Topographical consideration for landslide prediction
Les considérations topographiques pour la prédiction des glissements de terrain

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SYNOPSIS The major Tertiary mudstone zone where landslides can be frequently triggered by rainfall and snow-melting action, consists in the central region of the side of Sea of Japan (the so-called HOKURIKU DISTRICT). There, landslide occurrences are strongly influenced by groundwater run-off from the surrounding valleys. The establishment of a good method of landslide prediction based on a viewpoint of groundwater run-off has recently been recognized as one of the important matters in engineering practice. This paper proposes a methodology for landslide prediction to make it possible to evaluate the characteristics of groundwater run-off by using unique indices for topographical conditions around landslide areas. This methodology is very effective to easily predict dangerous landslide areas having a potential for landslide occurrence in the future and to determine the suitable construction locations for the important structures in mountanous areas.

INTRODUCTION

The two important matters of landslide prediction are the followings:

(i) it is possible to estimate a landslide type either successively approaching failure or remaining in a stable state (prediction of landslide failure) and

(ii) dangerous area where a potential for landslide occurrence in the future can be predicted (designation of landslide area)

The former that has been published by some researchers (Kawamura, 1985, 1987: Saito, 1961) is a methodology for landslide prediction based on field observations. This good prediction is available in order to either allow inhabitants near the landslide area to evacuate to safe place or not and to determine the most appropriate counter-measure to be taken immediately. The latter is a landslide prediction method from a topographical standpoint considering the characteristics of groundwater run-off. This paper proposes a unique technique for this prediction problem.

In this Tertiary mudstne zone, the authors attempted to investigate the rate and the amount of groundwater inflow into the actual landslide areas to be now in progress, because these landslide occurrences have started in either the season of snow-melting or heavy rainfall. However, as is well known, groundwater run-off and seepage analyses are still not well established because of various uncertainties such as inevitable analytical errors, complicated ground conditions and insufficient information of site investigations. A landslide prediction method in which the new topographical indices are introduced to quatitatively evaluate both the rate and the amount of groundwater run-off is proposed in this paper. Each topographical index is very effective to evaluate the degree of influence of groundwater run-off on landsilde occurrence. It can be shown in a practical engineering that this methodology can predict a potential area of sliding occurrence under dangerous topographical condition and contribute to not only make the best plan of land use but also how to determine the construction location of the important structure such as dams, bridges and highways.

ACTUAL LANDSLIDE AREAS

The Tertiary mudstone zone in the central region of the side of Sea of Japan is famous for a typical landslide area in Japan. The Noto Peninsula located at the edge of west-northwest direction of this mudstone zone has about 700 landslide areas both to be now in progress and in the past. Fig.1 shows the distribution of Tertiary midstone zone and the designated landslide areas in the Noto Peninsula, respectively. In this figure, the landslide areas investigated for this paper are indicated, where all of them are now on the move. There, the characteristics of the Tertiary mudstone can be shown as follows:

(i) the brittle strata of the Tertiary sand stone and the conglomerate consist in this mudstone zone at romdom,

(ii) this mudstone zone has not been yet consolidated sufficiently because the elevation of this zone raised up immediately just after the sedimatation had formed in the shallow water regions,

(iii) the developments of discontinities and the folding structures appear everywhere in this mudstone. Hence, landslides are apt to take place repeatedly in the rainy and snow-melting seasons every year.

