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MECHANISM OF NATURAL DAM COLLAPSE FORMED IN A STEEP SLOPE CHANNEL AND SIMULATION

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In gorges of Mountain Rivers, banks with weak geological configuration and landslide-prone, formation of natural dams is common and such kinds of dams exist every year in Nepal, chiefly, in rainy season.

The present study discusses on mechanism of natural dam collapse and makes an effort to simulate collapse mechanism of the dams in a steep gradient flume made up with two kinds of mixtures. Firstly, using fine uniform particles; and secondly, a mixture of coarse and fine particles, i.e., non-uniform mixture. Natural dams, trapezoidal in shape, with downstream frontal slope nearly equal to the angle of repose of dam forming materials, were made in the channel for the experiment. One-dimensional momentum and continuity equations for unsteady flow in open channel and Janbu method of slope stability were used to verify the experimental results.

***Key words**: Collapse mechanism, Debris flow, Mountain River, Natural dam, Simulation*

1. INTRODUCTION

Field observations and investigations indicate that following three activities generally result in debris flows. Firstly, landslide that turns into debris; secondly, destruction of a naturally built dam turning into debris flow; and lastly, surface water flow on a gully bed during heavy rainfall, which mobilizes the accumulated mass. Destruction mechanism of natural dams varies with the properties of dam forming materials, hydraulic and physical characteristics of the stream channels in which the dams are formed. Failure or destruction mechanism can broadly be classified into three categories as per observation made by various researchers: erosive destruction due to overtopping, abrupt sliding collapse, and progressive failure depending on the characteristics of dam forming materials.

In this paper, destruction process and simulation of the destruction phenomena of natural dams made of two kinds of mixtures: (a) uniform fine sand with mean diameter 1mm and (b) non-uniform mixture of fine sands and gravel with mean diameter 5.43mm, in a steep slope of experimental flume, are presented. Large flow rate from the upstream and low rate of permeability of the dam forming materials cause to impound the water upstream of the dam. Later, the impounded water flows over the dam eroding particles from the surface. Both uniform and non-uniform cases reveal almost similar patterns of the destruction except the time taken for complete wash out of the dam from initial position. For example, in the both cases, failure mechanism of the frontal part of the dam can be considered as slope failure and the body part as erosion. The distinction between land sliding and debris flow is analogous to that between sand that slips incrementally along discrete failure surfaces, as may happen underfoot on a beach, and sand that flows rapidly, as may happen in a steep dune face[1)].

Knowledge of debris flow largely based on the pioneering work of Bagnold (1958)[2)] and intensive and extensive study of some Japanese researchers, e.g., Takahashi (1978)[3)] and others. Many researchers have done almost similar studies regarding the failure mechanism and mobilization of channel bed using specific shape of dam and flow conditions[4)5)].

Present study attempts to discuss different type of failure mechanism in a dam, e.g., landslide at the

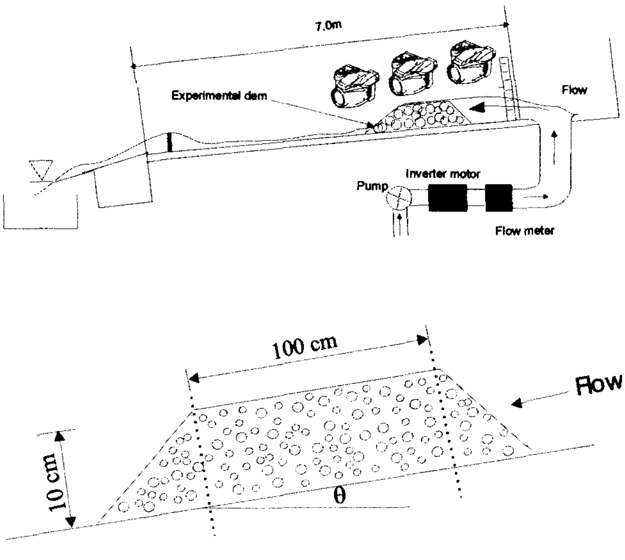


Fig. 1 Schematic diagrams of experimental set-up and dam Section

frontal part and bed load transportation by erosion or mobilization of bed as debris flow at the body part making use of trapezoidal shape of natural dam with downstream frontal slope nearly equal to the angle of repose of dam forming materials. Moreover, temporal eroded volume from the dam body is also calculated. This study employs Janbu method of slope stability[6] and equations of one-dimensional unsteady flow in open channel for simulation.

