13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 128

SIMPLE ESTIMATING METHOD OF DAMAGES OF CONCRETE GRAVITY DAM BASED ON LINEAR DYNAMIC ANALYSIS

Takashi SASAKI[1], Kenichi KANENAWA[2], Yoshikazu YAMAGUCHI, Dr. Eng.[3]

SUMMARY

The crack in concrete dam body is considered as a typical damage to concrete gravity dams during large earthquakes, and lots of researches on a nonlinear dynamic analysis method considering the occurrence and progress of cracks have been carried out in order to evaluate this behavior. But there are some problems to evaluate the safety of dam using nonlinear analysis: that the influence which the set material properties have on the results of nonlinear analysis is large, and that the results of nonlinear analysis differ greatly according to the damage estimation models or analysis programs. We, therefore, researched on evaluation indices which correlate well to crack progress in a concrete gravity dam based on the results of linear analysis, by comparing the results of crack progress analysis (nonlinear dynamic analysis) using smeared crack model in order to explore the possibility of estimating damages by the linear analysis method. This paper reports the evaluation indices based on linear dynamic analysis method and the characteristics of the progress of cracks in concrete gravity dams with different shapes using nonlinear dynamic analysis method.

1. INTRODUCTION

Due to the occurrence of large earthquakes like the Kobe Earthquake in 1995, it is desired strongly to verify seismic resistance of dams against much larger earthquake motions than those considered in the present design standard in Japan. The crack in concrete dam body is considered as a typical damage to concrete gravity dams during large earthquakes [1], and the methods of evaluating the safety of dams considering damage in dam body have been studied in order to evaluate the seismic resistance of dam [2]. But there are some problems to evaluate the

[1] Senior Researcher, Dam Structure Research Team, Hydraulic Engineering Research Group, Public Works Research Institute (PWRI), JAPAN
[2] Researcher, ditto
[3] Principal Researcher, ditto

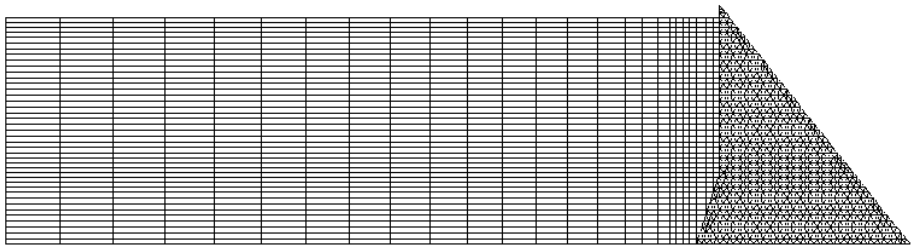
safety of dam using nonlinear analysis: the way of setting the material properties [3], the damage model, analytical code and so on.

We researched on evaluation indices in order to estimate the degree of damage (crack length) to a concrete gravity dam based on the results of linear analysis, by comparing the results of crack progress analysis (nonlinear dynamic analysis) using smeared crack model with those of linear dynamic analysis for exploring the possibility of estimating damages by the linear analysis method. In this paper, we report results of the consideration of such simple evaluation indices.

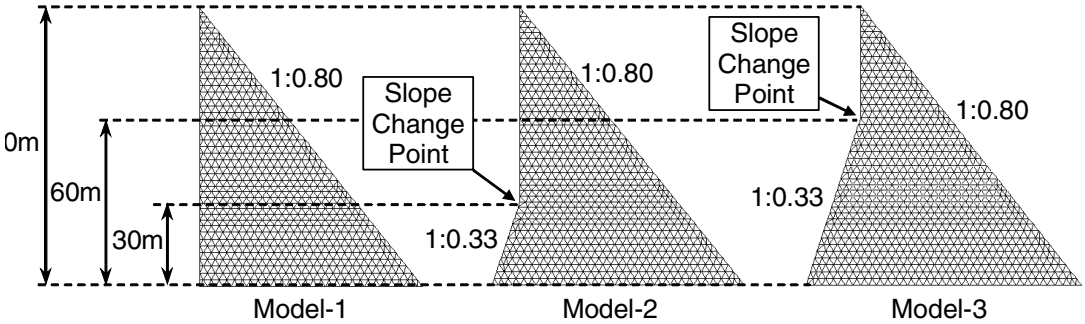
2. STUDY USING SINUSOIDAL WAVE

2.1 Analysis Model and Conditions

Crack progress analyses for concrete gravity dams were carried out by the smeared crack model using sinusoidal waves as input waves. The analytical models are concrete gravity dams with a height of 100m and 3 different upstream surface shapes as shown in Figure 1. The boundary condition of a bottom of a dam body was set as rigid and an effect of a reservoir was considered by a consistent added mass matrix obtained assuming water was incompressible fluid. The uplift pressure was not considered. The material properties of concrete used for the analysis are summarized in Table 1. The damping was set as the Rayleigh type damping using the first and third natural frequencies for the linear model without considering crack generation. And the analyses were carried out using a tension-softening curve expressed by the single straight line shown in Figure 2. Self-weight and hydrostatic pressure were considered as static loads. We inputted the sinusoidal wave with the first natural frequency of the dam at acceleration amplitude of 150gal horizontally from the bottom of the dam body with the downstream side as positive. The input wave used for the analysis of Model-2 is shown in Figure 3, and the specifications of the input waves used for each dam are summarized in Table 2. The general-purpose finite element method analysis program "Diana" [4] was used for the analysis. For the comparison, linear analysis without considering crack occurrence in concrete was also conducted.



