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AN INTEGRATED APPROACH TO PREDICT OUTFLOW HYDROGRAPH DUE TO LANDSLIDE DAM FAILURE BY OVERTOPPING AND SLIDING

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Formation and failure of landslide dam are one of the significant natural hazards in the mountainous area all over the world. In the event of catastrophic failure of landslide dam, we have to predict resulting outflow hydrograph. It will serve as an upstream boundary condition for subsequent flood routing to predict flood hazard in the downstream. Most of the existing models are applicable to overtopping failure of landslide dam. In this study an attempt has been made to incorporate integration of three separate models to predict the outflow hydrograph resulted from failure of landslide dam by overtopping and sudden sliding through flume experiments and numerical simulations. The main advantage of an integrated model is that it can detect failure mode due to either overtopping or sliding based on initial and boundary conditions. The proposed model is tested for three different experimental cases of landslide dam failure due to overtopping and sliding and reasonably reproduced the resulting hydrograph.

Key Words **:** *landslide dam, slope stability, seepage flow, overtopping flow, flood/debris flow hydrograph*

1. INTRODUCTION

Formation and failure of landslide dam are one of the significant natural hazards in the mountainous area all over the world. Landslide dams are also common in Japan because of widespread unstable slopes and narrow valleys exist in conjunction with frequent hydrologic, volcanic and seismic landslide triggering events[1]. Historical documents and topography have revealed the formation of many landslide dams, some of which broke and caused major damage in Japan[2]. The 2004 Chuetsu earthquake resulted in many landslide dams particularly in the Imo River basin. In 2005, typhoon 14 caused a large landslide dam near the Mimi-kawa river[3].

Sudden, rapid and uncontrolled release of water impounded in landslide dam has been responsible for some major disasters in mountainous region. To provide adequate safety measures in the event of such a catastrophic failure we have to predict resulting outflow hydrograph. It will serve as an upstream boundary condition for subsequent flood routing to predict inundation area and hazard in the downstream. Peak discharge produced by such events may be many times greater than the mean annual maximum instantaneous flood discharge.

There are two methods to predict probable peak discharge from potential failure of landslide dam[4]. One method relies on regression equations that relate observed peak discharge of landslide dam failure to some measure of impounded water volume: depth, volume, or some combination thereof[5,6] and regression equations that relate experimental peak discharge to some measure of impounded water volume: depth, torrent bed gradient and inflow discharge[7]. The other method employs computer implementation of a physically based mathematical model. Several researchers have developed physically based model such as Fread[8], Singh et al.[9], Takahashi and Kuang[10], Takahashi and Nakagawa[11], Mizuyama[3] and Satofuka et al.[12]. Although, landslide dam failure is frequently studied as an earthen dam failure, very few models are developed for landslide dam failure that can treat the flow as both sediment flow and debris flow. If the concentration of sediment is above 10%, non-newtonian viscous flow has to be taken into account. During surface erosion of landslide dam, sediment concentration increased more than 10%, so the model to predict the flood/debris flow hydrograph due to landslide dam failure should be capable to treat all types of flow based on sediment concentration.

Most of the existing models are applicable to overtopping failure of landslide dam. In this context, an attempt has been made to incorporate integration of three separate models: (i) model of seepage flow analysis, (ii) model of slope stability and (iii) model of dam surface erosion and flow to predict the outflow hydrograph resulted from failure of landslide dam by overtopping and sudden sliding. The main advantage of an integrated model is that it can detect failure mode due to either overtopping or sliding based on initial and boundary conditions.

2. NUMERICAL MODEL

The model of the landslide dam failure to predict outflow hydrograph consists of three models. The seepage flow model calculates pore water pressure and moisture content inside the dam body. The model of slope stability calculates the factor of safety and the geometry of critical slip surface according to pore water pressure and moisture movement in the dam body. The model of dam surface erosion and flow calculates dam surface erosion due to overflowing water. General outline of proposed integrated model is shown in **Fig. 1**. A brief description of each model is given below.

