

# EVIDENTIAL STUDY ON FORECASTING OCCURRENCE OF SLOPE FAILURE

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## Abstract

This paper describes an outline of three types of the procedure on forecasting occurrence of slope failure, that is to say, rough estimation based on steady-state strain rate in the secondary creep range, close estimation through calculation or graphical analysis using substituted logarithmic formula and final precise estimation based on linearity on a semi-logarithmic graph assuming temporary rupture life. Considered from several case studies it can be said that the method of forecasting failure time based on creep-rupture characteristics is effective and reliable.

## 1 INTRODUCTION

Method of forecasting occurrence of slope failure based on creep-rupture characteristics of soil was published in series in the previous Proceedings of the International Conferences on Soil Mechanics and Foundation Engineering. I would like to explain the progress of development of the method, present trend of studying creep-rupture characteristics and evidential evaluation of the method with case studies on actual slope failure.

The word "forecasting" seems to have various phases and will be taken as different meaning according to person, object or occasion.

In some cases, it means to select those slopes which may cause failure or intolerable movement in near future, although they seem to be stable at present. Our present knowledge, however, is not sufficient to give this judgment, and forcing such judgment will be often blamed for one-sided prejudice. It must be evaluated with actual case studies whether the judgment was right or not.

Sometimes the word "forecasting" is used as synonym to express "the degree of danger of slopes to failure"; it means possibility of occurrence of numerous slope failures within some limited region. In this case, it will be expressed with some conditions such as amount or intensity of rainfall or snow melting.

In most cases, however, "forecasting" means occurrence of slide or failure for a specified slope. It contains those of the spot or range, the type and the time of rapid movement. Among these items, the most desired and useful subject is to know the time of occurrence of landslide or slope failure; and so hereafter we may make a point of limiting the meaning of forecasting to that of failure time.

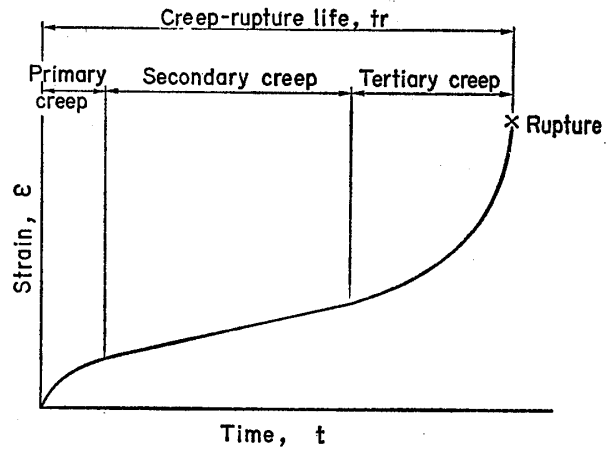
## 2 DEVELOPMENT OF THE METHOD OF FORECASTING THE TIME OF INITIATION OF INTOLERABLE MOVEMENT OF UNSTABLE SLOPES

### 2-1 Process to Develop Forecasting Methods.

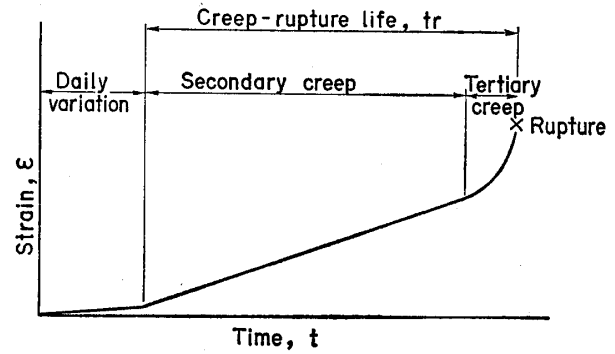
In order to develop forecasting method, it is necessary to find effective factors. Attributes

Approaches for studying rheological properties of materials			
Names	Micromechanistic solid-state physics	Macroanalytical phenomenological	Ad Hoc testing simulated service test
Level	Basic science	Applied science or "engineering"	"Practical" approach
Engineering utilization of each approach		Future	
		Present	
		Post	

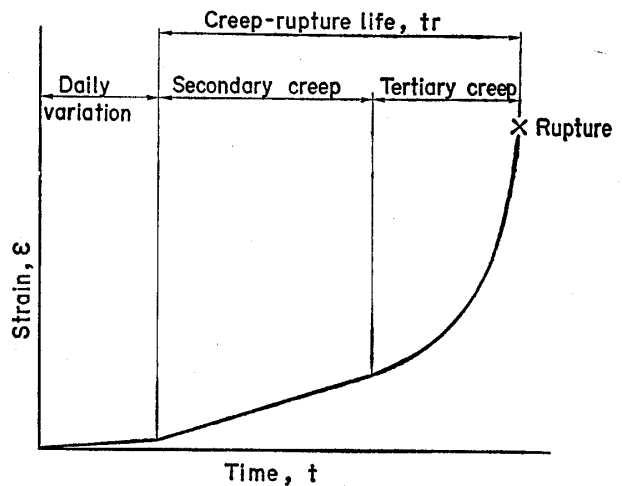
Fig. 1 Three approaches for studying rheological properties (Lazan, 1962)



(a) Creep rupture test on test piece



(b) Model test of slope failure



(c) Actual slope failure

Fig. 2 Typical expression of various creep-rupture curves

indispensable to effective factors for the purpose of forecasting are requested as that the factor will always appear before failure, that the level of factor is measured quantitatively and that the time length to failure after its appearance is not too short. And, moreover, it is desirable to the factor that its measurement is rather easy and decision can be done without confusion.

Forecasting factors may be divided into several groups;—the first group can be named as direct factor, such as horizontal or vertical displacement, inclination or strain of surfaces of slopes.—the second one as semi-direct factor, such as stress in the ground, pore-water pressure, rainfall, snow melting or shear strength of soil, as directly connected to the mechanism of the movement.—and the third one as indirect factor, such as temperature, geoelectric potential, acoustic emission, animal behavior, etc., as accompanied with, or influenced by movement of the ground.

Various types of approaches can usually be classified under the following three heading (Lazan, 1962).

- (1) solid-state or micromechanistic approach as basic science,
- (2) macroanalytical or phenomenological approach as engineering science, and
- (3) ad hoc testing or simulation service test as practical approach.

Fig. 1 shows correlation of these three approaches and the changing pattern of emphasis with time. The first one is the most desirable, but it does not yet provide an engineering tool for calculating the properties of engineering materials. The third one is a completely different type of approach against the first one. The result of this approach is directly applicable to the specific problem of interest, but has many serious disadvantages such as for long-term phenomena or not extendable to problems in different regime. Contrary to those approaches, the second one is considered most practical and successful to analyse behavior of engineering materials. Recognition of this classification is very much useful to find effective forecasting factors.

## 2—2 Development of Forecasting Method Based on Creep-Rupture Phenomena of Soils.

A shortcut to find forecasting factors is to carry out slope failure tests and thereby to see what factors are most sensitive or can show earlier changes. But the range of failure modes reproducible experimentally represents only a part of natural failure, and not all the results are applicable to actual failures.

In case of creep rupture test with soil specimens, for example, application of stress leads first to a period of transient creep, during which strain rate increases suddenly at first and then decreases continuously with time, followed by creep with steady-state strain rate, and then it turns to accelerating stage, finally leading to failure. These three stages are usually termed as primary, secondary and tertiary, as shown in Fig. 2(a).

In case of model tests of slope failure with artificial rainfall, however, there is no sudden increase of stress; therefore the primary creep does not appear, but the secondary creep can be seen, directly followed to daily variation of creep, and the tertiary creep range is rather small as shown in Fig. 2(b).

Actual slope failure is similar to a case of model test with no primary creep range, but the tertiary creep range is very large, especially regarding to total strain and strain rate, as seen in Fig. 2(c): therefore a model slope test is not used as substitute for actual slope failure. Nevertheless, it is sure that they will offer valuable tools for selection of forecasting factors. It can be said that these facts just show the merits and demerits as fatality of ad hoc testing aforementioned.

Through full-scale slope failure tests by artificial rainfall at Nou Experiment Station of Japanese National Railways (JNR) in 1949, it was found that strain measurement of slope surfaces is the most effective as forecasting factor (Saito & Uezawa, 1961; Saito, 1965). It was turned to creep-rupture tests in laboratories as phenomenological approach (Saito & Uezawa,

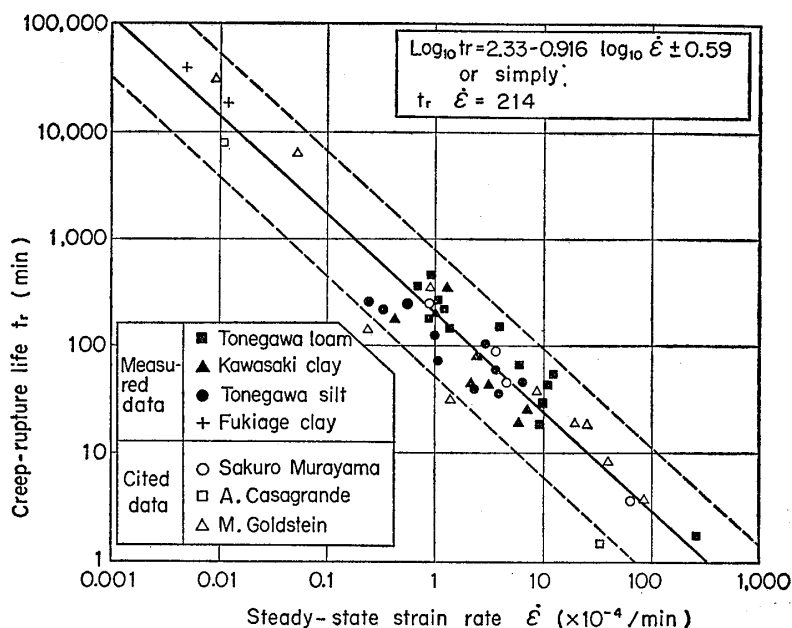


Fig. 3 Forecasting diagram using the relation between steady-state strain rate and creep-rupture life

