

NUMERICAL AND EXPERIMENTAL STUDY ON 3D TRANSIENT SEEPAGE AND SLOPE STABILITY OF LANDSLIDE DAM FAILURE

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The failure of landslide dam may occur with a variety of failure processes which includes overtopping, seepage or piping, and sudden sliding etc. This study focuses on three-dimensional (3D) transient seepage and slope stability analysis of landslide dam and prediction of the failure due to sudden sliding through flume experiments and numerical simulations. The 3D slope stability model coupled with transient seepage flow model is developed by using the limit equilibrium method. The proposed model is capable to predict time to failure by sliding according to pore water pressure and moisture movement in the dam body. Comparisons show that results of numerical simulations and experimental measurements are quite close in terms of movement of moisture in the dam body and predicted critical slip surface. However the time to failure of the dam body is earlier in the experiment compared with simulation.

Key Words : seepage flow, slope stability, 3D model, numerical simulation, laboratory experiment

1. INTRODUCTION

Temporary or permanent stream blockages by mass movements commonly occur in mountainous area due to heavy rains or earthquakes. Landslide dam formed by this process may fail by erosion due to overtopping, abrupt collapse of the dam body or progressive failure¹⁾. Water infiltrates through the landslide dam in a transient manner, so the slope stability analysis coupled with transient seepage analysis is useful to study stability of landslide dam.

Many researchers used different slope stability analysis method combined with hydrological model to analyse slope stability of natural slopes. Wilkinson et al.²⁾ used a combined hydrology and slope stability model by incorporating an automated non-circular search technique into the Janbu's method. Tsutsumi et al.³⁾ used combined hydrology and slope stability model to analyse deep-seated

landslide triggered by the Typhoon in Taketa City, Oita Prefecture. Some researchers focused on transient stability analysis of a collapsible dam using dynamic programming combined with finite element stress fields (e.g. Pereira et al.⁴⁾; Brito et al.⁵⁾) and very few studies analysed transient slope stability of embankments (e.g. Staiano et al.⁶⁾, Gitirana and Freduland⁷⁾). Most of these studies are limited to 2D (two-dimensional) analysis. A 2D analysis is only valid for slopes which are long in the third dimension. However, failure of natural slopes and landslide dams confined in a narrow U- or V-shaped valley occurs in three dimensions. Therefore 3D (three-dimensional) approach is more appropriate to analyze such stability problems.

This study focuses on 3D transient slope stability analysis of landslide dam and prediction of the failure due to sudden sliding through flume experiments and numerical simulations. The

numerical procedure used for the identification of critical noncircular slip surface with the minimum factor of safety is based on dynamic programming and the simplified Janbu method. The 3D slope stability analysis based on dynamic programming and random number generation incorporated with 3D simplified Janbu method⁸⁾ is used to determine minimum factor of safety and the corresponding critical slip surface for landslide dam in the V-shaped valley. This approach is applicable to an arbitrary shape of slip surface, whereas most of the existing methods are just applicable for particular type of slip surface such as ellipsoidal, cylindrical, log spiral etc. This study extended model of slope stability (3D) by coupling with model of transient seepage flow (3D). Thus proposed model is capable to calculate the factor of safety, the geometry of critical slip surface and time to failure according to pore water pressure and moisture movement in the dam body.

2. NUMERICAL MODEL

The limit equilibrium method is employed to evaluate the transient slope stability. It involves calculating the factor of safety and searching for the critical slip surface that has the lowest factor of safety according to infiltration of water inside the dam body.

The model consists of two models. The transient seepage flow model calculates variation of pore water pressure and moisture content inside the dam body due to gradual increase of water level in the upstream reservoir. The slope stability model calculates the factor of safety and the geometry of critical slip surface according to change in pore

water pressure and moisture movement in the dam body. Water level in the upstream reservoir (W_L) in each time step is determined by water-volume balance equation considering inflow discharge (Q_{in}), rate of infiltration inside the dam body (Q_{sh}) and flume geometry (width and slope). General outline of coupled model is shown in **Fig. 1**. A brief description of each model is given below.

