Sediment Problems: Strategies for Monitoring, Prediction and Control (Proceedings of the Yokohama Symposium, July 1993). IAHS Publ. no. 217, 1993.

Study for prediction of occurrence of hillside landslides

S. HIRAMATSU
Pacific Consultants Co. Ltd, 7-5, Sekido 1-chome, Tama city, Tokyo 206, Japan
T. MIZUYAMA
Faculty of Agriculture, Kyoto University, Kitashirakawa, Sakyo-ku, Kyoto 606, Japan
S. OGAWA
Faculty of Agriculture, Ehime University, 3-5-7, Tarumi, Matsuyama 790, Japan
Y. ISHIKAWA
Public Works Research Institute, Ministry of Construction Government of Japan, Asahi-1, Tsukuba city, Ibaraki 305, Japan

Abstract In this study, a hillside landslide model is presented that takes into consideration:
(a) The mountain slope distribution in a three-dimensional space: and
(b) The transient flow of water in saturated-unsaturated soils which profoundly affect the potential occurrence of hillside landslides and the time of occurrence, was proposed.

This simulation model was applied to a basin where many hillside landslides occurred. The model predicted locations of landslides and was accepted as valid. Evaluation of parameters affecting the stability of the mountain slope were made through numerical experiments. The following matters were confirmed by this study:
(a) The model simulated accurately changes of groundwater level with time for hillsides of different shapes.
(b) The value of the hydraulic conductivity is most important in predicting the timing of hillside landslides.

NOTATION

C	specific moisture capacity
c	cohesion of soil
G_s	specific gravity of soil particles
h	groundwater depth
I_x and I_y	hydraulic gradients in x-axis and y-axis directions
k	hydraulic conductivity
k_s	saturated hydraulic conductivity
n	porosity
q_x and q_y	fluxes in x-axis and y-axis directions
q_z	amount of water supplied from unsaturated domain
t	time
X, Y and Z	distances along X-axis, Y-axis and Z-axis directions
β	angle of inclination of unit slope

γ_w	unit-volume weight of water
θ	water content in percent of total weight
λ	effective porosity
ϕ	internal friction angle of soil
φ	moisture tension
Δ_z	vertical soil layer division width.

INTRODUCTION

Hillside landslides frequently occur in many parts of Japan in the period of heavy rains every year, thus forming a major source of sediment production in the basins. Hillside landslides are triggered by heavy rain and are explained as the physically transient process of the surface soil layer on the mountain slope. In this study, a model of hillside landslides was proposed through saturated-unsaturated infiltration analysis, taking note of the storm water hydrological process in the interior of the surface soil layer on the mountain slope, and we studied the effectiveness of the model by applying it to a small basin which has experienced frequent hillside landslides.

GENERAL DESCRIPTION OF STUDY AREA

The study area is a small basin (catchment area: 0.52 km^2) in the upper stream of the Tenryu River basin in Japan as depicted in Fig. 1. In this basin, many hillside landslides occurred in the heavy rain caused by Typhoon No. 10 in 1982, affecting 1.33% of the area. The amount of continuous rainfall was 403.0 mm and the maximum hourly rainfall intensity was 45.0 mm.

PREPARATION OF HILLSIDE LANDSLIDE MODEL

Construction of the model

To predict the location of the hillside landslides and its scale and determine the degree of danger of basin collapse, it is necessary to evaluate the storm water hydrologic process on a hillslope in a realistic manner. In this study, hillside landslides were regarded as a phenomenon whereby a slope surface layer moves as it becomes destabilized from decrease of soil strength due to increased weight brought about by the infiltration of storm water into the interior of the hillside slope or the formation of a groundwater zone and the rise of saturation.

