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Shallow Landslide Modeling for Heavy Rainfall Events

Raj Hari SHARMA* and Hajime NAKAGAWA

* Graduate School of Civil and Earth Resources Engineering, Kyoto University

Synopsis

A landslide simulation model based on the Richards equation for the ground water flow and with assumptions of soil matrixes comprising three horizontal layers was prepared to simulate rainfall induced shallow landslides. The model is capable to explicitly calculate the change in pore pressure in response to transient rainfall. Infinite slope failure was assumed for the slope stability module. The numerical solution of the unsteady pore-water pressure was experimentally verified by the physical experiment.

The model was used to reproduce the landslides occurred in 1973/10/26 at the Takora basin located upstream of Kizu river basin. Comparison of the result of transient rainfall model and steady state model was done by applying both models to simulate the landslide produced by the same rainfall. Performance of the transient response model is better compared to steady state model as the latter highly over-predicted the instability.

Sensitivity analyses of some of the model parameter were also done which indicates that depth of the layers, soil angle of repose and soil density have great influence on the stability of the soil domain. Correct representation of their values and their proper spatial distribution are vital to enhance the performance of the model output.

Keywords: heavy rainfall, shallow landslide, Richards equation, slope stability

1. Introduction

Shallow landslide typically occur on steep slopes are often triggered by individual rainstorm events after increase in pore water pressure. The generation and subsequent dissipation of pore water pressure in surficial soils as a result of rainfall, is also governed by site characteristics as hillslope morphology, upslope catchment area and soil strength related parameters. Hence, the location of the failure depends on the temporal variation of ground water table during the rainstorms, which is controlled by distributed properties of site variables as topography and soil properties. In this situation the proper prediction of the landslide in different rainfall scenarios is important to save human life and property who are at high risk.

Due to increase in expansion of development in landslide-potential environment, the risk of human casualties and economic losses are also increasing. In order to reduce the risk, attempt were made to build slope stability model which can be used as landslide hazard warning tool.

In this scenario, a great deal of research, concerning slope instability hazard has been developed over last few decades as an urgent demand for slope instability hazard information for the planning and forecasting purposes. Landslide inventory model, geomorphic analysis technique, empirical method of hazard analysis, bivariate statistical analysis, fuzzy logic, multivariate statistical model and mechanistic model etc all available approaches were developed in search for better result. Broadly classifying landslide modeling approaches can be illustrated in a)Black Box Model: not based on physical but strictly on the statistical analysis, b) Grey Box Model: based partly on physics and partly on statistics and c) White Box Model: based on physical theories (slope stability model and hydrological model) - also referred as mechanistic model. After advances in temporal and spatial resolution in precipitation, availability of relatively detailed digital data and computing power efforts has led to advances in mechanistic modeling of shallow landslide hazard, through coupling simple mechanistic slope stability and hillslope hydrological models. Ability of such model to incorporate spatially variable soil properties data and rainfall pattern also support their utility. This type of model can explicitly take account the non-homogeneity of soil, topography and wavering rainfall. This approach can be applied to new catchments also where previous histories of landslides were not recorded.

Despite the effort the model which can be applied universally to landslide prediction is yet to be developed. Due to strong influence of local controls as seepage, root strength, soil thickness, bedding etc, it is quite difficult to delineate potential landslide locations because local properties are difficult to assess and are difficult to incorporate widely due to their large extent of variation. Hydrological response of the soil to transient rainfall also adds a complexity to the problem.

Hydrological response is generally dealt in two ways; first with steady state model and second with transient hydrological response model. As rain infiltrates into the soil, it increases the pore-water pressure within the soil, which in turn reduces the shear strength of the soil. Increase in pore water pressure depends on the rainfall intensity, rainfall duration and various soil and topographic characteristics as permeability, soil thickness, layering effects and slope angle etc. High intensity and short duration rainfall are the major causes of the landslide generation in many cases. The hydrological processes that lead to land sliding are local and the time scale of response to storm precipitation variations may be just minutes (Casadei et al., 2003). Steady state model cannot simulate the response of pore pressure due to high intensity and short duration rainfall. Theories that disregard transient rainfall entirely cannot account for its effect on landslide (Iverson, 2000). Since, the response of the soil domain to the pore-water pressure is most important for the landslide model, especially that to be used for forecasting, the advective mechanism used for water recharge term should be correct.