2. EXPERIMENTS

(1) Experimental set-up and procedure

The experiments were conducted in a glass-sided indoor laboratory flume that was 10-m long, 0.15-m wide, and 0.30-m deep. The flume was equipped with adjustable bed slope mechanism.

A dam (15cm wide, 10 cm deep and 1 m long), was constructed at the upstream part of the flume, for each run by using uniformly graded fine materials and a mixture of gravel-sand with mean diameter of 1 mm and 5.43 mm respectively. The downstream frontal slope of the dam was almost similar to the angle of repose[7] of the materials used in forming the dam.

A constant water discharge was supplied from upstream until the destruction of dam out of its initial position completed and the rate of flow was reckoned manually using a measuring bucket and a stopwatch. Three video cameras were set at different locations to record the destruction process of the dam. The schematic figures of the experimental set-up are shown in **Fig. 1**.

(2) Experimental condition

Table 1 Experimental conditions
Bed slope of channel = 1/5.57

Run No.	Grains size (d_m) mm	Discharges (cm^2/sec)				
		q1	q2	q3	q4	q5
1	Uniform d_m= 1mm	20.67	26.00	34.67	63.83	84.67
2	Non uniform d_m= 5.43mm	50.67	69.93	72.00	93.33	106.0

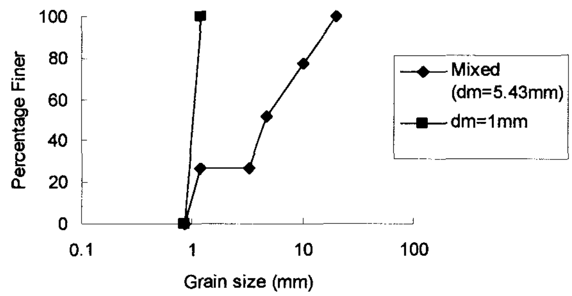


Fig. 2 Grain size distribution curves

Experiments were conducted in two runs; each run was carried out with five different amounts of discharge. Both runs were conducted at a channel slope of 1/5.57. Two different mixtures, one uniform and the other non-uniform, were used to form natural dams in experimental flume: in the case of run one, almost uniform sand and for run two, non-uniform mixture of sand and gravel. Experimental conditions are summarized in **Table 1**.

(3) Grain size distribution curve

The grain size distribution curves of (a) uniform fine sand and (b) non-uniform mixture, which was prepared in the laboratory by mixing sand and gravel, lacks some sizes, are shown in **Fig. 2**.

3. FUNDAMENTAL EQUATIONS

Theoretical one-dimensional continuity and momentum equations formulated by T. Takahashi, for an unsteady flow in open channel, are as follow[8].

Momentum equation:

$$\frac{1}{gh}\frac{\partial q_T}{\partial t}+\frac{2q_T}{gh^2}\frac{\partial q_T}{\partial x}=\sin\theta-\left(\cos\theta-\frac{q_T^2}{gh^3}\right)\frac{\partial h}{\partial x}$$
$$-\frac{q_T^2}{C^2h^2R^{2p_p}}-\frac{q_T}{gh^2}i\{c_*+(1-c_*)s_b\} \quad (1)$$
$$\times\left\{(1+\kappa_c)\frac{\rho_{*T}}{\rho_T}-1\right\}-\frac{q_T}{gh^2}r\left(2\frac{\rho}{\rho_T}-1\right)$$

