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The crack behavior at the downstream face of a concrete gravity dam caused by wintertime air temperature variation

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ABSTRACT: Crack behaviors at the downstream face of a concrete gravity dam caused by wintertime air temperature variation were investigated in this article. Various initial cracks according to crack locations and directions were assumed. Numerical analysis was first done by the ADINA-T to obtain thermal distribution inside of the dam and the equivalent stress intensity factors at the crack tips for the various situations were calculated using the FRANC2D. Crack propagation possibilities were evaluated and crack propagation paths were investigated if the equivalent stress intensity factors exceed the fracture toughness. In addition, behaviors of cracks located at the upstream face were partially studied.

1 INTRODUCTION

As the downstream face of a concrete gravity dam has a wide surface and the surface is directly exposed to air temperature, the face repeatedly expands and contracts due to air temperature change in the summer and winter seasons. As a result, the dam crest moves to the upstream side during the summer season and to the downstream side during the winter season. In addition to these repeated actions, cracks can occur at the upstream and downstream faces of the dam by the alkali-aggregate reaction and non-uniform settlement of the foundation, etc. (Durcheva & Puchkova 1986, Jang et al. 1999, Lo & Ashraf 1999, Zhang & Ma 1991).

In this study, the behaviors of the initial cracks which have been assumed to occur at the downstream face were mainly investigated under the wintertime air temperature. And crack behaviors at the upstream face were partially investigated.

According to other research sources, ten percent of the annual variation in air temperature can be felt at 7.6m in depth from the concrete gravity dam surface and one percent at 15m from the surface (Higgison et al. 1970, Malla & Wieland 1999). Thus, in a location 15m from the surface, it can be estimated that the annual temperature cycle cannot give any influence on the interior temperature variation of a concrete gravity dam. Internal temperature of the dam during operation has been indicated as 10~15℃ according to other sources (Hagashigawa et al. 1992, Zhang & Ma 1991). Therefore, it was assumed in this study that the internal temperature of the dam is constant at 15℃ in the inner region 15m under the dam surface.

Temperature distributions between the 15℃ constant area and the dam surface were first calculated by the ADINA-T considered by reservoir water temperature, the constant temperature area with 15℃, and air temperature. The equivalent stress intensity factors at crack tips were calculated using the FRANC2D (Wawryznek & Ingraffea 1995) according to various initial cracks and various reservoir water levels. These values were used as an index to decide propagation possibility of the assumed initial cracks.

2 SHAPE OF DAM AND CONDITIONS OF ANALYSIS

Shape, dimensions of the dam, and boundary conditions used in this study are shown in Figure 1. The height, bottom width, and crest width of the dam are 96m, 86.46m and 9m, respectively. The material properties of the dam body and the foundation are given in Figure 1. Initial crack locations from the rock foundation at the downstream face (H_d) are assumed to be 87m, 69.6m, 52.5m, 34.8m and 17.4m. These values were determined considering finite element mesh, and the cracks were named A, B, C, D, E in order. At the upstream face, the same locations (H_u) were used except crack A. The angles of the initial crack (α) at the downstream face were assumed to be 22.5°, 0°, -22.5°, -45° and -67.5° in the clockwise. However, the angle considered at the upstream face was limited to 0° only.
The length of the initial crack (L) was assumed to be 1.0m. Measured reservoir water temperature was