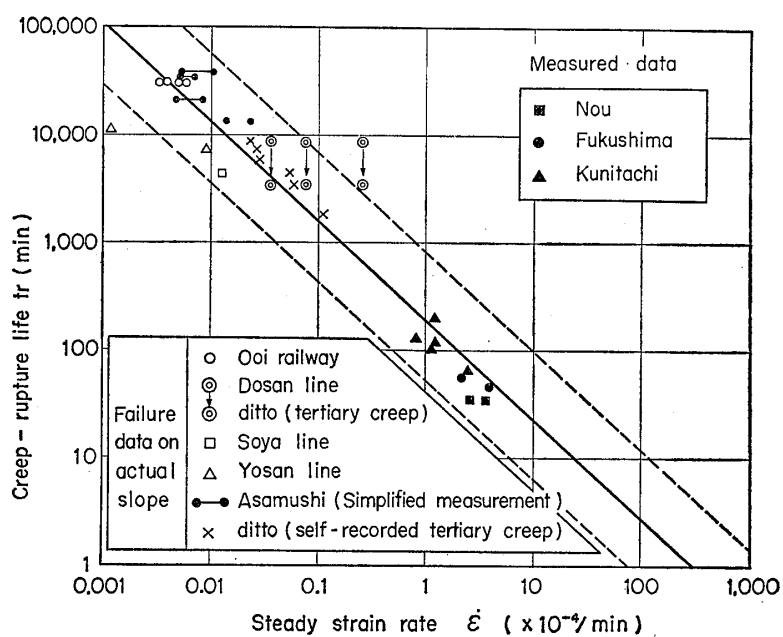


Fig. 4 Validity of forecasting diagram using data of slope failure tests and actual slope failures

1961). The results are shown in the forecasting diagram indicating inversely proportional relationship between steady-state strain rate and creep-rupture life as shown in Fig. 3.

This relationship was examined with actual slope failure records (Saito, 1965), and verified effective to forecast the rupture life as shown in Fig. 4. It was found, furthermore, through the case study at Asamushi Landslide that the inversely proportional relationship can be extended to the tertiary creep range with some modification (Saito, 1969), that is called as graphical analysis and explained with the direction of arrows in Fig. 5. Actual application of

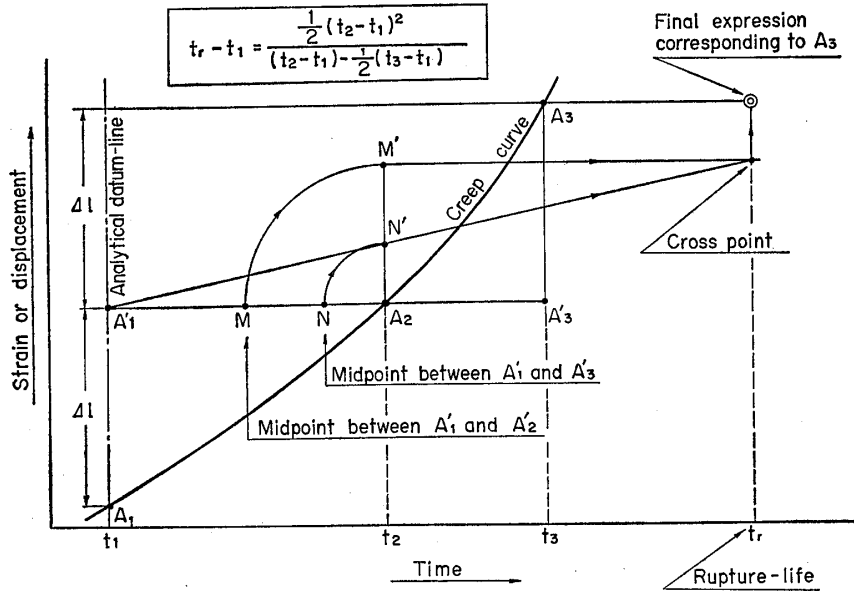


Fig. 5 Procedure of graphical analysis for creep-rupture life in the tertiary creep range

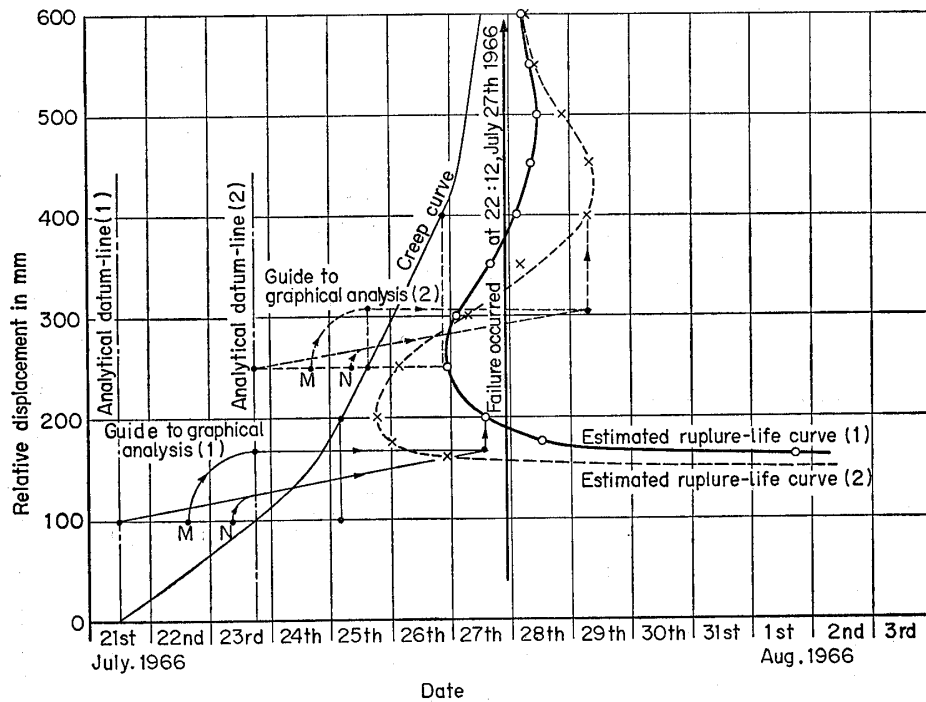


Fig. 6 Forecasting failure time of Asamushi Landslide by means of graphical analysis

this method to Asamushi Landslide is shown in Fig. 6 (Saito, 1969).

Thus, the forecasting method based on creep-rupture characteristics has been established (Saito, 1968) and is expressed as follows:

In the secondary creep range, rupture life of slope is found in the forecasting diagram (Fig. 3), or calculated with the following formula

$$\log_{10} t_r = 2.33 - 0.916 \log_{10} \dot{\epsilon} \pm 0.59,$$

or simply expressed

$$t_r \cdot \dot{\epsilon} = 214,$$

where

- $t_r$  : creep-rupture life, in min.,
- $\dot{\epsilon}$  : steady-state strain rate, in  $\times 10^{-4}$  per min.

In the tertiary creep range, a following logarithmic formula is applicable as an empirical one

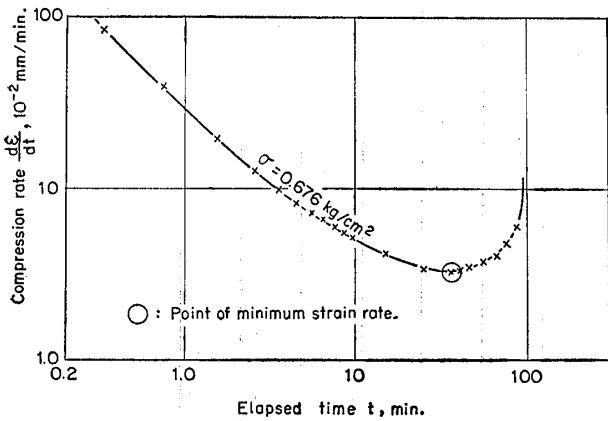
$$\epsilon - \epsilon_0 = A \log \frac{t_r - t_0}{t_r - t},$$

or

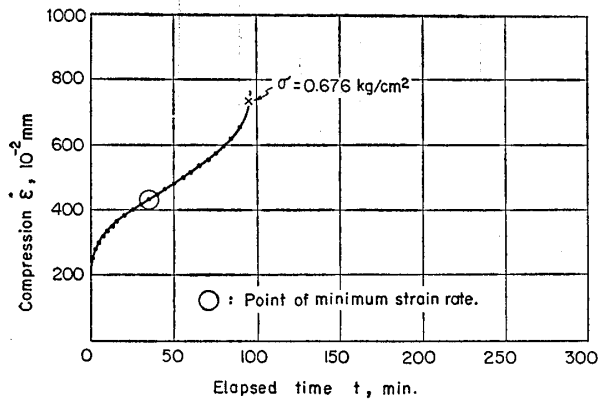
$$\Delta l = 1A \log \frac{t_r - t_0}{t_r - t},$$

where

- $t_r$  : creep-rupture life left before failure,
- $t_0$  : reference time,
- $\epsilon$  : strain at optional time,
- $\epsilon_0$  : strain at  $t_0$ ,

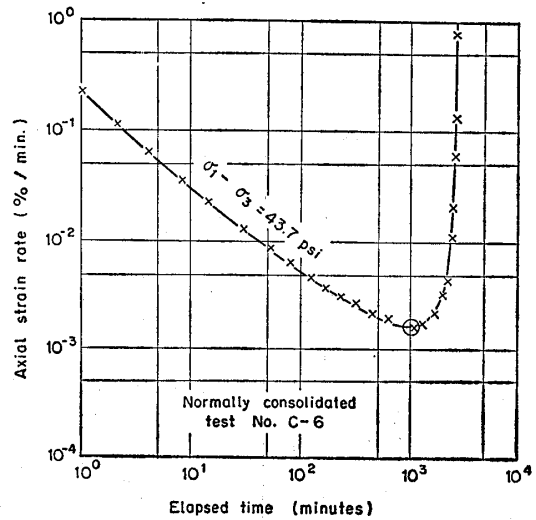


(a) log compression rate versus log elapsed time

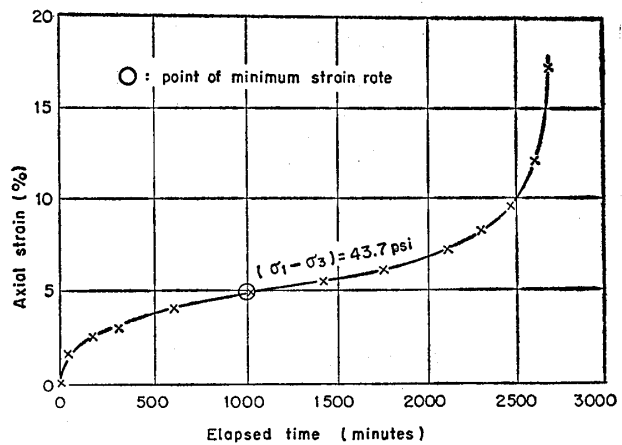


(b) Compression versus elapsed time

Fig. 7 Different expression of a creep-rupture curve published by Murayama & Shibata (1956)



(a) log axial strain rate versus log elapsed time



(b) Axial strain versus elapsed time

Fig. 8 Different expression of a creep-rupture curve published by Finn & Snead (1973)

$$\Delta l = \epsilon \cdot l : \text{relative displacement.}$$

Rupture life before failure is obtained with the empirical logarithmic formula by calculating, by graphical analysis or by plotting on semi-logarithmic graph applied with measured values.

