Gf=300N/m, PGA=300gal）

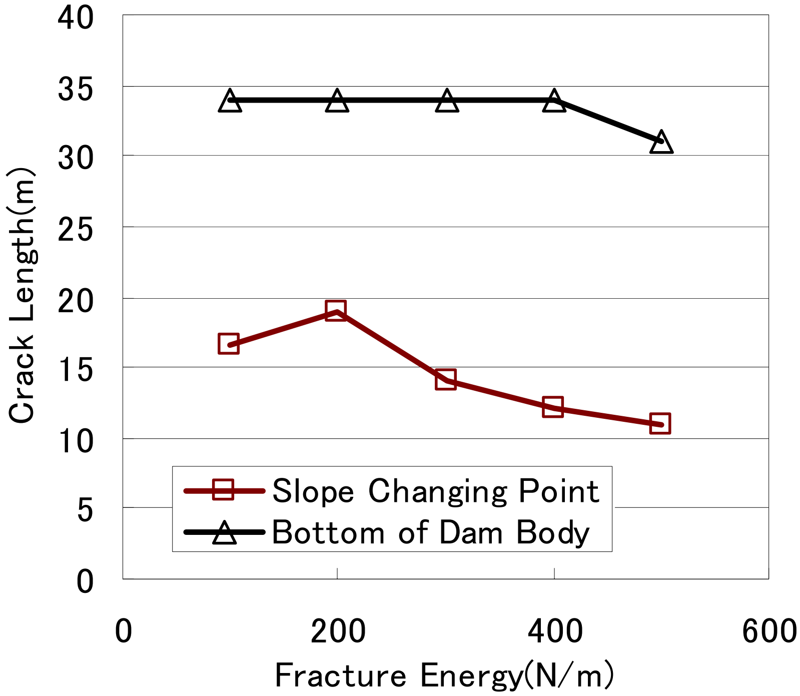
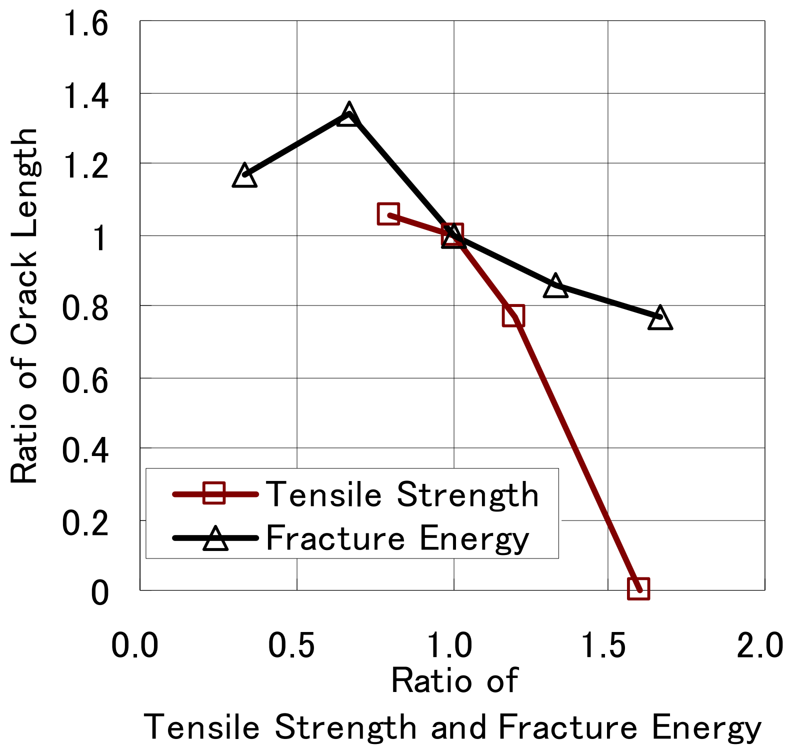
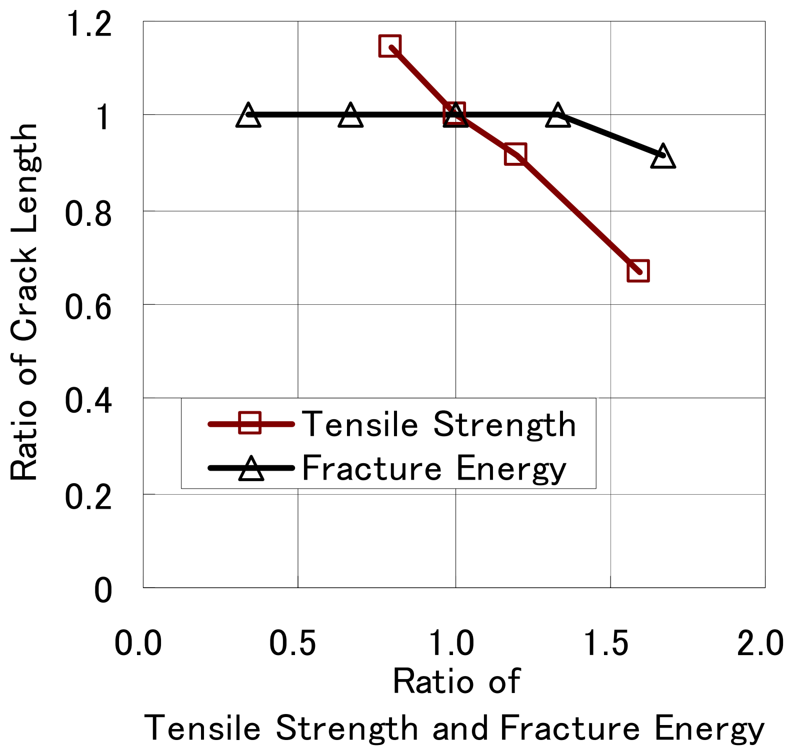


Figure 8 Relationship between Crack Length and Fracture Energy（ft=2.5MPa, PGA=300gal）



(a) Slope Changing Point



(b) Bottom of Dam Body

Figure 9 Relationship between Ratio of Crack and Ratio of Tensile Strength or Fracture Energy