PREDICTION OF RAIN-INDUCED LANDSLIDING BY USING SLOPE HYDRODYNAMIC NUMERICAL MODEL

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ABSTRACT

An accurate prediction of rain-induced landsliding is still difficult to be performed. This is due to the uncertainty in the slope hydrological conditions believed to be the key factor controlling landsliding, as well as the difficulty in observing such conditions. The incorporation of numerical modelling to simulate and predict slope hydrological behaviour in response to rainfall is suggested. The simulation results show that stability of slope with low permeability and shallow groundwater conditions can change within hours in response to rainstorm. How the rain intensity and duration as well as slope hydrological conditions, such as groundwater table, soil permeability and initial slope saturation, control slope stability also can be observed rigorously.

1. INTRODUCTION

Landslide (slope failure) is a downslope movement of soil or rock masses as a result of shear failure at the boundary of moving mass (Chowdhurry, 1978; after Skempton and Hutchinson, 1969). When the movement of the soil/ rock mass is mainly induced by rainfall then it is defined as rain-induced landslide.

To predict the landslide occurrence is simply to guess where and when landslide would occur. Actually, there had been quite a lot of studies attempted to do so. Those studies had been able to provide prediction on **where** the landslide may occur. Nevertheless, **when** it may occur remains uncertain. This may be because all of those studies merely relied on the empirical investigation. Admittedly, such investigation is relatively simple and useful for rapid assessment where there is a time constrain. Yet, mechanism of landslide occurrence cannot be observed thoroughly, and thus inside assessment on all factors controlling such occurrence is difficult to be performed. In fact, they are crucial to enable the landslide occurrence to be predicted.

2. CONTROLLING FACTORS

There are several factors believed to be the major control of landslide occurrence. Those are the geology and terrain conditions, shear strength characteristics of soil/ rock material forming the slope, soil/ rock structures within the slope, climate and slope hydrological conditions, as well as landuses. How those factors control the occurrence of

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landslide has been discussed in Sampurno (1975); Hencher, S.R. and Masey, E.W. (1984); Tjojudo (1985); Heath, W. and Sarosa, B.S. (1988); Sarosa, B.S. (1992) and Karnawati (1996). Among those factors, the slope hydrological conditions is the most difficult one to be investigated. Since it is very sensitive to change through space and time in response to climatic changes (i.e. rainfall). Indeed, the heterogeneity of slope forming materials brings about more complex hydrological behaviour, which may be unable to be observed empirically.

3. MECHANISM OF RAIN-INDUCED LANDSLIDE

Gostelow (1991) suggested four consecutive steps leading to failure due to the rain infiltration. These are :

a. the storm or rainfall event
b. infiltration
c. groundwater table rise in the slope and reduction in shear strength
d. failure and displacement along a shear surface

However, the groundwater table rise is only one of several ways in which the rain infiltration affects slope stability . These include :

a. soil unit weight variation as saturation changes
b. decreasing pore suction in the unsaturated zone
c. pore water pressure rise

Which one of those mechanism will proceed, depends on the slope hydrology and geology conditions. When the initial groundwater table is relatively shallow, landslide is most likely due to the pore water pressure rise, whilst such occurrence due to the soil unit weight variations is the most unlikely one (Karnawati, 1996).

4. RAIN-INDUCED LANDSLIDE PREDICTION

4.1 Approach

To predict the landslide occurrence is simply to guess where and when the slope failure will occur by identifying what the likely rainfall characteristics (i.e. the intensity and duration of rainfall) which can result in the intensive rain infiltration into the slope, and then cause the excessive rise of groundwater table and pore water pressure, reduce the slope stability, and finally result in slope failure (landslide). All of those could be conducted numerically.

Once the characteristics of triggering rainfall can be identified, the trend of rainfall which reduce the slope stability can be approximated, and hence the occurrence of slope failure can also be predicted.

Therefore, in the study of rain-induced landslide, the numerical simulation is used to replicate slope hydrology behaviour in response to rainfall, and then to predict (analyse) the slope stability in response to such behaviour.