(1) Model of seepage flow

The seepage flow in the dam body is caused by the blocked water stage behind the dam. The transient flow in the dam body after formation of landslide dam can be analyzed by Richards' equation. To evaluate the change in pore water pressure in variably saturated soil, pressure based Richards' equation is used[13].

$$C\frac{\partial h}{\partial t}=\frac{\partial}{\partial x}\left(K_x(h)\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial z}\left(K_z(h)\left(\frac{\partial h}{\partial z}+1\right)\right) \quad (1)$$

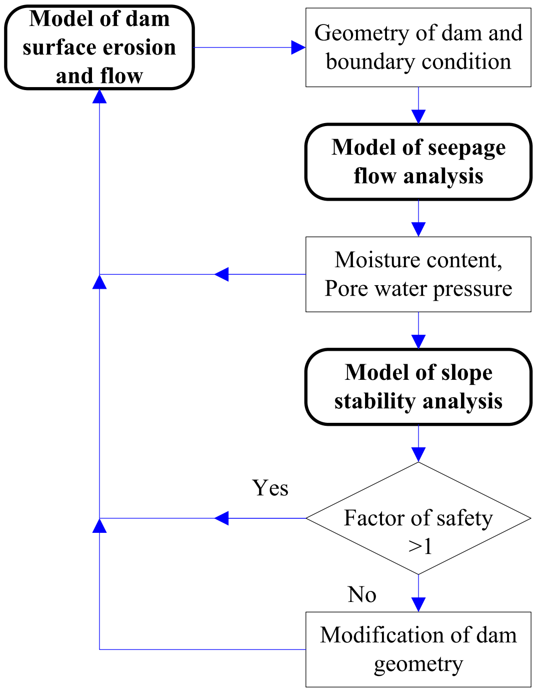

Fig. 1: Model of landslide dam failure to predict flood/debris flow hydrograph

where h is the water pressure head, $K_x(h)$ and $K_z(h)$ are the hydraulic conductivity in x and z direction, C is the specific moisture capacity $(\partial\theta/\partial h)$, θ is the soil volumetric water content, t is the time, x is the horizontal spatial coordinate and z is the vertical spatial coordinate taken as positive upwards. Eq.(1) represents flow in both the unsaturated domain as well as in the saturated domain. Line-successive over-relaxation (LSOR) is often a very effective method of treating cross-sectional problem grids. LSOR scheme is used in this study for the numerical solution of Richards' equation.

In order to solve Richards' equation, the constitutive equations, which relate the pressure head to the moisture content and the relative hydraulic conductivity, are required. In this study, constitutive relationships proposed by van Genuchten[14] are used for establishing relationship of $K-h$ and $\theta-h$, with $m=1-(1/\eta)$.

(2) Model of slope stability

The evaluation of transient slope stability of landslide dam by the limit equilibrium method involves calculating the factor of safety and searching for the critical slip surface that has the lowest factor of safety. Many attempts have been conducted to locate the position of critical slip surface by using general noncircular slip surface theory coupled with different non-linear programming methods. The numerical procedure behind the identification of critical noncircular slip surface with the minimum factor of safety based on dynamic programming and the Janbu's simplified method is mainly based on research by Yamagami and Ueta[15]. The algorithm combines the Janbu's simplified method with dynamic programming on the basis of Baker's successful procedure.

Janbu's simplified method can be used to calculate the factor of safety for slip surfaces of any shape. The sliding mass is divided into vertical slices and the static equilibrium conditions of each slice are considered as sum of the vertical forces equal to zero and sum of the forces parallel to failure surface equal to zero. For the soil mass as a whole, sum of the vertical forces $\sum F_y = 0$ and sum of the horizontal forces $\sum F_x = 0$ are considered as equilibrium condition.

Based on the above considerations the factor of safety, F_s for Janbu's simplified method is defined as:

$$F_s = \frac{1}{\sum_{i=1}^{n} W_i \tan \alpha_i} \times \sum_{i=1}^{n} \left\{ \frac{c l_i \cos \alpha_i + (W_i - u_i l_i \cos \alpha_i) \tan \phi}{\cos^2 \alpha_i \left(1 + \frac{1}{F_s} \tan \alpha_i \tan \phi \right)} \right\} \quad (2)$$

where W_i is the weight of each slice including surface water, l_i is the length of the base of each slice, u_i is the average pore water pressure on the base of the slice, α_i is the inclination of the base to the horizontal, n is the total number of slices, and c and ϕ are the Mohr-Coulomb strength parameters.

