Awal, Ripendra; Nakagawa, Hajime; Kawaike, Kenji; Baba, Yasuyuki; Zhang, Hao

Transient Slope Stability Analysis of Landslide Dam Failure

TRANSIENT SLOPE STABILITY ANALYSIS OF LANDSLIDE DAM FAILURE

Ripendra Awal[1], Hajime Nakagawa[2], Kenji Kawaike[3], Yasuyuki Baba[4] and Hao Zhang[5]

[1] Graduate Student, Department of Civil and Earth Resources Engineering, Kyoto University
Katsura Campus, Nishikyo-ku, Kyoto 615-8540, Japan, e-mail: ripendra@uh31.dpri.kyoto-u.ac.jp
[2] Professor, Disaster Prevention Research Institute, Kyoto University
Shimomisu, Yoko-oji, Fushimi-ku, Kyoto 612-8235, Japan, e-mail: nakagawa@uh31.dpri.kyoto-u.ac.jp
[3] Associate Professor, Disaster Prevention Research Institute, Kyoto University
Shimomisu, Yoko-oji, Fushimi-ku, Kyoto 612-8235, Japan, e-mail: kawaike@uh31.dpri.kyoto-u.ac.jp
[4] Assistant Professor, Disaster Prevention Research Institute, Kyoto University
Shimomisu, Yoko-oji, Fushimi-ku, Kyoto 612-8235, Japan, e-mail: baba@uh31.dpri.kyoto-u.ac.jp
[5] Assistant Professor, Disaster Prevention Research Institute, Kyoto University
Shimomisu, Yoko-oji, Fushimi-ku, Kyoto 612-8235, Japan, e-mail: zhang@uh31.dpri.kyoto-u.ac.jp

ABSTRACT

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 failure. However this study focuses on transient slope stability analysis of landslide dam and prediction of the failure due to sudden sliding through flume experiments and numerical simulations. A slope stability model coupled with a transient seepage flow model is used for numerical simulation. The model is applicable for both 2D and 3D cases of transient slope stability analysis. The results of numerical simulations and experimental measurements are quite close in terms of movement of moisture in the dam body, predicted critical slip surface and time to failure of the dam body.

Keywords: seepage flow, slope stability, 2D and 3D models, 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 failure (Takahashi, 1991). The peak discharge produced by abrupt collapse of the dam body is very high compared with failure due to overtopping. However, in-depth knowledge of the mechanism of the dam failures and measured data are still lacking.

Many researchers used different slope stability analysis method combined with hydrological model to analyse slope stability of natural slopes. Wilkinson et al. (2002) used a combined hydrology and slope stability model by incorporating an automated non-circular search technique into the Janbu's method. Tsutsumi et al. (2007) 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., 1996; Brito et al., 2004) and very few studies analyzed transient slope stability of embankments (e.g. Staiano et al., 2001, Gitirana and Freduland, 2003). 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 transient slope stability analysis of landslide dam and prediction of the failure due to sudden sliding through flume experiments and numerical simulations. A stability model coupled with a transient seepage flow model is used for numerical simulation. The model is applicable to analyze both 2D and 3D cases of slope failure of landslide dam. The coupled model can be used to calculate the factor of safety and the geometry of critical slip surface 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 numerical procedure used for the identification of critical noncircular slip surface with the minimum factor of safety is based on dynamic programming and the Janbu's simplified method. The 3D slope stability analysis based on dynamic programming and random number generation incorporated with 3D simplified Janbu's method is also used to determine minimum factor of safety and the corresponding critical slip surface for landslide dam in the V-shaped valley.

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. General outline of coupled model is shown in Figure 1. A brief description of each model is given below.