It is, therefore, advisable that the time of initiation of slope failure is roughly estimated with steady-state strain rate in the secondary creep range, and closely estimated using substituted logarithmic formula in the tertiary creep range. Besides, the estimation method in the secondary creep range may be used for forecasting in the tertiary creep range as a rough estimation, but warning should be paid to be in danger side within one hour before failure.

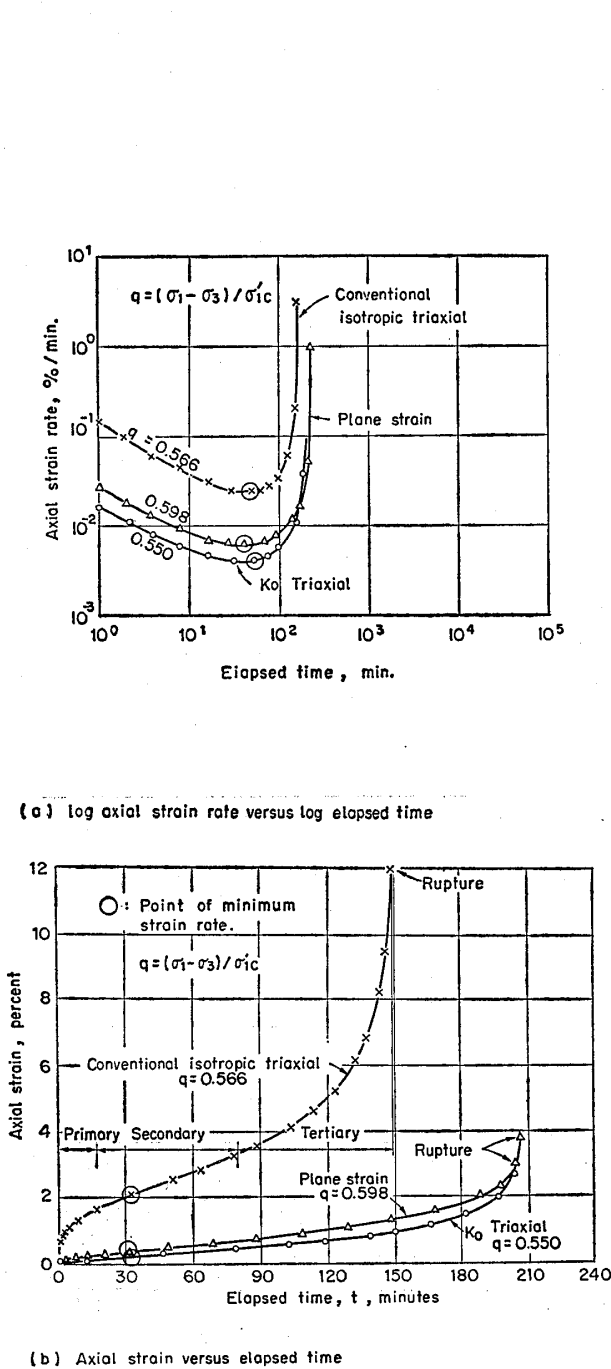


Fig. 9 Different expression of creep-rupture curve published by Campanella & Vaid (1974)

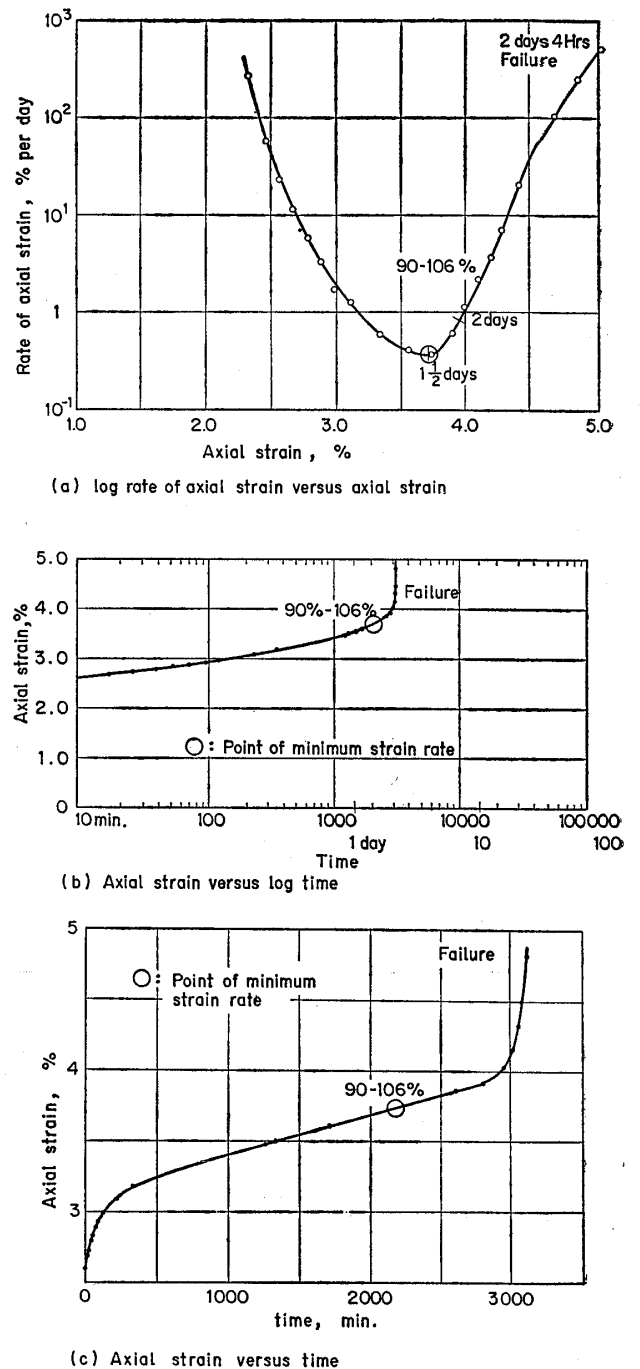


Fig.10 Different expression of a creep-rupture curve published by Bishop (1966)

## 2-3 Compilation of Experimental Data on Creep-Rupture Tests.

There can be found fairly many papers that deal with creep-rupture tests on specimens of soil or rock, and also found many opinions on interpretation and treatment of the test results.

First of all, there is a noteworthy opinion that the secondary creep range does not exist even where strain rate is considered constant, that is to say, strain rate continuously decreases and thereafter increases until rupture. This circumstances are clearly perceived, if strain rate and elapsed time are plotted on a full-logarithmic graph as shown by Murayama & Shibata (1961, 1965), Finn & Snead (1973) and Campanella & Vaid (1974), or if axial strain rate and axial strain are used as with the similar manner, such as presented by Bishop (1966) as seen in Fig. 7~10, respectively. This expression is quite correct as far as full-logarithmic scale is used. But, this is a kind of magic of presentation, because each equal increment on the coordinate scale does not mean the same length.

Logarithmic expression is to display the smaller parts extremely large and to demonstrate the larger parts extremely small. Therefore, in case of full-logarithmic coordinates of strain rate and elapsed time, the difference of strain rates within the range of a cycle near minimum strain rate is fairly small; nevertheless, a cycle of elapsed time near minimum strain rate means substantially very long time, by reason of long progress after initiation of creep: the last point of a cycle of elapsed time is enough ten times to the initial point of the cycle. The point of minimum strain rate is situated toward right-hand side on the logarithmic time axis; therefore, variation in creep rate on the time axis is small around this point, and thus, the apparent constant secondary creep rate computed from the strain-time plot with ordinary scale is essentially the same as the minimum creep rate as admitted by Campanella & Vaid (1974). The secondary creep range is, therefore, granted to exist actually.