(a) Reservoir and Dam Body (Model-2)



(b) Only Dam Body

Figure 1 FE-Model

Table 1 Material Properties of Concrete

Young's Modulus of Elasticity *E* (MPa)	3.00E+04
Poisson's Ratio *v*	0.2
Stress at Beginning of Tension-Softening *ft* (MPa) (Tensile Strength)	2.0, 2.5, 3.0, 4.0
Fracture Energy *Gf* (N/m)	300
Unit Mass ρ (kg/m^3)	2,300
Damping Ratio *h* (%)	10 (Rayleigh damping, the first and third natural frequencies)

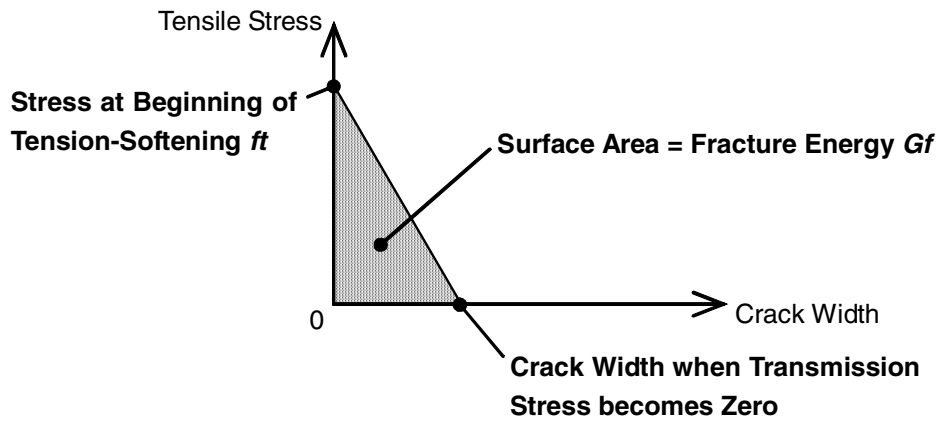


Figure 2 Tension-Softening Curve (Single Straight Line Approximation Model)

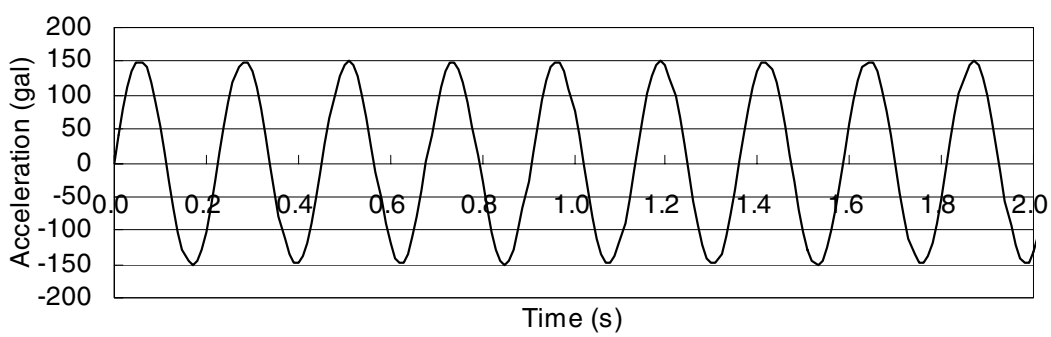


Figure 3 Input Wave (Sinusoidal Wave)

Table 2 Specifications of Input Wave

Model #	Model-1	Model-2	Model-3
Frequency (Hz) (First Natural Frequency)	4.10	4.41	5.18
Period (s) (First Natural Period)	0.24	0.23	0.19
Acceleration Amplitude (gal)	150	150	150

2.2 Results of Analysis

2.2.1 Locations of Occurrence of Cracks during Earthquake

Figure 4 shows the locations (black colored elements) where cracks occurred as the results of the crack progress analysis in the three models on the condition that stress at beginning of tension-softening is 3.0 MPa. The figure reveals that during the earthquake the crack occurs near the bottom of the dam body in Model-1, and near the slope change point and near the bottom in Model-2 and Model-3. Because the foundation was not included in this analysis model, the stress concentration occurred at the upstream heel of the body and the progress of the crack in such part was conspicuous.