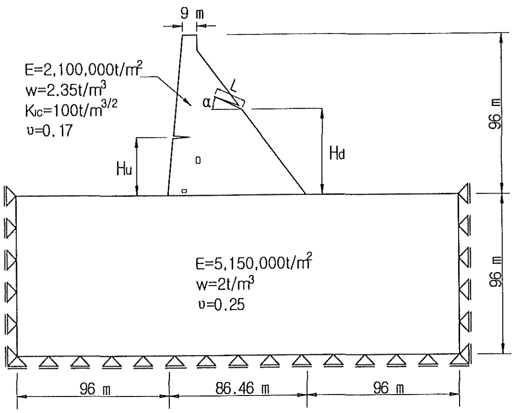

Figure 1. Dam cross section and boundary condition

used for thermal analysis and the temperature of the rock foundation was assumed to be 15℃ constantly. Air temperature values used were -20℃, -10℃, 0℃ and 10℃. 5t/m ice pressure was considered at the upstream face when the air temperature fell below zero. The considered reservoir water levels were 100%, 80%, 60% and 40% of full water level. Uplift pressure was considered and the fracture toughness (K_{Ic}) of the concrete gravity dam was assumed to be $100t/m^{3/2}$ (Ingraffea 1990).

3 THERMAL TRANSFER ANALYSIS

As air temperature varies in an almost sinusoidal function over a period of one year, the temperature distribution within a concrete dam can also be approximately estimated by the sinusoidal function. Therefore, the temperature fluctuation at a distance x from the surface at any time t can be written in the following form,

$$T(x,t) = T_0 e^{-ax} \sin(\omega t - ax) \tag{1}$$

where T_0 = the amplitude of the temperature fluctuation at the dam surface; ω = the circular frequency of the temperature fluctuation (ω=7.27× 10^{-5} rad/sec for daily cycles and ω=2.0×10^{-5} rad/sec for annual cycles); $a=(\omega/2h)^{1/2}$; h = the thermal diffusivity. Eq. (1) shows that the amplitude of the temperature fluctuation decays exponentially with the distance from the surface (Malla & Wieland 1999). Therefore, the ratio of temperature fluctuation between at any distance from the surface and the dam surface can be computed from,

$$\frac{T_x}{T_o} = e^{-x\sqrt{\omega/2h}} \tag{2}$$

where T_x and T_0 are the temperature fluctuation at distance x from the surface and at surface (x=0), respectively (Higginson et al. 1970).

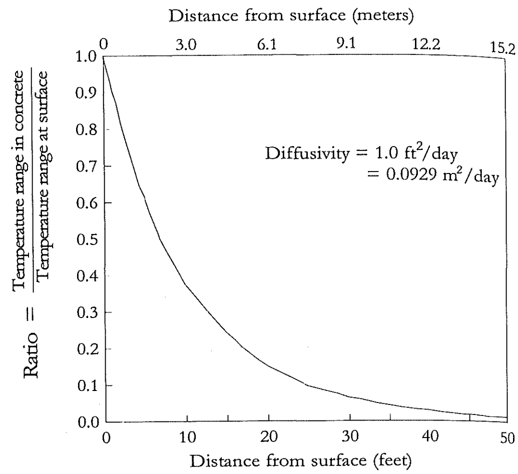

Figure 2. Ratio of temperature variation with depth

For an average concrete gravity dam, $h=1.00ft^2/day$ $(=0.0929m^2/day)$ is generally used for a diffusivity and the penetration depth of the annual temperature cycle according to Eq.(2) is shown in Figure 2.

As shown in Figure 2, it can be seen that only one percent of air temperature variation is observed at 15m from the dam surface.

In this study, a diffusivity of $0.0839m^2/day$ was calculated from the conditions and material properties. The region that the annual temperature cycle cannot give any influence on the interior

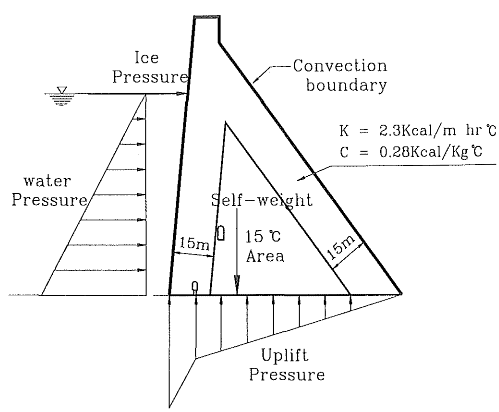

Figure 3. Applied loads and thermodynamic properties for thermal transfer analysis

temperature variation of concrete gravity dam was 14.35m from the surface. Therefore, 15m was used in this study for constant temperature region.

