EXPERIMENTAL STUDY ON PREDICTION OF FAILURE MODE OF LANDSLIDE DAMS

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Process of failure of landslide dam can be classified into three types; overtopping, instantaneous slip failure and progressive failure. For similar hydraulic conditions peak discharge produced by failure of landslide dam depends on failure modes. Potential disaster in the downstream largely depends on magnitude of peak discharge so this study attempted to derive graphical relationships to predict failure mode by laboratory experiments in the flume. Critical channel slope for sediments, Mix 1-6 and Mix 1-7 are derived from flume experiments. Morevere, experimental data shows peak discharge produced by progressive failure is higher compare with peak discharge produced by instantaneous slip failure and overtopping. The concept of physically based integrated model is essential which can detect failure mode based on initial and boundary conditions and predict outflow hydrograph based on predicted failure mode for downstream hazard management.

Key Words : *experimental study, landslide dam, failure modes, peak discharge*

1. INTRODUCTION

Process of failure of landslide dam can be classified into three types; overtopping, abrupt collapse of the dam body (instantaneous slip failure) and progressive failure. Infiltration rate is one of the main factors which govern failure mode. When the infiltration rate is small, overtopping results. When the infiltration rate is very large, seepage which appears on the lower part of the downstream face brings collapse around it and then the collapse proceeds upstream. Large failure occurs at the moment the collapse reaches near the blocked water. When infiltration rate is intermediate, water levels both upstream and inside the dam body rise simultaneously and a large scale slippage can result[1)]. For similar hydraulic conditions peak discharge produced by failure of landslide dam depends on failure modes. Potential disaster in the downstream largely depends on magnitude of peak discharge so this study attempted to derive graphical relationship to predict failure mode by flume experiments.

Very few studies attempted to predict mode of failure of landslide dam and some research was focused on prediction of behavior of landslide dam. Takahashi and Kuang[1)] mentioned infiltration rate and strength of dam body as the main factors which determine failure mode. Canuti et al.[2)] and Casagli and Ermini[3)] used blockage index (BI) to determine the landslide dam either stable or unstable based on database of cases collected in Northern Apennines. Ermini and Casagli[4)] used geomorpholoigical dimensionless blockage index (DBI) to predict the behavior of landslide dam based on 84 events inventoried worldwide. Liao and Chou[5)] studied the debris flow generated by seepage failure of landslide

