Methodology for landslide prediction

Méthodologie pour la prédiction des glissements de talus

K. KAWAMURA, Professor of Civil Engineering, Kanazawa Institute of Technology, Kanazawa, Japan

SYNOPSIS Landslides can be triggered by rainfall, melting snow, freezing and thawy action and seismic effect due to earthquakes in Japan. They often occur in major Tertiary mudstone and Green-tuff zones. In engineering practice, it is considered very important to be able to predict landslides in some way. This paper describes a methodology for landslide prediction based on field observations. The first half of the paper proposed a technique to make it possible not only to evaluate a landslide type either successively approaching failure or remaining in a stable state but also how to determine the characteristics of movement, such as convergence and divergence, if required. In the second half of the paper, the practical application of the proposed prediction method is discussed based on the comparisons with the results observed for actual landslides. It can be shown that this methodology is very effective and easy to use from a practical standpoint.

INTRODUCTION

The establishment of good method of prediction based on field observations has recently been recognized as one of the important matters in a series of optimum design and construction procedures for earth work, because these can make it possible to resolve various uncertainties such as inevitable analytical errors in idealization of the complicated actual behavior, variation of soil properties and insufficient imformation due to the limited number of samples. (Matsuo and Kawamura, 1975, 1980, Matsuo, Kuroda, Asaoka and Kawamura, 1977). It is also considered quite important in engineering practice that a good method of prediction of the successive behavior of landslides is available in order to either allow inhabitants near the landslide location to be evacuated to a safe place or not and to determine the most appropriate countermeasures to be taken immediately if necessary. For these reasons, a methodology of landslide prediction based on field observations has been proposed in this paper. The significant points of this methodology are the following:

(i) it is possible to easily estimate either landslide movement to divergence indicating imminent failure or convergence no failure,

(ii) results as shown in (i) above can be successively modified by using new imformation obtained from field observations,

(iii) results of observations are analyzed statistically in order to make the best use of the prediction system.

Next, the applicability of the proposed methodology to practical use is examined by comprison with the actual data obtained recently from large-sized landslides. In addition, the actual result of application to a real landslide in progress is presented. Based on the results of these examinations, it has been determined that this methodology can be very effective for practical use.

PROPOSED METHODOLOGY FOR LANDSLIDE PREDICTION

Landslide movement is normally described as one of creep behavior. As the results of many observed data and numerical analyses utilizing the creep theory, an inductive model of landslide can be expressed as follows:

$$\left(\frac{dt}{dy}\right) = A\cdot(B-t)\cdot t \qquad (1)$$

where y denotes the displacement or strain, t the time and A, B the constants, respectively. Solving Eq.(1) under the initial condition $t=t_0$ in y=0, the general solution is easily given as follows:

$$y = \frac{1}{A\cdot B}\ln\left\{\frac{t}{B-t}\cdot\frac{B-t_0}{t_0}\right\} \qquad (2)$$

As shown in Fig.(1), it can be seen that Eq.(1) under both A>0 and B>0 is regarded as a divergent y curve indicating landslide failure and while under A<0 and B≑0 convergent y curve approaching a stable state. Accordingly, exact determination of the constants A and B based on observed data is very important in order to be able to apply Eq.(1) to actual landslide prediction.

For the purpose mentioned above, now, the j-th observed displacement or strain can be defined as $y_j=y\cdot j$ and the corresponding time t_j as $t_j=t(y_j)$, respectively, as shown in Fig. 1.

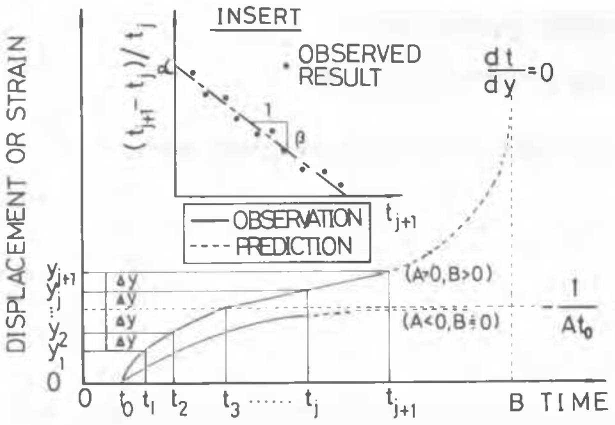


Fig. 1 Proposed Prediction Model

The defference equation equivalent to Eq.(1) can be obtained as follows:

$$\left(\frac{t_{j+1}-t_j}{t_j}\right) = \alpha - \beta t_{j+1} \qquad (3)$$

where α and β are the constants. Solving Eq.(3) under same initial condition as Eq.(1), the general solution can be obtained from the following equation:

$$t_j = \frac{(1+\alpha)^j \cdot t_0}{1+[\{1+\alpha\}^j-1\} \cdot B \cdot t_0/\alpha]} \qquad (4)$$