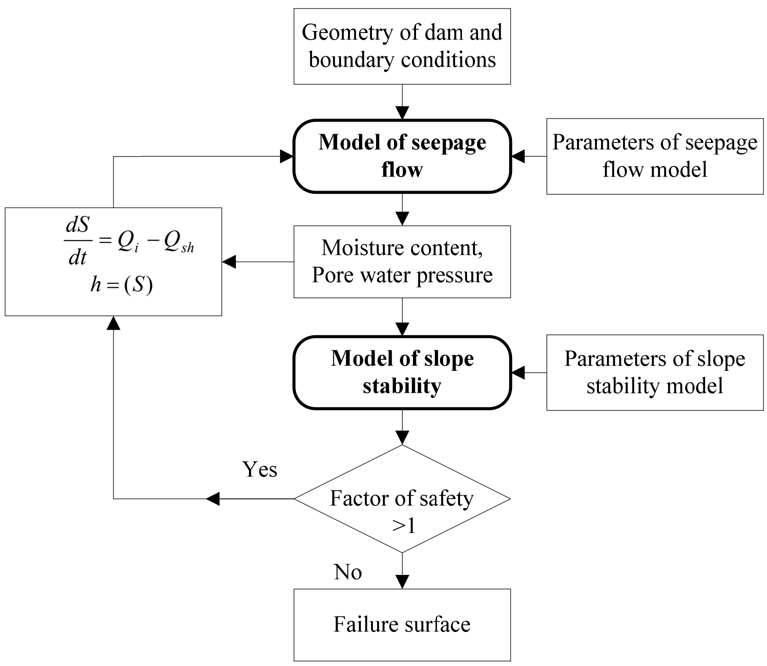


Figure 1 General flow chart of coupled model for transient slope stability analysis

2.1 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 (Awal et al., 2007)

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

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 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 (1980) are used for establishing relationship of $K-h$ and $\theta-h$, with $m=1-(1/\eta)$.

2.2 Model of slope stability (Two-Dimensional, 2D)

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 made 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 the research of Yamagami and Ueta (1986). The algorithm combines the Janbu's simplified method with dynamic programming on the basis of Baker's successful procedure (1980).

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:

$$F_s=\frac{1}{\sum_{i=1}^{n}W_i\tan\alpha_i+A_L}\times\sum_{i=1}^{n}\left\{\frac{cl_i\cos\alpha_i+(W_i-u_il_i\cos\alpha_i)\tan\phi}{\cos^2\alpha_i\left(1+\frac{1}{F_s}\tan\alpha_i\tan\phi\right)}\right\} \tag{2}$$

where W_i is the weight of each slice including surface water, A_L is the resultant external water force in the upstream side of slope (horizontal component), 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. (2007).

2.3 Model of slope stability (Three-Dimensional, 3D)

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. Ugai (1988) and Ugai and Hosobori (1988) extended the simplified Janbu method and Spencer method in 2-D 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^o), 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 simplified (Yamagami and Jiang, 1997). The model of slope stability incorporates 3D simplified Janbu method proposed by Ugai et al. couple 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 Figure 2. Figure 3 shows the forces acting on a typical column taken from Figure 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 (1988), 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 constant. In addition other symbols in Figure 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.

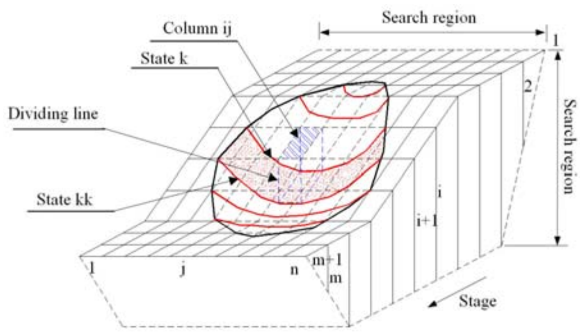


Figure 2 A stage-state system and dividing scheme for a 3D slope (Modified from Yamagami and Jiang, 1997)