Modeling change in pore water pressure due to rainfall is one important part of mechanistic landslide modeling. Most of the “wetting front advancing infiltration model” used in the shallow landslide prediction is gravity plug movement of the moisture.2) but the real scenario provokes differently. In reality the wetting front have variable moisture distribution throughout and is highly dependent on the soil characteristics and the rainfall intensity.

The thickness of soil mantle and its homogeneity are other critical parameter in mechanistic modeling. Even in the top soil mantle the permeability of the soil is different throughout the depth. Presence of highly permeable upper layer above the less permeable layer can be seen in most of the watersheds (Takahasi T. and Nakagawa H.,1986). Incorporation of organic matter and the activity of roots results a relatively high permeable layer in the surface soil horizons. Layers with lower conductivity may originate in subsurface horizons from clay enrichment, cemented soil horizons, compacted layers, or consolidated bedrock. The formation of a soil crust on cultivated bare soils, resulting from the direct impact of raindrops on the surface, is also known to produce the layering effect (Robert T. and Francis P. B., 2001).

The purpose of this paper is to present a transient rain induced landslide predicting model which can be used to simulate the performance of short duration and high intensity rainfall on shallow landslide generation. Transient unsaturated-saturated flow and its corresponding change in pore water pressure is computed using Richards equation (RE). We use RE so that negative/positive pore pressure can be included in the infinite slope stability model. The soil domain is assumed to consist of three layers with different soil properties.

2. Hydrologic Modeling

Hydrology plays a significant role on the shallow landslide modeling. More precisely the moisture distribution on the soil can be assessed; more exactly the location and the timing of the landslide can be estimated. In most cases effect of seepage on landslide is addressed by assuming saturated steady state flow is taking place over a given fraction of soil depth. But in order to simplify the analysis as a “worst-case” infiltration scenario, it is often assumed that the surface rises to coincide with the slope surface and that the slope is completely saturated.

For the slopes that are initially unsaturated, the effect of rainfall at the slope will have a dramatically different effect. The pore water pressure pattern that develops in the soil will occur as a transient process as the infiltration water moves downward into the soil profile. To perform unsaturated stability analyses properly, several factor not taken into account in saturated analyses should be incorporated. The shear strength of soil mass will depend on the degree of suction (negative pore pressure). The development of seepage forces in the slope will also depend on the evolution of the pore water pressure profile (Brain D. et al., 2004). To calculate the change of pore water pressure profile, the equations for the flow of water through an unsaturated soil must be utilized.

To evaluate the change in pore water pressure, pressure based RE given as in Eq.(1) is used because pressure profile exhibits fairly uniform shape but there may be strong discontinuity of the moisture content profile at the interference of the two layers. Fig.1 also supports the arguments showing sharp discontinuity of moisture content profile at the interface of the layers.

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

where, h is pressure head, C is rate of change in moisture content per unit change in pressure head ($\partial\theta/\partial h$), θ is soil volumetric water content, t is time, α is slope angle, $K_x(h)$, $K_y(h)$ and $K_z(h)$ are hydraulic conductivity in x y and z directions (Fig.2), respectively. The hydraulic conductivities may vary

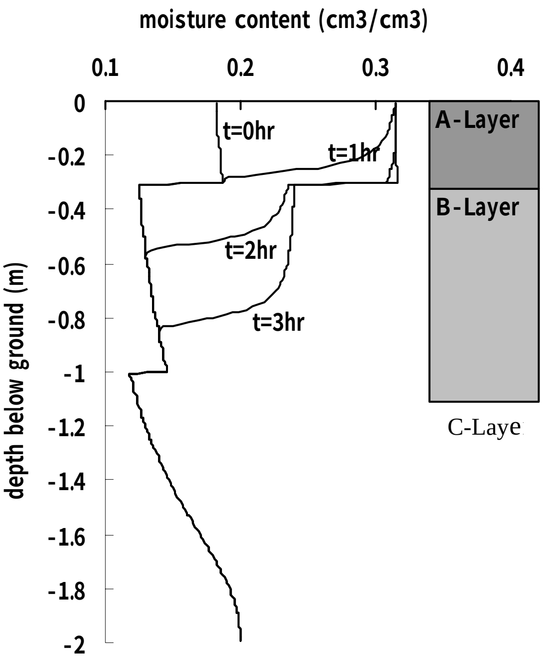

Fig. 1 Conceptual representation of three-layered soil column and the change in moisture distribution in vertical direction in different time steps using RE

owing to variations of h at the unsaturated state, at saturation they becomes saturated hydraulic conductivity K_s

In order to solve RE, the constitutive equations which relate the pressure head to the moisture content and the relative hydraulic conductivity are required. In this study, following constitutive relationships (Eq.(2), Eq.(3) and Eq.(4)) proposed by van Genuchten are used for establishing relationship of $K-h$ and $\theta - h$, with $m = 1-(1/n)$.