This study focused on the crack at the slope change point, and the bottom of the dam body is also considered here as the slope change point in Model-1. Figure 5 shows the time history of the tensile side principal stress of the furthest upstream element of crack (evaluation element of principal stress, the round symbol shown in Figure 4) based on the results of linear dynamic analysis performed separately for Model-1 using the same input wave. From this figure, it is found that the tensile stress that exceeds stress at beginning of tension-softening occurs in the linear analysis, and that the gap between the enveloping tensile principal stress that occurs at a certain time, $\sigma_t(t)$, and stress at beginning of tension-softening, ft, becomes large as time passes. Here, we study the relationship between crack length at the slope change point and two indices of (σ_t) and ($\sigma_t - ft$).

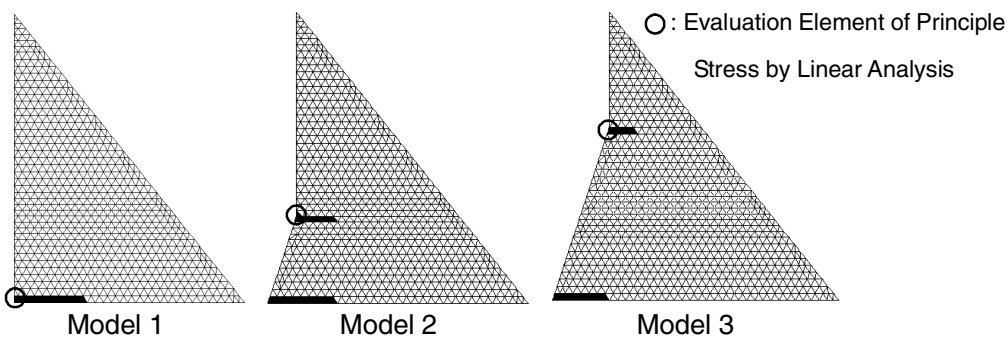


Figure 4 Location of Generated Cracks

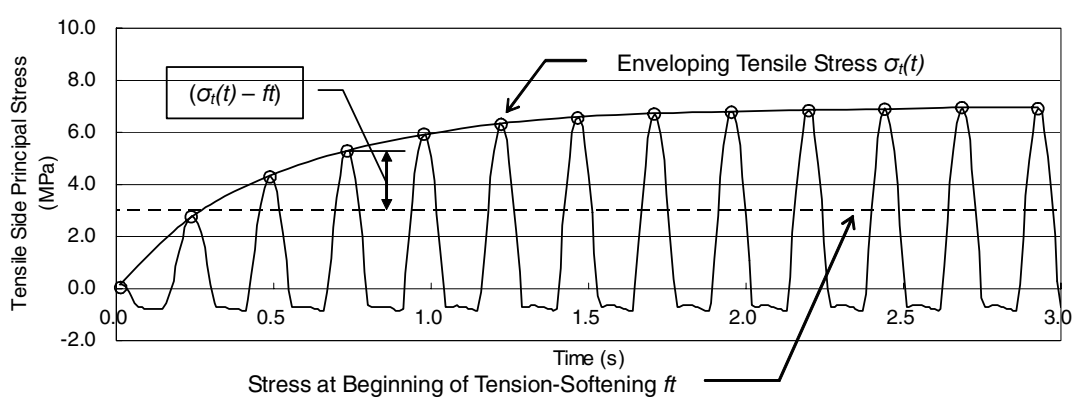


Figure 5 Time History of Tensile Side Principal Stress by Linear Dynamic Analysis (Model-1)

2.2.2 Effect of Stress at Beginning of Tension-Softening on Crack Progress

Figure 6 shows the relationship between crack length and σ_t at the evaluation element of the principal stress for Model-1, and Figure 7 shows the relationship between crack length and ($\sigma_t - ft$) for *ft* of 2.0, 2.5, 3.0 and 4.0 MPa, respectively. Figure 6 shows that in cases of the same σ_t, the smaller *ft* is, the longer the cracks become and the longer the final cracks become. It is found that even when the wave with the same acceleration amplitude is continuously inputted, cracks converge at a certain length without keeping extending. Therefore it can be considered that the progress of the crack is small if input does not come at higher level than the input as the crack occurred. From Figure 7, the relationship between crack length and ($\sigma_t - ft$) shows the almost same tendency regardless of *ft*. Although the figures are not shown in this report, the same tendency is observed in Model-2 and Model-3.