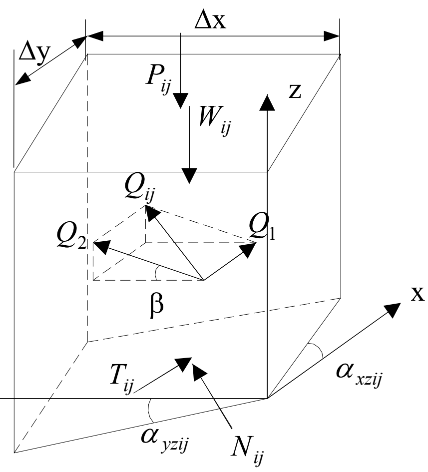


Figure 3 Forces acting on a typical column

Applying equilibrium conditions in horizontal and vertical directions for the entire sliding mass, Ugai (1988) 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 (Ugai, 1987; Jiang and Yamagami, 1999). For small 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 $\eta = 0$ (Ugai, 1987; Jiang and Yamagami, 1999) and based on this approximation, factor of safety F can be expressed by following expression:

$$F = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n}\left[\left(c_{ij} - u_{ij}\tan\phi\right)\Delta x\Delta y + \left(W_{ij} + P_{ij}\right)\tan\phi\right] / \left[\left(1/J + \sin\alpha_{xzij}\tan\phi / F\right)\cos\alpha_{xzij}\right]}{\sum_{i=1}^{m}\sum_{j=1}^{n}\tan\alpha_{xzij}\left(W_{ij} + P_{ij}\right)} \quad (3)$$

where, c_{ij} and ϕ are the effective strength parameters of soil, u_{ij} is the pore water pressure at the column base, and $J = \left(1 + \tan^2\alpha_{xzij} + \tan^2\alpha_{yzij}\right)^{1/2}$.

This simplified formula can provide sufficiently accurate results when the slope is less than 45^o (Ugai and Hosobori, 1988).

A search procedure for determination of critical 3D surfaces developed by Yamagami and Jiang (1997) is used in this study. This study extends their work to transient slope stability analysis by incorporating seepage flow model. In Eq. 3, 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 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.

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. The grain size distribution of sediment mixture is shown in Fig. 4. 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 2.

Water content reflectometers (WCRs) were used to measure the temporal variation of

Table 1 Summary of experiments

S. No.	Expt.	Flume slope	Discharge (cm^3/s)	Dam size in cm			Remarks
				Ht.	U/S L	D/S L	
(I) 2D in channel bed without cross slope							
1	2D-1	17	30.5	20	18	66	To measure moisture profile.
2	2D-2	17	30.5	20	18	66	To observe failure surface.
(II) 3D in channel bed with cross slope of 20^o							
3	3D-1	20	29.8	30	22.5	120	To measure moisture profile.
4	3D-2	20	30.5	30	22.5	120	To measure moisture profile.
5	3D-3	20	29.8	30	22.5	120	To observe failure surface.
6	3D-4	20	30.1	30	22.5	120	To observe failure surface.

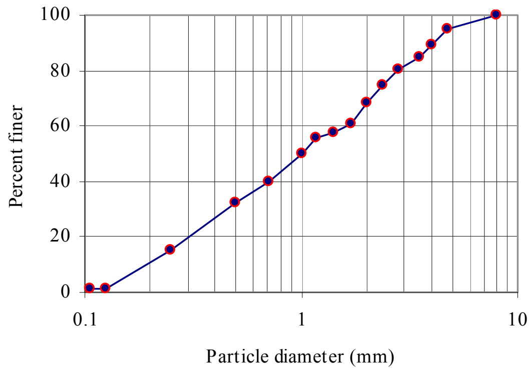


Figure 4 Grain size distribution of sediment mix

Table 2 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

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 experiments were carried out in different flumes for 2D and 3D cases:

3.1 Transient slope stability analysis (2D)

A rectangular flume of length 500cm, width 20cm and depth 21cm was used. The slope of the flume was set at 17°. The shape and size of the dam and arrangement of location of WCR's are shown in Figure 5.