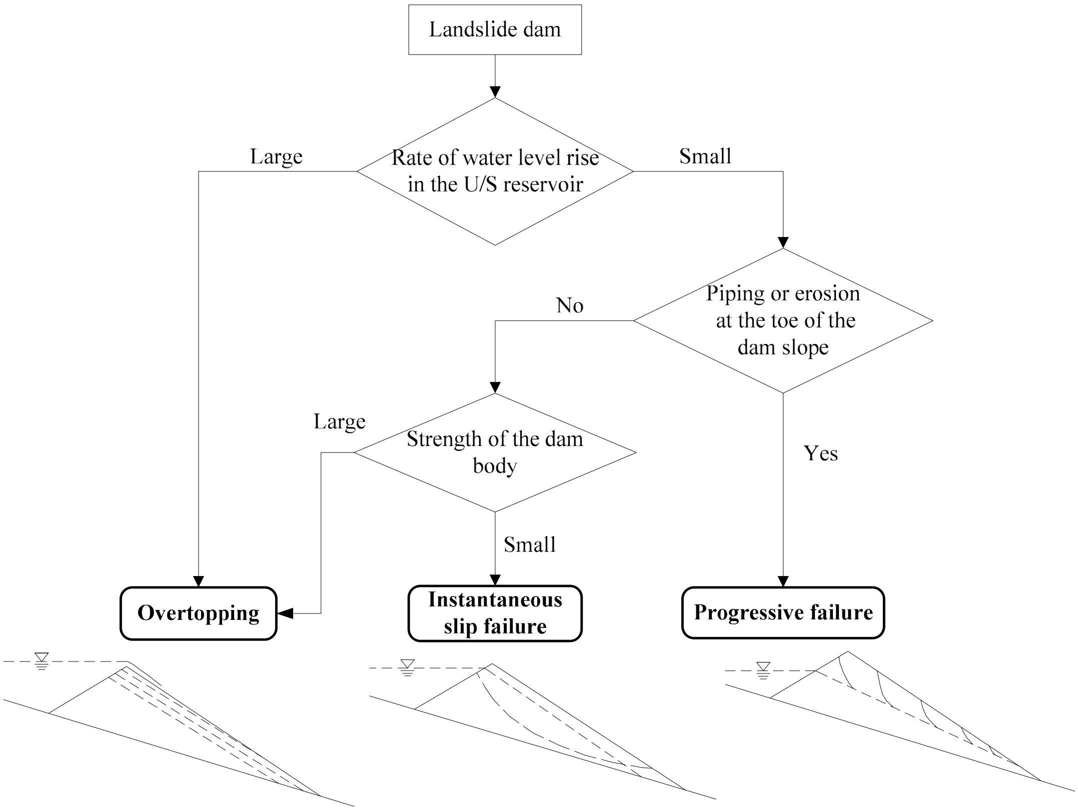

Fig. 1 Failure modes of landslide dam (Modified from Takahashi & Kuang, 1988)

dams and attempted to determine threshold lines of landslide dam failure for different grains (0.58mm, 1.48mm, and 7.85mm). Weidinger[6)] proposed a diagram which correlates the grain, boulder and block size of landslide material and the stability of a dam (life span of the dammed lake). The analysis of twenty case studies from India, Nepal and China shows that the greater the average diameter of the components, the longer the life of the dam and the lake. Awal et al.[7)] proposed an integrated model to predict outflow hydrograph due to landslide dam failure by overtopping and sliding. The model is capable to predict failure modes (overtopping or instantaneous slip failure) based on initial and boundary conditions.

Mechanism of failure as well as peak discharge produced by landslide dam failure is different according to failure modes. Individual models (erosion by overtopping, instantaneous slip failure and progressive failure) can be used to predict outflow hydrograph if we can predict the failure mode in the beginning. Experimental data can be used to derive graphical relationships to predict failure modes and for the validation of process based integrated model (model which can identify failure mode based on different initial and boundary conditions). From series of experimental studies in the laboratory flume at different flume slopes, it is clear that the failure mode is highly influenced by rate of water level rise in the upstream reservoir. Based on this, the failure mode may be overtopping, instantaneous slip failure or progressive failure as shown in **Fig. 1**. This study atempted to determine relationship to predict failure modes based on laboratory experiments.

2. DIMENSIONAL ANALYSIS

The rate of water level rise in the upstream reservoir depends on many factors. The water level in the reservoir at any time depends on, flow condition (q_{in}), dam size (α, H), characteristics of landslide dam ($\phi, K_s, \theta_s, \theta_i, d$), reservoir volume ($\alpha$, H) and fluid properties. The upstream and downstream faces of landslide dam are slightly shallower than the angle of repose of the sand mixture in all cases of experiments. So the size of the dam body and upstream reservoir depends on height of the dam and flume slope.

Landslide dam in the actual field may have some cohesive strength. However in this study sediment mixes without cohesive strength are used. The measured internal friction angles (ϕ) for both sediment mixes are about 34^{o}, so, ϕ values are taken