Based on Eqs.(2) and (4), the following relationships between the constants A, B and α, β are determined, respectively:

$$\left.\begin{aligned} \alpha &= \exp(\Delta y \cdot A \cdot B) \\ \beta &= \alpha/B \end{aligned}\right\} \quad (5)$$

where Δy denotes the equal diving value in y as shown in the ˙ ted figure of Fig. 1. Arranging the observed data on the basis of Eq.(3), the constants α and β can be immediately calculated by using the method of least squares as follows:

$$\left.\begin{aligned} \alpha &= \frac{\sum_i w_i \left(\frac{t_{j+1}-t_j}{t_j}\right)_i - \beta \sum_i w_i (t_{j+1})_i}{\sum_i w_i} \\ \beta &= \frac{\sum_i w_i \{\sum_i w_i (t_{j+1})_i \left(\frac{t_{j+1}-t_j}{t_j}\right)_i\} - \{\sum_i w_i \left(\frac{t_{j+1}-t_j}{t_j}\right)_i\}\{\sum_i w_i (t_{j+1})_i\}}{\sum_i w_i \{\sum_i w_i (t_{j+1})_i^2\} - \{\sum_i w_i (t_{j+1})_i\}^2} \end{aligned}\right\} (6)$$

where w_i denotes the weight of creep imformation in i-th arranged result. It is assumed that the later the data obtained will be, the larger the weight is. Finally, substituting α and β into Eq.(5), the constants A and B can be determined and consequently Eq.(1) makes it possible to predict the behavior of a landslide in the future.

APPLICATION OF PROPOSED MODEL TO LANDSLIDE PREDICTION

The most important point for this study is to be able to determine the engineering usefulness and the accuracy of the proposed methodology as follows:

Prediction of landslide failure

Initially, Fig. 2 shows a comparison between the observed data from an actual landslide failure near a Japan National Railway Line and the predicted behavior obtained by utilizing the earlist actual data in the proposed method. The table in Fig. 2 where actual field name, the observed failure time t_{fob}, the final time of observed data used for prediction t_u and the predicted failure time t_{fp} are summarized indicates the accuracy of this prediction method based on the various numbers of observed data used for prediction (each curve a, b and c under an actual field condition).

The case of the Dosan-Line shown in Fig. 2 is explained in detail. The soil conditions at this landslide location consists mainly of discontinuous Black-schist and a failure occurred in 1962. No trains were allowed to pass this landslide area for 41 days because a railway bridge was destroyed by a soil and rock landslide movement of about $60{,}000m^3$ volume. Initially, several tension cracks with 18cm in width appeared on the surface of slope. Immediately, field observations and landslide prediction were begun. The displacement of landslide progressed rapidly

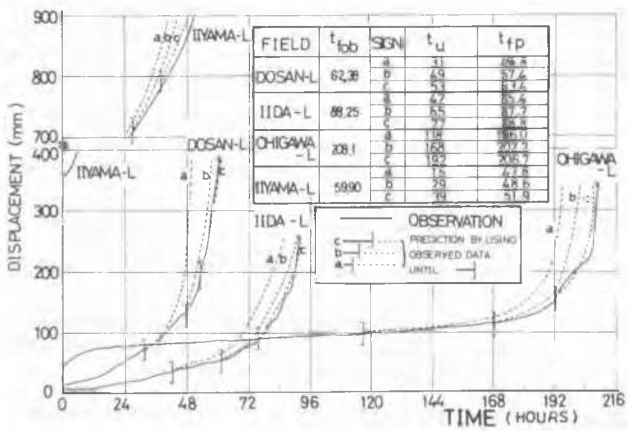


Fig. 2 Comparison between Observations and Predictions for Actual Cases of Failure

just after the observation system was completed and at that time, the rate of strain determined by a strain meter already indicated 2.68 x 10^{-5} /min. After a while, the rate of displacement gradually increased with time and suddenly, a definite failure occurred 62.38 hours later as shown in Fig. 2.