In this model, a hyetograph was modified using the concept of the theory of the one-dimensional vertical unsaturated infiltration flow. Storm water supplied to the bedrock surface was traced on the basis of this one-dimensional vertical unsaturated infiltration analysis as a saturated throughflow by Darcy's law (Ota *et al.*, 1983). For the construction of the model, the basin was mesh-divided as depicted in Fig. 2, providing each mesh with a vertical soil column using the thickness of the surface soil layer as its height, and this column was used as the basic element of the analysis (Hiramatsu *et al.*, 1990). Storm water supplied to the basic element infiltrates the

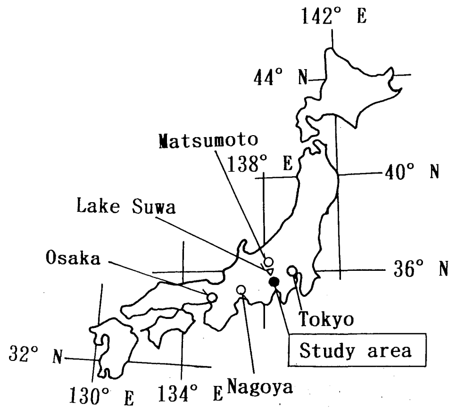


Fig. 1 Location of the study area.

unsaturated soil layers, reaches the bedrock, forms a saturated zone and moves between the elements as a saturated throughflow.

Infiltration analysis

Equation (1) led by Richards (Richards, 1931) by extending Darcy's law to the unsaturated domain was applied in analyzing the one-dimensional vertical unsaturated infiltration process of storm water in the unsaturated zone from the slope surface layer to the surface of the bedrock:

$$C \cdot \frac{\alpha\varphi}{\alpha t} + \frac{\alpha}{\alpha z}\left\{k \cdot \left[\frac{\alpha\varphi}{\alpha z} - 1\right]\right\} \tag{1}$$

The saturated throughflow process was traced, using the amount of water supplied to the surface of the bedrock by equation (1). The equation of continuity in this saturated throughflow process is expressed by:

$$\lambda \cdot \frac{\alpha h}{\alpha t} + \frac{\alpha q_x}{\alpha x} + \frac{\alpha q_y}{\alpha y} = q_z \tag{2}$$

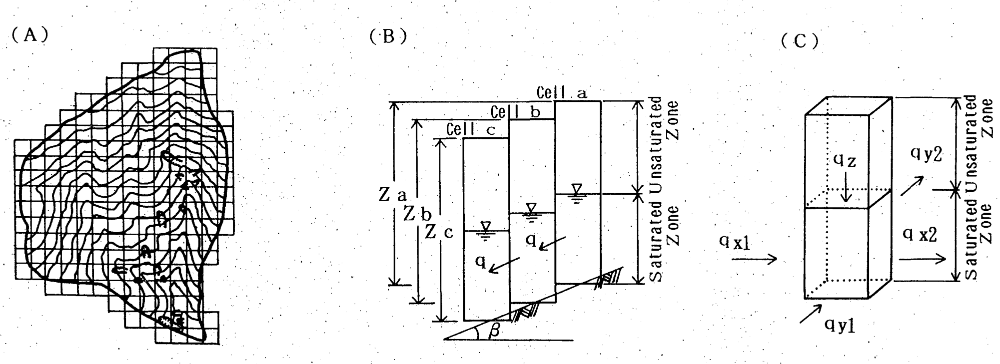


Fig. 2 Hydrologic process on a hillslope.

Also, the equation of motion is given by:

$$q_x = h \cdot k_s \cdot I_x, q_y = h \cdot k_s \cdot I_y \qquad (3)$$

according to Darcy's law.

Slope stability analysis

In a hillside landslide, generally the collapse length is greater than the collapse depth and the slip plane is often flat. So, estimation on slope stability was analyzed through the equation of stability analysis on an infinite-length slope:

$$Fs = \{c + \sigma_0 - h \cdot \gamma_w) \cdot \cos^2\beta \cdot \tan\phi\}/(\sigma_0 \cdot \cos\beta \cdot \sin\beta) \qquad (4)$$

$$\sigma_0 = \int_0^z \{\theta(Zi) \cdot \gamma_w + (1-n) \cdot G_s \cdot \gamma_w\} \cdot \Delta z \qquad (5)$$