The details of transient slope stability analysis of landslide dam by using dynamic programming and Janbu's simplified method can be found in Awal et al.[13].

(3) Model of dam surface erosion and flow

The mathematical model developed by Takahashi and Nakagawa[11] was used for the modeling of surface erosion and flow. The model was capable to analyse the whole phenomena from the beginning of overtopping to the complete failure of the dam as well as to predict flood/debris flow hydrograph in the downstream. The infiltration in the dam body was not considered in the model; therefore, time to overflow after formation of landslide dam can not be predicted from previous model. In this study, infiltration in the dam body is also incorporated.

The model is two-dimensional and it can also collapse to treat one-dimensional for overtopping from full channel width. In case of sudden sliding failure, simplified assumption is made for initial transformation of the dam body after the slip failure. Based on many experiments the slipped mass is assumed to stop at the sliding surface where slope is less than angle of repose and the shape of the slipped mass is assumed as trapezium. There is some time lag between slip failure and movement of the slipped soil mass but in the model, the time necessary for such a deformation is assumed as nil. The erosion process by the overspilled water is analysed for the modified dam shape.

The erosive action of the overtopping flow removes material from the top part of the dam. The overtopped flow grows to debris flow by adding the eroded dam material to it, if the slope and length of dam body satisfy the critical condition for the occurrence of a debris flow.

The main governing equations are briefly discussed here. The depth-wise averaged two-dimensional momentum conservation equation for the x-wise (down valley) direction is

$$\frac{\partial M}{\partial t} + \beta' \frac{\partial (uM)}{\partial x} + \beta' \frac{\partial (vM)}{\partial y} = gh \sin \theta_{bxo} - gh \cos \theta_{bxo} \frac{\partial (h + z_b)}{\partial x} - \frac{\tau_{bx}}{\rho_T} \quad (3)$$

and for the y-wise (lateral) direction,

$$\frac{\partial N}{\partial t} + \beta' \frac{\partial (uN)}{\partial x} + \beta' \frac{\partial (vN)}{\partial y} = gh \sin \theta_{byo} - gh \cos \theta_{byo} \frac{\partial (h + z_b)}{\partial y} - \frac{\tau_{by}}{\rho_T} \quad (4)$$

The continuity of the total volume is

$$\frac{\partial h}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = i\{c_* + (1 - c_*) s_b\} - q \quad (5)$$

The continuity equation of the particle fraction is

$$\frac{\partial (ch)}{\partial t} + \frac{\partial (cM)}{\partial x} + \frac{\partial (cN)}{\partial y} = i c_* \quad (6)$$

The equation for the change of bed surface elevation is

$$\frac{\partial z_b}{\partial t} + i = i_{sml} + i_{smr} \quad (7)$$

where $M = uh$ and $N = vh$ are the x and y components of flow flux, u and v are the x and y components of mean velocity, h is the flow depth, z_b is the elevation, ρ_T is the apparent density of the flow, $\rho_T = c(\sigma - \rho) + \rho$, c is the volume concentration of the solids fraction in the flow, σ is the density of the solids, ρ is the density of water, β' is the momentum correction coefficient, τ_{bx} and τ_{by} are the x and y components of resistance to flow, i is the erosion or deposition velocity, c_* is the solids fraction in the bed, s_b is the degree of saturation in the bed (applicable only in cases of erosion, when deposition takes place substitute $s_b = 1$), i_{sml} and i_{smr} are the mean recessing velocity of the left and right hand side banks of the incised channel, respectively, t is the time, g is the acceleration due to gravity and q is the infiltration rate.

Shear stress, erosion or deposition velocity and channel enlargement for overtopping from partial channel width were evaluated using the model presented in Takahashi and Nakagawa[11].

3. EXPERIMENTAL STUDY

A rectangular flume of length 5m, width 20cm and depth 21cm was used. The slope of the flume was set at 17 degree. Mixed silica sand of mean diameter 1mm was used to prepare triangular dam in the flume. The height of the dam was 20cm and the longitudinal base length was 84cm. The schematic diagram of the flume is shown in **Fig. 2.** van Genuchten parameters (including θ_r) were estimated by non-linear regression analysis of soil moisture retention data obtained by pF meter experiment. Some other parameters of mixed sand are listed in **Table 1**.