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

$$S_e = \begin{cases} \left(1+\left|\beta h\right|^n\right)^{-m} & for\, h<0 \\ 1 & for\, h \geq 0 \end{cases} \tag{3}$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{4}$$

where, K_s is the saturated hydraulic conductivity, β and n are parameters related with matric potential of soil and are measure of capillary fringe thickness and pore size distribution of soil respectively., S_e is the effective saturation θ_s and θ_r are saturated and residual moisture content respectively.

Soil moisture movement is highly dependent on the layering characteristic of the soil mantle (Fig.1). The most usual case is that, the upper layers are more permeable than the lower layers. In general, saturated hydraulic conductivity of the top 30 cm is around 72mm/hr, 30cm-100cm is around 36mm/hr and the layer below 1m has less then 4mm/hr (Takahasi T. and Nakagawa H., 1986). Hence, there will be surface runoff created if the rainfall is more than saturated hydraulic conductivity of the top layer and the water table in each layer will be created if the infiltration rate of the upper layer is larger than saturated hydraulic conductivity of the immediate lower layer. Lateral flow occurs under gravitational force parallel to the slope of the land, if surface water or water table within the soil layers exists.

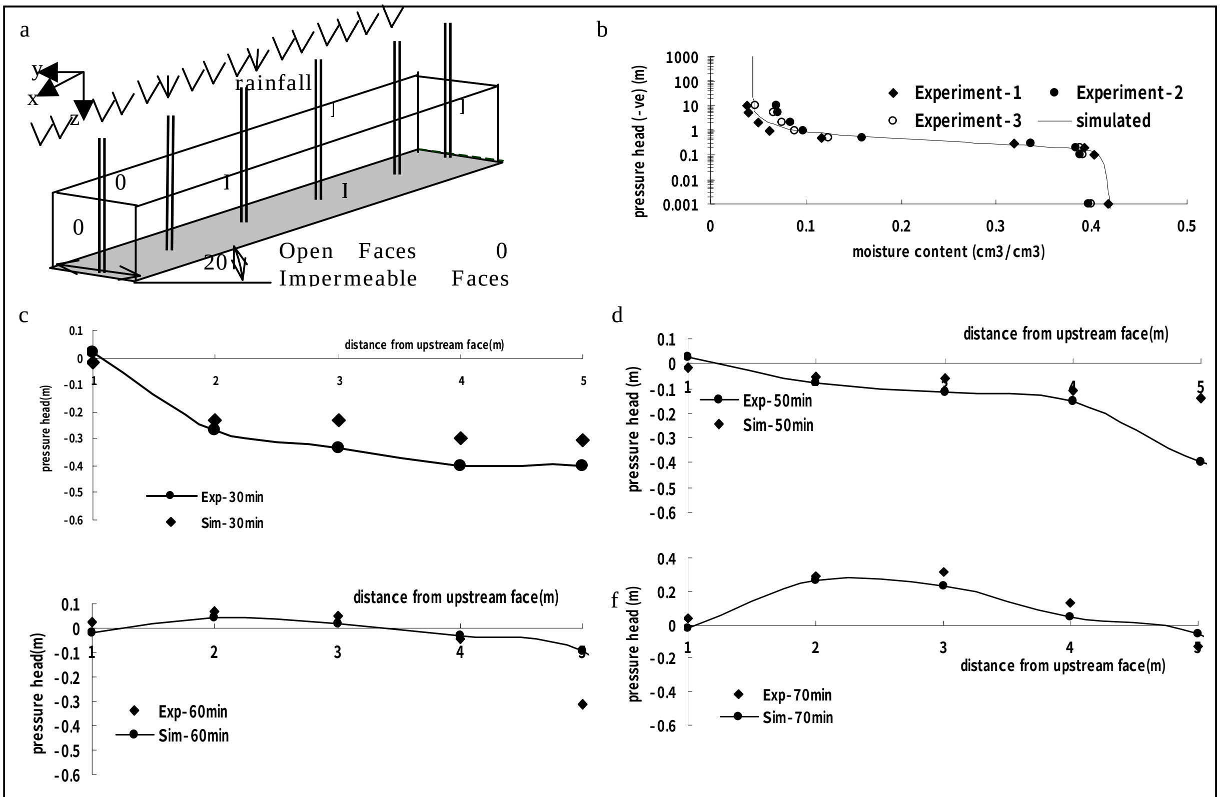

Fig. 2 a. Set up of experimental flume and tensiometers, b. calibration of the Richard's parameter and by c,d,e f. experimental and simulated soil moisture profile

