A Study on Stress in Concrete Gravity Dam using Seismic Data during Kobe Earthquake

by

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ABSTRACT

The Kobe Earthquake (the Hyogoken-Nambu Earthquake of January 17, 1995) inflicted severe damage on many structures in the Hanshin and Awaji areas such as had not been experienced in Japan in recent decades. However, there was no damage on dams which affected the their safety.

This paper introduces the characteristics of ground acceleration observed at dam sites during the Kobe Earthquake and discusses the effect of vertical seismic motion and the safety of concrete gravity dams in such big earthquakes. The result of the dynamic analysis shows that concrete gravity dams have the high safety against such big earthquakes.

Key Words: concrete gravity dam, dynamic analysis, Kobe Earthquake, seismic resistance, vertical ground motion

1. PREFACE

In the early morning of January 17, 1995, the Kobe Earthquake (Hyogoken-Nambu Earthquake) inflicted severe damage in the Hanshin and Awaji areas.

About 250 dams received the shock of the earthquake within 300 km of its epicenter. The Tokiwa Dam was located in a distance only 800 m from the Nojima earthquake fault. There were also a number of old dams in Kobe City where the earthquake damage was most severe. The dam safety inspection immediately after earthquake showed that there were no damage on the dams which affected their safety.

This paper introduces the characteristics of ground acceleration observed at dam sites during the Kobe Earthquake and discusses the effect of vertical seismic motion and the safety of concrete gravity dams in such big earthquakes.

2. CHARACTERISTICS OF EARTHQUAKE MOTION AT DAM SITES

2.1. Maximum Acceleration at Foundation of Dams

(1) Attenuation of Peak Acceleration

About 50 ground acceleration records were obtained at dam sites during the Kobe Earthquake. All the dams were constructed on the rock foundation. Table 1 shows the peak acceleration recorded at the foundation of dams during the earthquake (including the acceleration obtained at the lowest gallery in the concrete dams or at the gallery beneath the embankment dams). The maximum ground acceleration is 183 gal which was recorded at the lowest gallery of the Hitokura Dam (concrete gravity dam, height = 75 m). The dam

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was located in a distance of 47 km from the epicenter or only 10 km from the estimated earthquake source fault in the ground. The location of the earthquake source fault in the Kobe area was estimated from the distribution of aftershocks on January 17, while it coincides with the Nojima fault in the Awaji area.

The attenuation of the horizontal peak acceleration of the foundation of dams is shown in Figure 1, and the attenuation of the vertical peak acceleration in Figure 2. The envelopes of the peak acceleration can be expressed by a straight line in the semi-logarithm plot. They are expressed as follow:

$$\ln Ah = \ln 217 - 0.0170\,L$$

$$\ln Av = \ln 93 - 0.0114\,L$$

where

Ah : horizontal peak acceleration (gal)

Av : vertical peak acceleration (gal)

L : distance from the earthquake source fault (km)

From the figure and the above equation, it can be estimated that the maximum of horizontal peak acceleration induced at the rock sites near the earthquake source fault was about 220 gal.

(2) Horizontal Peak Acceleration versus Vertical Peak Acceleration

Figure 3 shows the relationship between the horizontal peak acceleration and the vertical peak acceleration observed at dam sites during the Kobe Earthquake. The ratio of the vertical peak acceleration to the horizontal peak acceleration ranges from 1/3 to 1/1. This ratio tends to decrease as the horizontal peak acceleration increases.

2.2. Acceleration Response Spectrum

The response spectra of the acceleration in the stream direction (damping ratio of 10%) at 21 dam sites in the Kobe Earthquake are shown in Figure 4. Each spectrum is normalized so that the maximum ground acceleration is equal to 1. The average value of the normalized response spectra is about 2 for the natural period ranging from 0.1 to 0.6 seconds. The response spectra decrease rapidly when the natural period exceeds about 0.6 seconds.

3. EFFECT OF VERTICAL SEISMIC MOTION

3.1. Model Concrete Gravity Dams

The concrete gravity dams used in the analysis have the typical cross section whose downstream slope is 0.8:1, and whose upstream slope is vertical (0.0:1). The height of the dams ranges from 25 m to 150 m. Figure 5 shows the finite element model of the dam, and Table 2 shows the physical properties of the material.

3.2. Methodology

The response spectrum method with the modal analysis was used in the analysis of dynamic stresses in dam body. The first 6 modes of vibration were considered. The damping ratio was assumed 10 %. This value is based on the results of behavior analysis of the Hitokura Dam (height = 75 m), where the acceleration of the foundation was 183 gal and the acceleration of the top gallery (8 m lower than the crest of the dam) was 482 gal in the Kobe Earthquake. Figure 6 shows the result of the analysis of the Hitokura Dam.