APPLICATION OF HILLSIDE LANDSLIDE MODEL

Conditions of analysis

The input conditions necessary for carrying out hillside landslide simulation were set for each of the unit slopes obtained by dividing the basin, using 25 m meshes, on the basis of a 1/5000 topographic map. Thickness of the surface soil layer was given at intervals of 0.1 m, using the range of 1.0 ~ 1.5 m for every unit slope and based on the collapse depth of a slope where a landslide had occurred in the past. For soil data,

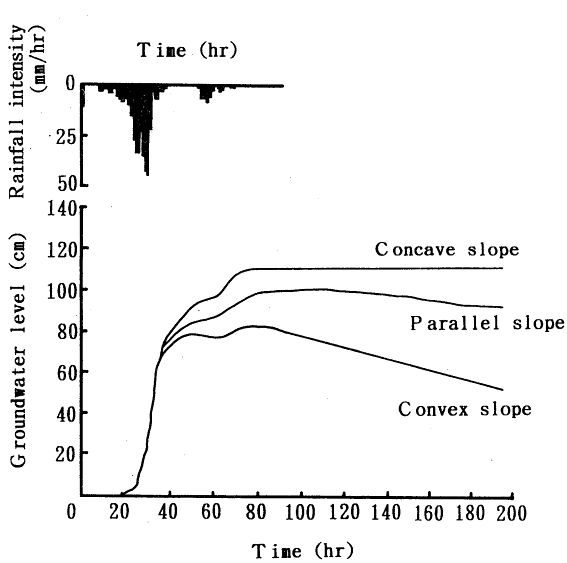


Fig. 3 Change with time of groundwater level for the difference of topographic conditions.

the results of a soil test by soil specimens taken from the basin was used. Our numerical simulation was carried out by inputting rainfall in Typhoon No. 10 of 1982 and using the time of rainfall start as the time of computation start.

Response characteristics of groundwater level for the difference of slope shapes

Figure 3 shows changes with time of groundwater level for the difference of topographic conditions for one typical slope selected from each of concave, parallel and convex slopes in the basin. In all slope shapes, groundwater levels began to rise suddenly 25 hours after the start of the rain. Then, the degree of rise began to decline 40 hours after the time of start of computation, i.e. the time of occurrence of peak rainfall. This decline of the degree of rise of the groundwater level was particularly noticeable for the convex slope. This probably occurs because the supply of storm water from the ground surface to the soil layers stops after the end of rainfall and the amount of one-dimensional vertical unsaturated infiltration decreases; furthermore, the amount stored in the interior of the slope flows toward the slopes in the vicinity as saturated throughflows for the convex slope.

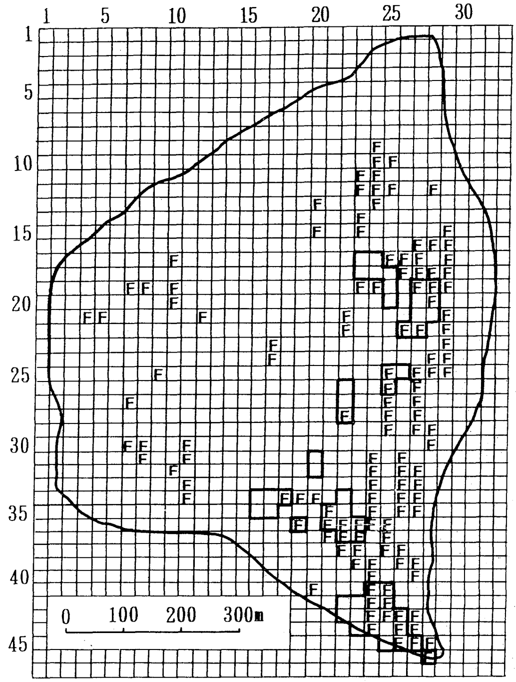
Occurrence of slopes with hillside landslides

Figure 4 shows the distribution of slopes with hillside landslides obtained by numerical computation. It indicates that slopes with safety ratios of less than 1.0 are generally consistent with slopes where landslides actually occurred and replicates fairly well the trend for landslides to occur in sites such as the upper reaches of the left tributary, the lower reaches of the right tributary and the lowest reaches of the basin itself. But in reality, landslides occurred on a few slopes with safety ratios of 1.0 or higher although generally on slopes with safety ratios of under 1.0. This may be attributable to the dispersion of input conditions such as the amount of rainfall, the thickness of the surface soil layer and soil strength and the accuracy of topography reproduction by meshes.

