THE PROPAGATION OF LIQUEFACTION PRESSURE AND DELAYED FAILURE OF A TAILINGS DAM DIKE IN THE 1978 IZU-OHSHIMA-KINKAI EARTHQUAKE

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SUMMARY

The dike of a tailings dam for a silver and gold concentration plant failed about 24 hours after the main shock (M=7.0) and about hours after the largest aftershock (M=5.8) of the 1978 Izu-Ohshima-Kinkai earthquake, while another larger dike failed due to the flow slide caused by liquefaction of the tailings during the main shock. The cause of the delayed failure was analysed by the propagation of liquefied pore pressure. The increase in the pore pressure with time at the slip surface caused the failure about 24 hours after the sudden liquefaction of the tailings behind the dike to a depth of about 9 m.

INTRODUCTION

On January 14, 1978, a destructive earthquake of magnitude 7.0 (M=7.0) on the Richiter scale occurred in Sagami Bay, central Japan and shook the Izu Peninsula (Ref.1). The aftershock zone shifted westward to the interior of the peninsula with the largest aftershock of M=5.8 taking place on January 15 under the peninsula (Fig.1).

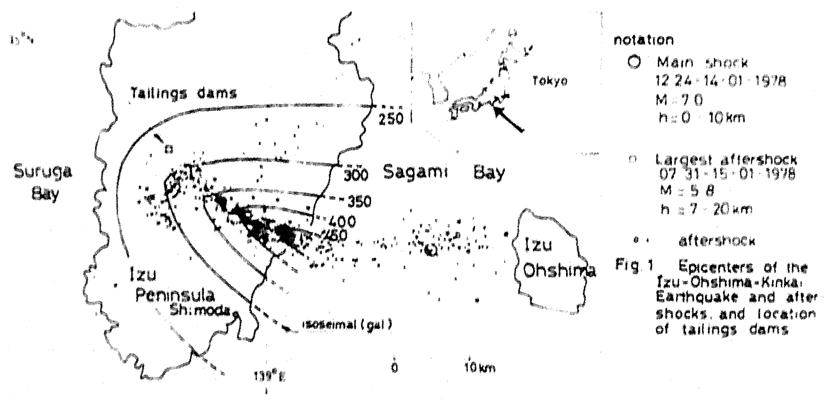

Fig 1 Epicenters of the Izu-Ohshima-Kinkai Earthquake and after shocks, and location of tailings dams

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The dike (No.2) of a tailings dam for a silver and gold concentration plant in use at Mochikoshi on the peninsula failed on January 15 about 24 hours after the main shock and about 5 hours after the largest aftershock (Fig.2). Another dike (No.1) of the same dam failed just after the main shock due to liquefaction of the tailings (Ref.2).

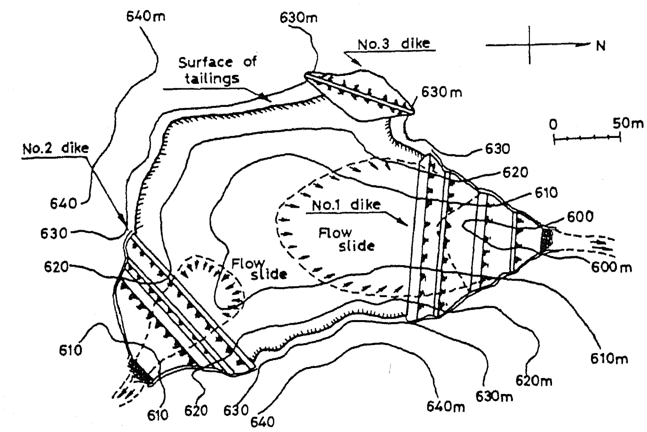

Fig.2
Plan of Mochikoshi
Tailings Dam

The cause for the delayed failure of the No.2 dike was hypothetically attributed to that the high excess pore-water pressure in the region behind the No.2 dike as induced by the main shock propagated through the tailings toward the dike, and that the process took about 24 hours to build the enough pore-water pressure to cause the failure. The dispersion of pore-water pressure is described by the same equation as that of consolidation. The problem was solved using the finite difference method for one dimensional cases under conditions where the excess pore-water pressure was suddenly increased to a level resulting in liquefaction to a depth of 8 to 9 m behind the No.2 dike, and that this high excess pore-water pressure was maintained for time, greater than zero. The phreatic surface in the dike advanced toward the dike surface according to the propagation of the pore-water pressure. The propagation of pore-water pressure was calculated for several horizontal levels with time, where the distances to the phreatic surface from the liquefied region were different. The distribution of the excess pore-water pressure on the slip surface was obtained with time.