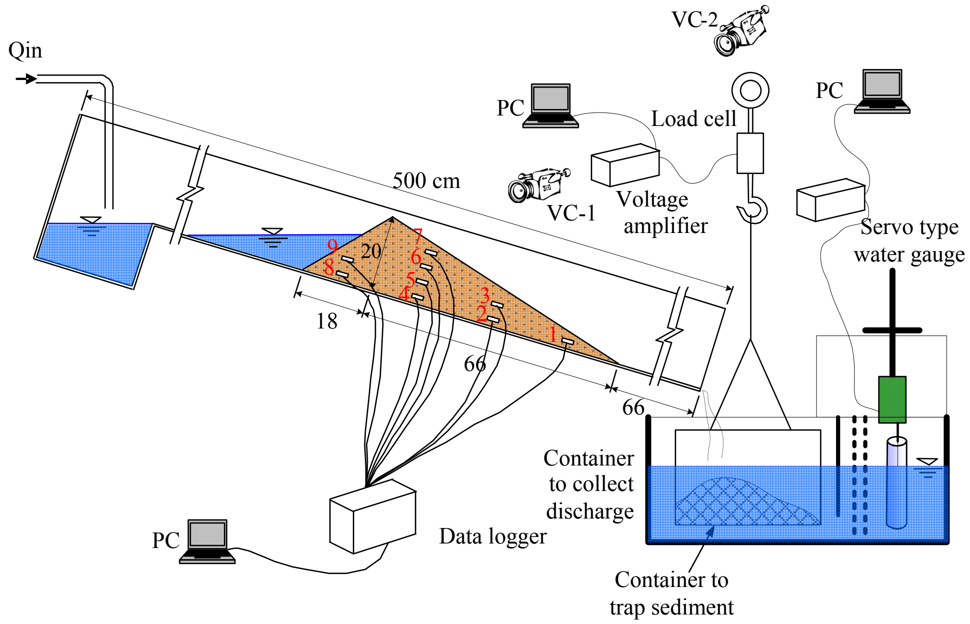

Fig. 2 Experimental setup

as constant. These parameters are neglected in the set of parameters of Equation 1. An attempt is made to develop a relationship among the different parameters using dimensional analysis technique (Buckingham Pi theorem). Buckingham Pi theorem provides a method for computing sets of dimensionless parameters from the given variables, even if the form of the equation is still unknown. Different failure mode of landslide dam depends on rate of rise of water level in the upstream reservoir. The water level in the reservoir at any time may be expressed as:

$$h = f(t, q_{in}, H, L, K_s, \theta_s, \theta_i, d, \alpha) \qquad (1)$$

where, h is the water level in the reservoir, t is the time after the formation of landslide dam, q_{in} is the inflow rate per unit width, H is the height of the landslide dam, L is the length of landslide dam, K_s is the saturated hydraulic conductivity, θ_s is the saturated moisture content, θ_i is the initial moisture content, d is the mean diameter of sediment and α is the flume slope.

Applying Buckingham Pi Theorem, above equation in dimensionless form can be expressed as

$$\frac{h}{H} = f\left(\frac{tK_s}{H}, \frac{q_{in}}{HK_s}, \frac{L}{H}, \frac{d}{H}, \theta_s, \theta_i, \alpha\right) \qquad (2)$$

According to Equation 2, the main factors which govern water level in the upstream reservoir are the time period after the formation of landslide dam, unit discharge, material properties, geometry of the dam body and the flume slope. Therefore, experiments are carried out for two sediment mixes in different channel slopes, dam geometries and discharges. For particular sediment mix (constant d) , if we use the same initial moisture content,. θ_s and θ_i can be consider as constant. As already mentioned, the failure mode of landslide dam is influenced by rate of water level rise in the upstream reservoir. However, it is difficult to relate rate of water level rise with failure modes. Thus, relationship between dimensionless parameters is used to derive condition for different failure modes.

3. LABORATORY EXPERIMENTS

A rectangular flume of length 5m, width 20cm and depth 21cm was used. The slope of the flume could be changed from horizontal to inclination of 20 degree or more. The schematic diagram of the flume including dam body, instrumentation and data acquisition system is shown in **Fig. 2**. Silica sand S1, S2, S3, S4, S5, S6 and S7 are mixed in equal portion to make the mixed sediment for dam body in sediment type “Mix 1-7” and S1 to S6 are mixed in “Mix 1-6”. The grain size distributions of sediment mixture are shown in **Fig. 3**.

The shape and size of landslide dam, grain size degree of compaction and moisture content of landslide dam material depend on the site condition and the process that have triggered dam forming landslides. However for simplicity, in these experiments, triangular dams of homogeneous material with uniform compaction and uniform initial moisture content were used. The upstream and downstream slopes of the landslide dams are slightly