3. Slope Stability Modeling

An infinite slope model has been widely used to compute Safety Factor (SF) provided the length of failure is larger (more than 10times) than the failure depth. This model assumes, therefore, that the resistances to movement along the sides and ends of the landslide are not significant. In this theory downslope component of the weight of the soil domain just at failure, is equal to the strength of resistance caused by cohesion (soil cohesion and/or root strength), and by frictional resistance due to the effective normal stress on the failure plane.

In this study we use a three-layer soil model (Fig.1). A-layer influenced by the vegetation has high permeability. B-layer is composed of the deposited materials that were dissolved in A-layer. C-layer is composed of weathering rocks on the fresh bedrocks. It is assumed that slope failures caused by heavy rainfalls can occur only on the bottom of A-layer or B-layer. Slip surface is regarded as parallel to the slope. We also assume uniform soil properties throughout the basin since such spatially variable data are generally unavailable in ungauged basins.

SF is calculated as a ratio of the resisting and driving shear stress developed at interface of two layers. The acting shear stress, τ_A and the resistance shear stress, τ_{AL} ,at the interface of A/B-layer, are expressed respectively by

$$\tau_A = g\sin\alpha\cos\alpha\begin{bmatrix} D_A(1-\lambda_A)\sigma_A + \\ \rho\left\{\int_0^{D_A-H_A}\theta dz + H_A\lambda_A + H_s\right\}\end{bmatrix} \tag{5}$$

$$\tau_{AL} = g\cos^2\alpha\begin{bmatrix}(D_A-H_A)(1-\lambda_A)\sigma_A \\ +\rho\int_0^{D_A-H_A}\theta dz \\ +H_A(1-\lambda_A)(\sigma_A-\rho) \\ +\rho H_s\end{bmatrix}\tan\phi_A + c_A \tag{6 }$$

In the same manner the acting shear stress, τ_B and the resistance shear stress, τ_{BL} , at the interface of B/C-layer, are expressed respectively by

$$\tau_B = g\sin\alpha\cos\alpha\begin{bmatrix} D_B(1-\lambda_B)\sigma_B + \\ \rho\left\{\int_{D_A}^{D_A+D_B-H_B}\theta dz + H_B\lambda_B + H_s\right\}\end{bmatrix} \tag{7}$$

$$\tau_{BL} = \begin{bmatrix}\tau_A\tan\phi_B/\tan\alpha + \\ +g\cos^2\alpha\begin{Bmatrix}(D_B-H_B)(1-\lambda_B)\sigma_B \\ +\rho\int_{D_A}^{D_A+D_B-H_B}\theta dz \\ +H_B(1-\lambda_B)(\sigma_B-\rho)\end{Bmatrix}\end{bmatrix}\tan\phi_B + c_B \tag{8}$$

where, D and H are thickness and seepage flow depth on soil layers and H_s is surface flow depth. Similarly $\lambda, \sigma, \rho, \phi$ and c are porosity of a soil layer, density of a sediment particle, density of water, angle of repose and cohesion respectively. g is acceleration due to gravity. Subscripts A or B denotes a value in A layer or B layer. When, $H_A \geq D_A$, it is set that $H_A = D_A$ and when $H_B \geq D$,the following equation is used instead of Eq.(5).

$$\begin{aligned}\tau_{BL} &= (\tau_{AL} - c_A)\tan\phi_B/\tan\phi_A \\ &+ g\cos^2\alpha D_B(1-\lambda_B)(\sigma_B-\rho)\tan\phi_B + c_B\end{aligned} \tag{9}$$

The safety factor SF_A and SF_B for A and B layer respectively are function of time dependent parameters H_A, H_B and H_s . SF for each time step, on each layer, is calculated using following equation;

$$\begin{aligned}SF_A &= \tau_{AL}/\tau_A \\ SF_B &= \tau_{BL}/\tau_B\end{aligned} \tag{10}$$

4. Numerical Simulation and experimental verification of soil moisture movement

Algorithms developed by Paceman/Rachford and Douglas/Gunn on Alternate Direction Implicit (ADI) are widely employed for diffusion equations. In this study we use the Douglas-Gunn Approach because the Paceman/Rachford approach has second order accuracy and is unconditionally stable only for the 2D problems. Douglas/Gunn approach is unconditionally stable in 3D (Ting. W and Charlie C., 2002).