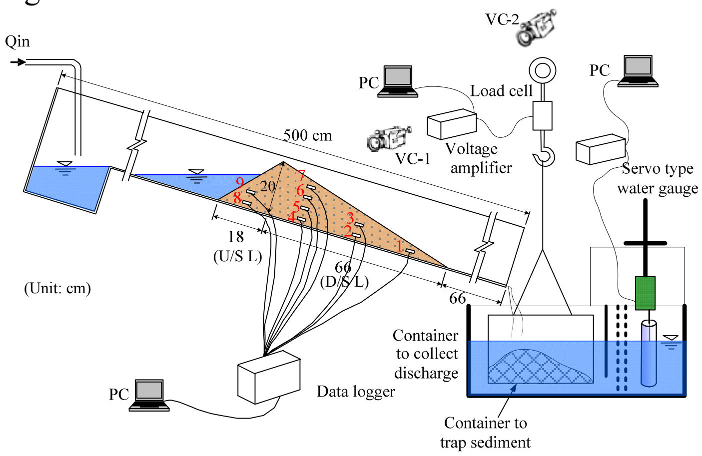


Figure 5 Experimental setup

3.2 Transient slope stability analysis (3D)

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 Figure 6 and 7. The arrangement of WCRs are shown in Figure 7. 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 of the dam body.

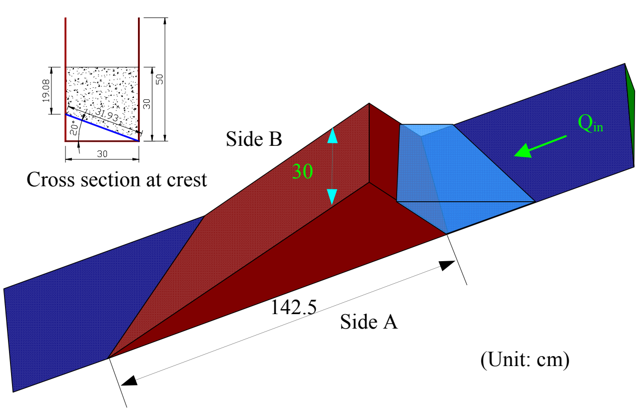


Figure 6 Shape of the dam body and cross section at crest

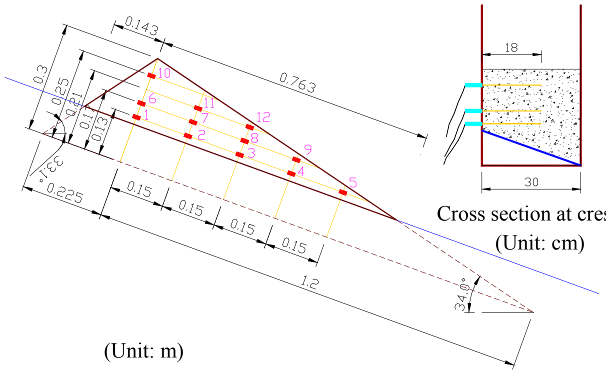


Figure 7 Arrangement of WCRs (1-12), view from Side B

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 water pressures.

4.1 Transient slope stability analysis (2D)

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. Moreover, the effects of interslice forces are ignored in Janbu's simplified method. Increase in shear strength due to the negative pore-water pressures are not considered in the formulation of factor of safety. Figure 8 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. Figure 9 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.

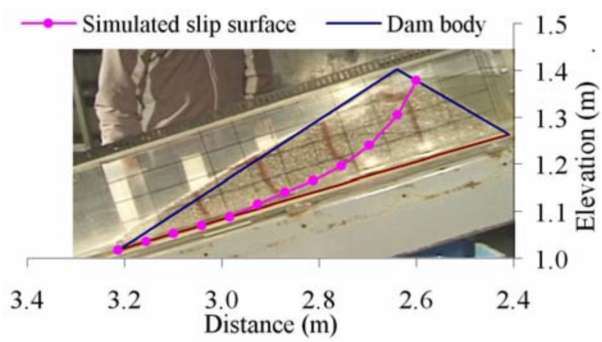


Figure 8 Comparison of simulated and experimental slip surface (2D)