4.2 Simulation code : Two Dimensional Combined Slope Hydrology and Slope Stability Model (2DCSHSSM)

Two Dimensional Combined Slope Hydrology and Slope Stability Model (2DCSHSSM) is a modelling package suggested to be used for predicting the landslide occurrence. This is a FORTRAN two-dimensional finite different modelling package combined with a slope stability analysis package and was developed by Anderson and Pope (1984) and Lloyd (1992).

a. Assumptions

Assumptions inherent in the code are :

i. the fluid phase has constant density and flow is governed by Darcy's Law

ii. the fluid is slightly compressible and homogenous

iii. flow is two dimensional (there is no flow in or out of the section). Furthermore, flow in unsaturated zone moves only in the vertical direction and flow in the saturated zone only in the horizontal direction.

iv. there is no hysteresis in the soil moisture-suction relationship

v. the failure surface is circular

vi. the soil strength parameters and bulk unit weight are constant.

b. Limitations

The code simulates only single-phase (i.e. water) flow and ignores flow of any second phase (i.e. air). The air pressure in voids is assumed to be atmospheric. The model does not adjust soil bulk unit weight in response to infiltration. However, the results of the simulations show that this did not significantly affect stability for the conditions investigated here. This is because there was a relatively small range of the soil volumetric water content between the residual and the fully saturated condition for the soils modelled (Karnawati, 1996). No graphical output is provided.

c. Governing equations

The hydrodynamic model is driven by fluxes from the surface boundary. Precipitation supplies water into each column at a rate up to the infiltrability. Once infiltrability is exceeded, water is stored at the surface until the detention capacity, i.e. the maximum height of water that can be pounded on the slope surface, is exceeded, after which the overland flow is initiated.

The basic geometric structure of the hydrodynamic model is illustrated in Figure 1 and the governing equations used are quoted in Equation 1, 2 and 3.

In Equations 2 and 3, K is the unsaturated hydraulic conductivity (L/T), θ is the soil volumetric water content (L^3/L^3), Ψ is the soil suction head (-L), z is the depth, t is time (T), $Q_L(M)$ is the lateral flux in saturated zone at column M (L^3/T), K_S is the soil saturated hydraulic conductivity (L/T), $WTH_{(M-1)}$ is the numbers of saturated cells at column (M-1), $WTH_{(M)}$ is the number of saturated cells at column (M) and A is the area perpendicular to the flow direction which is defined as the depth of the cell (L^2), as the model has unit thickness.

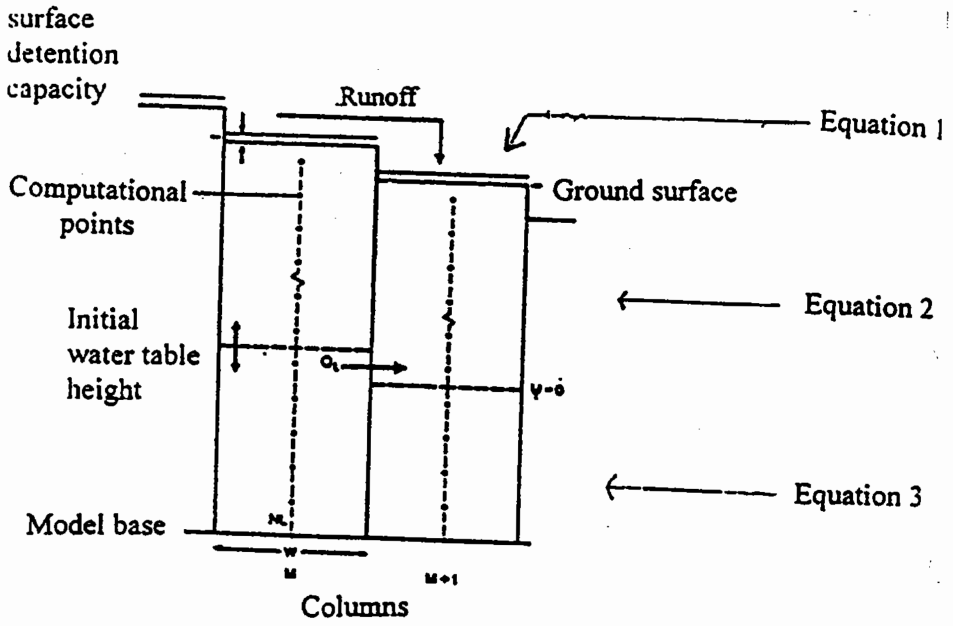


Figure 1. Two dimensional soil water model (Anderson and Kemp, 1991).