Figure 3 shows the interior region of constant temperature at 15℃, thermodynamic properties used in thermal transfer analysis, applied loads, and boundary conditions. Applied loads consists of dam self-weight, hydraulic pressure at the upstream face, uplift pressure at the dam foundation, and thermal stress caused by the air temperature.

4 ANALYSIS OF BEHAVIOR FOR INITIAL CRACKS

The equivalent stress intensity factor (K_{eq}) used in this study can be derived by substituting the stress intensity factors K_I and K_{II} calculated at the crack tip into Eqs. (3) and (4) based on the maximum circumferential tensile stress criterion (Erdogan & Sih 1963),

$$\tan\frac{\theta}{2} = \frac{1}{4}\frac{K_I}{K_{II}} \pm \frac{1}{4}\sqrt{\left(\frac{K_I}{K_{II}}\right)^2 + 8} \quad (3)$$

$$K_{eq} = \cos\frac{\theta}{2}\left[K_I \cos^2\frac{\theta}{2} - \frac{3}{2}K_{II}\sin\theta\right] \quad (4)$$

where θ = the crack propagation angle. Crack is propagated if the equivalent stress intensity factor exceeds the fracture toughness.

4.1 *Equivalent stress intensity factors according to crack locations and directions*

Table 1 shows that the equivalent stress intensity factors are changed according to locations and directions of initial cracks and to variations of air temperature. In this case, the considered reservoir water level is 80 % of the full water level. The (-)sign in Table 1 indicates that the equivalent stress intensity factor has a minus value. This means that the crack is closed in a physical sense.

As the air temperature falls below zero, it can be seen that the equivalent stress intensity factors exceed the fracture toughness (shaded part in Table 1). Therefore, it can be stated that air temperature in the wintertime can propagate the existing crack. Figure 4 shows the equivalent stress intensity factors according to initial crack locations and directions for -10℃ air temperature. The equivalent stress intensity factors exceed the fracture toughness in all cases except near the crest of the dam (crack A). At crack C and D, the equivalent stress intensity factors have a relatively large value in comparison with other locations. Also, in regards to crack direction, the equivalent stress intensity factors obtained from the downward direction cracks are generally larger than other directions.

Table 1. Equivalent stress intensity factors at the downstream face according to variation of the air temperatures

Crack	Crack direction (°)	Equivalent stress intensity factor ($t/m^{3/2}$) -20℃	-10℃	0℃	10℃
A (H_d=87.0m)	22.5	-	-	-	-
	0	-	-	-	-
	-22.5	-	-	-	8.518
	-45	-	-	-	26.886
	-67.5	-	-	-	-
B (H_d=69.6m)	22.5	49.555	73.438	25.208	77.038
	0	93.590	112.364	34.100	39.480
	-22.5	139.302	156.789	38.261	-
	-45	109.076	153.574	50.008	63.461
	-67.5	108.106	148.883	54.019	64.944
C (H_d=52.2m)	22.5	298.789	283.349	108.733	-
	0	393.900	308.585	164.900	36.410
	-22.5	439.437	348.233	191.706	38.086
	-45	493.802	383.350	211.590	71.360
	-67.5	419.599	333.058	195.046	59.453
D (H_d=34.8m)	22.5	324.070	234.364	149.187	-
	0	495.900	348.976	229.000	128.80
	-22.5	555.977	391.840	224.800	34.526
	-45	558.464	403.386	245.615	59.363
	-67.5	520.645	371.534	218.789	67.152
E (H_d=17.4m)	22.5	258.110	137.053	41.997	-
	0	366.600	194.851	47.270	-
	-22.5	394.446	203.341	46.760	-
	-45	399.201	204.644	50.894	-
	-67.5	357.551	184.688	49.007	-