The stability of the tailings and dike was analyzed by conventional slice method. The factor of safety for the critical slip surface of the No.2 dike was around 2.8 under static conditions. When the increases in the pore-water pressure with time at the slip surface and in the permeability of the dike material by the shock are taken into account, the factor of safety decreases rapidly to about 1.3 over several hours. After that, it gradually decreases to nearly unity 24 hours after sudden liquefaction to a depth of approximately 9 m from the lagoon surface behind the No.2 dike.

PROPAGATION OF EXCESS PORE-WATER PRESSURE

The equation for continuity of water through a compressible porous medium is expressed by,

$$\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = \rho(\alpha \frac{\partial f}{\partial t} - n\beta \frac{\partial U}{\partial t}) \tag{1}$$

where ρ is density of water, u, v, and w are discharge velocities of water in the direction of the Cartesian x-, y- , and z- axes, n is porosity of the porous medium, α is volume compressibility of the porous skeleton, f is mean effective stress in the medium, t is time, β is compressibility of water and U is excess pore-water pressure in the porous medium. Let the mean total stress in the medium be p, then

$$p = f + U \tag{2}$$

Darcy's law is expressed by,

$$u = -\frac{k}{\rho g}\frac{\partial U}{\partial t}, \quad v = -\frac{k}{\rho g}\frac{\partial U}{\partial t}, \quad w = -\frac{k}{\rho g}\frac{\partial U}{\partial t} \tag{3}$$

where k is coefficient of permeability, and g is acceleration of gravity. Employing (2) and (3) in (1) results in,

$$\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2} + \frac{\partial^2 U}{\partial z^2} = \frac{\rho(\alpha + n\beta)g}{k}\frac{\partial U}{\partial t} - \frac{\rho\alpha g}{k}\frac{\partial p}{\partial t} \tag{4}$$

where it is assumed that the changes in the coefficient of permeability, k, and in the water density, ρ, are negligible during the time in question. After the earthquake shock and the pore-water buildup, the total stress, p, can be taken as constant for several days. Therefore, (4) becomes,

$$\frac{\partial U}{\partial t} = \frac{k}{\rho\alpha(1 + n\beta/\alpha)g}\left(\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2} + \frac{\partial^2 U}{\partial z^2}\right) = \frac{k}{\rho\alpha g B}\nabla^2 U \tag{5}$$

where B is Skempton's pore-pressure coefficient.

CALCULATING METHOD

Approximately 24 hours after the main shock the No.2 dike failed. The rupture measured aboutd 55 m in width and 12 m in height including the four raised dams (Fig.3). About 3,000 m^3 of dike material and tailings escaped slowly into a valley in a relatively dry state compared to the slushy tailings flowing from the first dike failure immediately subsequent to the main shock. The material and tailings only advanced about 150 m and spontanously stopped in the valley on a slope of about 20°.

It was later confirmed that liquefaction of the tailings occurred up to between 8 and 10 m in depth from the lagoon surface behind the top raised dam of the second dike. The x axis was taken horizontally toward the second dike and the z axis positively upward as shown in Fig.3. It was assumed that liquefaction of the tailings occurred in the region shown in Fig.3 due to the main shock and the excess pore-