The effect of reservoir water was accounted for as the added mass matrix in the modal analysis. The added mass matrix is calculated assuming that reservoir water is incompressible.

3.3. Acceleration Records Used in Analysis

Acceleration records (sets of horizontal and vertical acceleration) obtained at the foundations of 21 dam sites. These records include data measured in the bottom gallery in the dam. Two types of acceleration were used in this section. One is the acceleration record which adjusted so that the maximum value was 100 gal for both horizontal and vertical acceleration. And the second is original acceleration record.

3.4. Results of Analysis

(1) Tensile Stress for Ground Acceleration of 100gal

Figure 7 shows the results of the tensile stress at the heel of the dam for the horizontal seismic motion and the vertical seismic motion. The horizontal motion and vertical motion are separately applied to the dam. Figure 7 (a) is the results for the full reservoir, and (b) is the results for the empty reservoir. The symbols are the individual result and the solid line indicate the average value for each dam height. These figures show the tensile stresses at the heel of the dam for the horizontal motion and the vertical motion are in proportion to the dam height, and the stresses for horizontal motions vary more widely than the stresses for vertical motions.

Figure 8 compares the results of the tensile stress when the horizontal seismic motion and the vertical seismic motion are separately applied. Figure 8 (a) is the results for the full reservoir and (b) is the results for the empty reservoir. The figures show that the tensile stress at the heel of the dam generated by the vertical seismic motion is about 20% - 40% of the tensile stress generated by the horizontal seismic motion in the case of the full reservoir, and about 30 - 60% in the case of the empty reservoir. And the greater the tensile stress for the horizontal seismic motion is, the smaller the effect of the vertical seismic motion becomes.

(2) Tensile Stress for Original Ground Acceleration

Figure 9 compares the results of the tensile stress at the heel of the dam when the horizontal seismic motion and the vertical seismic motion are separately applied. Figure 9 (a) is the results for the full reservoir and (b) is the results for the empty reservoir.

When the tensile stress at the heel of the dam generated by the horizontal seismic motion become large, the tensile stress generated by the vertical seismic motion decrease to less than 10% of the tensile stress generated by the horizontal seismic motion in the case of the full reservoir, and to less than 20% in the case of the empty reservoir. In general speaking, the time when the stress by horizontal motion gets maximum value and the time when the stress by vertical motion gets maximum value do not coincide. So, the above-mentioned estimations are the upper limits of effects of vertical ground motions. The vertical ground motions, therefore, have less effects in the actual situation.

4. EVALUATION OF SEISMIC RESISTANCE OF CONCRETE DAMS

4.1. Conditions for Analysis

The model concrete gravity dam and the methodology used in this chapter is the same in Chapter 3.

4.2. Acceleration Records Used in Analysis

In Chapter 3, the effects of vertical ground motions are very small especially in the case of the full reservoir. So, only horizontal ground motions are considered in this chapter.

Two types of acceleration were used in the analysis. At first, 21 original acceleration records were used and the results of the analysis were examined with regard to the distance from the earthquake source fault. Then, the typical 4 acceleration records (ACC-1 to ACC-4) which were observed at the dam sites near the earthquake source fault were used. In this case, the horizontal peak acceleration was enlarged as much as 220 gal. It is the estimated maximum acceleration in the Kobe Earthquake. Figure 10 shows the response spectrum of acceleration records ACC-1 to ACC-4 (damping ratio = 10 %).

4.3. Results of Analysis

(1) Maximum Tensile Stress versus Distance from Earthquake Source Fault

The maximum tensile stress was induced at the bottom portion of the upstream face of the dams in all cases. Figure 11 shows the maximum tensile stress in the dams excluding static stress with regard to the distance from the earthquake source fault. The envelope is almost in a straight line, although the maximum tensile stress has wide range depending on the characteristics of the acceleration records. Figure 12 shows the maximum tensile stress in the dams including static stress with regard to the distance from the earthquake source fault. It can be estimated from the figures that the maximum tensile stress induced in the dams near the earthquake source fault is about 3.1 N/mm^2 in 150m high dams, 2.2 N/mm^2 in 100 m high dams and 0.4 N/mm^2 in 50 m high dams.

(2) Maximum Tensile Stress for Ground Acceleration of 220 gal

Figure 13 shows the maximum tensile stress in the dams of the different height induced by the ground acceleration of ACC-1 to ACC-4. The stress includes the static stress in all cases. The acceleration ACC-1 produces the largest stress in higher dams, since the dominant period of the acceleration is close to the natural period of those dams. On the contrary, the acceleration ACC-4 produces the lowest stress in higher dams, since the dominant period of the acceleration is far from the natural period of those dams.