Continuity equation:

$$\frac{\partial h}{\partial t}+\frac{\partial q_T}{\partial x}=i\{c_*+(1-c_*)s_b\}+r \qquad (2)$$

where C = Resistance coefficient; R = Hydraulic radius; i = erosion or deposition velocity; q_T = water and sediment discharge per unit width; c_* = packing concentration of the materials used for experiments; ρ_T = apparent density of debris flow; ρ_{*T} = apparent density of static bed $\{=c_*\sigma+(1-c_*)\rho s_b\}$; r is the inflow rate per unit length; and κ_c = a coefficient. For the normal Newtonian fluid P_p = 1/2 and P_p = 3/2 for the Bagnoldian dilatants fluid; h = depth of flow; g = gravitational acceleration; and s_b = degree of saturation.

Equation (1) can be simplified as following neglecting all the terms except friction loss and bed slope and reduces to:

$$q_T=ChR^{P_p}\sin^{1/2}\theta \qquad (3)$$

Considering the unsaturated sediment bed be eroded by tractive force of surface flow on a steep slope as in the individual particle transportation in a channel, T. Takahashi developed equation to calculate erosion or deposition velocity. In the case of unsaturated region and $C_L < C_{L\infty}$, erosion or deposition velocity is given by the equation

$$\frac{i}{\sqrt{gh}}=\mathrm{K}\sin^{3/2}\theta\left\{1-\frac{\sigma-\rho_m}{\rho_m}C_L\left(\frac{\tan\phi}{\tan\theta}-1\right)\right\}^{1/2} \times\left(\frac{\tan\phi}{\tan\theta}-1\right)(C_{L\infty}-C_L)\frac{h}{d_L} \qquad (4)$$

where C_L = volume concentration of the coarse fraction in the total volume; $C_{L\infty}$ = equilibrium concentration of the coarse fraction in steady uniform debris flow; and d_L = mean diameter of the coarse sediment in the debris flow. K is a coefficient and its value is 0.06 (Takahashi, 1991).

The change in height of the dam is calculated as

$$\frac{\partial Z}{\partial t}+i=0 \qquad (5)$$

4. EXPERIMENTAL RESULTS

(1) Pattern of collapse

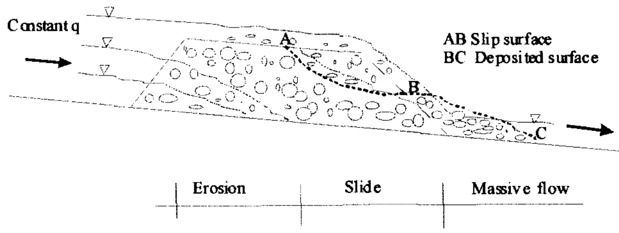


Fig. 3 Image of destruction of the dam

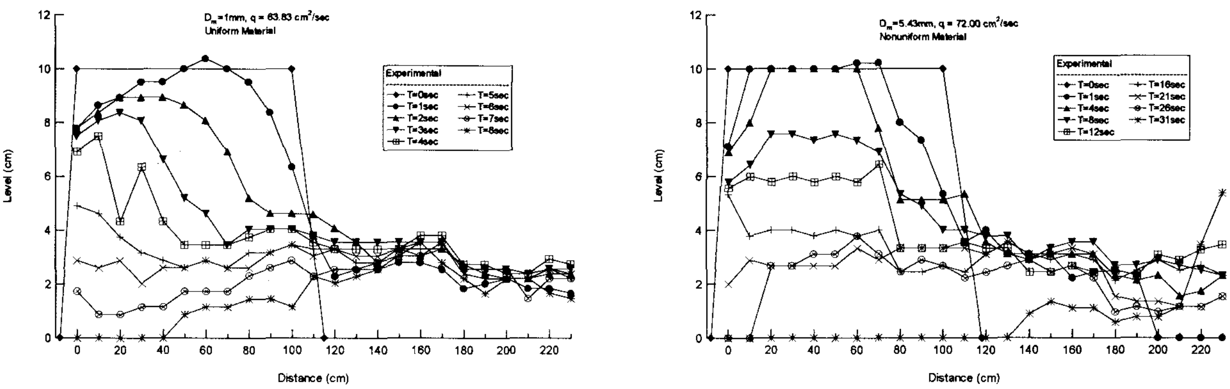
Experimental observations revealed similar pattern of destruction for both dams made of uniform fine particles and non-uniform mixture, except time taken for complete collapse.

