論　　文

Evaluation of Probabilities of the Occurrence of Hillside Landslides

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山腹崩壊発生の確率的評価について

小　川　　滋

要　旨　山腹崩壊発生の水理学的モデルを提案し，この発生モデルを現地に適用するために，このモデルに用いられている要因の現地的な評価を行った。このモデルの要因である斜面勾配，斜面長，表層土層厚，透水係数の現地的な変化が考慮され，特に計測困難で場所的に変動している表層土層厚を確率的に評価することによって，崩壊発生を確率的に算定する方法を示した。

Summary: A hydraulic model of a hillside landslide was proposed, and the factors being used to construct this model were evaluated in order to apply this model to an actual hillside. The variation of the factors, i.e. slope gradient, slope length, depth of surface layer and hydraulic conductivity were taken into account, and the depth of the surface layer which was very difficult to measure and varied spatially, was evaluated stochastically. The probability of the occurrence of a landslide was calculated using these factors.

Ⅰ. INTRODUCTION

Much attention has been paid to determining the various factors which cause hillside landslides. These factors are all related, making it difficult to isolate their individual effects.

The methods which have been employed to clarify the relationship of these factors are divided into two main methods: the stochastic and dynamic methods. However, the relationship presented by the stochastic method can not be universally applied, while the dynamic method is very difficult to apply in the field due to the fact the dynamic factors are scattered widely over the actual hillside. Therefore, in this paper, we propose a hydraulic model which has universality and for which the hydraulic factors were estimated taking into account those variations in the field. This model was applied to an actual hillside.

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II. MODEL OF OCCURRENCE OF HILLSIDE LANDSLIDES

It is thought that hillside landslides are induced by the saturation of the surface layer, which is caused by subsurface flow, especially interflow. The author devised a hydraulic model of landslide occurrence, as shown in Fig.1. This model can explain hillside landslides on an average. Although soil mechanics are also an important consideration, saturation of the surface layer appears to be the principle factor causing landslides.

The factors of this model are precipitation, surface layer depth, slope gradient, slope length and permeability of the surface layer.

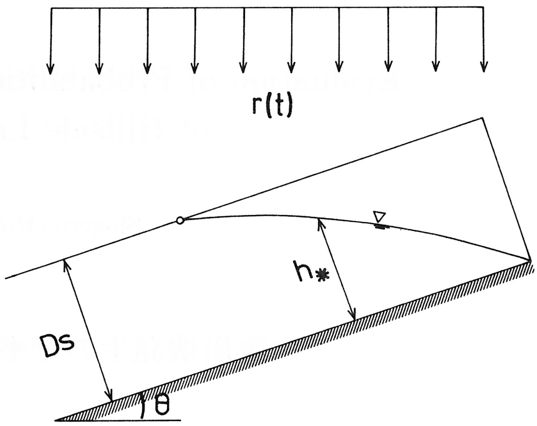

Fig.1 Hydraulic model of occurrence of hillside landslides

III. MODELING OF A HILLSIDE AND MODEL PARAMETER

In order to make these factors correspond to an actual hillside, the hillside was modelled as follows;

1) Slope length and slope gradient

The slope length and slope gradient can be measured using a topographical map, by which a vertical section of the slope is obtained. In this paper, the profile of the hillside slope was measured as follows:

Measuring points were chosen so that an equal interval held along the channel of the watershed, and the hillside slopes right and left of the channel were measured from these points to the watershed devided. One of the measured vertical sections is shown in Fig.2, in which the slope lengths of each section and their slope gradients are represented as the symbols l_{0i} and θ_i, respectively. The slope length (L_i) is given as the sum of l_{0i}. The distribution of slope lengths in the watershed is estimated by the measured slope lengths, and the mean value and standard deviation are calculated.