The landslide prediction was made by substituting the actual data up to t_u= 31.0 hours later into Eq.(3). The number of data is 8 for use under Δy=12mm and defining the weight w_i as i^4 in Eq.(6), the constants α and β were determined to be 0.52 and 0.011, respectively. The constants A=7.3 x 10^{-4} and B=4 8.8 from Eq.(5) and the prediction curve with t_{fp}=4 8.8 hours can be described as a dotted line a of Dosan-Line in Fig. 2. Similarly, the prediction curves obtained by using the actual data up to t_u=49.0 and 53.0 hours later are both shown as dotted lines b and c with t_{fp}=57.4 and 63.4 hours respectively.

Comparing t_{fp} with t_{fob} for several landslide areas, it becomes clear that, (1) the more data avaiable for prediction, the more exact the prediction method can be and (2) landslide prediction can be accomplished at any time with sufficient engineering accuracy.

The latter shows a difference from the conventional prediction method where t_{fp} is predicted based on the second creep rate (a constant creep rate) has been published by Saito and Uezawa. (Saito and Uezawa, 1961).

Prediction of convergent movement

A comparison between the predicted behavior obtained from the proposed methodology and the actual data from landslides where the movement have all temporarily stopped or have continuously decreased is shown in Fig. 3. In the case of Field-S where the observed convergent displacement y_{fob} is 0.12m, substituting a set of observed data up to 54 days later into Eq.(1) under the initial condition of t_0=1.2 days in y_0=0, the constants α=0.156 and β=1.55 x 10^3 are determined and therefore the constants A= -0.29 and B=-100.3 can be obtained from Eq.(5).

Since (dt/dy) becomes positive if the constants A<0 and B<t in Eq.(1), Eq.(1) with a sufficiently small value of B is redefined as follows:

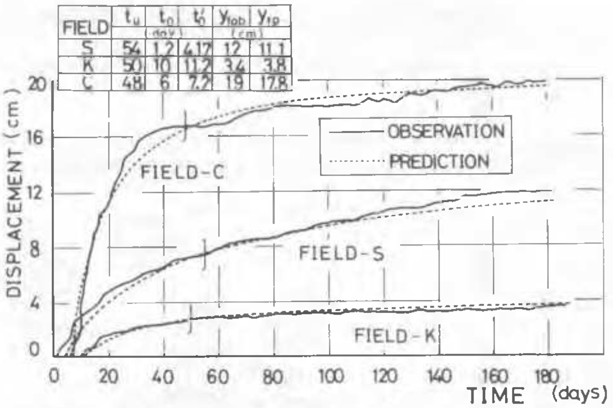
$$\left(\frac{dt}{dy}\right) = -A't^2 \qquad (7)$$

The difference equation equivalent to Eq.(7) can be shown as follows:

$$\left(\frac{t_{j+1}-t_j}{t_j}\right) = -\beta' t_{j+1} \qquad (8)$$

Based on both general solutions of Eqs.(7) and (8), the relation between the constants β' and A' is easily given as follows:

$$\beta' = A' \cdot \Delta y \qquad (9)$$



FIELD	t_u	t_0	t_0'	y_{fob}	y_{fp}
	(day)			(cm)	
S	54	1.2	4.17	12	11.1
K	50	10	11.2	3.4	3.8
C	48	6	7.2	19	17.8

Fig. 3 Comparison between Observation and Predictions for Actual Cases of Non-failure

Accordingly, the convergent displacement y_{fp} can be obtained as $-(1/A' \cdot t_0')$ where t_0' denotes the initial time modified by Eq.(8).

The initial time t_0 of Field-S can be modified as t_0'=4.17 days and at once the predicted convergent displacement y_{fp} can be calculated to be 0.111m nearly consistent with the actual data y_{fob}=0.12m.

Examining other fields using the same procedure as mentioned above, it is determined from Fig. 3 that this prediction method can almost be applied to actual field conditions where the movement tends to be less than the critical state.

Example of practical application

The proposed methodology has been applied to an actual Tertial mudstone landslide area where a landslide is now in progress. Signs of landslide failure, such as a small movement along the slope and a small cracks occurrence in the rice field near the toe of slope as shown in Fig. 4, had appeared and therefore the observation system was started in August, 1982. Although some tension cracks appeared near the top of slope, heaving in the rice field and channel destruction near the toe of slope were observed in December, after some time, the movement of landslide stopped for several months. This methodology was applied for landslide prediction in May, 1983 and a failure could be forseen 13 months later from this point. Countermeasures such as a retaining structure and lateral holes for removal of ground water were immediately undertaken in July. After that, in November, the second prediction made while the countermeasures were being implemented indicated the failure would occur earlier than the first prediction. The inhabitants near the landslide area were obliged to be evacuated to safe places. Since the rate of displacement tended to countinuously increase in spite of the completion of lateral holes for removal of ground water in November, 1983, the construction of the retaining struc-