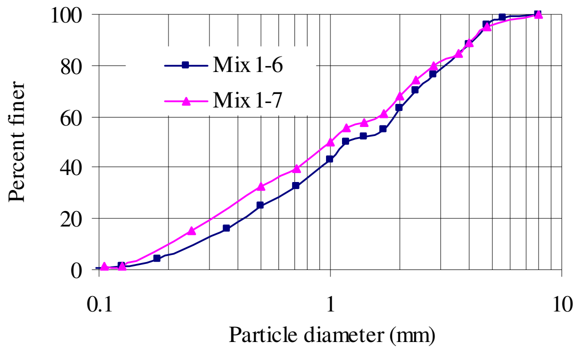

Fig. 3 Grain size distribution of different sediment mixes

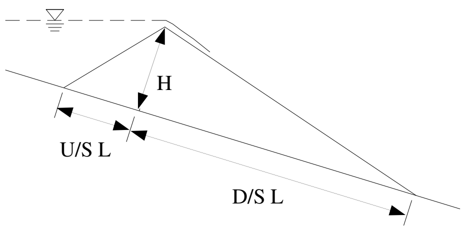

Fig. 4 Shape and size of the dam body

Table 1 Size of the dam body

Flume slope	H (cm)	U/S L (cm)	D/S L (cm)
20	20	16	82
17	20	18	66
13	20	20	52.5
13	19	18	51
13	18	18	48

smaller than the angle of repose of the sand mixture. The shape and size of the dam body for different channel slopes are shown in **Fig. 4** and **Table 1**.

Triangular dam was prepared on the rigid bed of flume by placing mixed sand on the flume. The upstream and downstream faces of landslide dam are slightly shallower than the angle of repose of the sand mixture. The sediment placed in the flume was leveled and compacted in every thickness of approximately 5cm by using timber plate. The final shape of the dam body according to flume slope was prepared by removing extra sediment and smoothing the surface of the dam. To measure the movement of the dam slope during sliding, red colored sediment strip was placed at the face of the flume wall before preparation of the dam body.

4. RESULTS AND DISCUSSIONS

4.1 Condition for different failure mode

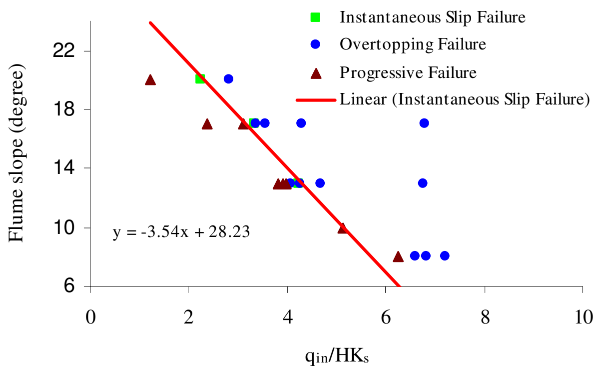

Fig. 5 Graphical relationship to predict failure modes (Sediment Mix 1-7)

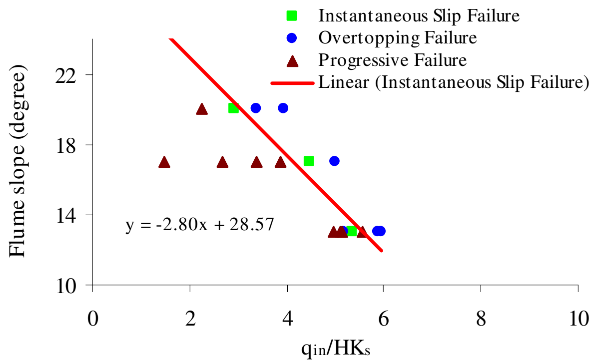

Fig. 6 Graphical relationship to predict failure modes (Sediment Mix 1-6)

The condition for different failure mode of landslide dams are experimentally studied using an inclined flume with slope varying from 13^o to 20^o. As already explained, landslide dam may fail by overtopping, instantaneous slip failure and progressive failure. However overtopping is common in all types of failure mode although initiation may be different. Following relationships are derived from series of experiments (**Fig. 5** and **6**) which can be used for particular sediment mix:

For sediment Mix 1-7

$$\alpha_{cr} = 28.23 - 3.54\left(\frac{q_{in}}{HK_s}\right) \qquad (3)$$

For sediment Mix 1-6

$$\alpha_{cr} = 28.57 - 2.80\left(\frac{q_{in}}{HK_s}\right) \qquad (4)$$

Relationship for critical channel slope is proposed as shown in equation 3 and 4 for sediment Mix 1-7 and Mix 1-6. Flume slope close to this angle may cause instantaneous slip failure and progressive failure will occur if the flume slope is smaller than critical channel slope. Overtopping will occur if the flume slope is greater than critical channel slope. Collapse of the crest at once before appearance of sliding in the downstream is considered as instantaneous slip failure. Whereas, collapse of the crest after sliding partly in the downstream is taken as progressive failure, so some points are very close to line of critical channel slope.