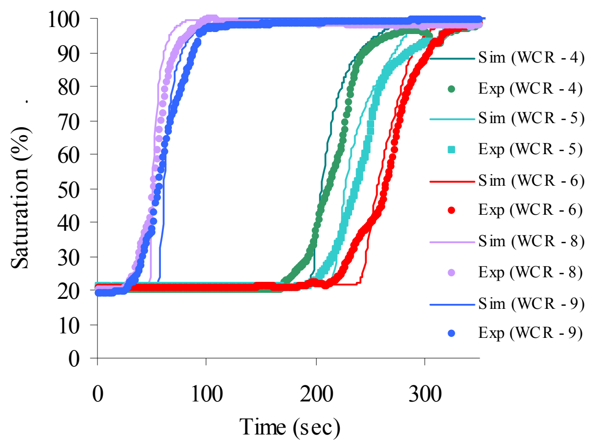


Figure 9 Simulated and experimental results of water content profile for different WCRs (2D)

4.2 Transient slope stability analysis (3D)

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 (Figure 7). The moisture along WCR may not be constant due to three dimensional effect of water movement inside the dam body. The comparison of measured moisture profile for ‘Expt: 3D-1’ and ‘Expt: 3D-2’ are shown in Figure 10. Although discharges used in both experiments are nearly equal, the variation of moisture profile for different WCRs is slightly different. This may be due to variation of 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. Figure 12 shows the movement of slide in case of ‘Expt: 3D-3’. Although the movement appears at about 930sec the distinct movement can be seen just at about 978sec. In case of ‘Expt: 3D-4’, failure was observed at 1030sec and slide mass is also deeper than ‘Expt: 3D-3’ as shown in Figure 13. This may be due to difference in non uniformity in sediment mixing, compaction, 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 the simulation are Q_{in} = 29.8cm^3/sec, K_s =0.0003m/sec, $\Delta t = 0.01$ sec, block size of 10mm was used in seepage flow model. Column size of $\Delta x = 5cm$ and $\Delta y = 3cm$ were used in slope stability model. Convergence criterion (difference between the factors of safety from the final two interactions) of less than 0.002 was used.

Figure 11 shows the comparision simulated and experimental results of moisture profile at different WCRs which are in good agreement. The simulated critical slip surface at 770 sec is shown in Figure 14. 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 29cm^3/sec to account evaporation as well as reduced saturated hydraulic conductivity of 0.00028m/sec to account uncertainty of hydraulic conductivity. In both cases dam was failed at 790sec. The simulated failure time was 830sec for saturated K_s = 0.00025m/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

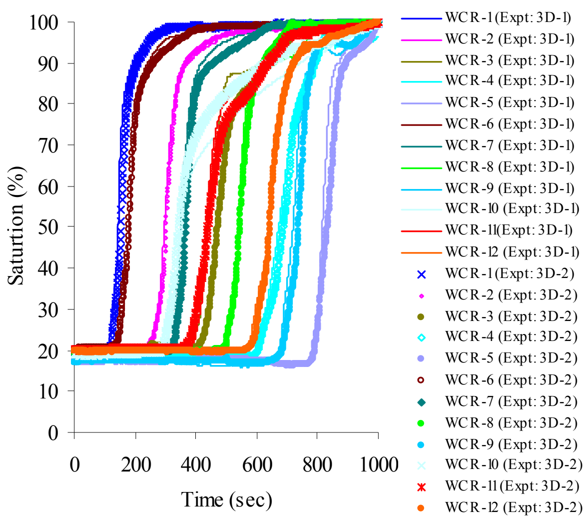


Figure 10 Comparison of moisture profile (Expt. 3D-1 and 3D-2)