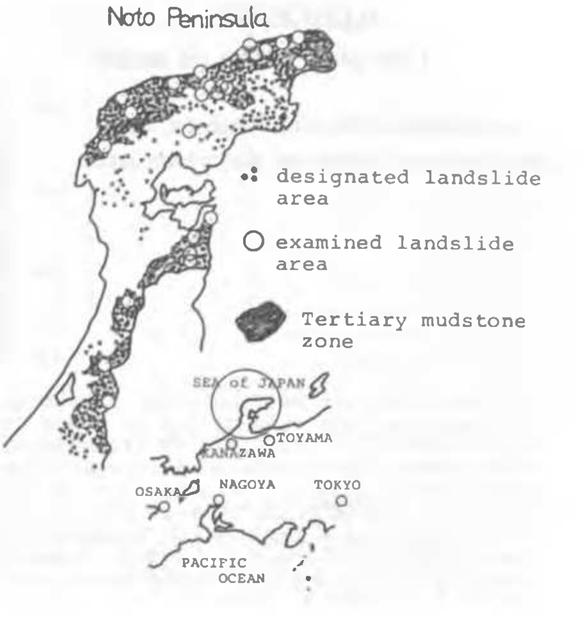

Fig.1 Landslide Areas in the Noto Peninsula

As the important facts of the so-called Noto Peninsula Landslide, depth of sliding surface is located everywhere under a stational groundwater level and the slope of this landslide areas with 7° to 25° in average gradient and mainly the frequent occurrences with 15° to 18°, as shown in Fig.2(a). The results of the safety factors of landslide areas calculated using the effective stress method with considering the groundwater level and without, are shown in Fig.2(b), where the groundwater level denotes the depth of water surface under the condition of over seven continuous days of no rainfall and the effective cohesion c' and the effective angle of internal friction ϕ' as the parameters of soil strength are obtained by using triaxial compression tests. Fig.2(b) indicates that neither the safety factors in the case of considering groundwater level nor without are mostly less than unity, though a few cases of dangerous landslide areas being less than unity can be found out. This fact implies the strong influence of groundwater inflow into landslide area on sliding occurrence (Ogawa, et al.,1987).

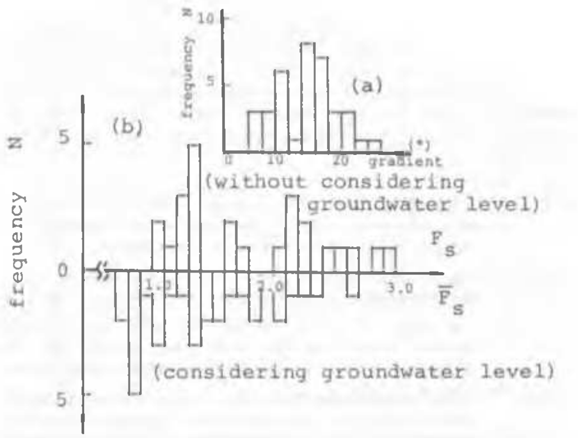

Fig.2 Average Slope Gradient (a) and Safety Factor (b) in Landslide Areas

TOPOGRAPHICAL CONDITION AROUND LANDSLIDE AREA

As mentioned-above, each landslide in the Tertiary mudstone zone is considered to be triggered by the influence of groundwater run-off through the surrounding valleys. However, a quantitative influence of groundwater can not be exactly examined, because the required seepage and run-off analyses are still not well established due to various uncertainties such as inevitable analytical errors in idealizations of the complex actual ground conditions and behaviors and/or , difficulties in setting initial and boundary conditions. Instead, it is emphasized from topology-based design that groundwater run-off is strongly dependent on the surrounding topographical conditions (Ishirara, et al., 1967: Eagleson, 1970). This paper also proposes a unique methodology based on topography to make it possible to evaluate the rate and the amount of groundwater run-off acting on landslide areas. As shown in Fig.3 and Table I, several new indices related to topographical condition around landslide area are taken in order to examine this groundwater run-off. The indices proposed to indicate the rate of run-off are shown as follows: (i) the so-called Form Factor of the drainage basin f equal to A / L_0^2 where A denotes the drainage basin area and L_0 the length of a main valley, (ii) L_0, (iii) the length of mountain slope l equal to $A/2L$ where L denotes the total length of all valleys in the drainage basin area, (iv) the average gradient of a main valley s and (v) the average gradient of mountain slope e. While a new index demonstrating the amount of groundwater run-off is (vi) the drainage basin area A (Strahler, 1964). As an example, Fig.4 shows the characteristics