Infiltration inside the dam body is one of the main factor which affect the rate of water level rise in the upstream reservoir. In each and every experiment effort was made to follow same procedure to prepare dam body and tried to mix the sediments uniformly. However it is difficult to mix sediment uniformly and difficult to achieve same degree of compaction. This affects the failure mode when channel slope for particular discharge and hydraulic conductivity is very close to critical channel slope.

Expression for critical channel slope for sediments Mix 1-6 and Mix 1-7 based on number of experiments can be used to quick guess of failure mode. However numbers of assumptions are made to derive these expressions like slope of dam body, constant channel width, homogeneous and non-cohesive dam body, and uniform moisture content throughout the whole dam body close to residual moisture content. It is difficult to derive such all parameters for actual landslide dam. If we can predict failure mode in the beginning we can use individual model to predict outflow hydrograph based on predicted failure mode.

4.2 Comparison of peak discharge for different failure mode

Set of flume experimental data was used to compare the peak discharge for different failure modes. From **Fig. 7, 8** and **9**, it is clear that peak discharge produced by progressive failure is highest among different failure mode in all cases of channel slope. In progressive failure, as shown in **Fig. 10**, partial collapse of the dam body proceeds upward until it ends as a large failure at the moment the partial collapse reaches the location of the blocked water behind the dam. At that moment the collapsed mass move very fast and height of the collapsed mass around crest of the dam body is also higher compared with instantaneous slip failure of the dam body. These are the main reasons behind higher peak discharge in the case of progressive failure compared with other failure modes. However, the peak discharge in progressive failure will be influenced by the water level in the upstream reservoir.

The data set of peak discharge for different failure modes of actual landslide dam failure are not

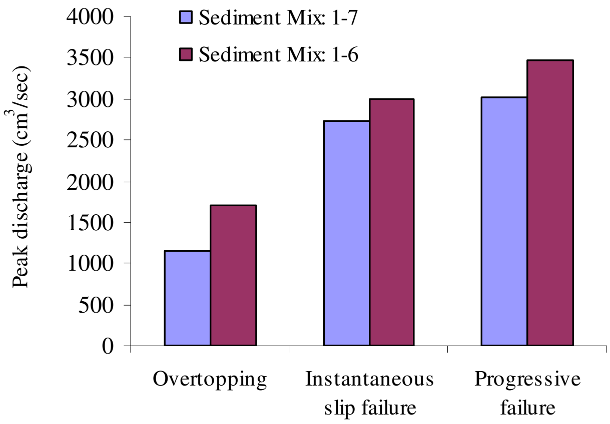

Fig. 7 Comparison of peak discharge for different failure mode (Channel slope = 13^{o})

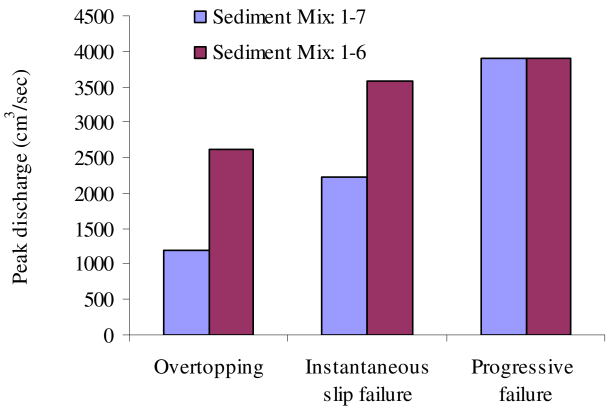

Fig. 8 Comparison of peak discharge for different failure mode (Channel slope = 17^{o})