The pore pressure simulation capacity of the model was verified with the flume experiment data (Diazo. et. al, 2004). The experimental data of change in pressure of initially unsaturated soil in 5m long flume sloped at 20^0 with average rainfall of 82mm/hr was used for the purpose. The result of simulated and experimental pore water pressure is shown in Fig.2.

The result of 3D numerical simulation and experimental data of the transient pore pressure change (Fig.3) encourage extending the model for landslide prediction. Uniform soil moisture distribution in vertical direction was assumed as an initial condition. The result is almost close to the experimental data.

5. Application of the transient response model

The prepared model was applied on 0.3812 km^2 Takora basin, for determination of the temporal and spatial distribution of the landslides due to that rainfall. The DEM with grid size of 10m was created from the topographic map available, after digitizing the contours.

A short-duration and high-intensity rainfall event had impacted the Takora basin, on 26th September 1973. The length of the event was 10hr with the total rainfall amount of 282.25mm. Within 7th, 8th and 9th hour of

Fig. 3. Location Map of Takora Basin

event almost 218 mm of rain fell within the study area, triggering many landslides. Air photos were taken in the year 1975 for locating the shallow landslides distribution in the area. No other major rainfall events appear to have occurred within the time window covered by the time of that major rainfall and time of taking air photo. Hence, all the landslide scars seen in the map were assumed to be caused by heavy rainfall of 1973. Fig. 3 shows the location of Takora Basin which lies upstream of Kizu river.

The model parameters were used from the literatures of the previous landslide study of the area. Saturated hydraulic conductivity was taken as 72mm/hr, 36mm/hr and 7.2mm/hr for layer A, B and C respectively. Similarly, soil depth as 0.3 and 0.52m, density 2.4g/cm^3 and 2.6g/cm^3 were taken respectively for layer A and B. Cohesion of soil is neglected (Takahasi T. and Nakagawa H.,1986). Static pressure distribution was assumed as initial condition before rainfall with zero matric potential is assumed at bottom of B-layer and decrease upward to be in static equilibrium. Stability is calculated for the failure of B layer since; the historical data shows that depth of the landslides in basin was 0.82m.

The landslide analysis model was then applied to the Basin to calculate the SF. It was assumed that if the SF reduces than 1 than such grid will fail (Eq.10). Fig.4 shows the stability of the area after 7, 8, 9 and 10 hour of rainfall. Fig.5 shows the rainfall event of 1973/10/26.