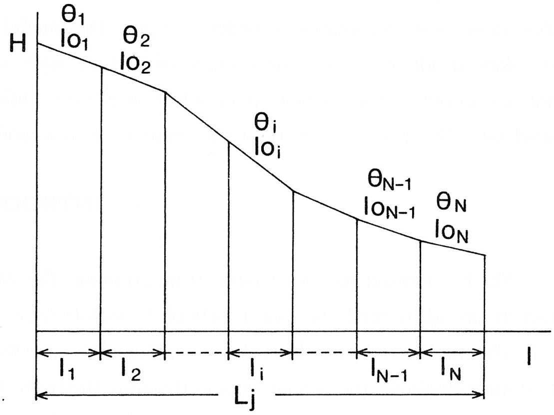

Fig.2 The measured vertical section

2) Surface layer depth

Surface layer depth is one of the most important factor. It is considered on an average that the surface layer depth increases with a decrease in the slope gradient, therefore it can be presumed as a function of slope gradient. The surface layer depth of the section (D_{Si}), in this study, is given as,

$$D_{S\,i} = a\,(2\cos\theta_i - 1) \qquad \cdots\cdots\cdots\cdots\cdots(1)$$

where, a is parameter and the range of θ_i is from 0° to 60°.

However, the surface layer depth of an actual hillside, varies widely around an average value. This variation can be represented by the parameter 'a', given as a probability variable, and the probability density function of 'a' is given as $g(a)$. Therefore, the probability density function of surface layer depth, $G(D_{S\,i})$, is given as follows;

$$G(D_{S\,i}) = g(a)/(2\cos\theta_i - 1) \qquad \cdots\cdots\cdots\cdots\cdots(2)$$

IV. CALCULATION OF SURFACE LAYER DEPTH CAUSED LANDSLIDES

The depth of subsurface flow, as shown in Fig.1, was computed using the rainfall-runoff model proposed by OGAWA [1] in a related study. This model is based on the principle that the hydraulic conductivity increases with an increase in the depth of interflow, and can be expressed mathematically as follows:

Considering the effective hydraulic conductivity (k_0) as the function of effective depth of flow (h_*), k_0 is represented as,

$$k_0 = \beta\, h_*^{\,n} \qquad \cdots\cdots\cdots\cdots\cdots(3)$$

where, β and n are constant.

Using eq. (3), the equation of motion is given as,

$$h_* = k q^P \qquad \cdots\cdots\cdots\cdots\cdots(4)$$

in which,

$$k = (1/\beta \sin\theta_i)^P \qquad \cdots\cdots\cdots\cdots\cdots(5)$$

$$P = 1/n + 1 \qquad \cdots\cdots\cdots\cdots\cdots(6)$$

where, q is the discharge of unit width.

Next, the equation of continuity is,

$$\partial h_*/\partial t + \partial q/\partial x = r(t)\cos\theta_i \qquad \cdots\cdots\cdots\cdots\cdots(7)$$

where, r(t) is effective rainfall, t is time coordinate and x is space coordinate.

For the computation of h_* a characteristic curve was used. The effective depths of flow were computed in the downstream end points of each section, using the characteristic curves as shown in Fig.3. The maximum depth of flow (h_{*max}) among the computed depths, which was obtained from each section, were considered as the maximum saturated depth of surface layer. Therefore, the maximum depth of the surface layer of the occurrence ($D_{C\,i}$) is given as follows;

$$D_{C\,i} = h_{*max\,i}/\varepsilon \qquad \cdots\cdots\cdots\cdots\cdots(8)$$

where, ε is effective porosity of the surface layer and suffix 'i' shows the slope section i.

As an additional condition, it is considered that a given depth of surface layer is needed for the occurrence of landslides, for which the critical depth is given as the symbol 'b_C'.