Schematic diagram of **Fig. 3** shows a conceptual diagram from the experimental observations. It explains how the water flows through the dam body, accumulates in upstream, erodes the material from surface and collapses the frontal part of the dam.

Some portions of flow enters into the dam body itself and the remaining part accumulates and sets the upstream water level rising. Surface flow that appears over the dam as the water level surpasses the height of the dam results in erosion of surface particles. Seepage and over-topped flow advances in downstream. As overtopping of flow begins, it erodes particles from the surface and some parts of the downstream face collapses, thus, initiating the destruction of the dam and destruction continues as erosion on body part of the dam. It shows erosive destruction at body, slide at the frontal part and these two destructions simultaneously and synergistically results in the mass flow. Permeability of the dam forming material is one of the important parameters, which govern the rate of flow inside the dam body. In the present study, permeability of both samples is almost equal.

Graphs (a-1) and (a-2) of the **Fig. 4** on the following page represent actual data of destruction phenomena took place in the experimets with the dams made up uniform sand and the non-uniform gravel-sand mixture respectively. In the both cases, collapse advanced as described above in **Fig. 3**.

Time taken for complete removal of the dam with similar physical dimensions and conditions made of uniform and non-uniform cases is different for almost similar discharges of water despite similar pattern of destruction. Non-uniform particles took longer time. This can be attributed to mechanical bonding by filling pore spaces up by small particles and thus making dam more firm and stable. Other reason of delay is obviously the size of particles.



(a-1) (a-2)

Fig. 4 Actual destruction of the dam

5. SIMULATION

A simple outline of the simulation process is below.

Calculation of slide volume from the first slip surface using Janbu method of slope stability

↓

Assumption of the slid volume deposited at toe of the dam and calculation of a new downstream frontal slope equating slid and deposited volumes which causes erosive failure than slide failure

↓

Calculation of erosion or deposition velocity, i.e., *i* over the body part

↓

Calculation of bed levels using deposition or erosion velocity *i*

↓

Calculation of temporal eroded volume and temporal bed changes over different locations

(1) Frontal part

As the downstream frontal slope is almost same as the angle of repose, this part of the dam collapsed at the beginning as landslide. For such a bed slope, it is uncommon to produce debris flow in advance of occurrence of landslide. Therefore, the destruction of frontal part of the dam, with frontal slope nearly equal to the angle of repose, is considered as landslide.

The unsaturated soil mass above the critical slip surface deforms and moves downstream and deposits at the toe of dam. The surface slope of deposit is estimated by equating the deposited soil mass with collapsed soil mass and that brings about a new slope. It is considered that lower than the new surface slope erosion or debris flow is likely to occur. It is assumed that the activities of collapse

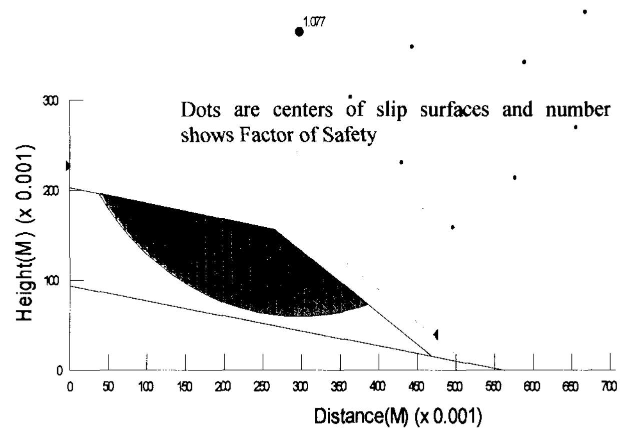


Fig. 5 Typical destruction of frontal part of the dam

and deposition occur in a very short or fairly within no time.