The shape of the dam body at different time step due to surface erosion after overtopping and the shape of slip surface during sliding were measured by analyses of video taken from the flume side. Water content reflectometers (WCRs) were used to measure the temporal variation of moisture content during seepage process. Load cell and servo type water gauge were used to measure sediment and total flow in the downstream end of the flume. pF meter with automatic pressure controller was used to determine the van Genuchten parameter of sand mixture used for the landslide dam.

4. RESULTS AND DISCUSSIONS

Numerical simulations and flume experiments were performed to investigate the mechanism of landslide dam failure and resulting hydrograph due to overtopping and sudden sliding. Experimental conditions and parameters used for simulations in different cases are shown in **Table 2**. K and δ_d are the parameters of erosion and deposition velocity respectively. Following three cases are considered:

Case I: Overtopping (from full channel width)

Steady discharge of 550 cm^3/sec was supplied from the upstream part of the flume. The model started simulation after the start of inflow. Overtopping occurred after the filling of the reservoir. Overtopped water proceeds downstream eroding the crest as well as the downstream slope of the dam body.

The simulated and experimental outflow hydrograph at 66cm downstream of the dam are

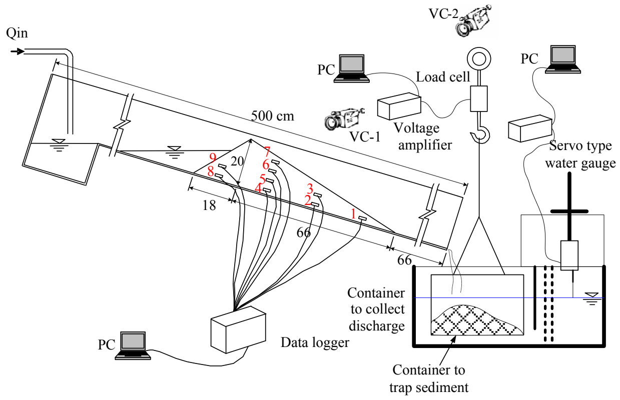

Fig. 2 Experimental setup

Table 1 Some parameters of the sediment considered

Sediment type	SMix
Saturated moisture content, θ_{sat}	0.287
Residual moisture content, θ_{res}	0.045
α	5.50
η	3.20
Specific gravity, Gs	2.65
Mean grain size, D_{50} (mm)	1.00
Angle of repose, ϕ (degree)	34

Table 2 Experimental conditions and parameters for simulation

Case	Q (cm^3/sec)	Water content	Permeability K_s (m/sec)	K	δ_d
I	550	50%	0.00018	0.11	0.005
II	49	50%	0.00018	0.11	0.005
III	30.5	20%	0.00030	0.11	0.005

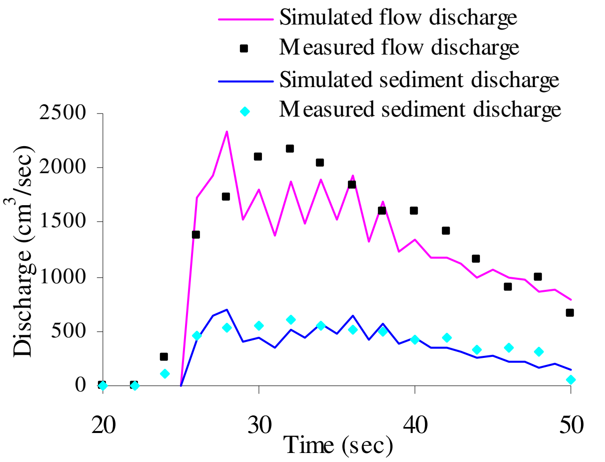

Fig. 3 Outflow hydrograph

represented in **Fig. 3**. Transformation of the dam body with time is shown in **Fig. 4.** The shape of the simulated surface of the dam body at each time steps are similar to observed. The simulated outflow hydrograph is not matching perfectly due to