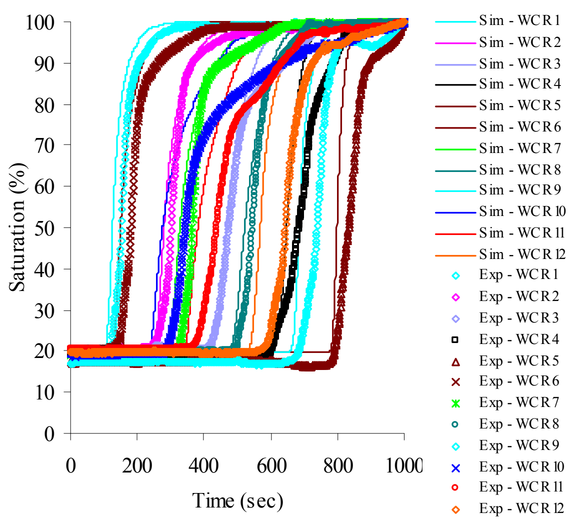
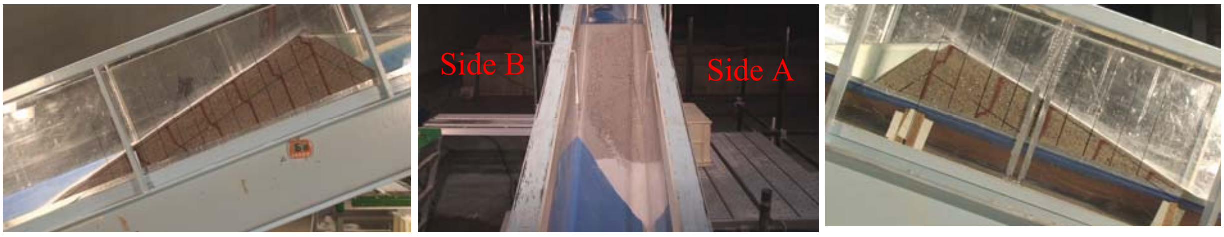
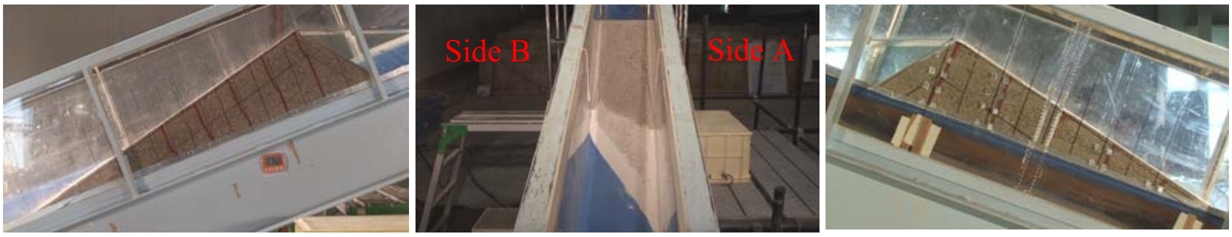


Figure 11 Comparison of moisture profile (Simulated and Experimental)



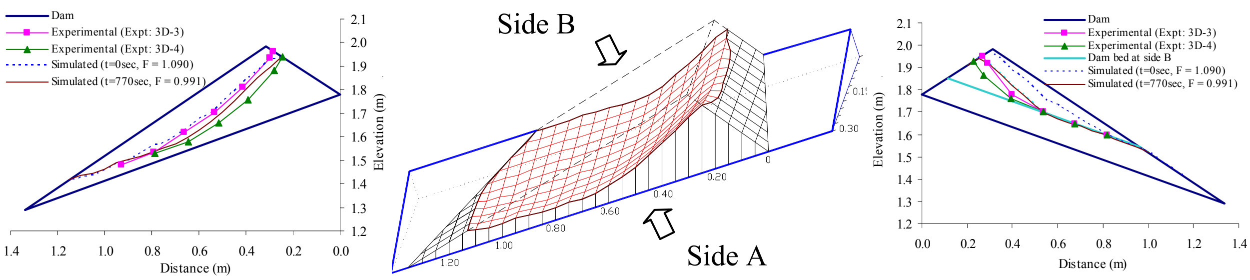
Side View (Side A) Front View Side View (Side B)

Figure 12 Sliding surface at 978sec (Experiment: 3D-3)



Side View (Side A) Front View Side View (Side B)

Figure 13 Sliding surface at 1070sec (Experiment: 3D-4)



Critical slip surface in side A Critical Slip surface in side B

Figure 14 Simulated slip surface (3D)

that the resultant interslice forces are horizontal while a correction factor is applied to account for the vertical interslice forces in 2D analysis. However, the correction factor is only available for 2D slope stability analysis and no correction is available for the intercolumn forces in the extended 3D slope stability method. For the same critical slip surface factor of safety calculated by other methods which also satisfies moment equilibrium will be higher. Moreover, the friction in the side wall of flume was also ignored in the computation. The comparison of failure surface in two faces of flume (Figure 14) 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 (2D and 3D) 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 for both 2D and 3D cases. Comparisons show that results of numerical simulations and experimental measurements are quite close in terms of movement of moisture in the dam body, predicted critical slip surface and time to failure of the dam body. 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.