The next problem is the definition of failure. In case of clay specimen, it is possible often to see shear crack develop shortly after the reversal of slope in the time curve takes place. Time to failure in creep-rupture test is, therefore, sometimes defined as the point of initiation of acceleration, that is to say, the point of the minimum strain rate as asserted by Casagrande

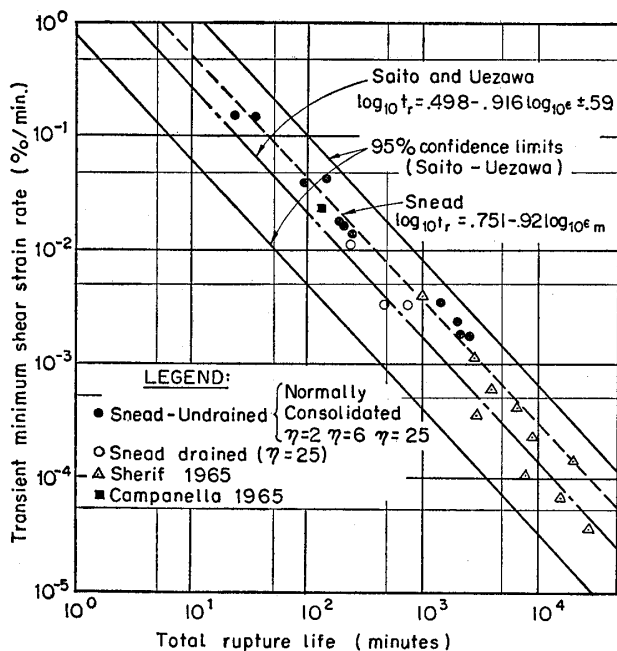


Fig.11 Relation between transient minimum shear strain rate and total rupture life published by Finn & Snead (1973)

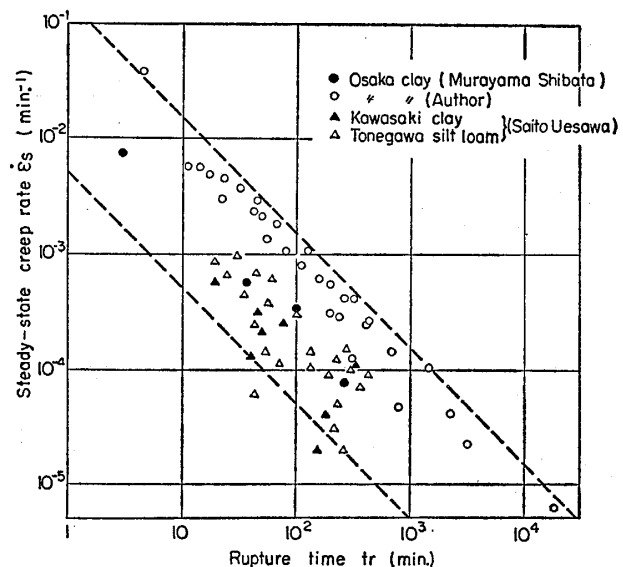


Fig.12 Relation between steady-state creep rate and rupture time published by Kurihara (1972)



& Wilson (1951), Singh & Mitchell (1969) and Finn & Snead (1973). But, this opinion seems to be rather strange and is not approved by all means. The reason is that this opinion has been derived from creep-rupture phenomena of metals, which is very dangerous and becomes out of use according to increase of strain rate, such as jet engines under high temperature and high pressure. On the contrary, in case of soil, usually there remains fairly long time and large movement before failure after passing the point of minimum strain rate as seen in Figs. 7~10. There is no reason why this tertiary creep range is abandoned as failure zone. In case of soil, therefore, failure should be defined with the final and macroscopic state of separation.

If we look round our surroundings, there can be found many useful contributions in recent papers. Fig. 11 shows the relation between transient minimum strain rate and total rupture life published by Finn & Snead (1973). Fig. 12 shows the relation between steady-state creep rate and rupture time published by Kurihara (1972). Fig. 13 shows the relation between minimum creep rate and time to failure published by Sekiguchi (1977). Fig. 14 shows the relation between strain rate and time to failure obtained on rocks published by Morlier (1964).

Upon admitting those consideration before mentioned, minimum strain rate is not considered to be very different from steady-state strain rate, so we may deal with both strain rate data in the same meaning. Fig. 15 shows the compilation of results from all creep-rupture tests in various publications. Most plots are situated within the range of 95 % confidence limits proposed by Saito & Uesawa (1961). Hereupon, Morlier's data are obtained with rocks. It is interesting that potassium is plotted within the range but chalk is found fairly below the range. On the other hand, aluminum alloys are found far above the soil range, but parallel to this range. As a result, it is concluded that creep-rupture life is longer for ductile material such as metals, and shorter for brittle material such as rocks.

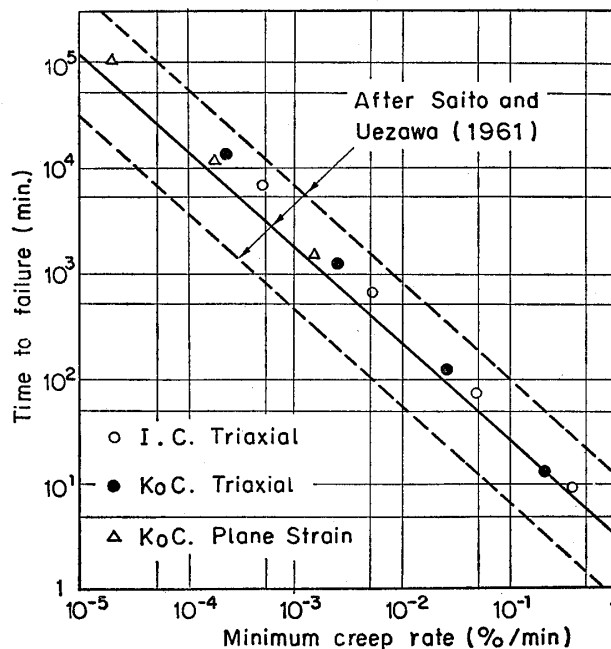


Fig.13 Relation between time to failure and minimum creep rate published by Sekiguchi (1977)

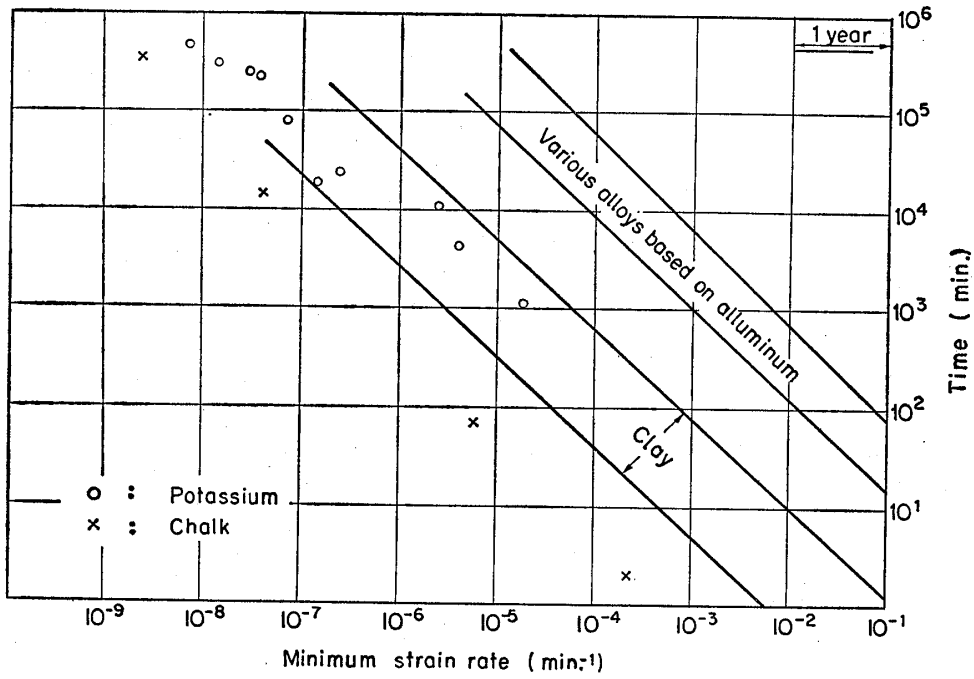


Fig.14 Relation between strain rate and rupture time published by Morlier (1964)

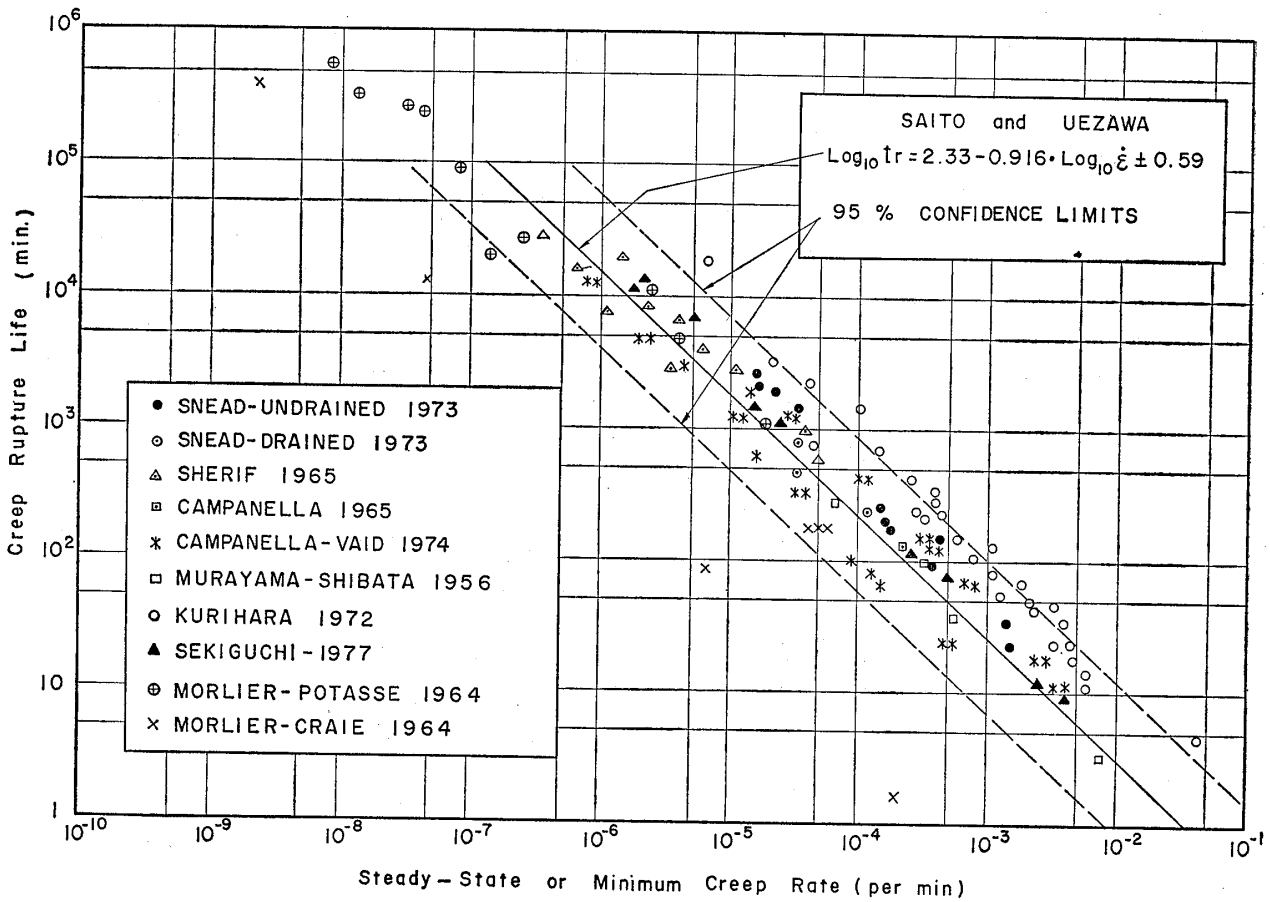


Fig.15 Compiled relationship between creep rate and creep-rupture life

### 3 RHEOLOGICAL INTERPRETATION FOR CREEP-RUPTURE OF SOIL.

Recently, rate process theory has come to gain ground to explain creep phenomena of soil, and it is afraid that such illusion would be impressed that all creep phenomena including creep-rupture characteristics could be explained with this theory.