Finally, the range of surface layer depth

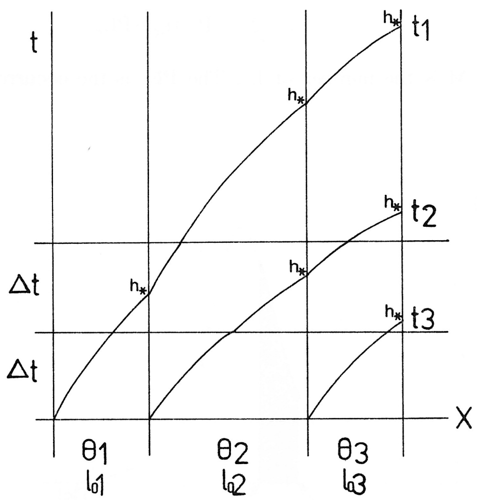

Fig.3 Computation of h_* in each section using characteristic curves

caused landslides, can be expressed as,

$$b_C \leqq D_{Si} \leqq D_{Ci} \qquad \cdots\cdots\cdots\cdots\cdots(9)$$

where, D_{Si} is the surface layer depth of i-slope section.

V. OCCURRENCE PROBABILITY OF HILLSIDE LANDSLIDES

The occurrence probability in the slope section 1_{0i}, $P_{ri}(1_{0i})$, is considered as the probability of surface layer depth caused landslides, which was computed using the probability density function, $G(D_{Si})$, as shown in Fig.4. Therefore, the occurrence probability is as follows;

$$P_{ri}(1_{0i})' = \int_{b_C}^{D_{Ci}} G(D_{Si})dD_{Si} = \int_{a_1}^{a_2} g(a)da \qquad \cdots\cdots\cdots\cdots\cdots(10)$$

in which,

$$a_1 = b_C / 2\cos\theta_i - 1, \quad a_2 = D_{Ci} / 2\cos\theta_i - 1 \qquad \cdots\cdots\cdots\cdots\cdots(11)$$

The slope gradient must next be taken into consideration to clarify the cause of landslides. As might be suspected, the occurrence probability increases with an increase in slope gradient, thus, its effect (I_P) is given as the following simple method.

$$I_P = \sin\theta_i / \sin 60^{0} \qquad \cdots\cdots\cdots\cdots\cdots(12)$$

$$P_{ri}(1_{0i}) = P_{ri}(1_{0i})' \cdot I_P \qquad \cdots\cdots\cdots\cdots\cdots(13)$$

The occurrence probability of each slope length is written as,

$$P_{rj}(L_j) = \sum_{i=1}^{N} P_{ri}(1_{0i}) / N \qquad \cdots\cdots\cdots\cdots\cdots(14)$$

where, $P_{rj}(L_j)$ is the occurrence probability in the slope length L_j and N is the number of the slope sections in L_j.

Next, the occurrence probability of watershed (Pw) is shown as the sum of the product of $P_{rj}(L_j)$ and occurrence probability of L_j computed from slope length probability distribution.

$$P_W = \sum_{j=1}^{M} \left\{ P_{rj}(L_j) \cdot PL_j \right\} \qquad \cdots\cdots\cdots\cdots\cdots(15)$$

where, M is the number of L_j. The PL_j is the occurrence probability of slope length and is computed from

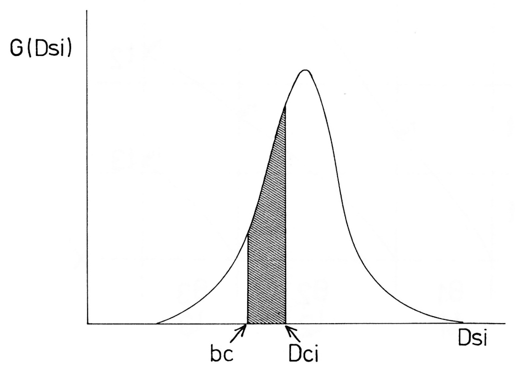

Fig.4 The probability of surface layer depth caused landslides

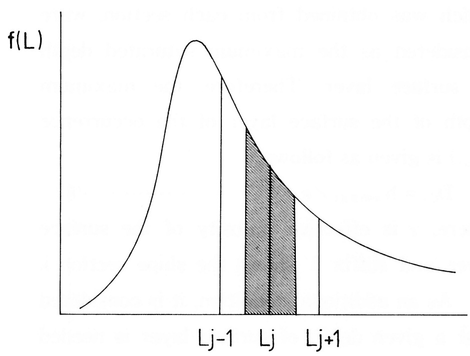

Fig.5 Slope length probability density function and computation of PL_j

slope length probability density function (f(L)) which is obtained from its distribution, as shown in Fig.5, that is,

$$PL_j = \int_{\frac{L_{j-1}+L_j}{2}}^{\frac{L_{j+1}+L_j}{2}} f(L)dL \qquad \cdots\cdots\cdots\cdots\cdots (16)$$