$$\text{Evaporation} = F_{max}\ \sin\left[2\pi\,(\text{time})\right] \qquad [1]$$

Unsaturated zone :

$$\frac{\partial\theta}{\partial t} = \frac{\partial K}{\partial y} - \frac{\partial[K\,\partial\psi]}{\partial y\quad\partial y} \qquad [2]$$

Saturated zone :
Lateral flow :

$$Q_{L(M)} = \frac{WTH\,(M-1)\ -\ WTH\,(M)}{W} K_S\ A \qquad [3]$$

The governing equation for the flow in unsaturated zone is similar to that proposed by Hillel (1977). It is a mass balance equation which is based on Darcy's Law and th continuity equation.

The hydraulic conductivity in the unsaturated zone K_i is not constant. It has a valu less than the saturated hydraulic conductivity K_S and depends upon the moisture content By assuming there is no hysteresis in both soil suction-moisture and the hydrauli conductivity-moisture relationships, unsaturated hydraulic conductivity is calculated b using the Millington-Quirk formulation :

$$Ki = \frac{Ks\theta i^{p}}{\theta s}\ \frac{\sum_{j=1}^{m}\left[(2j+1-2i)\psi_j^{-2}\right]}{\sum_{j=1}^{m}\left[(2j-1)\psi j^{-2}\right]} \qquad [4]$$

where p is the fitting coefficient (which depends on soil type). The suction moistur curve is devided into (m - 1) parts is the increment of volumetric water content (θ_i). K_i i the unsaturated hydraulic conductivity corresponding to a volumetric water content θ and θ_S is the saturated volumetric water content.

The soil-moisture suction relationship curve is required to calculate the so unsaturated hydraulic conductivity (K_i) from the volumetric moisture content θ_i a formulated in Equation 4. Such curve was measured by laboratory testing. However, th other parameter in Equation 4, i.e. the fitting coefficient p is always equal to 1 i 2DCSHSSM. According to Jackson (1972), a unity value allows acceptable determ nation of K_i for a wide range of soil types.

A good correspondence between the Millington-Quirk equation and experiment data for Guelph Loam and Sand (grain size is the range 50-500 µm) was reported b Anderson and Pope (1984), as illustrated in Figure 2. Equation 4 is probably valid f many sands and fine soils.

The hydrodynamic component of 2DCSHSSM redistributes soil water verticall within each column and laterally within the saturated zone. The height of the groun water table in each column is obtained from the number of continuous saturated cel above the base.