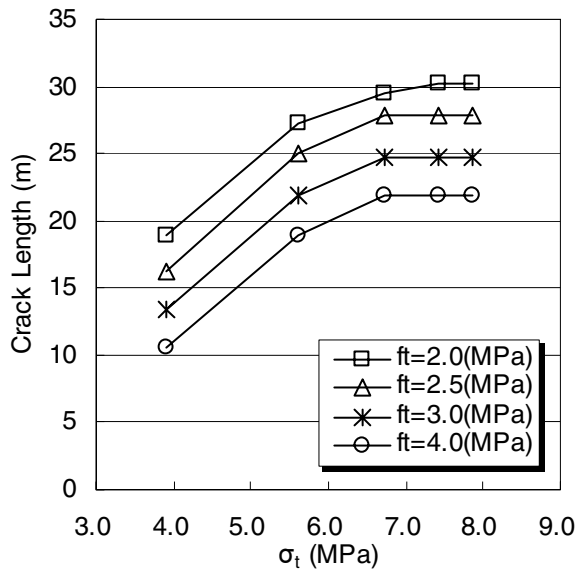


Figure 6 Relationship between Crack Length and σ_t (Model-1)

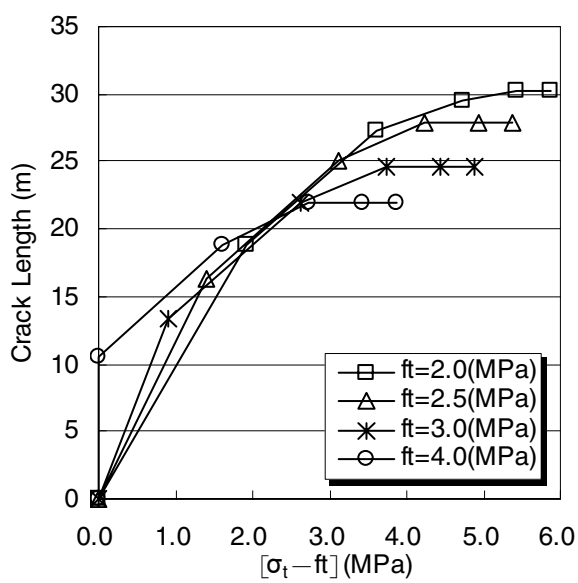


Figure 7 Relationship between Crack Length and ($\sigma_t - ft$) (Model-1)

2.2.3 Effect of Shape of Dam on Crack Progress

Figure 8 shows the relationship between crack length and (σ_t – *ft*) at the slope change point on the condition that *ft* is 2.5 MPa. Figure 8 shows that the lower the elevation of the slope change point is, the larger (σ_t – *ft*) becomes and the longer the cracks are. But the initial relationship between crack length and (σ_t – *ft*) shows almost identical curve at the beginning part near coordinate origin regardless of the dam model.

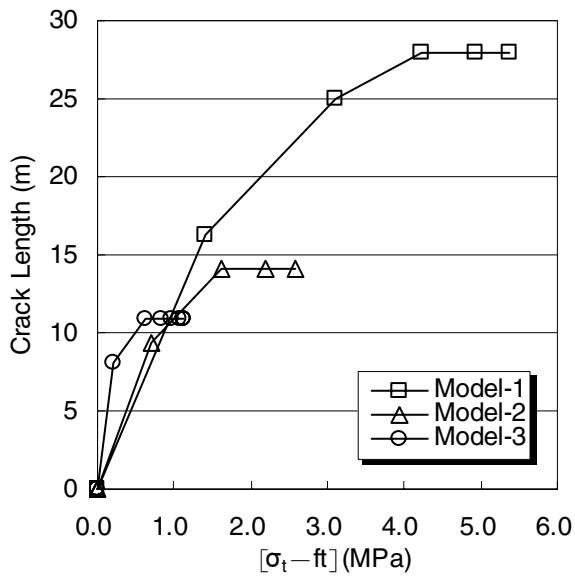


Figure 8 Relationship between Crack Length and (σ_t – *ft*) (*ft* = 2.5MPa)

3. STUDY USING OBSERVED SEISMIC WAVE

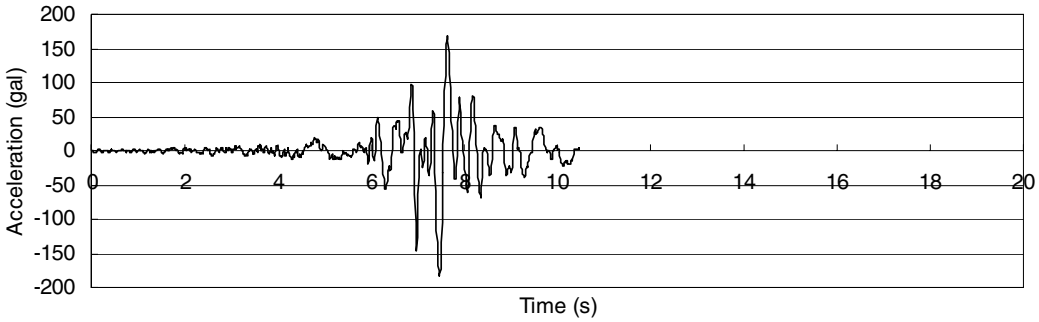
As aforementioned, it is found that the relationship between crack length and (σ_t – *ft*) is almost identical curve regardless of *ft* and the shape of dam body. Here, crack progress analyses for concrete gravity dam were conducted by the smeared crack model using observed seismic waves, and the relationship of crack length with some evaluation indices based on linear dynamic analysis method was studied.