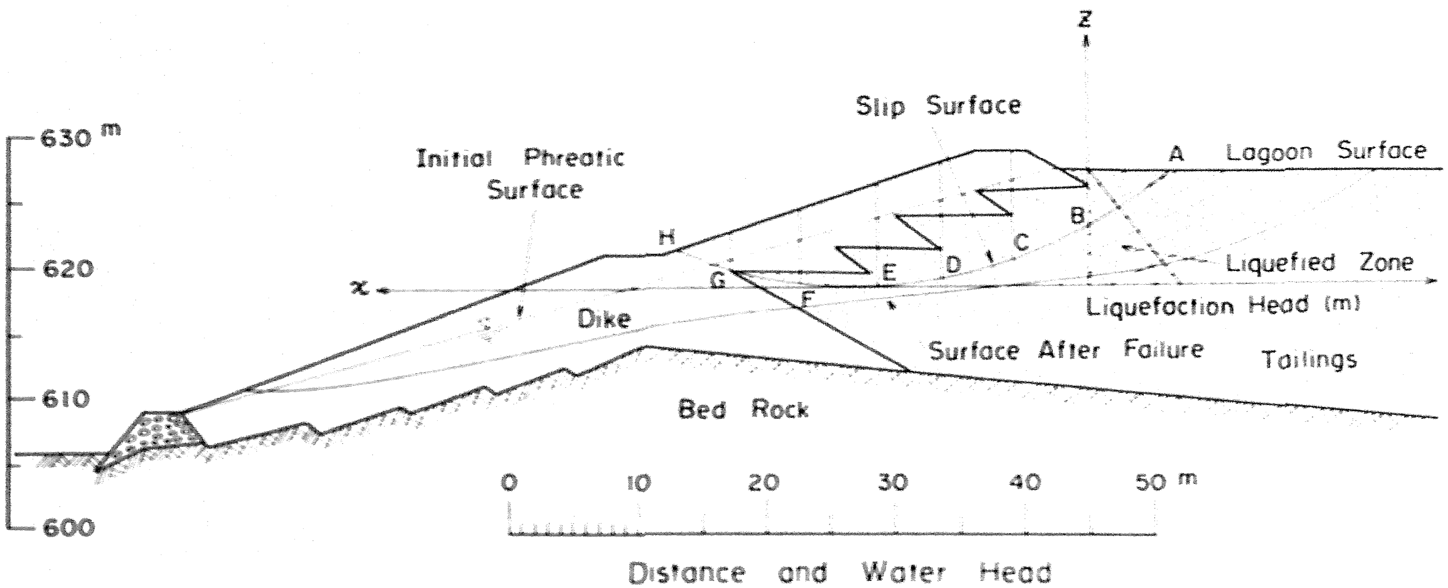

Fig.3 Typical Section of No.2 Dike and Slip Plane

water pressure propagated being dissipated in the horizontal x direction. In the liquefied region, the excess pore-water pressure at any depth was assmed to be equal to the submerged over-burden pressure of the tailings, though a pore-water pressure more than zero might have been produced at the surface because numerous sand volcanoes were found on the lagoon surface after the second dike failure. The propagation of the excess pore-water pressure would not have occurred in the direction of the first dike failure, which happened just after the main shock, because fine slurry tailings with high water content remained near the slip surface of the first dike failure. Therefore, the problem can be considered as being one-dimensional in the positive x direction, and (5) becomes,

$$\frac{\partial U}{\partial t} = \frac{k}{\rho \alpha g B} \frac{\partial^2 U}{\partial x^2} = c \frac{\partial^2 U}{\partial x^2} \tag{6}$$

where

$$c = k/\rho \alpha g B \tag{7}$$

represents the coefficient of consolidation. The liquefaction pressure, U_0 , at any z is,

$$U_0 = \gamma'(z_0 - z) \tag{8}$$

where z_0 is the depth of the origin from the lagoon surface and γ' is the submerged unit weight of the tailings. The calculation was carried out at B, C, D, E, F, and G levels shown in Fig.3. The boundary conditions of each level are given in Table 1 below.

Table 1 Boundary Conditions

Level	A	B	C	D	E	F	G
Height (m)	627.5	624.5	621.0	619.5	619.0	619.0	619.8
Boundary Pressure U (kPa)	0	30.4	55.6	68.2	72.5	72.5	66.5
Distance to Phreatic Surface (m)		18.0	29.0	32.5	35.0	35.0	32.0
Distance to Slip Surface (m)	0	0	6.0	12.0	16.0	22.0	27.0

The finite difference form of (6) is,

$$U_{j+1,i} = \left(1 - \frac{2c\Delta t}{\Delta x^2}\right) U_{j,i} + \frac{1}{2}\left(U_{j,i+1} + U_{j,i-1}\right) \tag{9}$$

where Δx is finite difference of the distance, Δt is finite difference of the time, and the suffixes j and i indicate the time and the distance, respectively.