The figure shows that the maximum tensile stress increases in proportion to the height of the dam. The envelope is expressed as:

$$\sigma = 0.0226\,H \quad \text{(at 220 gal)}$$

or

$$\sigma = (0.0129\,\alpha - 0.568)\,H/100$$

where

σ: maximum tensile stress (N/mm^2)

α: maximum ground acceleration (gal)

H: height of dam (m)

It can be estimated from the figure or the above equations that the maximum tensile stress by the ground acceleration of 220 gal is about 3.4 N/mm^2 even in 150 m dams. Since the dynamical stress occurs instantaneously, it is considered that dams can withstand such a level of tensile stress.

5. CONCLUSION

The Kobe Earthquake inflicted severe damage in the Hanshin and Awaji areas such as had never been experienced in Japan in recent decades. However, there was no damage on the dams affecting their safety.

This paper introduces the characteristics of ground acceleration observed at dam sites during the Kobe Earthquake and discusses the effects of vertical seismic motions on dam and the safety of concrete gravity dams in such big earthquakes. The results of the analysis are as follows:

(1) It is estimated that the maximum peak acceleration at rock sites induced

by the Kobe Earthquake was about 220 gal.

(2) The effect of the vertical seismic motion on the stress of dam body is very small as compared with the effect of the horizontal seismic motion. The tendency can be obvious when the stress by horizontal seismic motion is large, and the reservoir is full.

(3) It is estimated that the maximum tensile stress in the concrete gravity dams induced by the earthquakes is:

$$\sigma = 0.0226\,H \quad \text{(at 220 gal)}$$

or

$$\sigma = (0.0129\ \alpha\ - 0.568)\,H/100$$

where

σ : maximum tensile stress (N/mm^2)

α : maximum ground acceleration (gal)

H : height of dam (m)

Therefore, the maximum tensile stress in 150 m high concrete gravity dams induced by the ground acceleration of 220 gal is about 3.4 N/mm^2. Since the dynamical stress occurs instantaneously, it is considered that dams can withstand such a level of tensile stress. So, the concrete gravity dams are safe in such big earthquake as Kobe Earthquake.

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Table 1 Peak Acceleration Recorded at Foundation of Major Dams

Dam Site	Acceleration (gal) Horizontal Direction	Acceleration (gal) Vertical Direction
Hitokura	183	64
Minoo	128	75
Donto	111	-
Gongen	103	67
Kisenyama	90	44
Kurokawa	85	53
Tataragi	65	20
Shirakawa	50	48
Zao	49	25
Yasumuro	38	31
Nishidaira	38	25
Seto	35	12
Masaki	33	33
Senzoku	32	16
Fukui	32	15
Hase	30	22

Table 2 Physical Properties of Materials

Item	Value
Concrete	
Density	2300 kg/m^3
Elastic Modulus	30 kN/mm^2
Poisson's Ratio	0.2
System	
Damping Ratio	10%