3.1 Analysis Model and Conditions

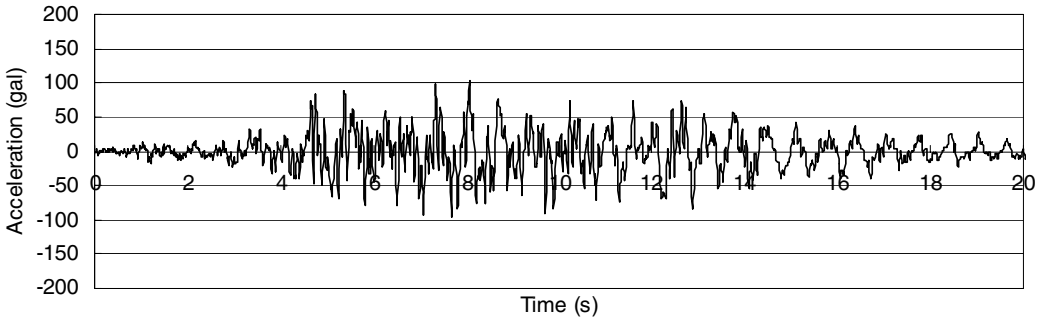
Crack progress analyses of concrete gravity dam were carried out by the smeared crack model. Model-2 shown in Figure 1 was used as the analytical model. The stress at beginning of tension-softening was 2.5 MPa. As the input wave, we used the horizontal acceleration wave observed at bases of Hitokura Dam, Gongen Dam and Minoogawa Dam during the Kobe Earthquake in 1995. Only the amplitude of their acceleration wave was enlarged as summarized in Table 3, and it was inputted in the horizontal direction from the bottom of the dam body with the downstream side as positive. Figure 9 shows the original wave observed at each dam. For the comparison, linear analysis without considering crack occurrence of concrete was also conducted.

Table 3 Analytical Cases

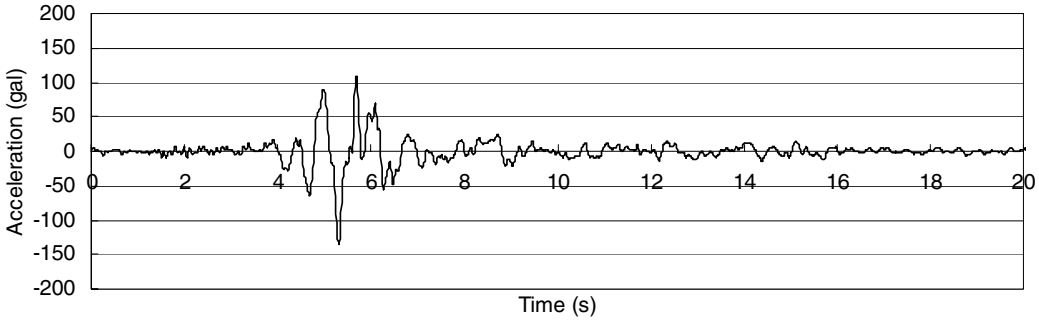
Wave Form (Waves measured during the Kobe Earthquake in 1995)	Max. Acceleration (gal)	
	Original	This Study
Wave observed at Hitokura Dam	182.1	250, 300, 400
Wave observed at Gongen Dam	135.0	400, 500
Wave observed at Minoogawa Dam	103.7	400, 500



(a) Hitokura Dam



(b) Gongen Dam



(c) Minoogawa Dam

Figure 9 Acceleration Wave Observed at Each Dam during the Kobe Earthquake in 1995 (Original)

3.2 Results of Analysis

3.2.1 Locations of Occurrence of Cracks during Earthquake

Figure 10 shows the location where cracks occurred in the crack progress analysis using the Minoogawa Dam Wave with a maximum acceleration of 500gal. The black colored elements in this figure show the locations of all cracks that occurred throughout the analysis. The cracks during large earthquakes are apt to occur at the bottom of dam body and near the change point of slope. The elements of the most upstream side of cracks is set to A and B as shown in Figure 10. Figure 11 shows the time history the tension side principal stress at points A and B obtained by linear dynamic analysis using the same input wave. Tensile stress that exceeds the tensile strength occurred several times, and cracks propagated in the nonlinear analysis result at approximately the time when large stress generated in the linear analysis result.