The coefficient of permeability for the tailings in the horizontal direction is reported to be on the order of 10^{-5}m/s (Ref.3).

The compressibility of the tailings, $\alpha Bg \simeq \alpha g$, as determined from the consolidation test under static loading on the order of the effective overburden stress, is around $10^{-6} m^2/kg$. Since ρ is 1000 kg/m^3

$$c = k/\rho\alpha gB = 36\ m^2/h$$

The coefficient of permeability of the dike material (crushed and compacted volcanis rock) is on the order of 10^{-5}-10^{-6}m/s. The compressibility of the dike material is on the order of 10^{-6}-$10^{-7}m^2/kg$. However, the permeability and compressibility of the dike material would have been reduced to some extent due to the shaking by the main shock and frequent aftershocks. Therefore, $4x10^{-5}$m/s and $4x10^{-6} m^2/kg$ were taken as the permeability and compressibility of the dike material (the case (1)). For comparison the calculation was carried out using the permeability of 10^{-6}m/s and the compressibility of $10^{-7}m^2/kg$, respectively (the case (2)). Therefore, the value of c obtained for the dike material is the same that for the tailings, and the propagation of the excess pore-water pressure through the dike is represented by the same numerical equation, (9). The calculation was carried out using the distance difference Δx = 1 m and the time difference Δt = 1/72 hour so that the first term of (9) disappears.

Though the excess pore-water pressure at the phreatic surface is zero at each level shown in Table 1 at t = 0, a hydraulic gradient is produced near the phreatic surface as the pressure propagates, resulting in an advance of the phreatic surface toward the dike surface. To estimate this advance of the phreatic surface, for t = 1 h the hydraulic gradient, Δh, between the phreatic surface and a point 1 m back from it was checked and the phreatic surface was assumed to advance during the next $\Delta t \doteq 1$ h due to this hydraulic gradient. The advance, Δl_{j+1}, at any time during Δt = 1(h) is approximately expressed by

$$\Delta l_{j+1}\ n\ (1 - S) = k\Delta h_j x1\ (h)/(l_j - l_{j-1})$$

where n is porosity, S is degree of saturation of the dike material and l_1 = 1 m. This procedure was repeated for each time and level.

STABILITY ANALYSIS

Stability analysis was carried out with the conventional slice method for the estimated slip plane which coincided with the least factor of safety of about 2.8 under undisturbed conditions. Soil parameters used for the analysis are shown in Table 2 below. In the calculation, the horizontal pore-pressure for each slice was taken into account. The sliding block was divided into seven slices as is shown in Fig.3.

Fig.4 presents the distributions of the excess pore-water head on the slip surface 1 hour and 24 hours after the main shock for the case (1). Fig.5 represents varations of the factor of safety and phreatic surface with time. It is clear that for the case (1) the

Table 2 Tailings and Dike Parameters

	Tailings	Dike
Specific Gravity of Particles	2.70	2.52
Unsaturated Unit Weight (kN/m^3)		15.97
Saturated Unit Weight (kN/m^3)	18.33	16.95
Degree of Saturation (%)	100	81
Void Ratio	0.95	1.08
Coefficient of Permeability (m/s)	10^{-5}	(1) $4x10^{-5}$ (2) 10^{-6}
Compressibility (m^2/kN)	$1.02x10^{-4}$	(1) $4.08x10^{-4}$ (2) $1.02x10^{-5}$
Cohesion c' (kN/m^2)	0	29.4
Angle of Internal Friction ϕ'	35°	35°