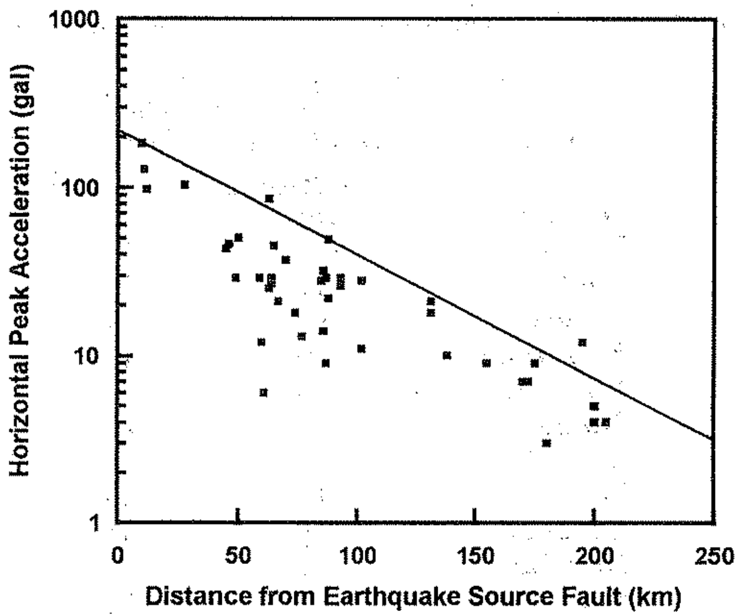


Figure 1 Attenuation of Horizontal Peak Acceleration

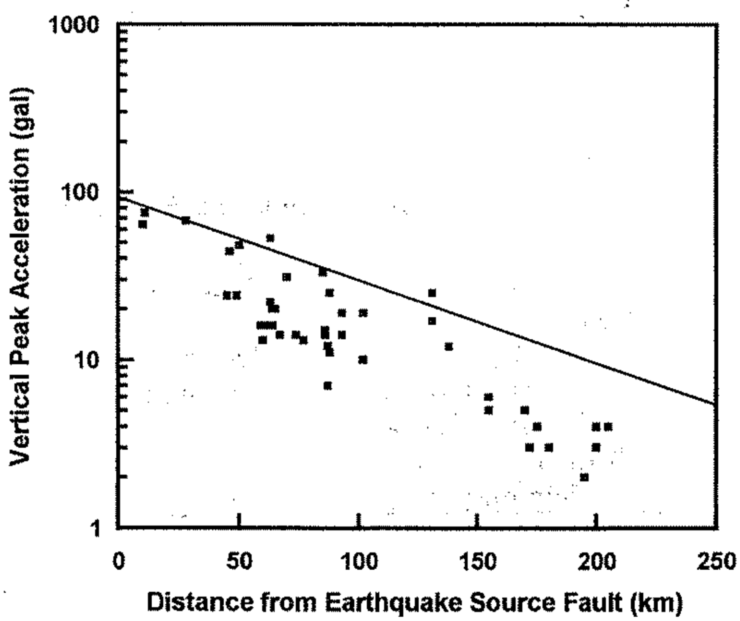


Figure 2 Attenuation of Vertical Peak Acceleration

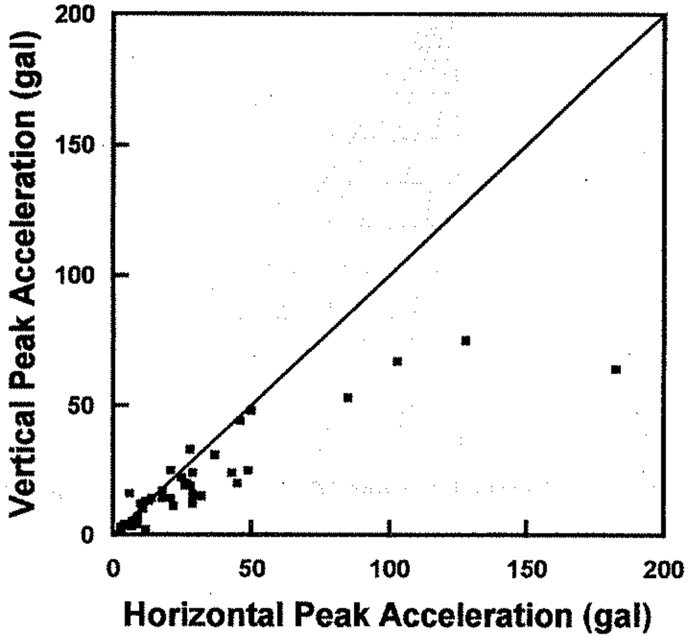


Figure 3 Horizontal Peak Acceleration versus Vertical Peak Acceleration

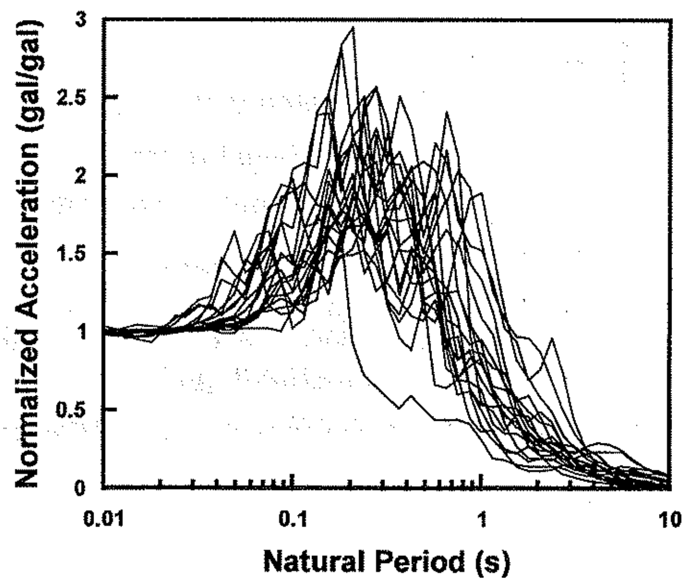


Figure 4 Normalized Response Spectrum of Acceleration (Horizontal Direction)