(1) Model of seepage flow

Seepage flows through landslide dam formed in narrow valleys are likely to have three dimensional effects. To consider 3D water infiltration into originally unsaturated landslide dam, 3D seepage flow model is developed by incorporating 3D Richards' equation. To evaluate the change in pore water pressure in variably saturated soil, pressure based modified Richards' equation is used⁹⁾

$$\frac{\partial}{\partial x} \left(K_x(h) \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_y(h) \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_z(h) \left(\frac{\partial h}{\partial z} + 1 \right) \right) = [C(h) + S_w S_s] \frac{\partial h}{\partial t} \quad (1)$$

where h is the water pressure head, $K_x(h)$, $K_y(h)$ and $K_z(h)$ are the hydraulic conductivity in x , y and z direction, $C(h)$ is the specific moisture capacity ($\partial\theta/\partial h$), θ is the soil volumetric water content, t is the time, S_w is the saturation ratio, S_s is the specific storage, x and y are the horizontal spatial coordinates 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. For saturated domain, $K_x(h) = K_y(h) = K_z(h) = K_s$, $\theta = \theta_s$, $C(h) = 0$ and $S_w = 1$, where K_s and θ_s are the saturated hydraulic conductivity and saturated water content respectively. S_s depends on compressibility of the solid matrix and fluid, so it approaches zero in the unsaturated and unconfined porous medium. Line-successive over-relaxation (LSOR) scheme is used in this study for the numerical solution of Richards' equation¹⁰⁾.

In order to solve Richards' equation, constitutive relationships proposed by van Genuchten¹¹⁾ are used for establishing relationship of $K-h$ and $\theta-h$, with $m = 1 - (1/n_v)$.

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \begin{cases} \frac{1}{(1 + |\alpha h|^{n_v})^m} & \text{for } h < 0 \\ 1 & \text{for } h \geq 0 \end{cases} \quad (2)$$

$$K = \begin{cases} K_s S_e^{0.5} [1 - (1 - S_e^{1/m})^m]^2 & \text{for } h < 0 \\ K_s & \text{for } h \geq 0 \end{cases} \quad (3)$$

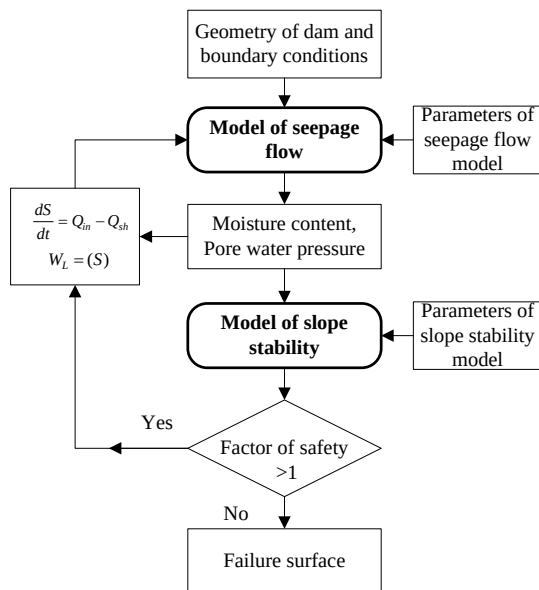


Fig.1 General flow chart of coupled model for transient slope stability analysis

where, α and n_v are van Genuchten parameters, S_e is the effective saturation, θ_s and θ_r are saturated and residual moisture content respectively.

(2) Model of slope stability

The evaluation of transient slope stability of landslide dam by the limit equilibrium analysis of columns involves calculating the factor of safety and searching for the critical slip surface that has the lowest factor of safety. Several methods have been proposed to determine factor of safety for three dimensions based on limit equilibrium analysis of columns which are valid for an arbitrary slip surface. Ugai¹²⁾ and Ugai and Hosobori¹³⁾ extended the simplified Janbu method and Spencer method in 2D problems to three-dimensions. 3D simplified Janbu method proposed by Ugai et al. is simple and comparatively rigorous one. The main advantage of this method is that when the slope under consideration is gentle (less than 45°), a factor of safety can be determined by only one formula rather than by simultaneous equations in general cases and therefore iterative procedures will be significantly simplified⁸⁾. The model of slope stability incorporates 3D simplified Janbu method proposed by Ugai et al. coupling with the minimization approach based on dynamic programming and the method of Random Number Generation. The model is further coupled with seepage flow model for transient slope stability analysis.

A 3D sliding mass and vertically divided columns within a slope is shown in **Fig. 2**. **Fig. 3** shows the forces acting on a typical column taken from **Fig. 2**.