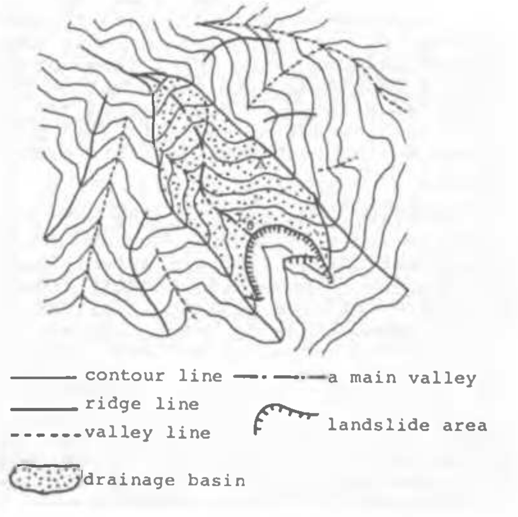

Fig.3 Topical Landslide Area

TABLE I

New Indices for Topographical Condition

grade	score	(i) f	(ii) (m) L_0	(iii) (m) l	(iv) (°) s	(v) (°) e	(vi) (m^2) A
1	0.1	under 0.3	over 450	over 90	under 9	under 12	under 1000
2	0.2	0.3 -0.6	400 -450	80 -90	9 -12	12 -15	1000 -2000
3	0.3	0.6 -0.9	350 -400	70 -80	12 -15	15 -18	2000 -3000
4	0.4	0.9 -1.2	300 -350	60 -70	15 -18	18 -21	3000 -4000
5	0.5	1.2 -1.5	250 -300	50 -60	18 -21	21 -24	4000 -5000
6	0.6	1.5 -1.8	200 -250	40 -50	21 -24	24 -27	5000 -6000
7	0.7	1.8 -2.1	150 -200	30 -40	24 -27	27 -30	6000 -7000
8	0.8	2.1 -2.4	100 -150	20 -30	27 -30	30 -33	7000 -8000
9	0.9	2.4 -2.7	50 -100	10 -20	30 -33	33 -36	8000 -9000
10	1.0	2.7 3.0	50 under	10 under	33 over	36 over	9000 over

of a main valley by using the calculated results with the drawn making of projection of stereophotography on the (1/10000) topographical map and the actual field surveys. It is obvious in this figure that a main valley mostly exists with dimensions of under 150m in length L_0 and 15° to 33° in average gradient s.

For the purpose that degree of influence of the surrounding topographical conditions on instability of landslide area may be examined, both the relationships between the drainage basin area A and/or the length of a main valley L_0 and the reduction safety factor of landslide area $(F_s-1)/F_s$ due to them are shown in Fig.5, where (F_s-1) denotes a difference between the safety factor F_s calculated under the condition of not considering groundwater level and unity at the time of landslide occurrence. It is evident in Fig.5 that the greater the drainage basin area A and/or the shorter the length of a main valley L_0 are, in other words, if a dangerous valley with a rapid rate and large amount of groundwater run-off should exist near the landslide area, the more the reduction of safety factor will be. Similarly, the other indices can be shown to be dependent on the safety factor of landslide area. Therefore, new indices introduced to this proposed method are reasonable to evaluate the rate and the amount of groundwater run-off through the surrounding valleys.

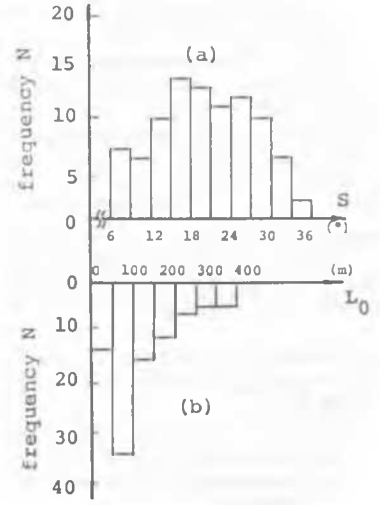

Fig.4 Average Gradient s and Length L_0 of a Main Valley

PREDICTION OF LANDSLIDE AREA

In this proposed prediction method for landslide area, new indices of topographical condition in the Tertiary mudstone zone are evaluated with the corresponding weighted scores for the defined ranges as shown in Table I, which is given by equally dividing the difference between the measured maximum value for actual landslide area and the minimum into ten stages. The characteristics of groundwater inflow into the landslide area can be evaluated with the total amount of weighted scores of these indices defined as the E-value. The weighted scores in Table I indicate that the greater the E-value is, the larger the rate and the amount of groundwater run-off are and therefore, there are the surrounding valleys which are dangerous to sliding occurrence. Fig.6 shows the relationship between the E-value and the same reduction of safety factor of landslide area as Fig.5. It can be obvious from Fig.6 that