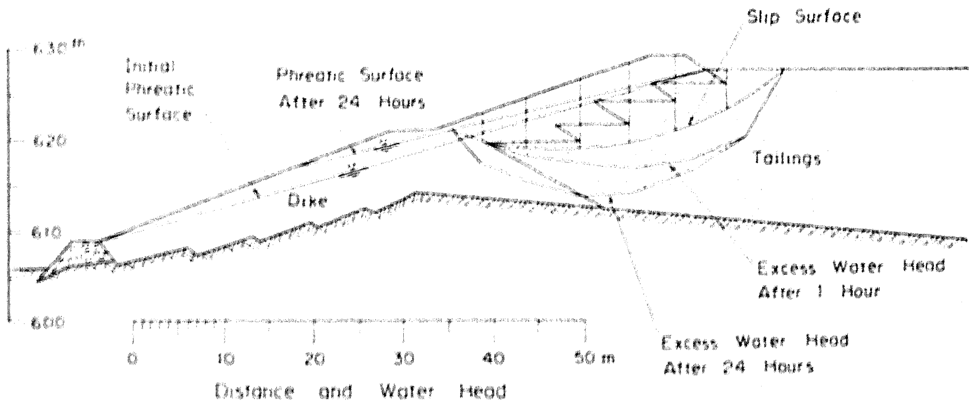

Fig.4 Excess Pore-Water Head Distribution on Slip Plane

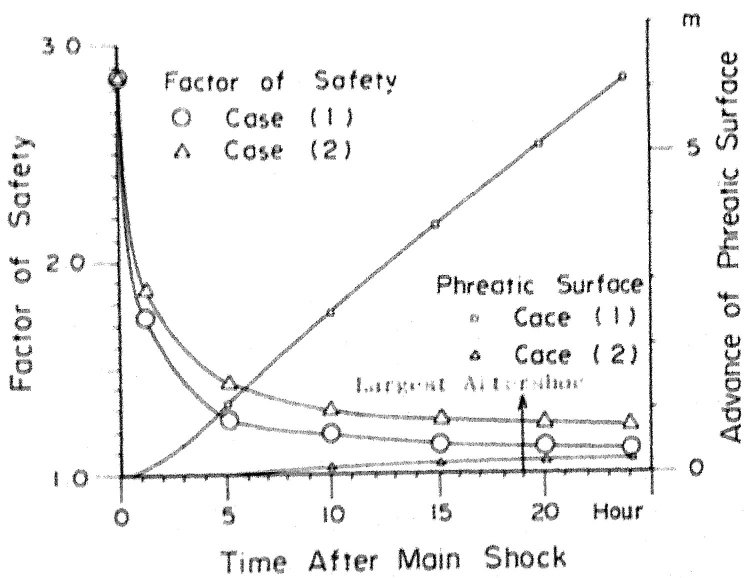

Fig.5 Variations of Factor of Safety and Horizontal Auvance of Phreatic Surface at z = 0

factor of safety decreases rapidly to 1.3 in about 5 hours and thereafter it gradually decreases to nearly unity about 24 hours after the sudden liquefaction behind the dike. For the case (2) the advance of the phreatic surface is small and the factor of safety still remains around 1.2 around 24 hours after the main shock.

The largest aftershock prior to the failure would have contributed to the increase in the permeability of the dike material, which in turn facilitated the propagation of pore-water pressure in the dike. The main shock and frequent aftershocks would have been responsible for lowering strength parameters of the tailings and dike material.

CONCLUSION

The No.2 dike of the Mochikoshi tailings dam had a safety factor of about 2.8 in an undisturbed state, and failed about 24 hours after the main shock of the Izu-Ohshima-Kinkai earthquake. The No.1 dike failed down directly after the main shock due to liquefaction of the tailings behind the dike. The tailings behind the No.2 dike also liquefied, but those under the raised dams of the No.2 dike did not liquefy. The excess pore-water pressure which caused liquefaction propagated toward the surface of the No.2 dike, and the pore-water pressure under the raised dams and in the dike gradually increased. Finally about 24 hours after liquefaction, the pore-pressure buildup became large enough to cause the failure of the No.2 dike along with the tailings.

The propagation of excess pore-water pressure depends on the ratio of the coefficient of permeability and compressibility of the medium, i.e., the consolidation coefficient. The greater the consolidation coefficient, the more rapid the propagation. The reasonable values of the consolidation coefficient for the tailings and dike material explain the delayed failure of the No.2 dike.

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