Fig. 5 shows a typical example of frontal part destruction by using the Janbu method of slope stability analysis using a software tool for geotechnical solutions provided by GEO-SLOPE International.

(2) Body part

Experiments reveal surface erosion at the body part of dam and collapse at unsaturated frontal part work together to deform the dam as a whole. Because of low permeability and large flow rate from upstream of the dam, flow appears flowing on the top of the dam eroding the particles from the surface.

Erosive destruction at the body part of the dam is simulated using erosive velocity calculated by equation (3). As this equation requires some coefficients, careful consideration and verification are necessary to select the appropriate values.

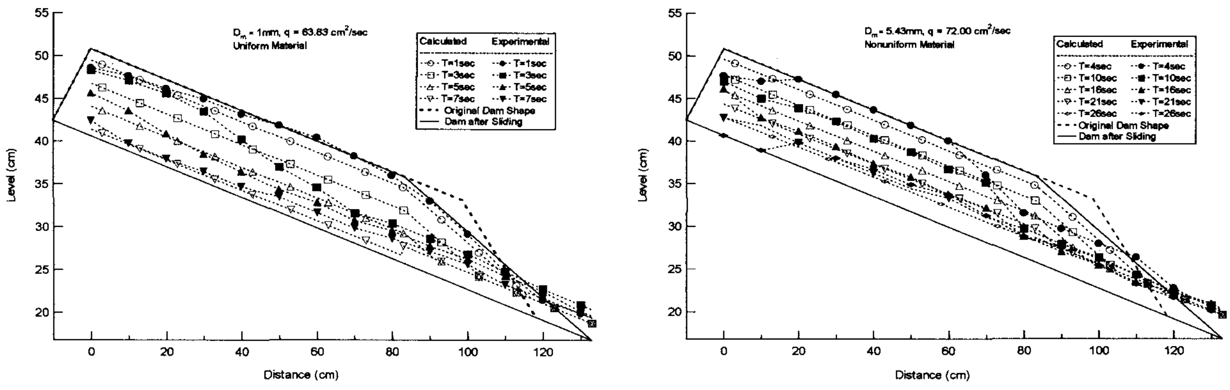


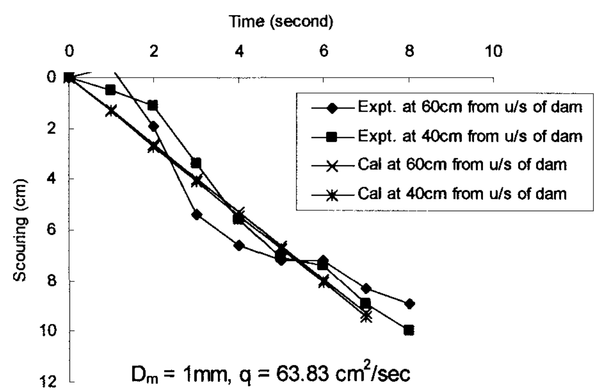
Fig. 6 Calculated and experimental results

Fig. 6 shows the erosion tendency and comparison of calculated and experimental results, where the numerals in the legends denote elapsed time in second from beginning of initial destruction of the front part. **Fig. 6** (a) and (b) depict the results of experiment and calculation for uniform sand and mixture of sand and gravel (non-uniform) respectively. Calculated and experimented results are in good agreement for both cases.