These forces are: W_{ij} is the weight of column, P_{ij} is the vertical external force acting on the top of the column, T_{ij} and N_{ij} are the shear force and total normal force acting on the column base, Q_{ij} is the resultant of all intercolumn forces acting on the column sides. According to Ugai's, Q_{ij} is decomposed to a component Q_1 parallel to x -axis and a component Q_2 inclined at an angle $\beta = \tan^{-1}(\eta \tan \alpha_{xzij})$ to the y -axis, where η is unknown constant¹²⁾. In addition other symbols in **Fig. 3** include: Δx and Δy are discretized widths of the columns in the x - and y -direction, α_{xzij} and α_{yzij} are the inclination angles of the column base to the horizontal direction in the xz and yz planes, respectively.

Applying equilibrium conditions in horizontal and vertical directions for the entire sliding mass, Ugai¹²⁾ defined two safety factors F_{sh} and F_{sv} . Both of these factors depend on η and they become equal to each other at a certain η value. It has been shown that the equation $F = F_{sh} = F_{sv}$ is usually satisfied at small η values^{14),15)}. For small

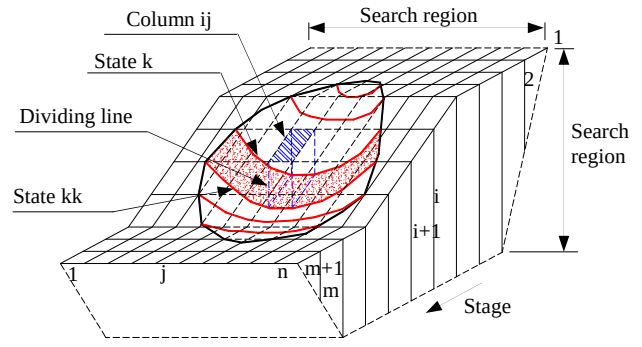


Fig.2 A stage-state system and dividing scheme for a 3D slope (Modified from Yamagami and Jiang⁸⁾)

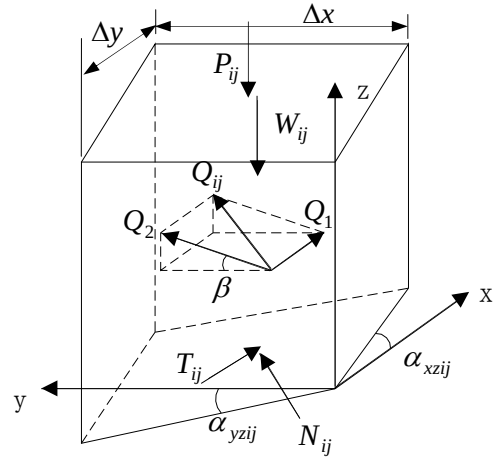


Fig.3 Forces acting on a typical column

values of η , calculated F_{sh} values show little change with variation of η . In other words, sufficiently accurate values of the 3D factor of safety can be calculated based on F_{sh} evaluated at $\eta = 0$ ^{14),15)} and based on this approximation, factor of safety F can be expressed by following expression:

$$F = \frac{\sum_{i=1}^m \sum_{j=1}^n (c_{ij} - u_{ij} \tan \phi) \Delta x \Delta y + (W_{ij} + P_{ij}) \tan \phi}{\sum_{i=1}^m \sum_{j=1}^n \left[\frac{1}{J + \sin \alpha_{xzij} \tan \phi / F} \cos \alpha_{xzij} \right]} \quad (4)$$

$$\sum_{j=1}^n \left[\tan \alpha_{xzij} (W_{ij} + P_{ij}) - \Delta V_{ij}^x \right]$$

where, c_{ij} and ϕ are the effective strength parameters of soil, u_{ij} is the pore water pressure at the column base, $J = (1 + \tan^2 \alpha_{xzij} + \tan^2 \alpha_{yzij})^{1/2}$ and $\Delta V_{ij}^x = XW_{ij}^L - XW_{ij}^R$. XW_{ij}^R and XW_{ij}^L are the resultant of water pressure acting on upstream and downstream face of the column.

This simplified formula can provide sufficiently accurate results when the slope is less than 45 degree¹³⁾.