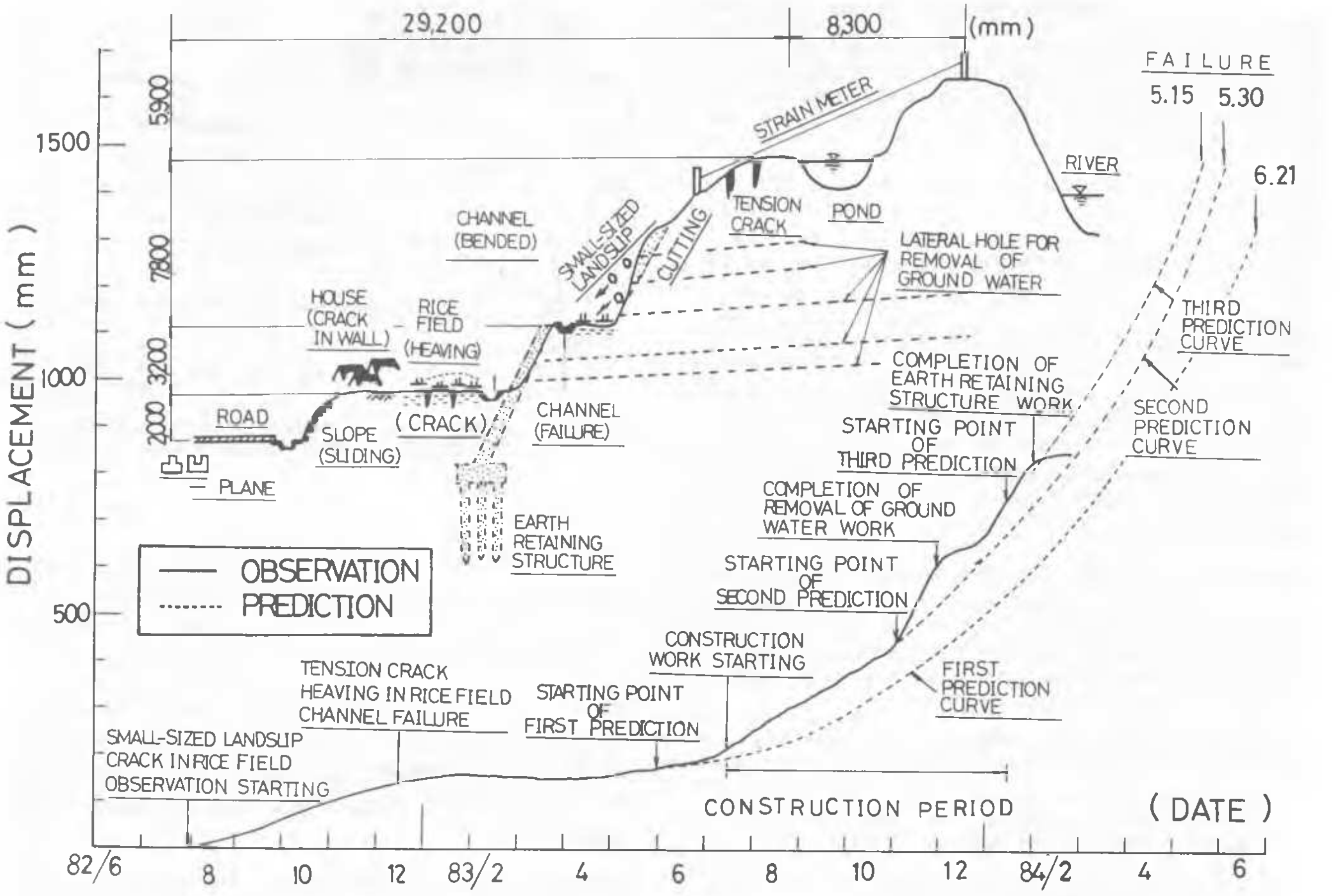


Fig. 4 Case History of an Actual Landslide

ture was undertaken more rapidly and a third prediction was made in January, 1984. This latest predicted failure based on the actual observation was found to be earlier than the previous two predictions. We are therefore observing this landslide very carefully in order to make more exact prediction.

CONCLUSIONS

Conclusions obtained from this study are summarized as follows:

(i) The methodology for prediction of the behavior of landslides based on field observation is proposed in order to keep inhabitants near landslide field safe and to protect various structures against landslide failure.

(ii) This methodology definitely makes it possible to estimate the landslide movement not only to divergence indicating imminent failure but also to convergence stable state.

(iii) This methodology can also be applied to prediction of failure and settlement of soft cohesive clay layer under surcharge load.

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