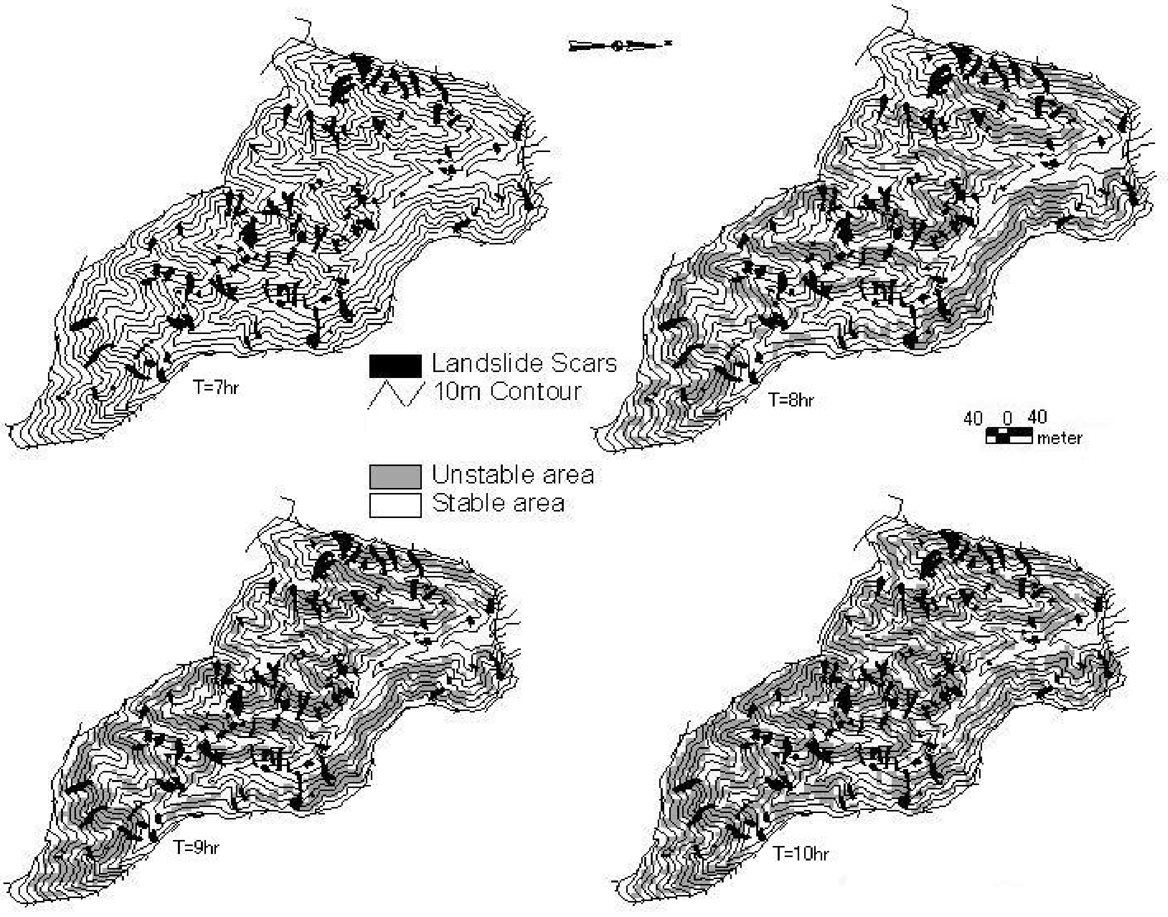

Fig. 4 Historical landslide scars and stability map of an area at the end of 7, 8, 9 and 10 hours of the rainfall event

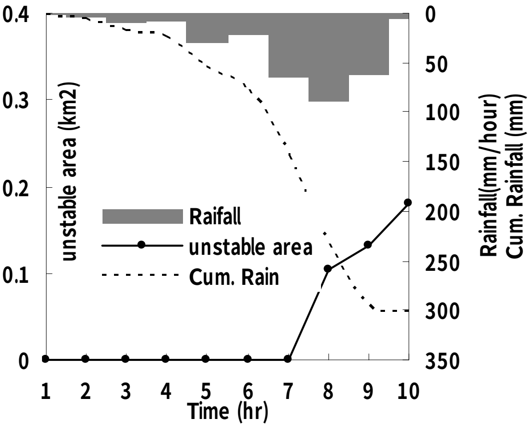

Fig. 5 Rainfall Event on 1973/10/26 and calculated unstable area

High intensity rainfall starts from the end of sixth hour and the landslides starts from the end of seventh hour till the end of the event. The time lag is the time required for rain water to infiltrate and generate sufficient pore water pressure for the failure. In 7th - 8th hour, rate of slope failure is very high compared to that of 8th - 9th and 9th - 10th hour.

After the end of 10 hour rainfall event 43% of the area was classified as unstable (FS<1), and 64% of the actual landslides were correctly localized within this area. This means the landslide model correctly predict the landslides with 64% accuracy.

6. Comparison with the steady state model

To compare the performance of the transient and steady state model, a steady state model was prepared and applied to same basin. In this model the ground water table modeling was calculated using the concept that were used to made the SHALSTAB (a model for mapping shallow landslide potential). The steady state water table is calculated as

$$h_w = D\frac{q}{T}\frac{a}{b\sin\alpha} \tag{11}$$

$$T = \cos\alpha\int_0^D K_s(z)dz \tag{12}$$

where, steady state h_w is ground water height, D is soil depth that is assumed to fail, q is the effective precipitation (rainfall minus evapotranspiration), b is width of grid cell and T is transmissivity (the vertical integral of the saturated conductivity) , a is upslope drainage area to that particular grid. Slope stability analysis was done using the same infinite slope failure model. Soil friction angle was taken same as 0.7 for entire grid as in transient model. In the steady state model the average daily rainfall on the area was taken as an input to calculate the steady state ground water table which was finally used to calculate the slope stability of an area. The result is shown in Fig. 6.