It may be well just so in the primary and secondary creep range, but there are many problems that can not be explained with this rate process theory in the tertiary creep range. Exactly speaking, it should be said that no creep theory is formed at present to be applicable to the tertiary creep range.

First of all, such a proposition is very questionable that soil fails soon after creep movement has attained at a definite quantity as asserted by Murayama & Shibata (1951, 1956) and Vyalov, Maslov & Karaulova (1977). Essentially, properties of material are divided in two categories; that is to say, structure-insensitive and structure-sensitive properties. The former is caused by additive contribution of material constitution such as atoms, molecules or particles to the properties, for instance, elastic coefficient, Poisson's ratio, specific gravity or coefficient of thermal expansion. The latter is not caused by additive contribution of material constitution, but caused by strong control of such defects as dislocations, cavities or fissures fairly large enough compared to the size of material constitution, for instance, strength, plasticity or permeability.

Originally deformation is of structure-insensitive properties, and failure strength is of structure-sensitive properties. If rupture is defined according to deformation, the limit of deformation will be even in a way, but it cannot exist that rupture will cause at the same deformation, if it means final and macroscopic state of separation.

Next, there are very few examples of strain-time curves in the tertiary creep range. It should be expressed with a formula relating strain or displacement and time. As a creep formula in the tertiary creep range, it is requested that quantity of strain or displacement becomes infinite at a limited time. If such a creep formula that strain or displacement is finite at a limited time is used, rupture must be defined with deformation; it is too much willful and far from reality.

The experimental formula by Singh & Mitchell (1969),

$$\epsilon = A e^{\alpha D \left( \frac{t_1}{t} \right)^m},$$

and also the formula by Vyalov, Maslov & Karaulova (1977),

$$\gamma = \gamma_0 + \frac{\tau}{\eta_0 [1 - n(\tau)]} \left[ (t+1)^{1-n(\tau)} - 1 \right],$$

are not suitable to make forecast close to failure, because they do not give infinite strain or displacement within limited time.

Contrary to these formulas, my experimental formula, i. e.

$$\epsilon - \epsilon_0 = A \log \frac{t_r - t_0}{t_r - t},$$

or

$$\epsilon = \frac{A}{t_r - t},$$

offers infinite strain and strain rate at a limited time, and can describe the form of creep curve close to the real displacement until the time of rupture. Therefore, this formula can be successfully applied to forecast the time of rupture.

### 4 CASE STUDIES OF ACTUAL SLOPE INSTABILITY.

#### 4-1 Landslides Failed after Long Creep Movement.

##### a) Takabayama Landslide on the Iiyama Line, JNR (Saito & Yamada, 1973)

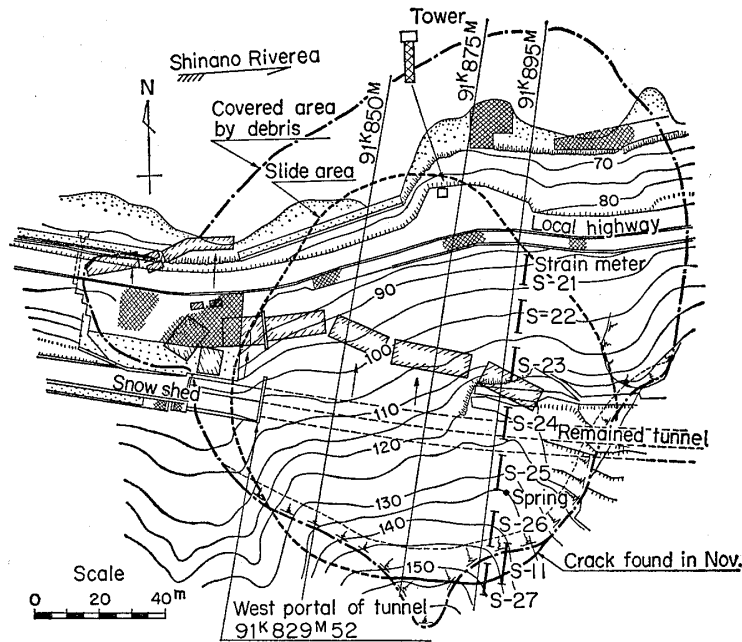


Fig.16 Plan of Takabayama Landslide

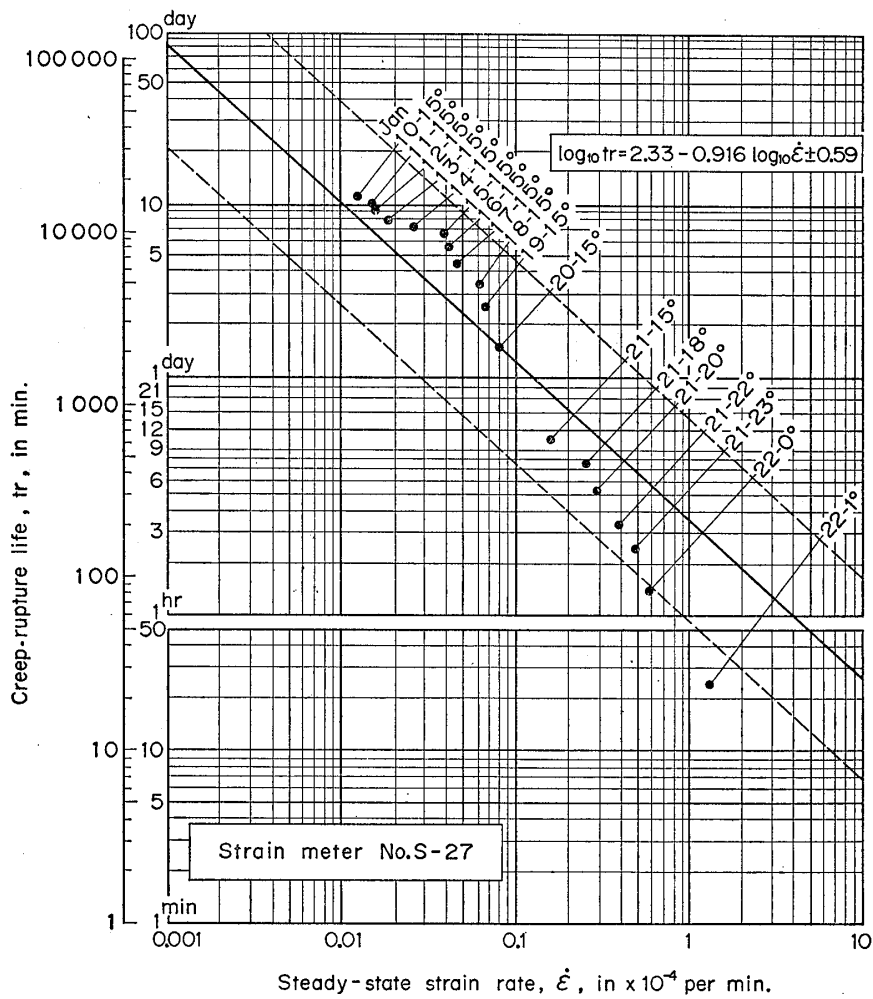


Fig.17 Reliability of forecasting failure time based on forecasting diagram in case of using transient strain rate, Takabayama Landslide

At the Moscow Conference in 1973, I reported Takabayama Landslide occurred in January, 1970, but I would like to explain again an outline of the accident, because forecasting of failure time was announced in advance to failure and it resulted in good coincidence with the actual failure time.

Takabayama Tunnel is located on the Iiyama Line, JNR. In April of 1969, unusual dislocation was found on the tunnel, and thereafter careful observation was performed continuously. In November, a long tension crack was found on the slope above the central part of the tunnel, and extensometers were set up across the crack in order to measure the relative movements. In the middle of December, heavy snowfall destroyed the measuring devices on the ground, then the extensometers of remote recording type were reset, buried in the ground and observations were resumed on 31st of December, 1969.