This study considers the constant K = 0.07 for non-uniform mixture, i.e., D_m = 5.43mm and 0.02 for the uniform fine materials, i.e., D_m = 1mm. Volume concentration of coarse fraction in total volume, C_L, is function of hydraulic conditions of the flow, which is taken 0.2 for the non-uniform samples and zero for the uniform samples.

a) Temporal scouring

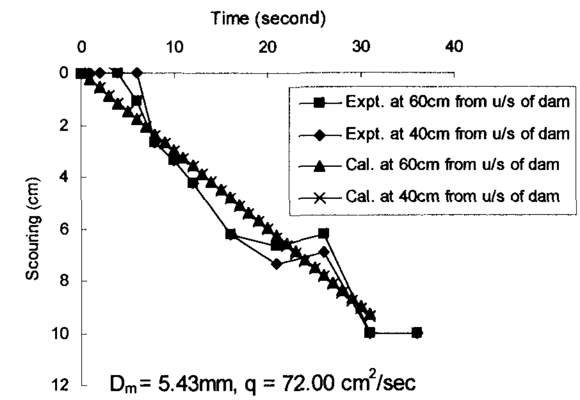
Fig. 7 (a) and (b) show scouring at the particular locations of the dam. Numerals in the legends indicate the distance in centimeters from upstream of the dam. The figures show a good agreement between computed and experimental results.



(a)

b) Temporal variation of eroded volume

Fig. 8 depicts the relationship of the accumulated eroded volume of the dam with the time for uniform and non-uniform materials. The supplied discharges were 63.83 and 72.00 cm^2/sec for the uniform and



(b)

Fig. 7 Comparison of calculated and experimental scouring at particular locations of the dam with time

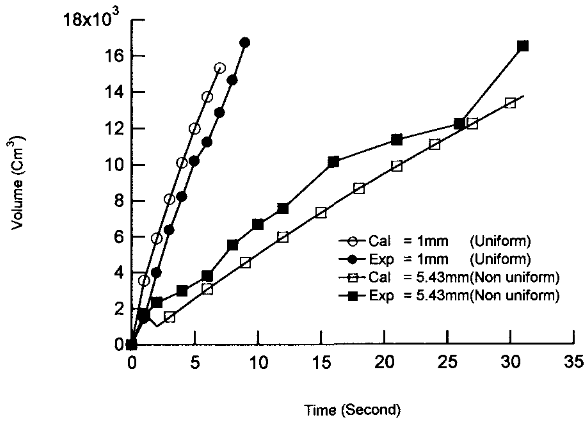


Fig. 8 Comparison of calculated and experimental accumulated eroded volume of the dam

non-uniform materials respectively. In the both cases, the calculated values agree well with the experimental results.

6. CONCLUSION

Calculated results are comparable to experimental results in terms of bed levels and accumulated eroded volumes. Conjunction of slip failure of the frontal part and erosive destruction of body part can give a satisfactory result if the natural dam in question has downstream frontal slope almost equal to the angle of repose of the dam forming materials and is made up with the materials of low permeability. One can infer that the use of simplified one-dimensional momentum, continuity equations of the sediment and water for the body part of the dam and Janbu method for the sliding part can comparably simulate the collapse of natural dam. However, more studies and field checks are needed to verify the values of coefficients used in calculation.

APPENDIX-NOTATION

The following symbols are used in this paper:

C = resistance coefficient;
C_L = volume concentration of the coarse fraction in the total volume;
$C_{L\infty}$ = equilibrium concentration of coarse fraction in a steady uniform debris flow with or without fine particles;
c_* = packing concentration of the solid materials;
g = acceleration due to gravity;
h = depth of flow;
i = erosion (> 0) or deposition (< 0) velocity;
P_p = 1/2 for the normal Newtonian fluid 3/2 for the Bagnoldian dilatants fluid;
q_T = water and sediment discharge per unit width;
r = inflow rate per unit length;
R = hydraulic radius;
s_b = degree of saturation;
Z = bed level from datum;
θ = slope of the channel;
κ_c = a coefficient to describe contribution of momentum and 1 or erosion and zero for deposition;
ρ = density of water;
ρ_m = apparent density of fluid incorporated with suspended particles;
ρ_T = apparent density of debris flow;
ρ_{*T} = apparent density of static bed $\{= c_*\sigma + (1 - c_*)\rho s_b\}$;
σ = density of the solid particles; and
ϕ = angle of repose.

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