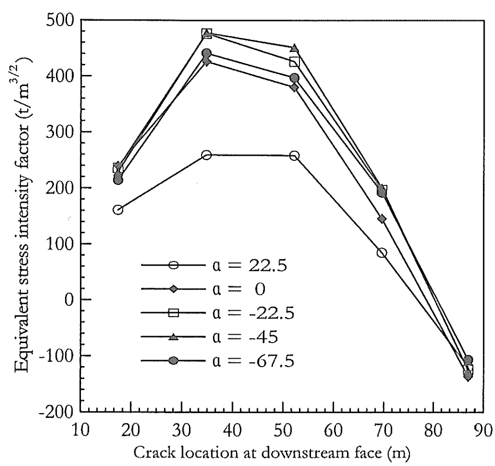

Figure 4. Equivalent stress intensity factors at the downstream face according to crack locations and directions (Air temperature = -10℃)

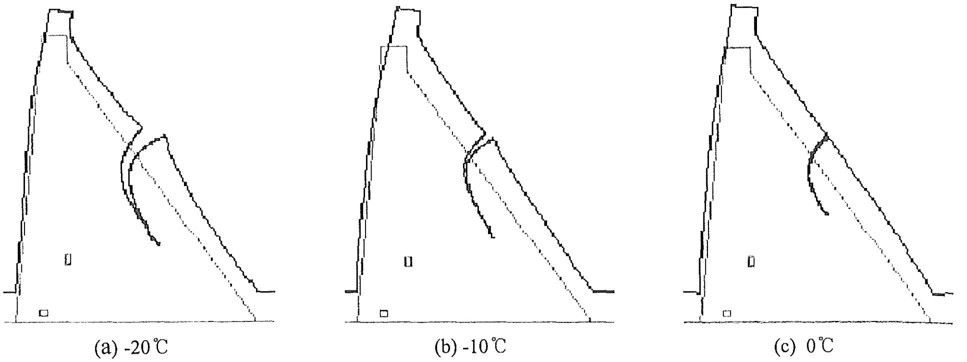

Figure 5. Configurations of crack propagation according to variation of air temperatures (crack C , α=-45°)

4.2 Configurations of crack propagation

Crack propagation analyses were performed if the equivalent stress intensity factors exceeded the fracture toughness. Typically, the propagation paths of a crack which is located at the middle height of a dam (crack C) having a *-45°* crack direction are shown in Figure 5. The cracks first developed inside the dam and then turned to almost a parallel direction with the downstream face. It can be seen that the propagation lengths and crack opening displacements gradually increased as the air temperatures decreased.

4.3 Crack behaviors at the downstream face according to variation of the reservoir water level

Crack behaviors at the downstream face were studied according to variation of reservoir water levels. The considered water levels were *100%*, *80%*, *60%*, and *40%* of the full water level. Air temperature was fixed to *-10 ℃*.

The equivalent stress intensity factors were calculated for the horizontal cracks ($\alpha=0°$) at five crack positions on the downstream face. Crack propagation paths were investigated if the equivalent stress intensity factors exceeded the fracture toughness. Figure 6 shows the equivalent stress intensity factors according to variation of water levels. It can be seen that the equivalent stress intensity factors increased with respect to the falling down of the reservoir water level. This might be a expected result due to the decreasing of hydrostatic pressure.