A search procedure for determination of critical 3D surfaces developed by Yamagami and Jiang⁸⁾ is

used in this study. This study extended their work to transient slope stability analysis by incorporating seepage flow model. In Eq.(4), W_{ij} , P_{ij} and u_{ij} ($c_{ij} = 0$ for cohesionless soil) are time dependent and can be determined at each time step by coupling with 3D transient seepage flow model. The output (pore water pressure and moisture content of each cell) and boundary condition (depth of surface water) of seepage flow model can be used to determine these quantities. The details of transient slope stability analysis of landslide dam by using dynamic programming and simplified Janbu method for 2D case can be found in Awal et al.⁹⁾. The main difference between application of dynamic programming for 2D and 3D case is the expression of factor of safety and states. States in each stage line are points in 2D case, whereas states in each stage plane are curves in 3D case. State curves in each stage plane are generated by method of random number generation⁸⁾.

3. EXPERIMENTAL STUDIES

The summary of experiments to measure moisture profile and to observe failure surface are shown in **Table 1**. Mixed silica sand of mean diameter 1mm was used to prepare a triangular dam in the flume. van Genuchten parameters (including θ_r) were estimated by non-linear regression analysis of soil moisture retention data obtained by pF meter experiment.

Water content reflectometers (WCRs) were used to measure the temporal variation of moisture content during seepage process. The probe rods disturb the sliding of the dam body so water content was measured in separate experiment under same experimental conditions.

To measure the movement of dam slope during sliding, red colored sediment strip was placed in the dam body at the face of flume wall. A digital video camera was placed on the side of the flume to capture the shape of slip surface due to sudden sliding. The shape of slip surface during sliding of the dam body was measured by analyses of videos taken from the flume sides.

The flume of 500cm long, 30cm wide and 50cm high was used. The rectangular shape of the flume was modified to make cross slope of 20°. The slope of the flume was set at 20°. The shape and size of the dam body is shown in **Fig. 4** and **Fig. 5**. The arrangement of WCRs are shown in **Fig. 5**. The holes were prepared in the side B of the flume and twelve WCRs were inserted inside the dam body from that side. Two set of experiments were carried out to measure moisture profile at different location

Table 1 Summary of Experiments

Expt. No.	Case	Discharge (cm ³ /s)	Remarks
1	3D-1	29.8	To measure moisture profile.
2	3D-2	30.5	To measure moisture profile.
3	3D-3	29.8	To observe failure surface.
4	3D-4	30.1	To observe failure surface.

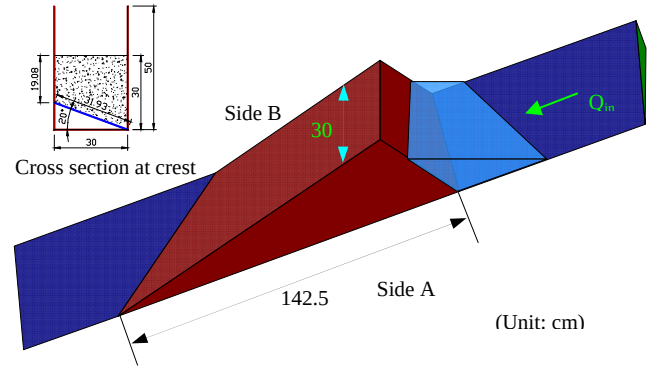


Fig.4 Shape of the dam body and cross section at crest

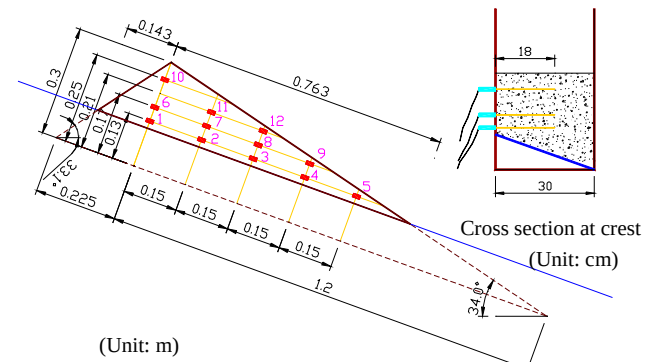


Fig.5 Arrangement of WCRs (1-12), view from Side B

of the dam body.

4. RESULTS AND DISCUSSIONS

A gradual rise of water level in the reservoir causes water to penetrate into the dam body and it increases both pore water pressures and weight of the dam body. Sliding of the dam body occurs when the mobilized shear stress which is increased by the weight increase of the dam body becomes larger than resisting shear stress which is decreased by the increase of the pore water pressures.