Forecasting of failure time was made with two ways; estimation with transient strain rate and graphical analysis for substituted logarithmic curve in the tertiary creep range. The methods are shown in Fig. 17 and 18, respectively. Public announcement for failure was made by the authority at 5 p.m. of the 21st that the slope would fail at the coming midnight or before dawn. The estimation of failure time was revised every hour. The final announcement was made at the midnight that the failure would occur at 1:30 on the 22nd, according to the

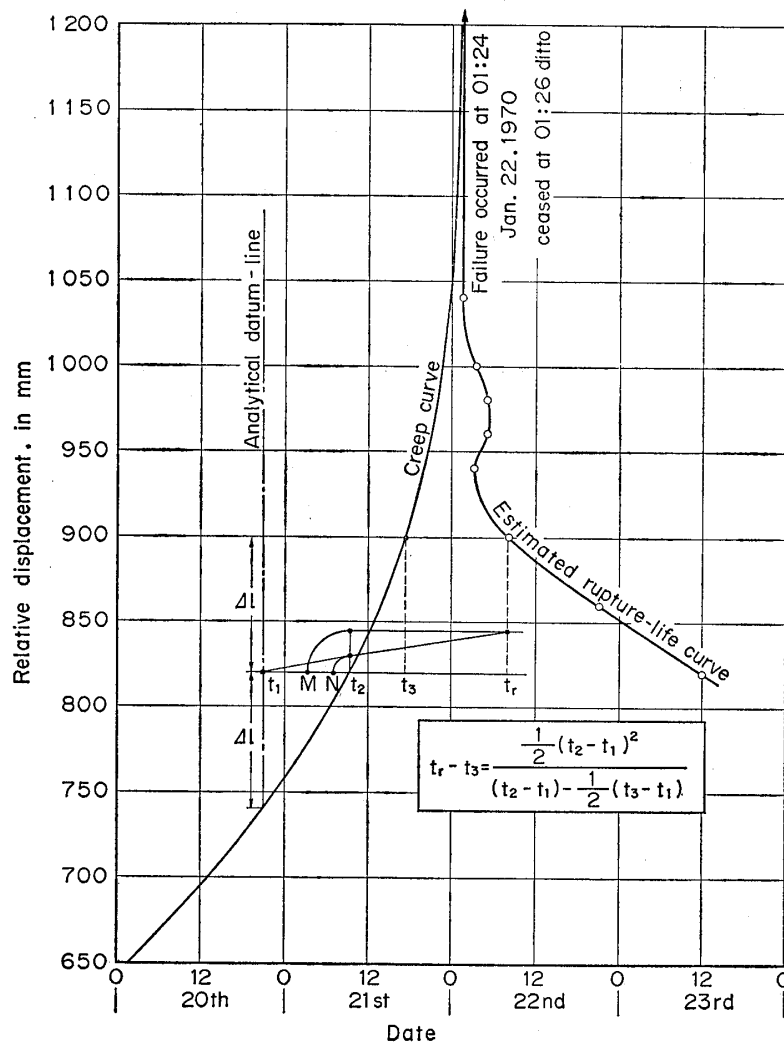


Fig.18 Forecasting failure time by means of graphical analysis in the tertiary creep range, Takabayama Landslide

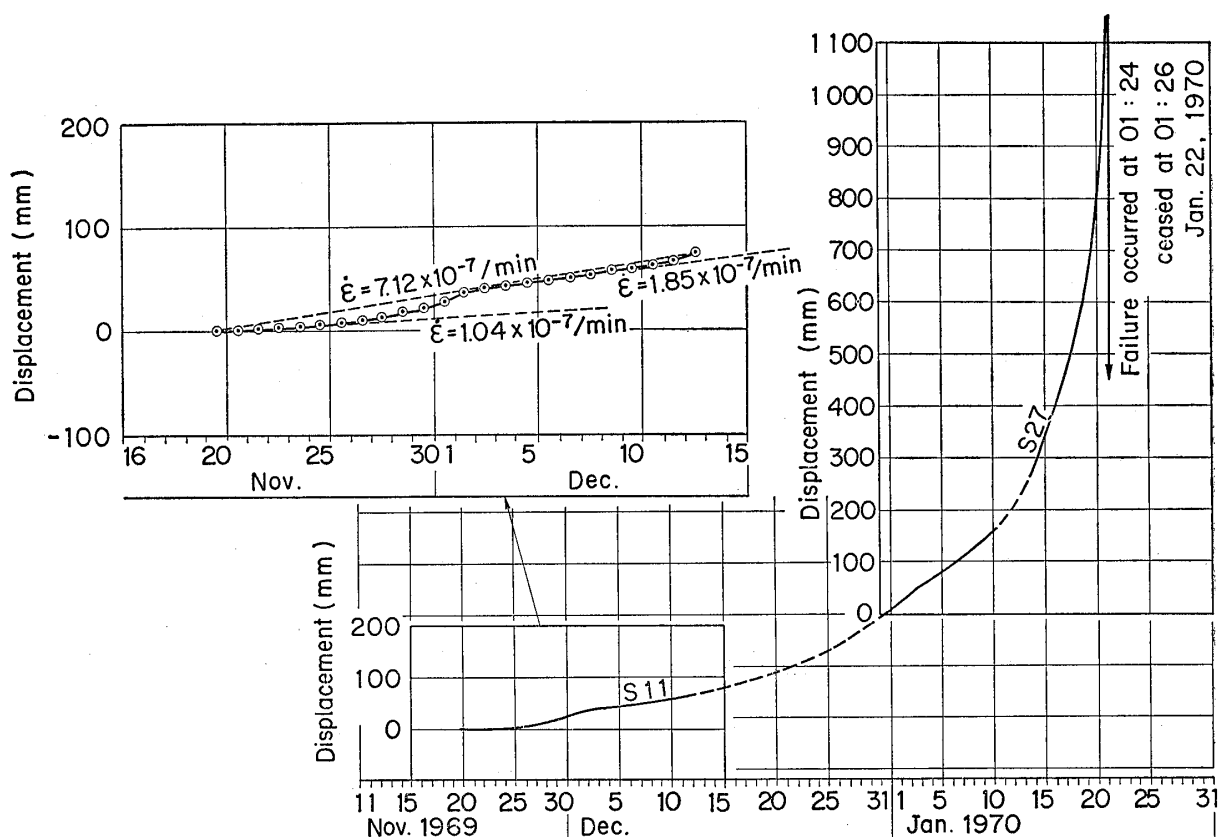


Fig.19 Relative displacement curve interrupted but connected under acceptable supposition, Takabayama Landslide

analysis in the tertiary creep range. After all, the slope above Takabayama Tunnel began to fail at 1:24 on the 22nd, and it ceased to move after two minutes. The difference between estimated and actual failure time is only 6 minutes. It was said that there was nothing else than a miracle.

Fig. 19 shows a curve of displacement which was made by connecting two curves obtained before and after snowfall in December under acceptable supposition. From three strain rates calculated on the curve obtained before snowfall, the failure time might be estimated as 30-60 days after the 13th of December, i. e. between the 10th of January and the 10th of February.

#### b) Agoyama Landslide in Fukui City (Watari, 1973)

About 5 km to the northwest of Fukui City, there occurred Agoyama Landslide in December 1972, which is a site of old landslide about 200 m wide, 80 m high and 180 m in slope length. This movement was caused by removing earth as borrow-pit at the foot of the slope. Bedrocks are composed of tuffaceous sandstone of Tertiary Period, and sliding surface is supposed on a fine grained layer of sandstone.

A long continued crack was found on a hillside of Agoyama in Oct. 4th of 1972, and observation was started at the 7th of the month after setting up measuring instruments. At first the movement was about 10 mm per day, but then the movement gradually increased and reached to 20mm per day at the end of October, and 100 mm per day after 20th of November. Analysis of forecasting failure time was carried out at Tokyo about 400 km apart from the site, and the result of analysis was informed to the person in charge of the site by telephone.

Graphical analysis in the tertiary creep range is shown in Fig. 21, and the failure time was guessed at about the late of November. But the supposition was disturbed with irregular

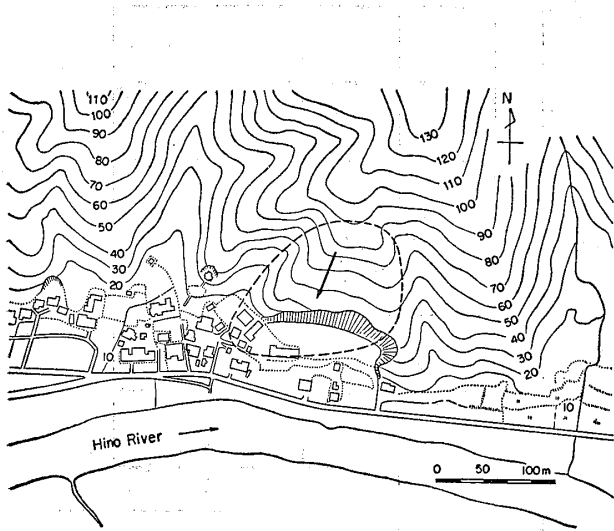


Fig.20 Plan of Agoyama Landslide

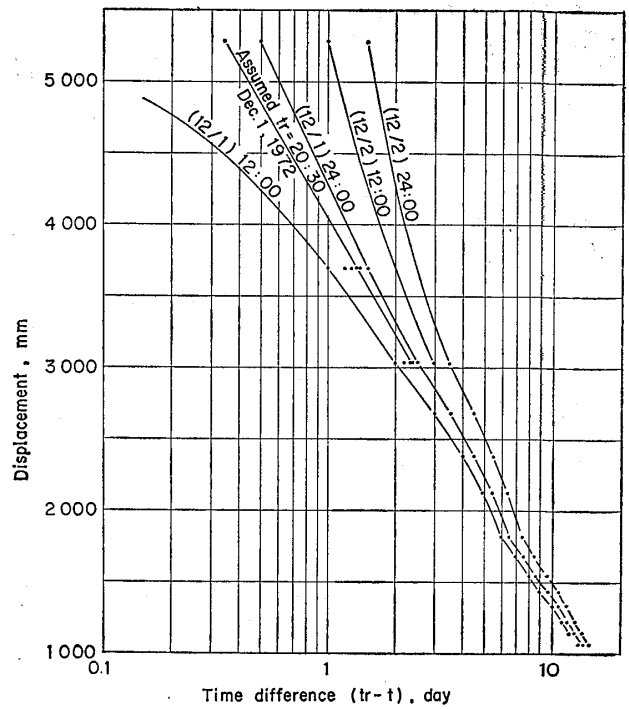


Fig.22 Forecasting failure time based on linearity on semi-logarithmic coordinates, Agoyama Landslide