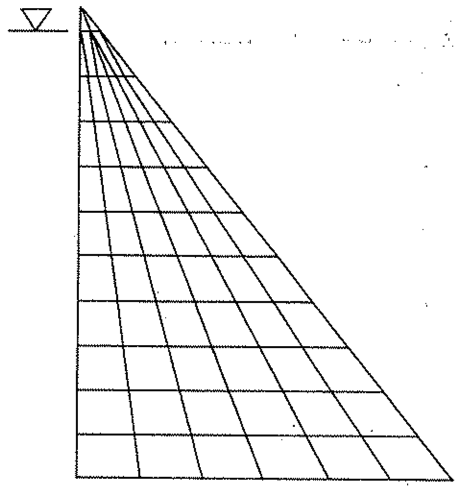


Figure 5 Finite Element Model of Concrete Gravity Dam

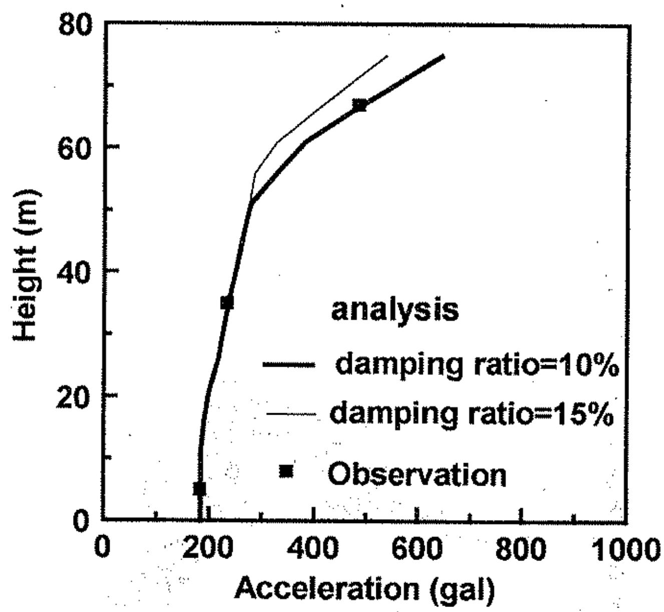
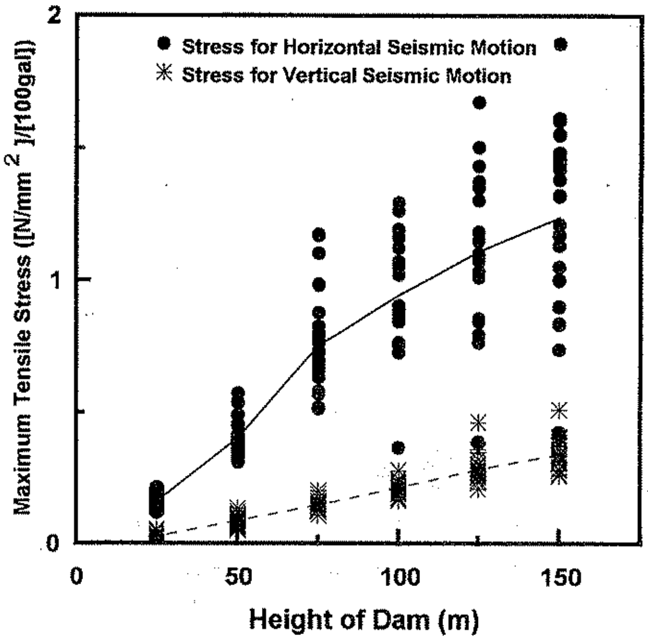
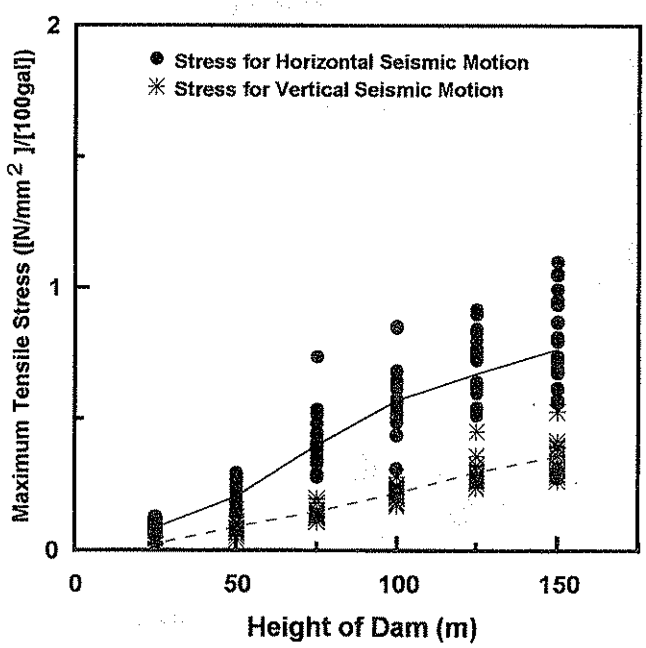