Steady discharge was supplied from the upstream of the flume. Moisture content in the dam body was measured by using WCRs. The measured moisture content is the average of 18cm length from the side of the flume (**Fig. 5**). The moisture along WCR may not be constant due to three dimensional effect of water movement inside the dam body. The measured moisture profile for 'Expt: 3D-1' and 'Expt: 3D-2' for different WCRs is slightly different

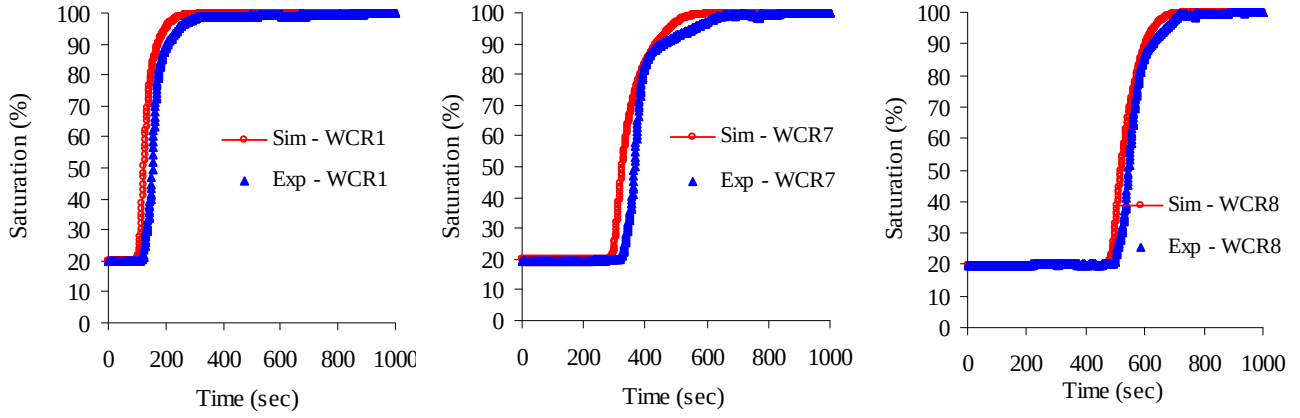


Fig.6 Simulated and experimental results of water content profile for different WCRs

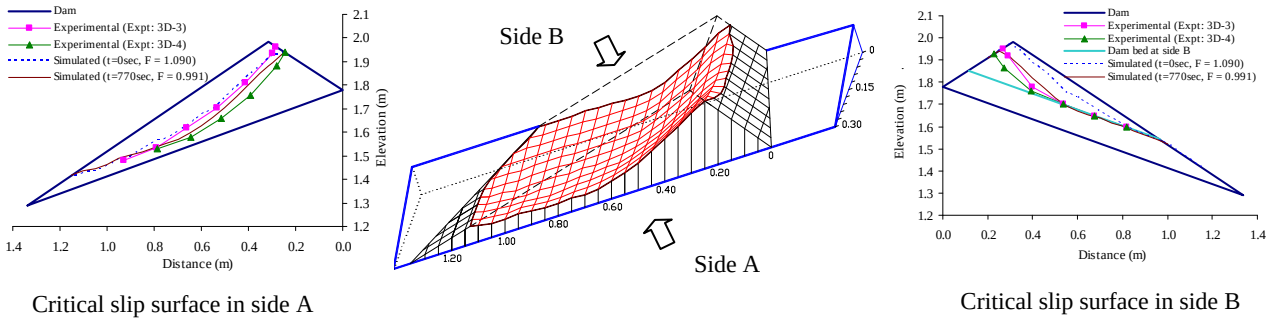


Fig.7 Simulated critical slip surface (3D)

although discharges used in both experiments are nearly equal. This may be due to variation of saturated hydraulic conductivity in two experiments.

Two experiments (Expt: 3D-3 and Expt: 3D-4) were carried out for nearly equal discharge to observe slope failure. Slope failure was observed at 930sec in 'Expt: 3D-3'. In case of 'Expt: 3D-4', failure was observed at 1030sec and slide mass is also deeper than 'Expt: 3D-3'. This may be due to difference in non uniformity in sediment mixing, compaction, and saturated hydraulic conductivity between two experiments. However efforts were made to make uniformity in both experiments.