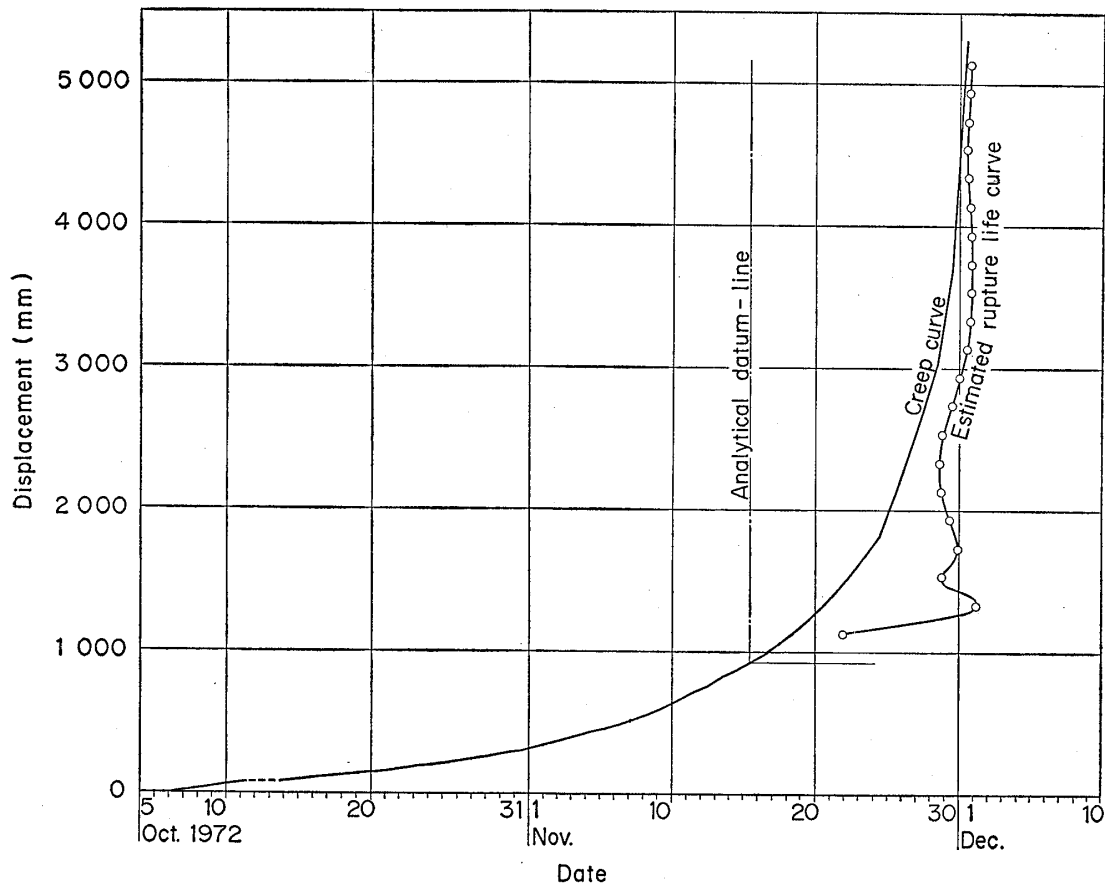


Fig.21 Creep curve and forecasting failure time by means of graphical analysis, Agoyama Landslide

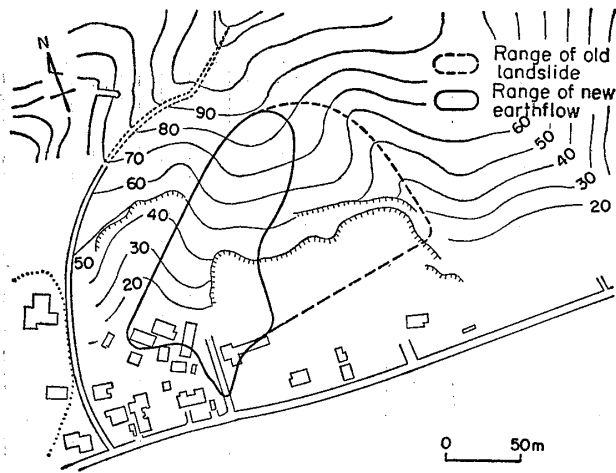


Fig.23 Finally failed area of Agoyama Landslide

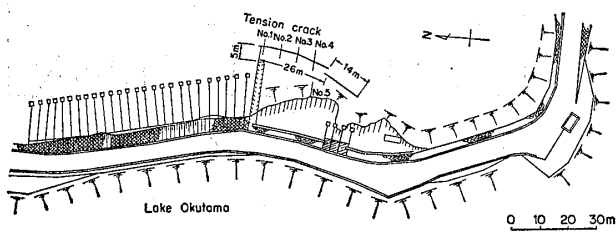


Fig.24 Plan of damaged area along Tama Lakeside Road

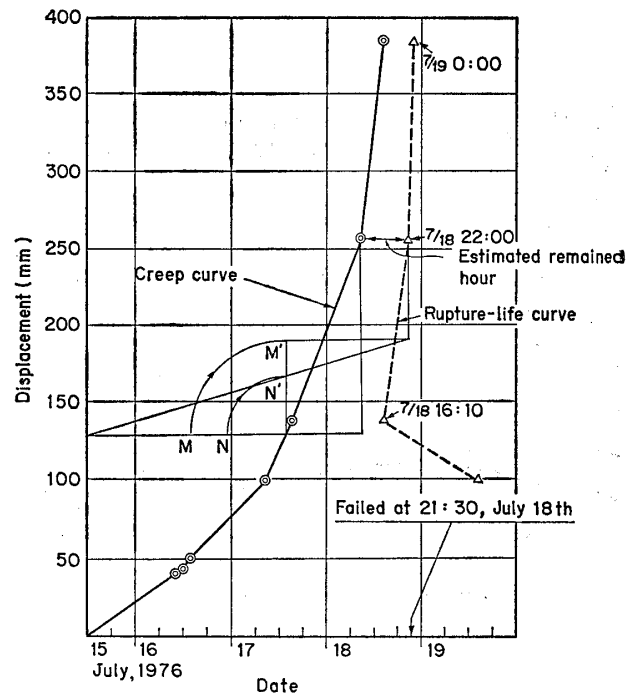


Fig.25 Forecasting failure time by means of graphical analysis, slope failure along Tama Lakeside Road

movement at the final stage; then, the method of semi-logarithmic representation to pursue linearity of creep curve was used together with graphical analysis, as shown in Fig. 22. The linearity of creep curve on semi-logarithmic graph was not attained easily, showing irregular bending. Last forecasting of failure time was decided as 20:30 of the 1st of December in the evening of the very day; actual failure time was 1:30 of the 2nd of December. Later it was made clear that this discrepancy was caused by the reason that movement of total mass was stopped at the final stage and only one third of the mass failed at all, as seen in Fig. 23.

#### c) Collapse of a steep slope at Tama Lakeside Road (Hasegawa & Kiuchi, 1977)

A slope failure with volume of  $9,500 \text{ m}^3$  occurred at Tama Lakeside Road, about 70 km west of Tokyo on July, 1976. Bedrocks are mainly composed of Jurassic slates, partly containing sandstone, splitted by shearing and altered to clay formation. The slope in question is about 70 m in slope length, and 0.6 : 1 in inclination.

Signs of instability of the slope were found in July 13th of 1976. Measuring points were set up at 5 spots across a tension crack at the upper part of the slope. Observations of the distance variation between measuring points were begun on 14th of the month.

Graphical analysis in the tertiary creep range is shown in Fig. 25. At 10:00 of 18th, failure time was suggested as after 12 hours, and actual failure occurred at 21:30 of the day; the difference is just half an hour, resulting good forecasting.

I found the fact in a paper published in a technical magazine, that this forecasting was made according to my method, though I had no relations with this work of forecasting.

#### d) Yunotai Landslide on the Esashi Line, JNR (Saruta & Ishibashi, 1976)

In April of 1975, a landslide with the volume of  $40,000 \text{ m}^3$  occurred between Yunotai and



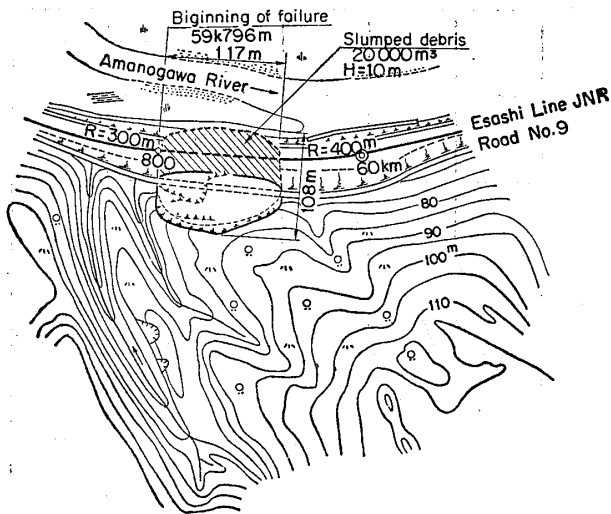


Fig.26 Plan of Yunotani Landslide

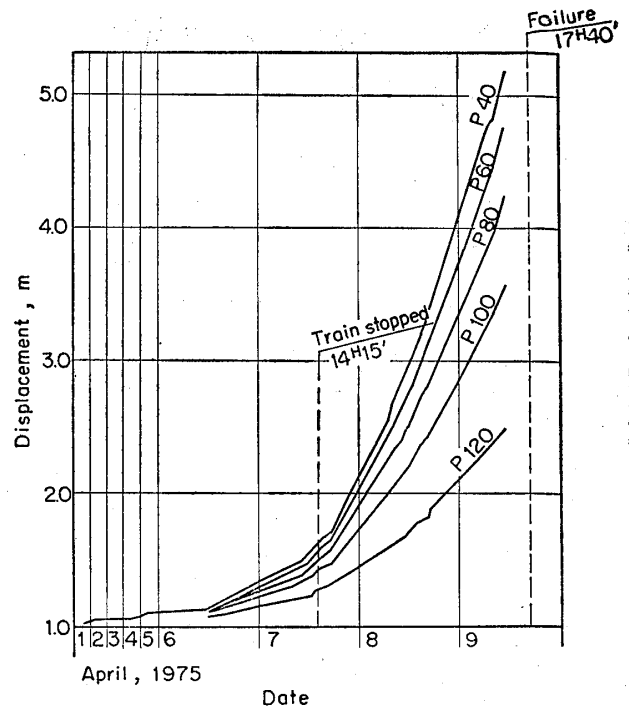


Fig.27 Progress of displacements of road, Yunotani Landslide

Miyakoshi on the Esashi Line, JNR. Railroad was covered with soil mass, about 10 m high, 117 m long and 20,000 m<sup>3</sup> of volume, and railway traffic was interrupted for 19 days. Bedrocks are composed of mudstone of Miocene Epoch, Tertiary Period and the site is considered as an old landslide area.