Crack propagation paths, with respect to variation of the water levels, were compared with horizontal cracks at the D location. The results are shown in Figure 7. It can be seen that deformations of the dam crest are in the opposite direction between full and 40% of the water level. For 40% of the full water level, the dam crest deformed toward the upstream

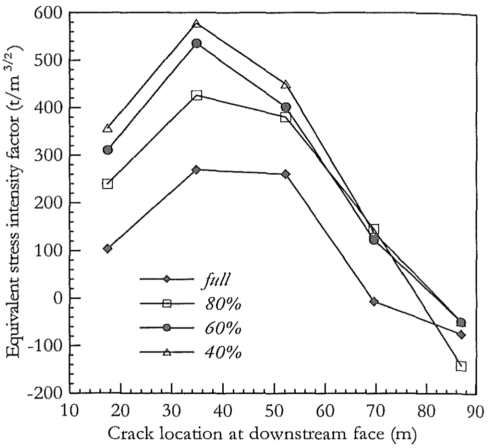

Figure 6. Equivalent stress intensity factor at downstream face according to reservoir water level variation

side of the dam in spite of the winter season due to the hydrostatic pressure reduction. The crack opening displacements and propagation lengths gradually increased as the water levels decreased.

4.4 Behavior analysis of initial cracks at the upstream face

To investigate the behavior of the cracks located at the upstream face according to air temperature variation, the equivalent stress intensity factors were calculated with respect to the initial cracks that are 1.0m in length and *0°* in direction at five locations. The air temperature was fixed to *-10 ℃* and the reservoir water level was 80% of the full water level. Hydrostatic pressure was applied inside of the cracks.

It could be known from table 2 that the equivalent stress intensity factors at the cracks located in the below of middle height of the dam at the upstream face exceeded the fracture toughness. Generally,

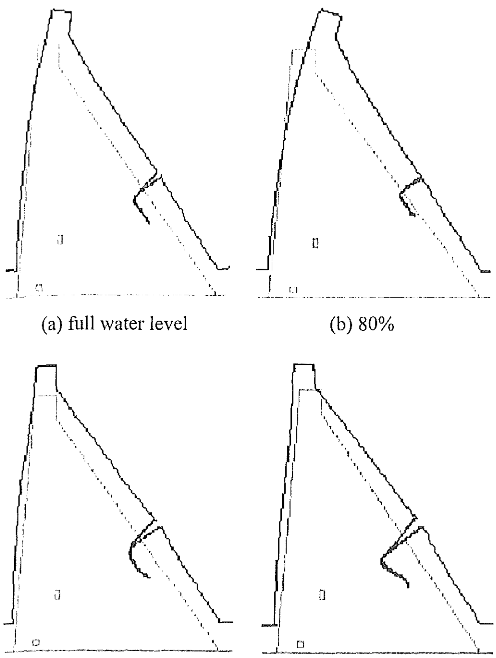

Figure 7. Configurations of crack propagation according to reservoir water level (crack D, α=0°)

Table 2. Equivalent stress intensity factors of initial cracks at the upstream face according to crack locations.

Crack	K_{eq} $(t/m^{3/2})$
B (H_u=69.6m)	32.140
C (H_u=52.2m)	296.500
D (H_u=34.8m)	372.000
E (H_u=17.4m)	294.200

there are no situations in which the equivalent intensity factor exceeds the fracture toughness when not considering air temperature. The reason for this is the influence of the large dam self-weight. However, in considering air temperature in the wintertime, it can be seen that the equivalent stress intensity factors exceed the fracture toughness. Therefore, there is a probability that a crack can develop both at the upstream face and the downstream face in the winter season.

5 CONCLUSIONS

(1) From results of the equivalent stress intensity factors at the crack tip of the downstream face due to air temperature variation, all values with the exception of a crack near the dam crest exceeded the fracture toughness below *0 ℃* air temperature. The values were relatively large both at the middle height of the dam and at below the middle height.

(2) In the air temperature of the winter season, cracks propagated to the parallel direction with the downstream face after developing a little bit towards the inside of the dam.

(3) In the air temperature of the winter season, the equivalent stress intensity factors increased as the reservoir water level decreased. The crack propagation lengths and crack opening displacements (COD) also increased.

(4) In the air temperature of the winter season, the equivalent stress intensity factors at the cracks located under the middle height of the upstream face exceeded the fracture toughness

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