Figure 6 Distribution of Acceleration at the Hitokura Dam

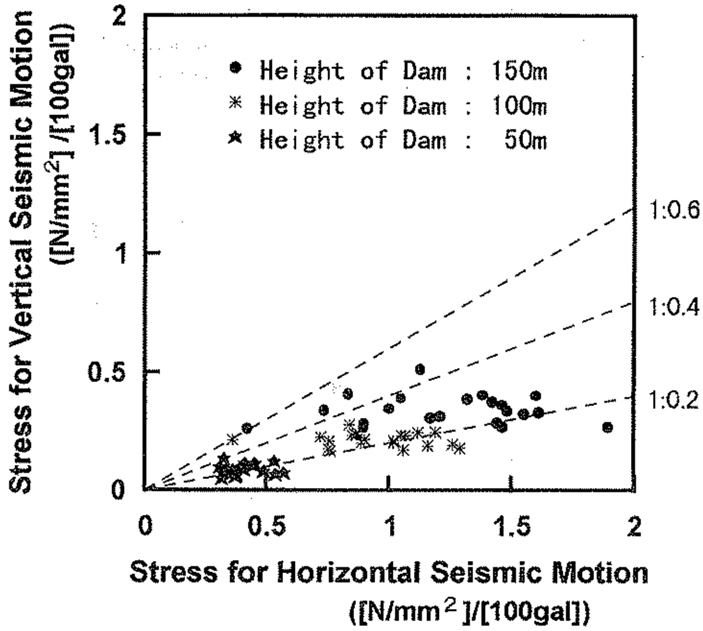


(a) Full Reservoir

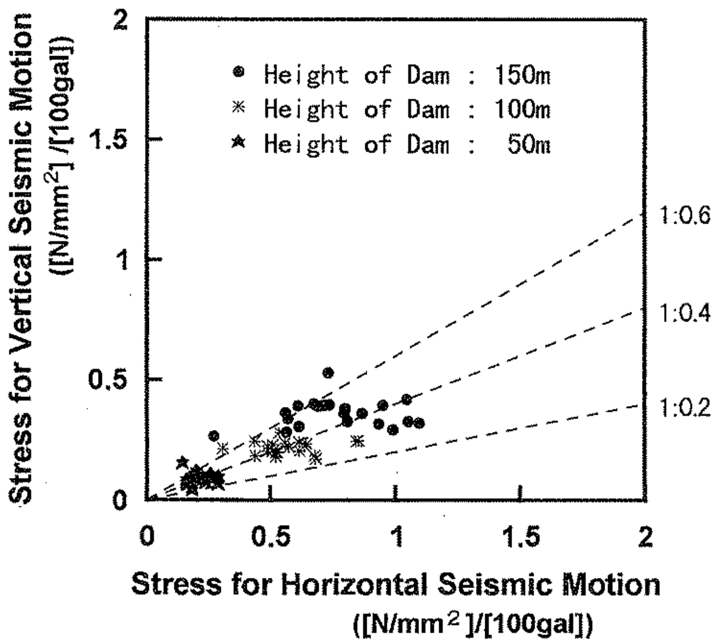


(b) Empty Reservoir

Figure 7 Height of Dam versus Maximum Tensile Stresses for Horizontal Seismic Motion and Vertical Seismic Motion