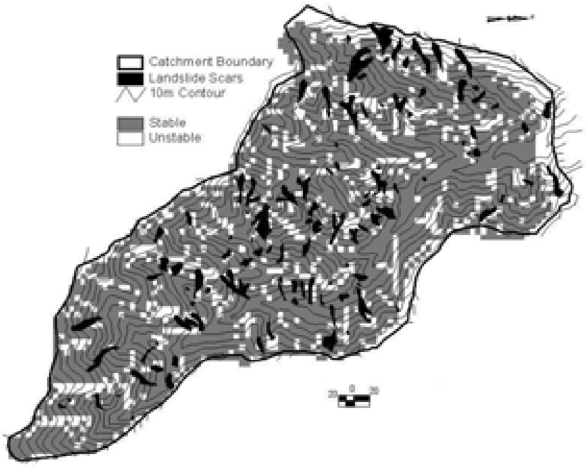

Fig. 6 Landslide scars and Stability map of area by steady state model

To evaluate the performance of model in quantitative way we formulated two sets of probability, P_o is probability of modeled unstable area on actual landslide zone and P_R is a probability of region modeled as unstable within entire area. Table 1 shows the performance of steady state and transient response model (Figure 2). Although steady state model predicts 80% of landslide area but it also model 78% of area as unstable. The result of transient response model is better and its performance can be enhanced by incorporating spatial variation of soil properties and rainfall in model.

Table 1Performance of transient and steady state model

Models	P_o	P_R
Steady State Model	0.80	0.78
Transient Model	0.64	0.43

A terrain stability model which captures more observed landslides in its unstable zone, while minimizing the extent of such area is a better demarcator of potentially unstable terrain. The outcomes of a model would be a) unstable at actual landslide location b) stable at actual stable location c) unstable at actual stable location and d) stable at actual landslide location. First two are the desired outcomes of the model whereas the last two are the errors in the modeling. Considering the third outcome, if some stiff soil/hard rock is located in the area with larger slope even though the model predicts the instability there may not be landslide. Last category of outcome indicates the area may have some different characteristics properties then was assumed e.g. presence of spring, presence of low strength soil patches making particular location weaker in terms of stability, also the absence of the landslide (from model) doesn't mean that a certain slope cannot experience land sliding under slightly different condition in the range of model uncertainty.

In the model all the parameters except the topography and the rainfall pattern are kept uniform. Other parameters such as soil friction angle, soil density,