REFERENCES

Awal, R., Nakagawa, H., Baba, Y. and Sharma, R. H. (2007), Numerical and experimental study on landslide dam failure by sliding, *Annual J. of Hydraulic Engineering*, JSCE, 51, pp.7-12.

Baker, R. (1980), Determination of the critical slip surface in slope stability computations, *International Journal for Numerical and Analytical Methods in Geomechanics*, 4, pp.333-359.

Brito, C. C., Pereira, J. H. F., Gitirana, G. F. N. Jr., and Fredlund, D. G. (2004), Transient stability analysis of a collapsible dam using dynamic programming combined with finite element stress fields, *IXth Int. Symp. on Landslides*, 2, pp.1079–1084.

Gitirana, de F.N.G. Jr., Fredlund, D.G. (2003), Analysis of Transient Embankment Stability Using the Dynamic Programming Method, *Proceedings of the 56th Canadian Geotechnical Conference,* Winnipeg, Manitoba, 1, pp.807-814.

Jiang, J.-C. and Yamagami, T. (1999), Determination of the sliding direction in 3D slope stability analysis, *Proc. 44th Symp. of the Jap. Geotech. Society*, pp.193-200 (in Japanese).

Pereira, J. H. F., and Fredlund, D. G. (1999), Numerical analysis of the post-filling performance of small collapsing earth dams, *XIth Pan- American Conf. on Soil Mechanics and Geotechnical Engineering,* 3, pp.1129–1140.

Staiano, T., Rinaldi, M. and Paris, E. (2001), Seepage and stability analysis of embankments during flood events, *XXIX IAHR Congress Proceedings*, Beijing, China, pp.16-21.

Takahashi T. (1991), *Debris flow, Monograph Series of IAHR*, Balkema, pp.1-165, 1991.

Tsutsumi, D., Fujita, M. and Hayashi, Y. (2007): Numerical simulation on a landslide due to Typhoon 0514 in Taketa City, Oita Prefecture, *Annual J. of Hydraulic Engineering*, JSCE, 51, pp.931-936.

Ugai, K. (1987), Three-dimensional slope stability analysis by simplified Janbu method, *Journal of Japan landslide Society*, 24(3), pp.8-14 (In Japanese).

Ugai, K. (1988), Three-dimensional slope stability analysis by slice methods, In *Proceedings of the 6th International Conference on Numerical Methods in Geomechanics*, Innsbruck, Austria, 2, pp.1369-1374.

Ugai, K. and Hosobori, K. (1988), Extension of simplified Bishop method, simplified Janbu method and Spencer method to three dimensions, *Proc. Japanese Society of Civil Engineers*, No. 394/III-9, pp.21-26 (in Japanese).

van Genuchten, M.Th. (1980), A closed-form equation for predicting the hydraulic conductivity of unsaturated soils, *Soil Sci. Soc. Am. J.*, 44, pp.892–898.

Yamagami, T. and Jiang, J.-C.(1997), A search for the critical slip surface in three-dimensional slope stability analysis*, Soils and Foundations*, 37(3), pp.1-16.

Yamagami, T. and Ueta, Y. (1986), Noncircular slip surface analysis of the stability of slopes: An application of dynamic programming to the Janbu method, *Journal of Japan Landslide* Society, 22(4), pp.8-16.

Wilkinson, P. L., Anderson, M. G. and Lloyd, D. M. (2002), An integrated hydrological model for rain-induced landslide prediction, *Earth Surface Processes and landforms*,27, pp. 1285-1297.