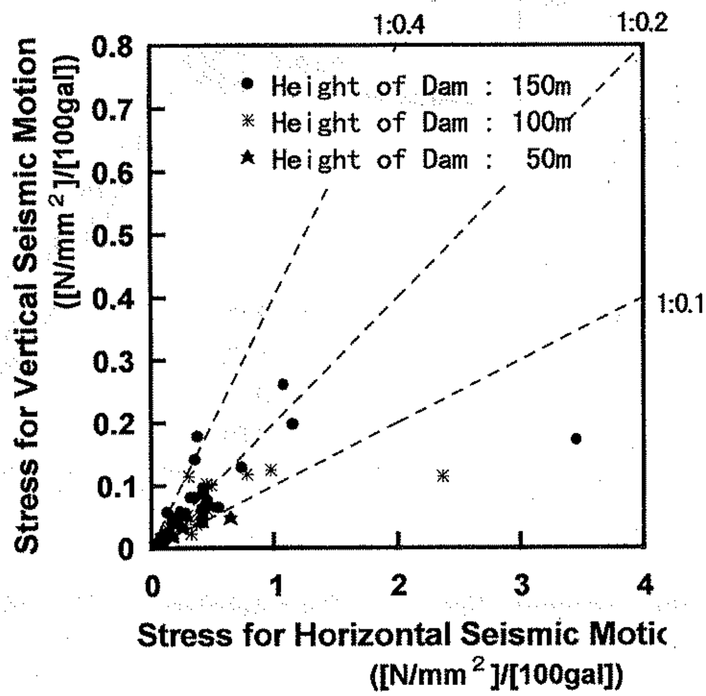


(a) Full Reservoir

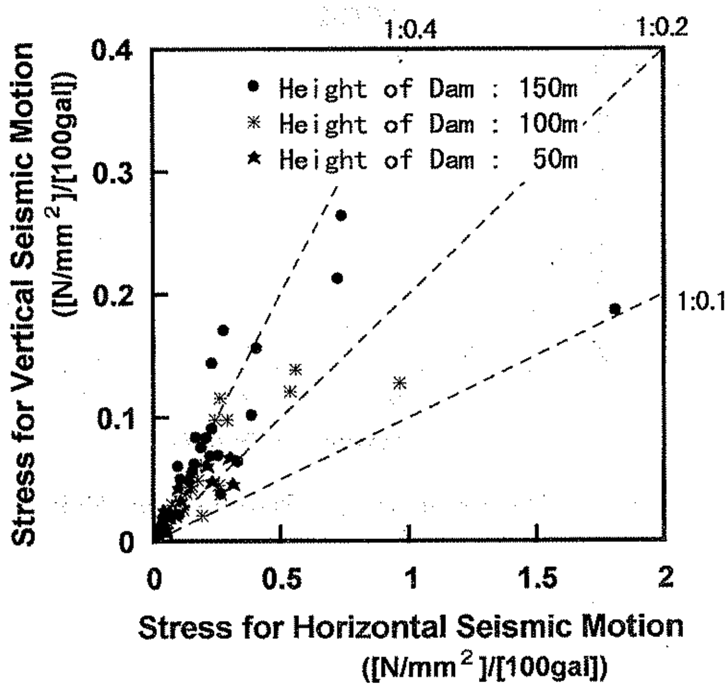


(b) Empty Reservoir

Figure 8 Comparison of Maximum Tensile Stresses for Horizontal Seismic Motion and Vertical Seismic Motion (Maximum Acceleration : 100gal)



(a) Full Reservoir



(b) Empty Reservoir

Figure 9 Comparison of Maximum Tensile Stresses for Horizontal Seismic Motion and Vertical Seismic Motion (Maximum Acceleration : Measured Value)

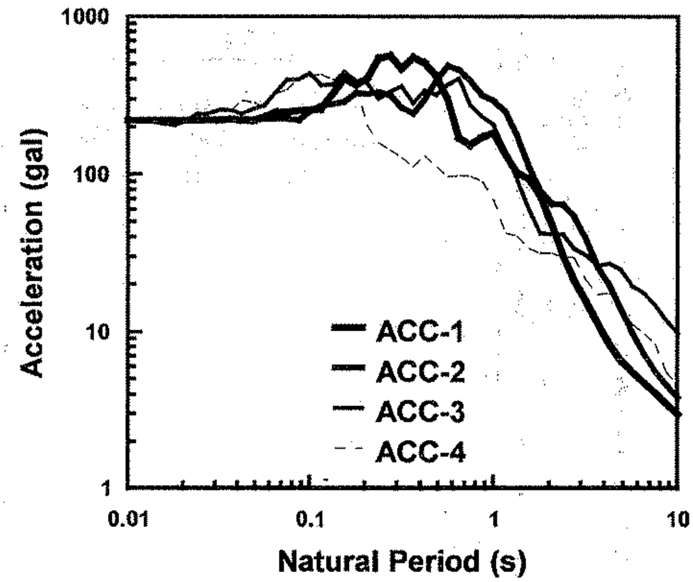


Figure 10 Modified Response Spectra of Four Acceleration Records (Horizontal Direction)

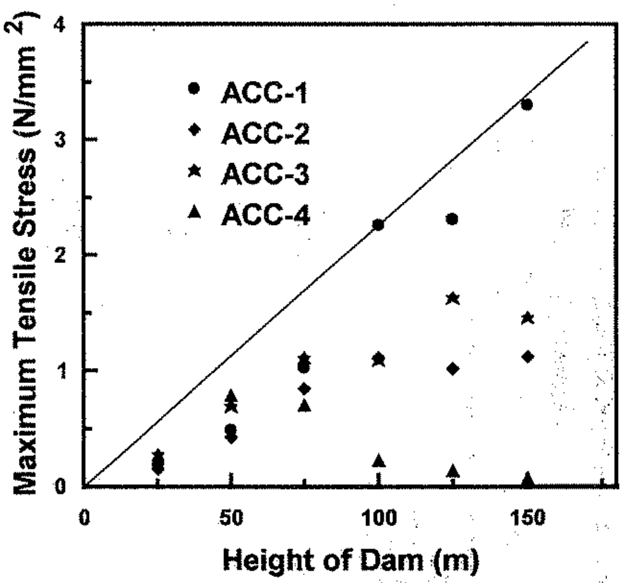
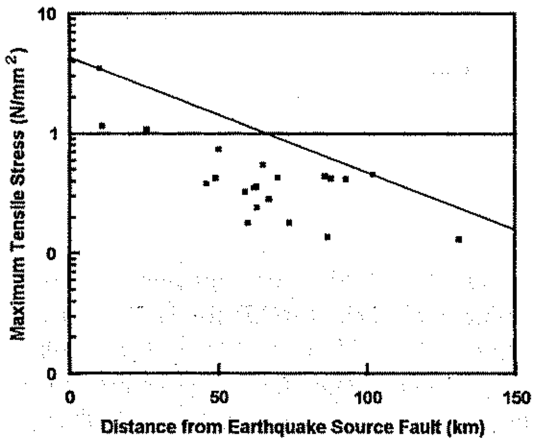
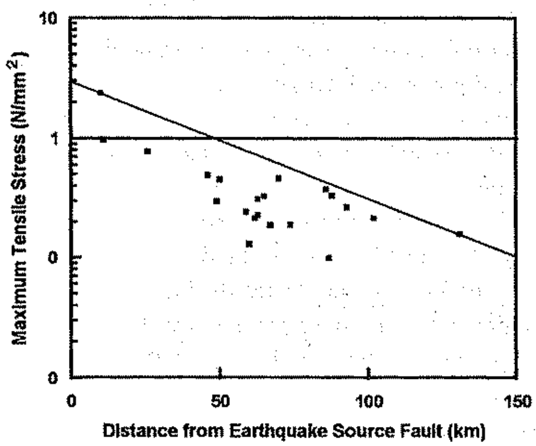