EVALUATION OF IMPACTS OF LANDSLIDE-CAUSING FACTORS

When using a numerical simulation model to determine whether hillside landslides will occur, the results are greatly affected by topographic conditions, such as the thickness of the surface soil layer and the slope gradient, by saturated hydraulic conductivity which governs the flow of storm water in the interior of slope soil layers and by soil strength constants in case that the amount of rainfall is constant. Here, we took note of surface soil layer thickness and saturated hydraulic conductivity — i.e. all the above factors, which can be determined relatively easily by topographic measurement, field exploration, etc. - and evaluated the extent to which these factors affect the stability of slopes, using the hillside landslide model mentioned in the preceding chapter.

Changes in slope stability with changing surface soil layer thickness of 120, 130 and 140 cm were examined. It was found that the predicted likelihood of a landslide



F : Sites of hillside landslides occurrence obtained by numerical calculation
□ : Sites of hillside landslides occurrence during heavy rainfall in 1982

Fig. 4 Distribution of slopes with hillside landslides.

increased with the thickness of surface soil layer. Also, comparing the change of groundwater levels and slope safety ratios by surface soil layer thicknesses, it was found that, during and after rainfall, the probability of slope collapse was high in proportion to the thickness of the surface soil layer.

It is supposed that saturated hydraulic conductivity greatly affects the change of groundwater depth because storm water which has infiltrated the surface soil layer and thereafter reached the surface of the bedrock can be calculated by Darcy's law (equation (3)) as a saturated throughflow. Change of slope stability pursuant to the change of saturated hydraulic conductivity was investigated using different values of saturated hydraulic conductivity: $k_s = 0.002$, 0.005 and 0.010 cm/s. It was found that the time of occurrence of hillside landslides was advanced with the increase of saturated hydraulic conductivity and the time taken to reach the final distribution of hillside landslides decreased accordingly. We also confirmed that differences in saturated hydraulic conductivity on the behaviors of the groundwater level began to have an effect from when the saturated throughflow exceeded water supplied from the unsaturated domain, and that the time of this appearance was advanced with the increase of saturated hydraulic conductivity. We deduced from these results that hillside landslides on concave slopes by the influx of a saturated throughflow are more likely with high saturated hydraulic conductivity, while on convex slopes, hillside landslides are less likely by increased runoff. Thus, it was concluded that saturated hydraulic conductivity is an important factor in predicting the occurrence of hillside landslides and especially the time of their occurrence.

FUTURE PROBLEMS

We have presented a saturated-unsaturated infiltration analysis for hillside landslides as a phenomenon of sediment production triggered especially by heavy rain, and have proposed a hillside landslide occurrence model which takes into consideration storm water infiltration and flow into the hillside surface soil layer. This model proved effective in predicting hillside landslides when applied to the local basin. However, there are still no established methods for setting surface soil layer thickness (especially values for slopes without landslides), saturated hydraulic conductivity and soil strength (dispersion from place to place), factors believed to be important in predicting hillside landslides. It is necessary therefore to establish methods for setting these parameters hereafter, to improve analysis accuracy and, at the same time, to develop a universal model by applying it to other basins as well.

Acknowledgements We would like to express our gratitude to Dr Hiroyuki Yoshimatsu of Ministry of Construction Government of Japan for his advice in conducting the numerical simulation in this paper.

REFERENCES

Hiramatsu, S., Mizuyama, T. & Ishikawa, Y. (1990) Study of a method for predicting hillside landslides by analysis of transient frow of water in saturated and unsaturated soils. *J. Japan. Saabo. Soc.* **43**(1), 5-15 (in Japanese).

Ota, T., Fukushima, Y. & Suzuki, M. (1983) Research on runoff from hillsides by one-dimensional transient saturated-unsaturated flow. *J. Japan. For. Soc.* **65**(4), 125-134 (in Japanese).

Richards, L. A. (1931) Capillary conduction of liquids through porous media. *Physics* **1**, 318-333.