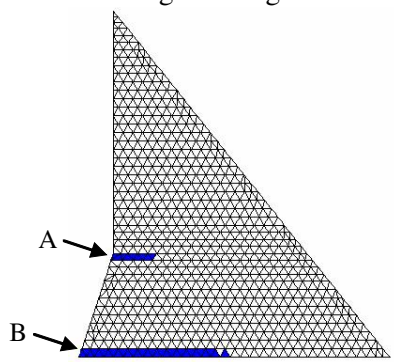
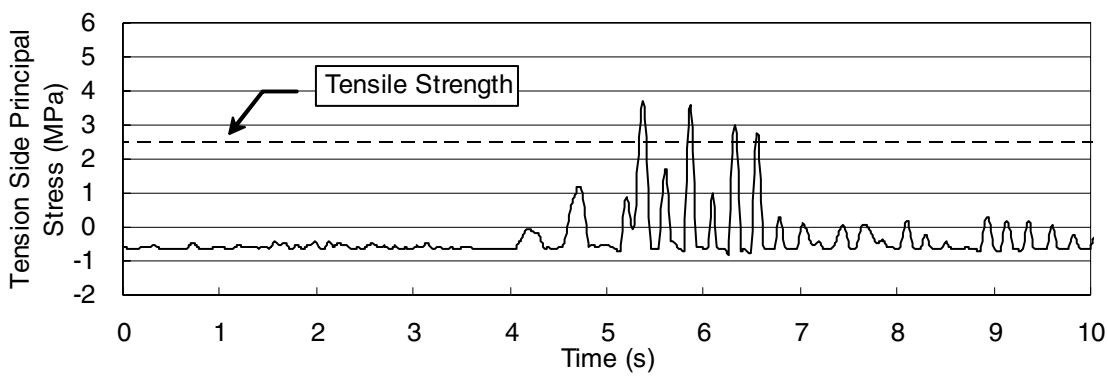
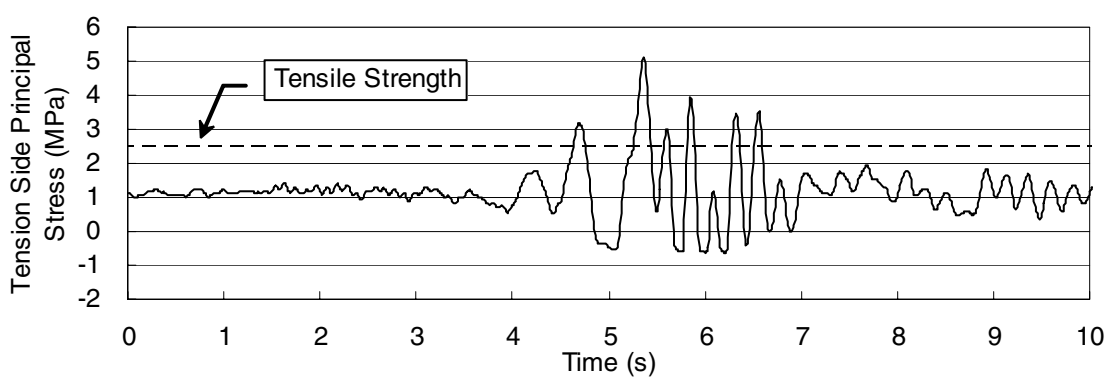


Figure 10 Locations of Generated Cracks



(a) Slope Change Point (Point A in Figure 10)



(b) Bottom of Dam Body (Point B in Figure 10)

Figure 11 Time History of Tension Side Principal Stress

3.2.2 Evaluation Indices of Crack Length Based on Linear Analysis Results

In order to compare the behavior of tensile stress in linear analysis result with the crack length in nonlinear analysis result, Figure 13 (a) shows the relationship of crack length with the cumulative time when the tensile stress exceeds the tensile strength (see Figure 12). Figure 13 (b) shows the relationship of crack length with the total area of the part above the tensile strength in tensile stress time histories shown in Figure 12 (the integration value of excess stress and time), Figure 13 (c) shows the relationship of crack length with the maximum tensile stress, and Figure 13 (d) shows the relationship of crack length with the area of the part above the tensile strength at the single wave while the maximum tensile stress occurred (see Figure 12). The figures show that even if the final crack lengths are the same, it is difficult to estimate crack length by the cumulative time above the tensile strength and the total area above the tensile strength. In contrast, it is found that the maximum tensile stress or the area above the tensile strength at the single wave shows the strong correlation with the crack length. This shows that although the cracks gradually progress in the nonlinear analysis, the conclusive crack length correlates closely with the maximum tensile stress experienced in the linear analysis regardless of the crack progress process.