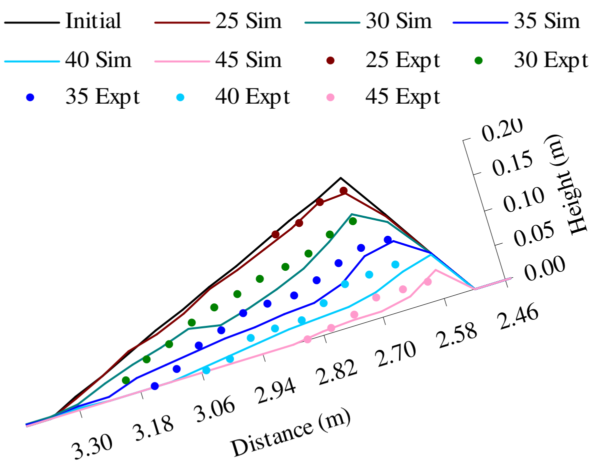

Fig. 4 Comparison of dam surface erosion

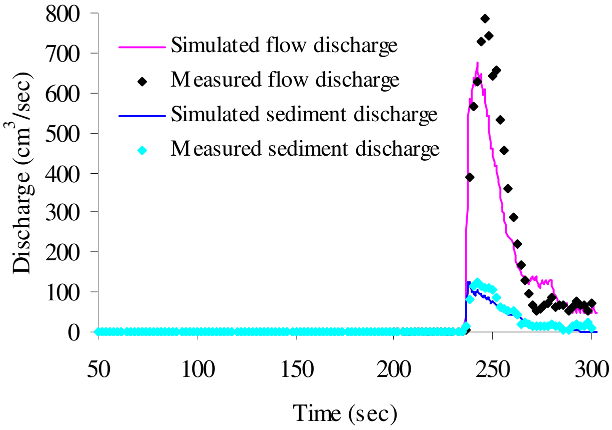

Fig. 5 Outflow hydrograph

difference in time to overspill the reservoir and rate of dam surface erosion between simulation and experiment.

Case II: Overtopping and channel breach (from partial channel width)

Notch of the width 5cm and depth 0.5cm was incised at the crest and downstream face of the dam in the left side of the dam body so that the erosion of the surface of dam body can be observed from left side of the flume. Steady discharge of 49.0 cm^3/sec was supplied from the upstream part of the flume, after the filling of the reservoir, it overflowed from the notch at the crest of the dam. The overtopping flow incised a channel on the slope of the dam and that channel increased its cross-sectional area with time caused by the erosion of released water. The simulated and experimental outflow hydrograph are represented in **Fig. 5**. **Fig. 6** shows the comparison of the simulated and experimental shapes of dam surface at different time steps. In both experiment and simulation the channel incised almost vertically that may be due to rapid drawdown of reservoir and small inflow rate. The overflowing water depth was very small so the shear stress due to flowing water in the side wall of incised channel was also small and above the water level there was some apparent cohesion added by water content and adhesion so the side wall is very steep. Armouring effect is also negligible due to small particle size of the dam body.