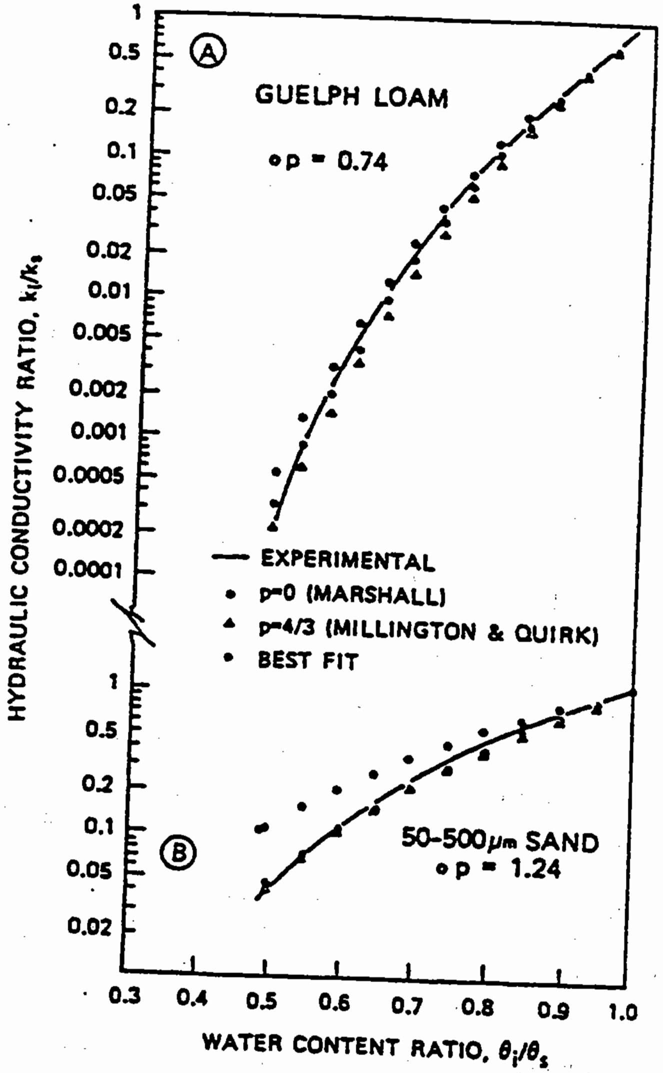


Figure 2. Comparison of methods for estimating unsaturated permeability (Jackson 1972 in Anderson and Pope, 1984)

At the end of each hour, the pore water pressure or suction for each cell is calculated. Suction is found from volumetric water contents for cells in the unsaturated zone, whilst for cells in the saturated zone, pore water pressure is found from the depth below the water table (hydrostatic head distribution is assumed in the saturated zone). These data are transferred into the stability model as piezometric heads located at points defined by the centre of each cell.

Slope stability is indicated by factor of safety (F) calculated using the Bishop Simplified method (Bishop, 1955) as formulated in Equation 5 and illustrated in Figure below.

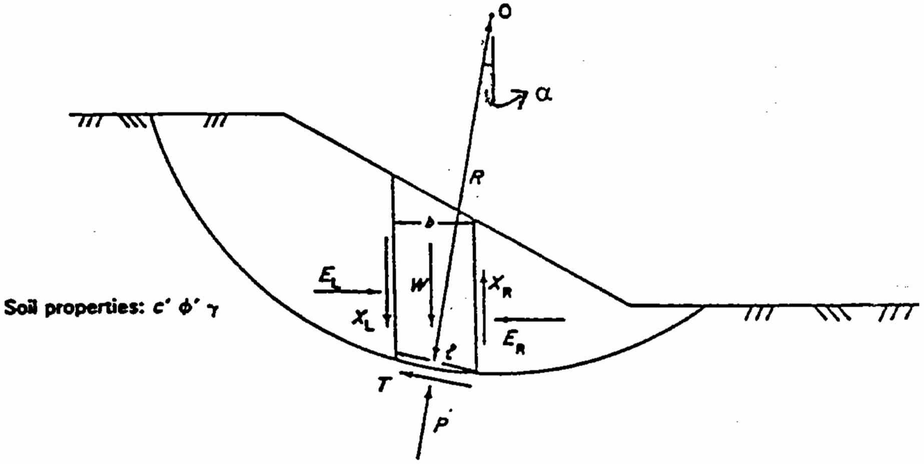
$$\text{Factor of Safety (F)} = \frac{\sum\left[c'l + (P - ul)\tan\phi'\right]}{\sum W \sin\alpha} \qquad [5$$

where :

$$P = \left[W - \frac{1}{F}\left(c'l\sin\alpha - ul\tan\phi'\sin\alpha\right)\right] m\alpha\ ,$$

and

$$m\alpha = \cos\alpha\left(1 + \tan\alpha\,\frac{\tan\phi'}{F}\right),$$



For slice shown: at base – normal stress σ, shear stress τ, pore pressure u

Mohr–Coulomb failure criterion: $s = c' + (\sigma - u)\tan\phi'$
Mobilized shear strength $\tau = s/F$ where F is factor of safety

Figure 3. Bishop Simplified Method of slope stability analysis (Bishop 1955 in Nash 1987)

meanwhile, c' is the effective soil cohesion, φ' is the soil frictional angle, u is the so pore water pressure and W is the weight of soil mass which is potential to slide.