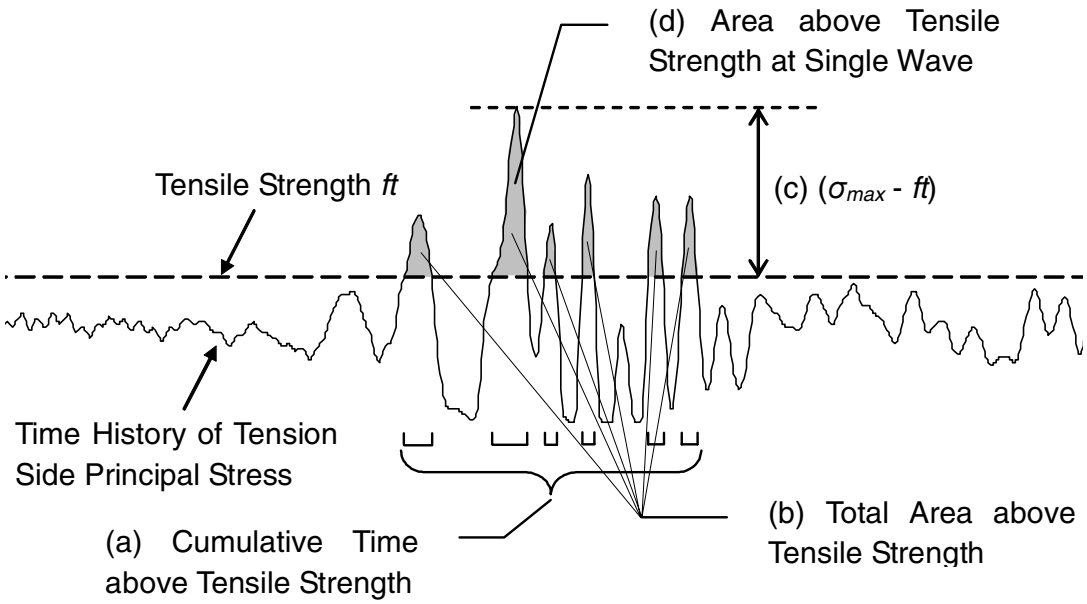
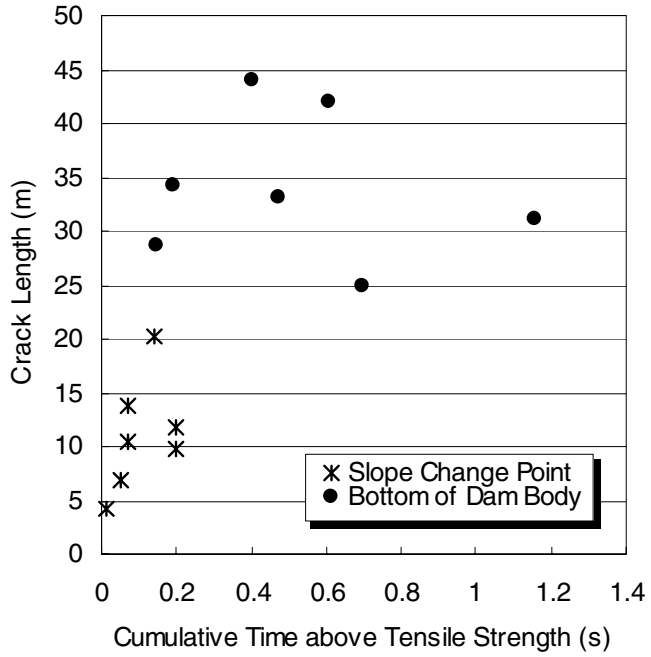
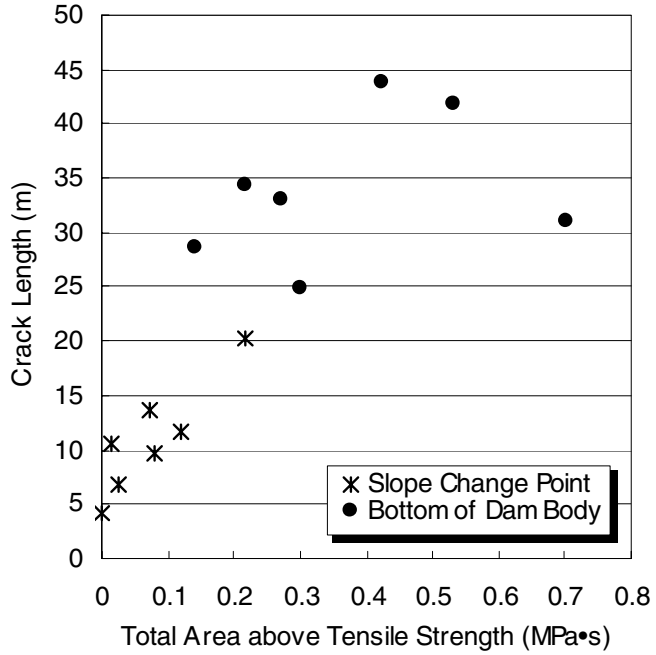