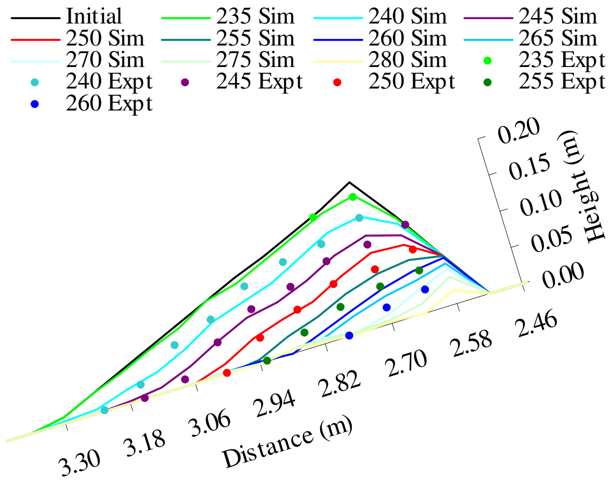

Fig. 6 Comparison of dam surface erosion at incised channel

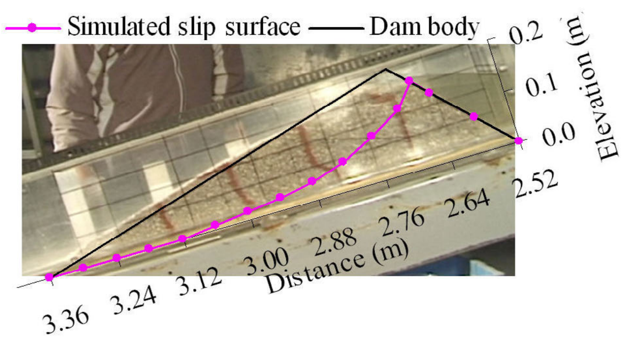

Fig. 7 Comparison of simulated and experimental slip surface

Case III: Sudden sliding

Steady discharge of 30.5 cm^3/sec was supplied from the upstream part of the flume. The sudden sliding of the dam body was observed at 447sec in the experiment whereas in the simulation it was observed at 410sec. The simulated time was slightly earlier than the experimentally observed time that may be due to the assumption of immobile air phase in unsaturated flow and variation of saturated hydraulic conductivity. **Fig. 7** shows the comparison of simulated and experimental slip surface. For the same experimental conditions, moisture content in the dam body was measured by using WCRs. **Fig. 8** shows the simulated and experimental results of moisture profile at WCR-4, WCR-5, WCR-6, WCR-8, and WCR-9 which are in good agreement. The geometry of predicted critical slip surface was also similar to that observed in the experiment.

Fig. 9 shows the simulated and experimental results of outflow hydrograph. There is some time lag between failure of dam and movement of the slipped soil mass but in the model, the time

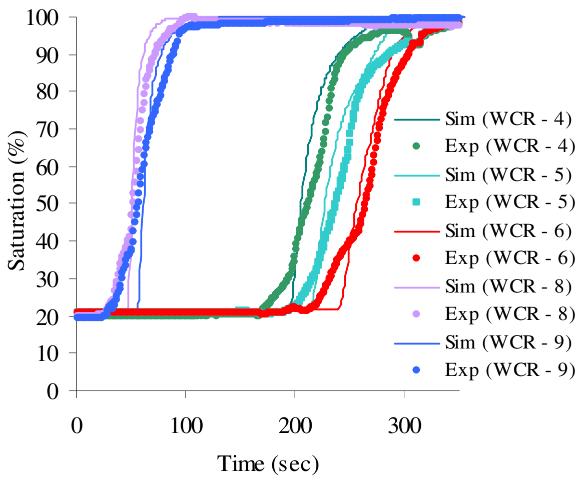

Fig. 8 Simulated and experimental results of water content profile for different WCRs

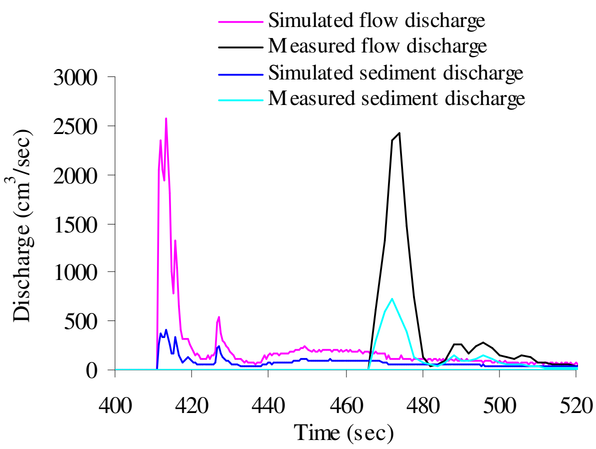

Fig. 9 Outflow hydrograph

necessary for such a deformation is assumed as nil so the simulated peak is earlier than experimental peak. Peak discharge depends on the shape of the dam body assumed after sliding and parameters of erosion and deposition velocity.

The movement of moisture in the dam body measured by using WCRs, critical slip surface observed in the experiment and predicted outflow hydrograph are close to the result of numerical simulation.

5. CONCLUSIONS

A combined numerical model is developed for simulation of outflow hydrograph due to landslide dam failure by overtopping and sliding. The proposed model is tested for three different experimental cases of landslide dam failure due to overtopping and sliding and reasonably reproduced the resulting hydrograph. The numerical simulation and experimental results of movement of moisture in the dam body, predicted critical slip surface and time to failure of the dam body are also in good agreement. The predicted hydrograph can be used for flood disaster mitigation in the downstream. The model can be further extended to three-dimensions for the better representation of failure process of landslide dam.

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