When the factor of safety (F) is less than 1, then the slope failure (landslide) occurs. After the most critical circle (indicated by the minimum factor of safety) is found, a factor of safety for this is output for each hour of simulation.

d. Input

The input parameters include :

i. Geometry of slope model such as number of columns, number of soil layers, number of cells per column, initial number of saturated cells per column, cell thickness (m) and column width (m)

ii. Definition of the search grid for circular failure analysis

iii. Material properties of the slope

- a. saturated volumetric moisture content (cm^3/cm^3)
- b. saturated hydraulic conductivity (m/sec)
- c. detention capacity (m)
- d. effective stress cohesion (kN/m^2)
- e. effective stress friction angle (degrees)
- f. saturated bulk unit weight (kN/m^3)
- g. unsaturated bulk unit weight (kN/m^3)

iv. Rainfall

- a. rain intensity (m/hour)
- b. rain duration (hours)
- c. maximum evaporation rate (m/s)

e. Output

The output consists of pore water The output results include the list of factor of safety values calculated at each hour of simulation, the value of the minimum factor of safety, co-ordinates of the centre together with the radius of the most critical circular failure surface and the time at which minimum stability occurs, as well as the values of water pressure head either positive or negative at each computational point (node) with nodal co-ordinates.

4.3 Example of simulation results and discussion

A numerical modelling combined with slope stability analysis by using 2DCSHSSM was carried out to predict the stability of 15° slope of halloysitic soil in response to 10 hours of rainstorm. The simulation was run for 50 hours. Admittedly, 10 hours of rainstorm is rather unlikely to occur in real conditions. Yet, it is deliberately selected to enable an extreme effect of rainstorm on slope stability to be predicted. Moreover, the longer the duration of simulated rainfall applied the more complete behaviour of slope hydrology conditions could be observed. This simulation also intends to assess how the initial groundwater table conditions, soil permeability and initial soil moisture conditions in the slope control the changes of slope stability. Model soil properties are listed in Table I.

Table I. Model soil properties

Soil properties	Magnitude
Shear strength parameters :	
a. Cohesion	8 kPa
b. Frictional angle	17.4 °
Specific gravity	2.68
Void ratio	1.4
Unsaturated bulk unit weight	15.6 kN/m^3
Saturated bulk unit weight	17.0 kN/m^3
Saturated permeability	2.51×10^{-7} m/s 2.51×10^{-6} m/s
Saturated volumetric water content (porosity) :	
a. allophanic clay	0.85 cm^3/cm^3
b. halloysitic clay	0.72 cm^3/cm^3

Two initial slope hydrological conditions were used in the modelling (Figure 4). These represent conditions in the wet and dry seasons commonly found in Java (Field observation). The model representing wet season conditions has a shallow water table, 1 m below the foot slope and 3 m below the top slope. The model representing dry season conditions has a water table 5 m and 10 m below the foot-slope and the top slope respectively.

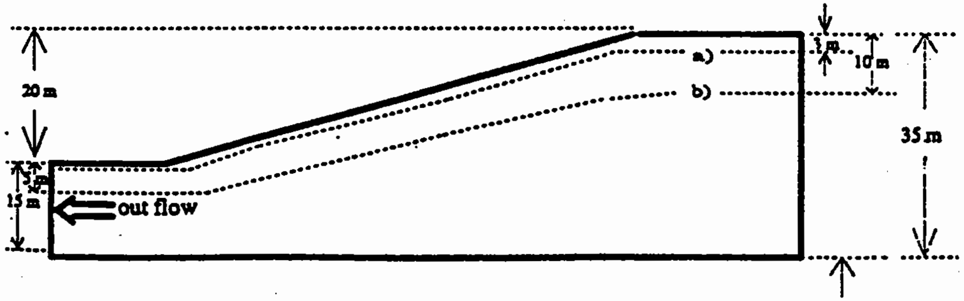


Figure 4. Initial groundwater table positions in a) wet season and b) dry season

The simulation results in Figures 5 and 6 show that slope stability changes through the time during the rainstorm. Such change is indicated by the fluctuation of factor of safety. This change is strongly controlled by the soil permeability and the position of initial groundwater table.