Based on preliminary analysis of 3D slope stability, thousand numbers of states were generated at each stage plane. The other hydraulic conditions/parameters and grid systems used in seepage flow model for simulation are $Q_{in} = 29.8\text{cm}^3/\text{sec}$, $K_s = 0.0003\text{m}/\text{sec}$, $\theta_s = 0.287$, $\theta_r = 0.045$, $\alpha = 5.5\text{m}^{-1}$, $n_v = 3.2$, $\Delta t = 0.01\text{sec}$ and block size of 10mm. Column size of $\Delta x = 5\text{cm}$ and $\Delta y = 3\text{cm}$ were used in slope stability model. Convergence criterion (difference between the factors of safety from the final two iterations) of less than 0.002 was used.

Fig. 6 shows the comparison of simulated and experimental results of moisture profile at different WCRs which are in good agreement. The simulated

critical slip surface at $t = 0\text{ sec}$ and $t = 770\text{ sec}$ is shown in **Fig. 7**. The simulated factor of safety (F) was higher than 1 in the beginning. The simulated factor of safety was less than 1 at 770sec however the observed failure time in the experiment was about 930sec. The simulations were also carried out for reduced discharge of $29\text{cm}^3/\text{sec}$ to account evaporation as well as reduced saturated hydraulic conductivity of $0.00028\text{m}/\text{sec}$ to account uncertainty of hydraulic conductivity. In both cases dam was failed at 790sec. The simulated failure time was 830sec for $K_s = 0.00025\text{m}/\text{sec}$. So, the failure time is also depends on saturated hydraulic conductivity. 3D simplified Janbu method satisfies the horizontal and vertical force equilibrium while it does not satisfy the moment equilibrium. In addition, the method assumes that the resultant interslice forces are horizontal. These assumptions produce factor of safety that are smaller than those obtained by more rigorous method that satisfy complete equilibrium. So the simulated failure time is earlier compared with observed failure time in the experiment. The preliminary analysis (**Fig. 8**) shows that the factor of safety calculated by using extended 3D Spencer's method^(12),16) is in the range of 1.05 to 1.06 when the landslide dam was failed (Factor of safety < 1) according to 3D simplified Janbu method. Thus failure time will be prolonged and close to observed time if we use more rigorous method of slope

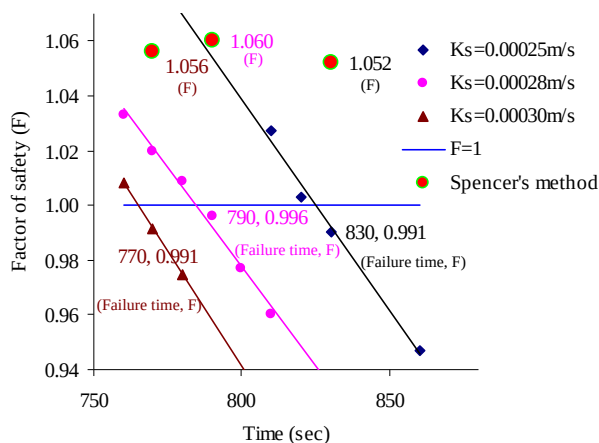


Fig.8 Simulated failure time for different K_s and corresponding factor of safety by extended Spencer's method

stability analysis. Moreover, the friction in the side wall of the flume was also ignored in the computation. The comparison of failure surface in two faces of the flume (**Fig. 7**) shows the good agreement with experiment.

The shape of the slip surface depends on many factors. Data of actual slip surfaces in natural landslide are still lacking to generalize the constraints to generate the state curves based on soil properties. Further improvement of model by incorporating more rigorous method of slope stability analysis is essential for the practical application of 3D transient slope stability analysis.

5. CONCLUSIONS

Sudden failure of landslide dam was studied in the experimental flume for steady discharge in the upstream reservoir. A gradual rise of water level in the reservoir causes water to penetrate into the dam body, increasing mobilized shear stress and causing dam to fail by sudden collapse after it becomes larger than resisting shear stress.

The slope stability model coupled with transient seepage flow model was developed by using the limit equilibrium method. Numerical simulations and flume experiments were performed to investigate the mechanism of landslide dam failure due to sliding. Comparisons show that results of numerical simulations and experimental measurements are quite close in terms of movement of moisture in the dam body and predicted critical slip surface. However the time to failure of the dam body is earlier in the experiment. The model can be further improved by incorporating more rigorous method of slope stability analysis so that the model can be used for the slope stability analysis of both landslide dam and natural slopes.

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