Figure 12 Evaluation Indices of Crack Length

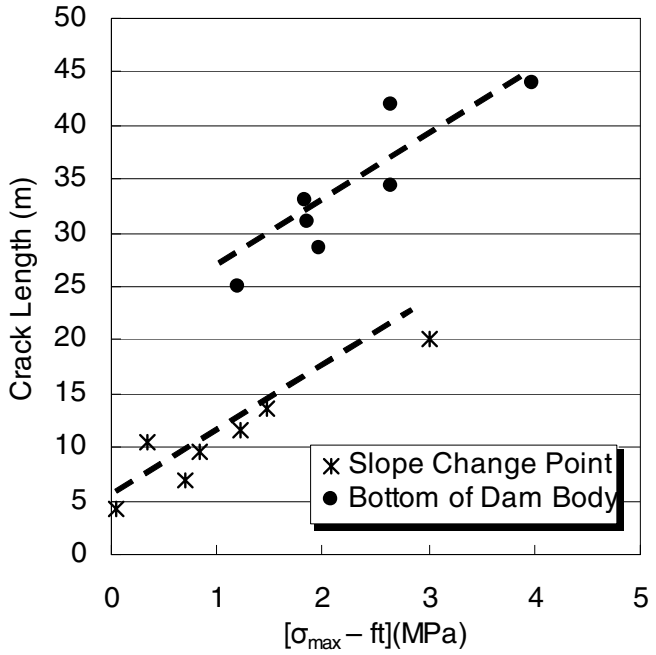


(a) Relationship with Cumulative Time above Tensile Strength in Tensile Stress Time History

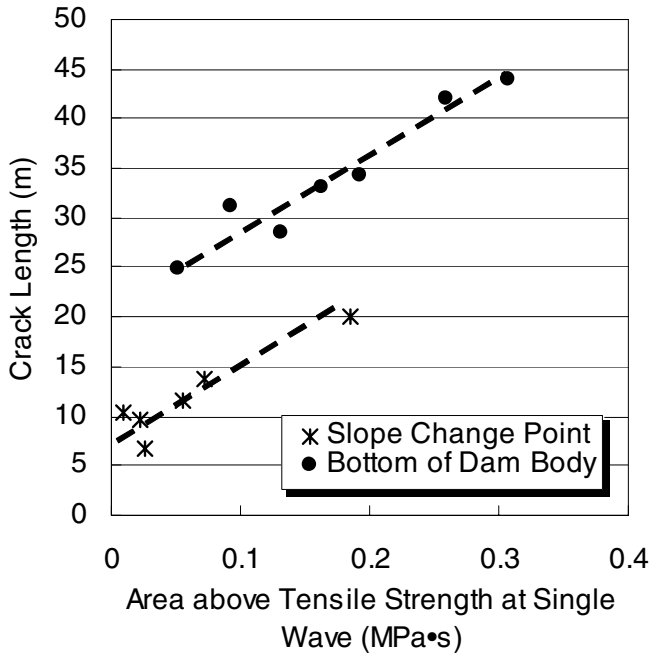


(b) Relationship with Total Area above Tensile Strength in Tensile Stress Time History

Figure 13 Relationship of Crack Length with Evaluation Indices



(c) Relationship with Maximum Tensile Stress



(d) Relationship with Area above Tensile Strength at Single Wave in which Maximum Tensile Stress Occurred

Figure 13 Relationship of Crack Length with Evaluation Indices

4. CONCLUSIONS

We studied the evaluation indices based on linear dynamic analysis method and the characteristics of the progress of cracks in concrete gravity dams with different shapes using nonlinear dynamic analysis method. The followings were found by this study.

(1) A crack tends to occur at the slope change point and near the bottom of the dam body.
(2) In the case of sinusoidal wave as input acceleration, the relationship between crack length and ($\sigma_t - ft$) shows almost identical curve regardless of ft and the shape of dam body.
(3) In the case of actual seismic wave as input acceleration, the indices of ($\sigma_{max} - ft$) and the area above the tensile strength at the single wave shows the strong correlation with the crack length.

If simple linear dynamic analysis is appropriately conducted to estimate tensile stress at potential locations of initiating cracks, the damage due to cracks would be predicted roughly.

REFERENCES

1. A. K. Chopra and P. Chakrabarti: The Koyna earthquake and the damage to Koyna Dam, Bull. Seism. Soc. Am., 63, pp.381-397, 1973
2. For example, G. L. Fenves: Earthquake induced cracking in concrete gravity dams, Structures Congress '89: Seismic engineering: research and practice, American Society of Civil Engineers, pp.337-346, 1989
3. K. Kanenawa, Y. Yamaguchi and T. Sasaki: A study of the effect of the nonlinear material characteristic on crack propagation in the dynamic analysis of concrete gravity dam, the proceeding of the 57th JSCE Annual Meeting, I-679, 2002 (in Japanese)
4. “DIANA”: general purpose structural analysis software for the civil engineering field, Public Information Journal SENAC, Vol. 32, No. 2, April 1999 (in Japanese)