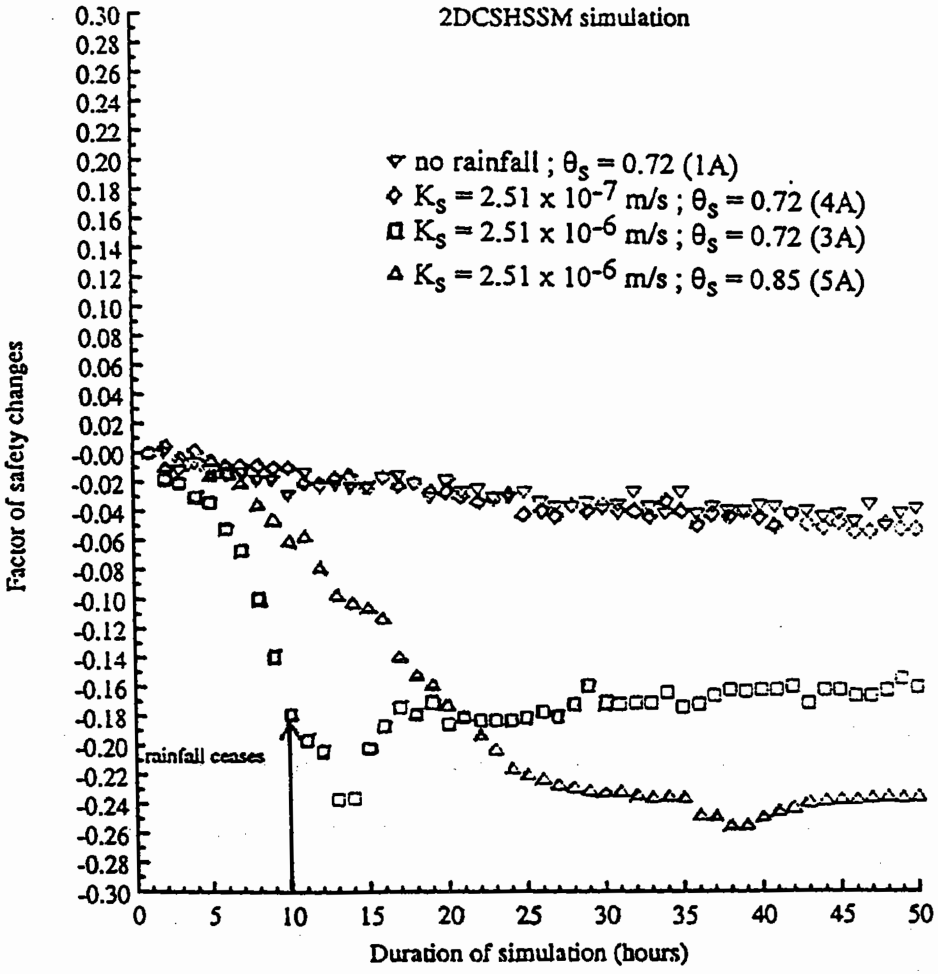


Figure 5. Factor of safety changes in response to 10 hours of rainstorm in various conditions of slope hydrology (shallow initial groundwater table)

Figure 5 illustrates that the maximum decrease in stability in the slope with shallow initial groundwater table where soil permeability was 2.51 x 10^{-6} m/s, was about 12 times higher than that in the slope with the permeability of 2.51 x 10^{-7} m/s. It is apparent that

the more permeable the slope the more rain flux can be infiltrated, so the more the groundwater table (the pore water pressure) rises, and finally the more the stability decreases.