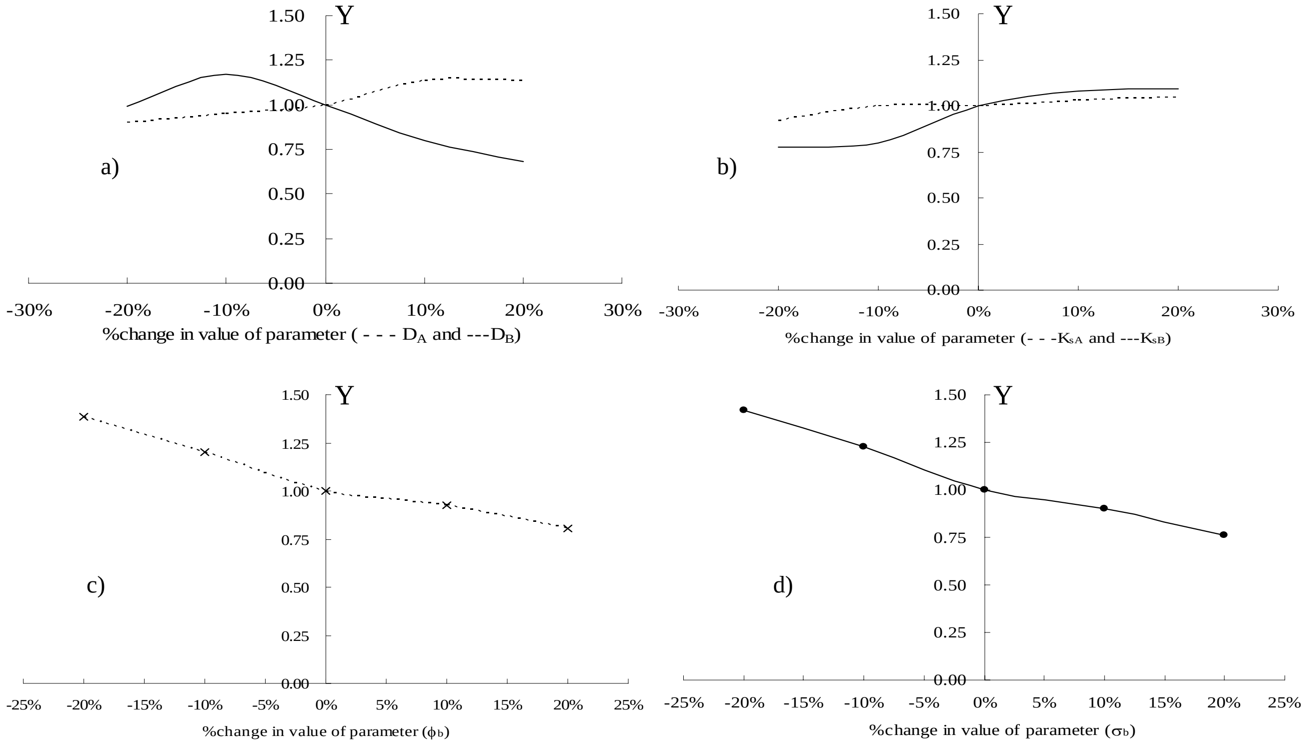

Fig.7 Sensitivity of parameters (Y axis is the ratio of unstable are after changed value of parameter and unstable area with original parameter value)

permeability of soil layers, depth of layers etc are also important factors that may change the landslide propensity. Hence, sensitivity analysis of some parameters was done so that their importance in future generalization of model can be treated aptly.

7. Sensitivity analysis

Depth and saturated hydraulic conductivity of soil layer A and B have significant influence on stability of the soil domain. The soil friction angle and specific density are other parameters that plays vital role in determination of the stability. To study the sensitivity of stability of area to variation on these parameters, each parameter was varied by ± 20% , so that correct influence of each parameter can be recognized. Sensitivity analysis is carried on to evaluate the failure of the layer B.

Fig.7a shows how soil depth of upper layer A influences the stability of layer B. Increase in depth of A layer reduces stability of A and B both layers. This happens as the hydraulic conductivity of layer A increases, there is chance of rapid increase in pore water pressure due to higher conductivity of A layer. In the other hand increase in the depth of layer B increases the stability because this increases the resisting shear stress of the soil after increment in depth. Increase in depth of B layer also increases the time required for sufficient pore water pressure development because the moisture have to move greater distance to reach the interface of B/C layer. The result shows the depth of layer B is of more vital than layer A for stability calculation.

Fig.7b indicates that increase in hydraulic conductivity of A or B layer both will reduce the stability of area. But the hydraulic conductivity of Layer A is less sensitive than that of layer B.

Fig.7c and d show that increase in soil friction angle and specific density of soil both reduce the unstable area. Influences of these two parameters seem to be vital in dictating the stability of area. This shows the importance of these spatially variable parameters for better model performance.

8. Conclusion

The result of numerical and experimental model of the infiltration has good agreement which indicates the model can simulate the pore water pressure. The numerical model was further developed as landslide simulation model and was used to simulate landslide triggered by the rainfall event in Takora Basin. The model was able to predict the landslide with 64% accuracy on the basin. Comparison was done with the result of the steady state model. The result shows the performance of transient response model has better ability to simulate landslide then steady state model.

The result of the sensitivity analyses show that for the landslide prediction, beside the groundwater condition other spatially variable soil properties as the depth of layers, hydraulic conductivities, angle of friction and density are also quite important and should be incorporated explicitly.

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豪雨性表層崩壊のモデリング

シャルマ ラジ ハリ[*]・中川　一

[*]京都大学大学院工学研究科社会基盤工学専攻博士後期課程

要旨

本稿は，豪雨時を対象とした表層斜面崩壊のモデリングについて示したものである。斜面の安定性は土層内の水分の消長に大きく依存するため、これを精度よく表現し得るリチャーズ式を導入している。降雨実験により、モデルの適用性を検討した後、無限長斜面を仮定した３層からなる斜面の安定性を、リチャーズ式によって評価される土壌水分の消長を考慮して検討している。この斜面安定性の解析法を木津川上流域のタコラ谷に適用し、実際の豪雨時斜面崩壊箇所との比較検討により、本モデルの適用性が確認された。さらに、透水係数、土層厚、安息角、土粒子密度など、モデル中のパラメータが崩壊発生個数に与える影響について感度分析を行い、斜面安定解析において重要なパラメータを特定している。

キーワード:豪雨，斜面崩壊，リチャーズ式，斜面安定性