Ⅵ. COMPUTATION OF LANDSLIDES PROBABILITY

As the exsample of the present method, the calculation of the probability is shown as follows:

The basins employed are situated in Ehime Prefecture in Shikoku. The surface layer is granite soil, the depth of which ranges from 0.5 meters to 1 meter on an average.

The designed hyetegraph was based on heavy precipitation of 1979 in this basin (Fig.6), $\beta = 0.0711$, $n = 0.842$ (m.s unit) in the surface layer of granite soil [2], $\varepsilon = 0.2$ and $b_c = 0.5$ meters were given. In this study, probability variable, a, was considered as normal distribution, and the distribution of slope length was represented as logarithmic normal distribution, as the result of the distribution of measured slope lengths.

The density of hillside landslides in these basins was surveyed using aerial photograph. The computation of the occurrence probability was done using the values of mean (M_a) and standard deviation (σ_a) of $g(a)$, so that the computed probability corresponded to the surveyed density of the hillside landslides in each basins.

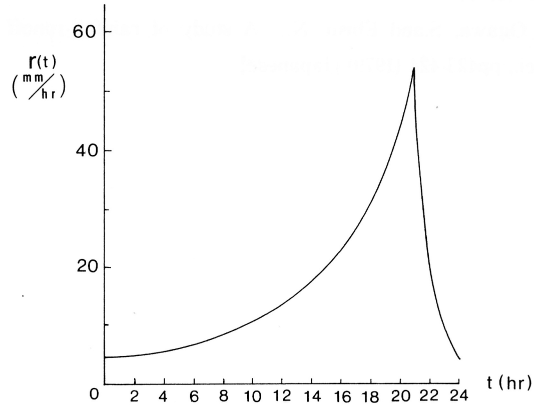

Fig.6 Designed hyetegraph

Table 1 Computed occurrence probability of hillsides landslides

Basin		area (ha)	g(a) Mean Ma	Standard diviation σ a	P_W (%)	density of landslides (Number／ha)
IDEGATANI	R.	49.33	0.5	1.0	2.56	0.324
TAKAMATSU	R.	143.50	0.5	1.0	3.67	0.488
NISHIYAMA	R.	87.08	1.0	0.5	5.52	0.827
TOKUNO	R.	83.73	1.0	0.5	3.76	0.764
KOJIMA	R.	69.49	1.0	0.25	4.94	0.874

The values of M_a and σ_a and the computed probability were as shown in Table 1.

Ⅶ. CONCLUSIONS

A hydraulic model which simulated hillside landslides was presented, the factors necessary to apply this model were discussed, and the modeling method for an actual hillside was proposed.

The surface layer depth was the most difficult factor to measure in the field, and was evaluated stochastically for this model. The occurrence probability of hillside landslides was computed as the probability between the saturated depth and the critical occurrence depth using the probability density function of the surface layer.

However, for the application of this method, the distribution of the surface layer depth of the actual hillside must be estimated. It is considered that this characteristic of distribution relates to the probability of the occurrence of hillside landslides.

REFERENCES

[1] Sue, K., Hirano, M.and Ogawa, S., A study of runoff on mountainsides, IAHS-AISH publ.No 117, pp247-253 (1975)

[2] Ogawa, S.and Ebisu, N., A study of rainfall-runoff flow in the watershed-layer (II), 90th Mtg.Jap.For. Soci., pp423-424 (1979) [Japanese]

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