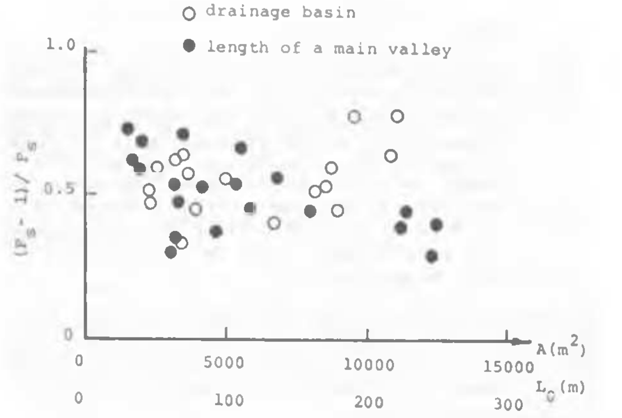

Fig.5 Relationships between Topographical Conditions and Reduction of Safety Factor in Landslide Areas

(i) in the mostly actual landslide areas where the value of F_s can be taken to be approximately over 1.3, the greater the E-value is, the larger the reduction of safety factor due to topographical condition is. This fact is considered to be very important because a landslide area with the sufficient safety factor for stability is not always safe if there are dangerous valleys into the landslide

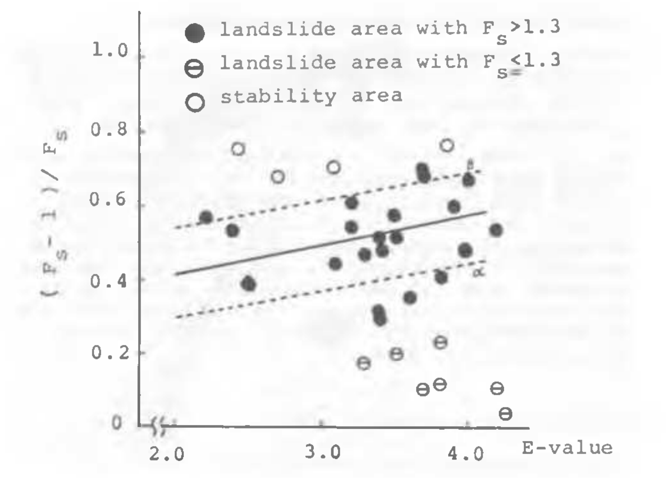

FIg.6 Reduction of Safety Factor due to E-value

area.

(ii) Several sliding areas with the safety factor F_s under 1.3 are independent on the E-value. That matter indicates that these sliding occurrences have not been triggered by groundwater run-off due to heavy rainfall and dominant snow-melting because all of the safety factors calculated under the condition of considering a stational groundwater level are less than unity.

The solid straight line obtained by using the method of least squares assuming a linear function and the data of landslide areas with over 1.3 in the safety factor F_s is shown by the following equation:

$$\frac{(F_s-1)}{F_s} = 0.07\,E + 0.28 \qquad (1)$$

Both the dotted straight lines α and β indicate the standard diviation of Eq. (1). It can be shown from Fig.6 that the actual land area where the calculated safety factor F_s plotted in the region under the obtained upper dotted straight line β has still a potential for sliding occurrence in the future. This line β , $(F_s-1)/F_s=0.07E+0.40$, can be accepted as a criterion for the prediction of dangerous landslide area in engineering practice, because the proposed line β can be applied satisfactorily to a few actual land areaswhere the sufficient safety factors for stability of landslide have been recognized from the slope stability analyses in full detail,as shown in Fig.6. It is considered very important to establish a good prediction method to make it possible to determine a landslide area either having a potential for sliding occurrence in the future or remaining in a stable state.

CONCLUSIONS

Conclusions obtained from this study are summarized as follows:

(i) Landslide analyses applied to the autual sliding area being now in progress in detail were considered very important for an evaluation of influence of the degree of groundwater inflow to landslide area.

(ii) Unique method for landslide prediction which makes it possible to quantitatively evaluate both the rate and the amount of groundwater run-off by using new indices for topographical condition around landslide area is proposed.

(iii) It can be shown that this proposed prediction method is very effective to determine a dangerous land area where there is a potential for sliding occurrence in the future and therefore, strongly contributes to the practical plan for construction locations of important structure such as a dam, a bridge, a highway and a railraod.

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