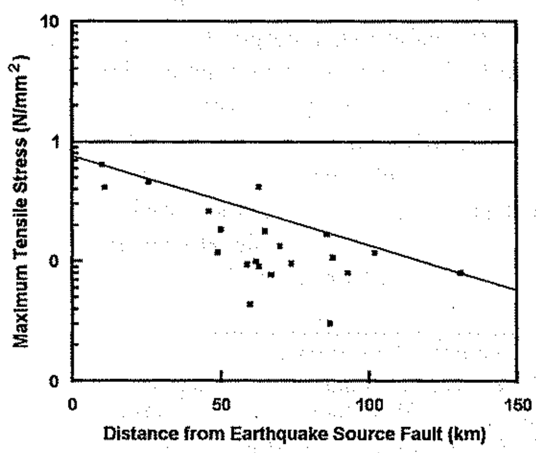
Figure 13 Maximum Tensile Stress versus Height of Dams



(a) Dam Height =150m

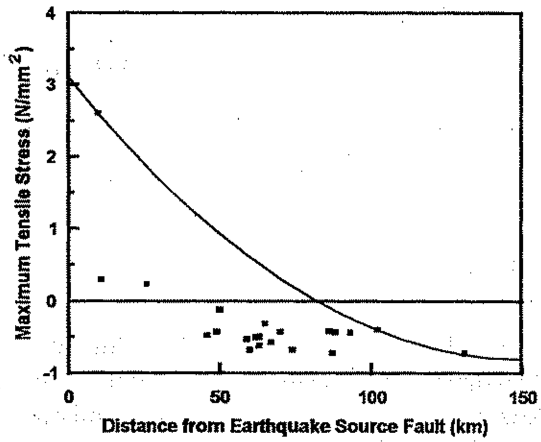


(b) Dam Height =100m

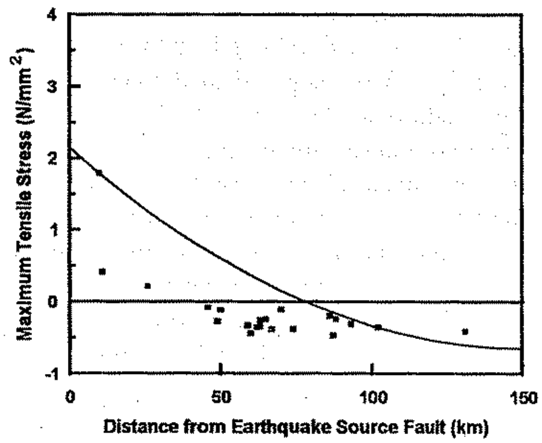


(c) Dam Height = 50m

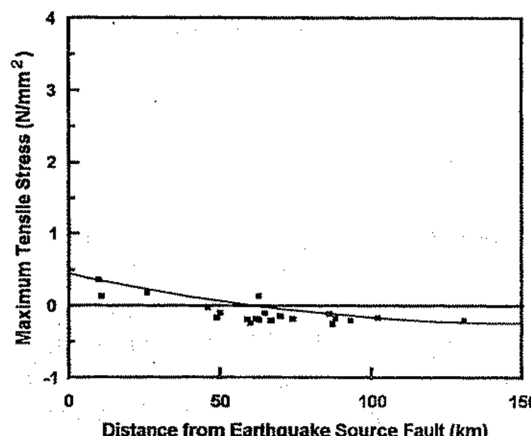
Figure 11 Maximum Tensile Stress versus Distance from Earthquake Source Fault (Excluding Static Stress)



(a) Dam Height =150m



(b) Dam Height =100m



(c) Dam Height = 50m

Figure 12 Maximum Tensile Stress versus Distance from Earthquake Source Fault (Including Static Stress)