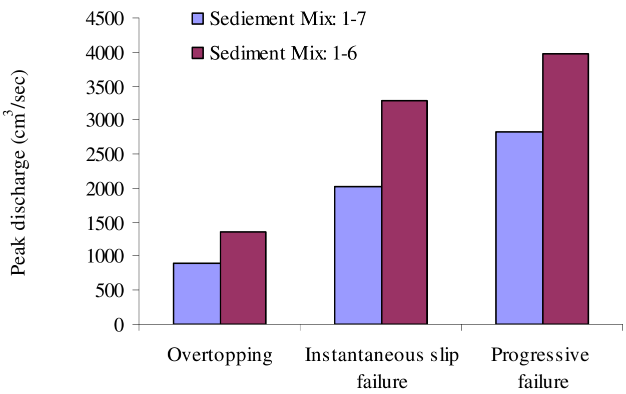

Fig. 9 Comparison of peak discharge for different failure mode (Channel slope = 20^{o})

available so the data set of embankment dam failure used by Froehlich[8] was used to check the peak discharge for different failure modes. **Fig. 11** shows the comparison of peak discharge produced by embankment dam failure for different failure modes. Froehlich classified failure modes as overtopping, piping or seepage or foundation defects. However **Fig. 11** just considered two failure modes i.e. overtopping and piping or seepage. From **Fig. 11** it is

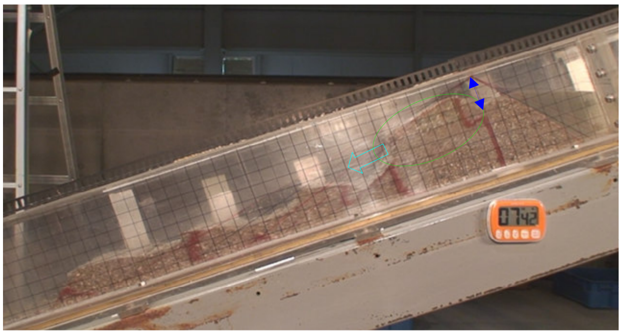

Fig. 10 Progressive failure

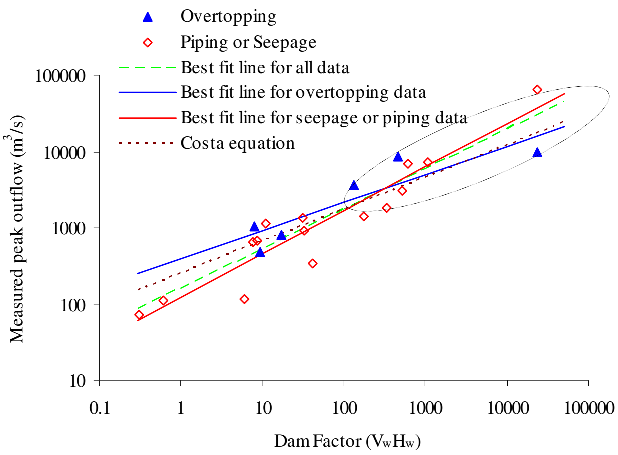

Fig. 11 Comparison of peak discharge for different mode of failure for embankment dam (Data Compiled by: David C. Froehlich,1995)

clear that peak discharge produced by seepage or piping is higher compared with overtopping for higher dam factor. This study used small data set and peak outflow discharge for all dam failures were estimated by either slope area measurement or reservoir volume change. So the peak discharge estimated by two methods may not be consistent.

5. CONCLUSIONS

Critical channel slope for sediments, Mix 1-6 and Mix 1-7 are derived from flume experiments. However these relationships are applicable only to those sediments. Number of assumptions is made to derive these expressions so it is difficult to apply for actual landslide dam failure. Peak discharge is also governed by failure mode. From experimental data it is clear that peak discharge produced by progressive failure is higher compared with peak discharge produced by instantaneous slip failure and overtopping. Data set of embankment dam failure also shows that peak discharge produced by piping or seepage is higher compared with overtopping for higher dam factor.

If we can predict failure mode in advance individual model can be used to predict outflow hydrograph based on predicted failure mode. The concept of physically based integrated model is another alternative which can detect failure mode based on initial and boundary conditions and predict outflow hydrograph based on predicted failure mode.

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