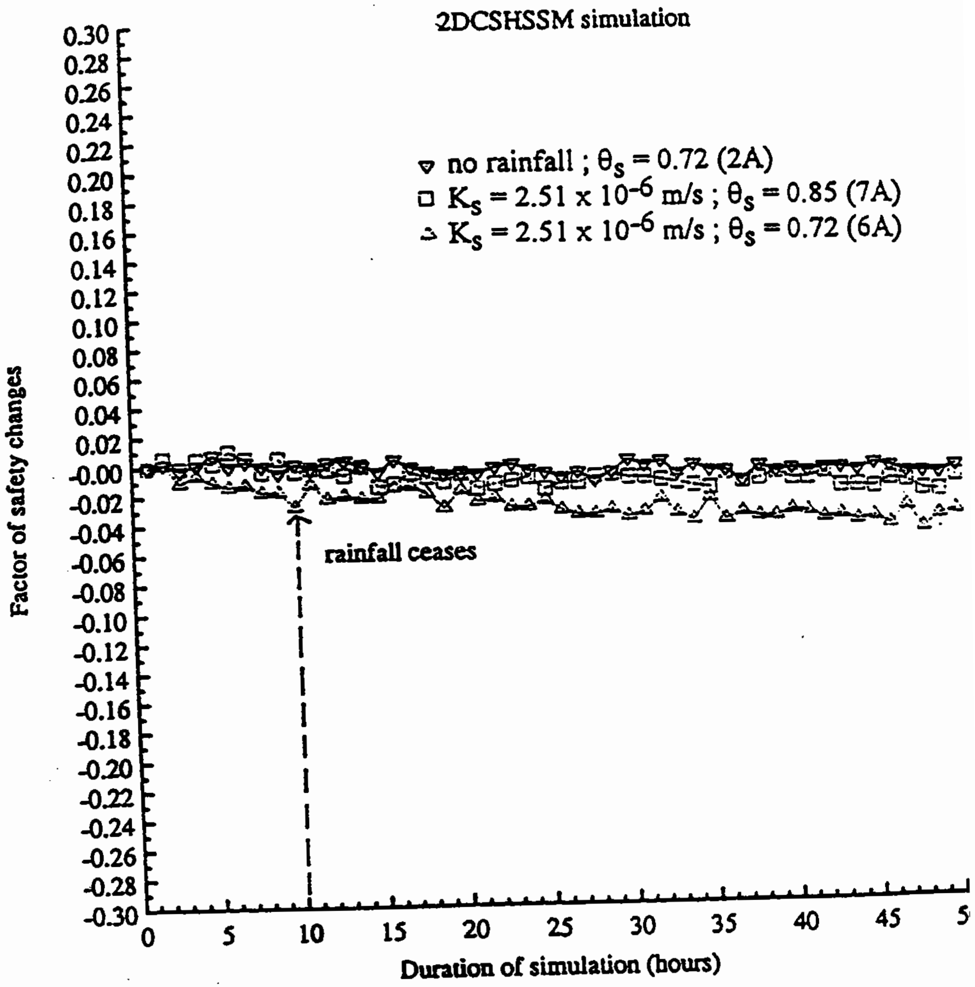


Figure 6. Factor of safety changes in response to 10 hours of rainstorm in various conditions of slope hydrology (deep initial groundwater table)

It is also shown in Figure 5 that the different conditions of soil saturation in th unsaturated zone, indicated by saturated volumetric water content (θ_s), does no significantly affect the magnitude of slope stability decrease but the duration fo achieving the minimum stability. In the more saturated slope (θ_s = 0.85) the minimun stability occurred 3 hours after rainstorm ceased. Meanwhile in less saturated slope ($\theta_s \approx$ 0.72), it occurred 25 hours later. This is because the more saturated the slope, the more rapid rain infiltration, thus the earlier the minimum stability occurs.

Figure 5 and 6 illustrate that in the slope with the same soil permeability (i.e. 2.51 x 10^{-6} m/s), where the initial groundwater table was shallower, the decrease of stability was about six times higher than that where the initial groundwater table was deeper. This may be because the deeper the initial groundwater table, the more flux of rainwater is required to rise the groundwater table to reduce the stability as much as that in the slope with shallower initial groundwater table. That is why, under the same amount of rain influx the less stability decrease occurs in the slope with deeper initial groundwater table.

4.4 Remarks

The simulation results discussed above shows that slope stability could changes within hours. In special cases where the soil is more permeable, the changes may occur within minutes. This may be overlooked in the empirical investigation due to the limited capabilities (such as the slow response) of monitoring equipment installed. Furthermore, the role of each variables controlling slope stability can be easily observed. However, calibration of the results above is still required, i.e. by comparing them with empirical results. Therefore, in order to provide accurate prediction on rain-induced landslide both numerical modelling and empirical investigation are necessary.

5. CONCLUSION

Among all factors controlling rain-induced landslide, the slope hydrological condition is the most complicated one to be investigated, due to its sensitivity to change through space and time in response to the rainfall. The incorporation of numerical modelling in the slope stability analysis could improve the accuracy of the landslide prediction.

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