In March 21st, a cave-in of road surface above the railroad was found; then; many cracks appeared over both road surface and railroad roadbed. In April 7th, the slope came to cover the railroad and railway track moved laterally as much as 300 mm, and at last on 17:40 of 9th the slope fell down with loud and terrible sound. Movements of observation points on the road surface are shown in Fig. 27.

The creep curves show that they were in the secondary creep range before April 6th, and then it entered rapidly in the tertiary creep range. By the noon of the 8th, failure time was supposed as within 11th day, but on 10:45 of 9th day, when the last observation was done, failure time was estimated as 18:10 of the 9th: contrary to this forecasting, actual failure occurred on 17:40 of the 9th, 30 minutes earlier than estimation.

In this case, also I had no relation with their work of forecasting, as the same with mentioned before.

4-2 Landslides That Finally Ceased without Failure after Rapid Movement.

e) Landslide at Kashiwara Interchange on Nishimeihan Expressway (Tokunō & Tatsumi, 1971)

Late in April of 1969, signs of instability came out at buildings of a hospital standing on flat area of a hillside, and then fears were made clear with many cracks all over the area. Similar cracks were found on the main lines, rampways and retaining walls of Nishimeihan Expressway. Covering these instable areas, the range of the landslide became clear gradually, with the width of about 250 m and slope length of 250 m, and this site was considered as old landslide area, revived at this time.

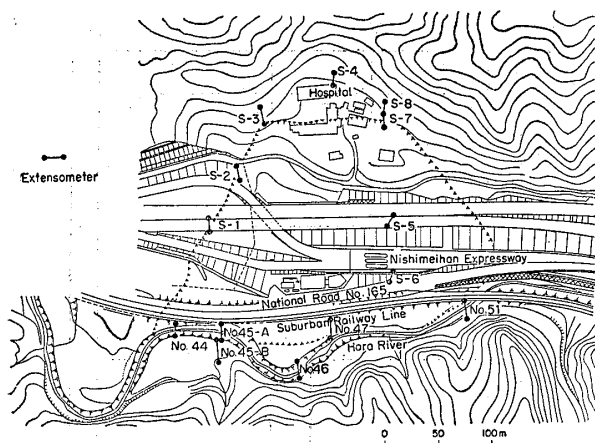


Fig.28 Plan of Landslide at Kashiwara Interchange

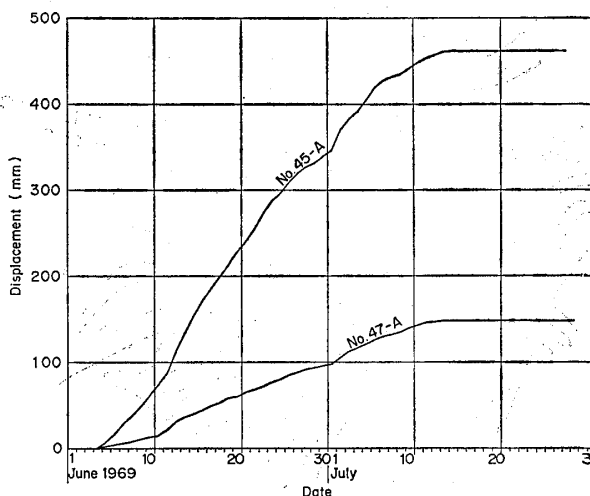


Fig.29 Progress of displacements of suburban railway line, Landslide at Kashiwara Interchange

Investigations and observations were set to work at the last of May. The range of the landslide was extended over national highway and suburban railway line situated below the expressway, and sliding movement became gradually larger, such as 470 mm for 40 days from June 4th to July 16th, and 24 mm per day in June 13th as the maximum daily displacement, measured with extensometer No. 45-A.

Rapid movement continued for fairly long duration, as shown in Fig. 29, and then movement gradually decreased. Horizontal drillings for dewatering were carried out since the last of June, and the movement ceased July 10th, accompanied with the effects of dewatering.

Let us calculate the maximum strain rate. The span length of extensometer No. 45-A is 15.540 m, so strain rate corresponding to the movement 24 mm per day is calculated as  $1.07 \times 10^{-6}$  per min. This value is not so large, but cannot be ignored. If this rate would continue invariably, the slope would fail in 9.5 days based on my method. Considered from the fact the strain rate did not become larger than this value, this landslide is supposed to be such a type of slide as that would finally cease without failure.

#### f) Iwadonoyama Landslide at Ohtsuki on Central Expressway (Harada, 1972)

The site of Iwadonoyama Landslide experienced slope failure twice during construction. Bedrocks are composed of alternate of tuff, lapilli tuff, tuff breccia and tuffaceous sandstone of Miocene Epoch, with dykes of andesite, and dip of bedding is against slope. The site is a cut slope of 32 degrees. It was in February 17th of 1972, that several lines of cracks were found around the area, and in March 2nd the range of about 60 m in width and 90 m in slope length was perceived as sliding area, with increase of cracks. Observations with invar-wire extensometers were set to work in Feb. 24th. After that, additional extensometers were supplemented according to expanding of sliding area, and remote-recording type extensometers were also set over the upper or lower end cracks, prepared for emergent situation.

As shown in Fig. 31, displacements increased rapidly since 21st of March, and on 26th transient strain-rate attained to  $6.14 \times 10^{-6}$  per min. On the other hand, such a serious situation was anticipated that failure would occur in a day and a half according to graphical analysis in the tertiary creep range. But after that, against our anxiety, strain rate did not increase beyond the value, and came to cease without failure.

As seen in this case, there are such a many examples that a slope does not fail but cease to move, even if considerably accelerating strain rate is seen in the tertiary creep range. In such a case, it is extremely difficult to forecast with our present knowledge whether such a

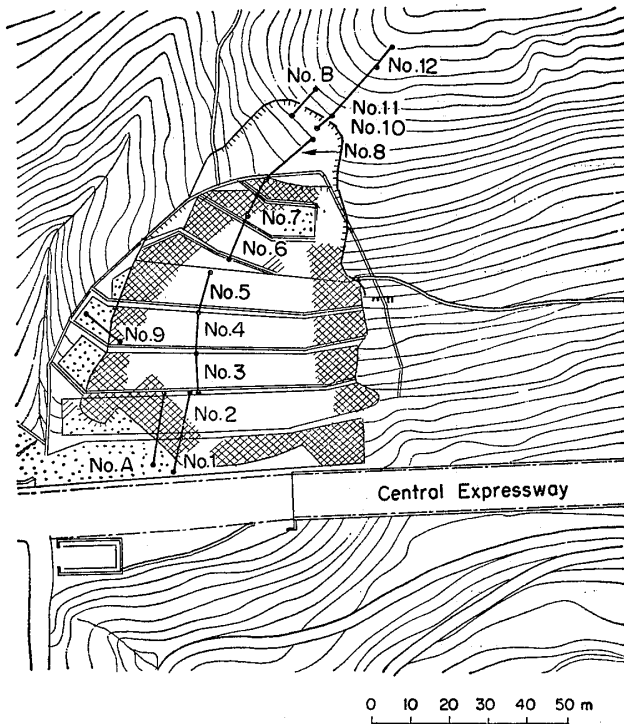


Fig.30 Plan of Iwadonoyama Landslide

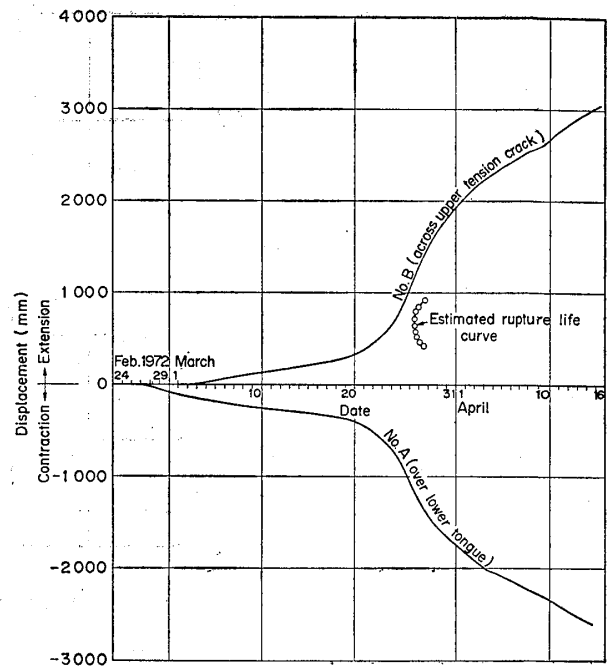


Fig.31 Progress of relative displacements crossing over upper or lower end cracks, Iwadonoyama Landslide

slope would fail presumably or not.

4-3 Split-Type Failure

g) Failure of a vertical cut in clay, Welland, Canada (Kwan, 1971)

Several years ago Mr. D. kwan of St. Lawrence Seaway Authority wrote to me that failure time estimated with my method did not coincide with actual one in a field test of vertical cut failure which he carried out for realignment of Welland Canal. In this case, I suppose, my method of forecasting failure time from steady-state strain rate cannot be applied because its type of failure is not sliding, but splitting and overturning separated by deep tension crack, and slip plane came out only near the toe of the vertical slope.

In this case, however, graphical analysis in the tertiary creep range can be applied to his test results and shows good astringency to the failure time as can be seen in Fig. 32.

4-4 Slope Failure Directly Caused by Rainfall.

h) Hiketa Landslide on the Kōtoku Line, JNR (Sakurai, 1974; Yano, 1976)

Hiketa Landslide is about 50 m wide, 80 m in slope length and supported with retaining wall at the foot. Owing to a typhoon in 1972, a tension crack about 60 m long and 50 cm wide, came out along the upper verge; so geological investigation was carried out and instrumentation such as extensometers and alarm fences were set up for guard over the area. Bedrocks are composed of sandstone of Mesozoic Era, fairly weathered and decomposed.

A typhoon in July of 1974 brought heavy rainfall such as 378 mm of total rainfall by the 7th day and 70 mm per hour of maximum rainfall intensity, and finally the slope failed down at 1:10 of th 7th.

Before failure occurred, an alarm bell in a lookout hut began to ring and guardmen, who were standing by in the hut, at once hurried on their ways of 6 km on foot, under a torrential rain. When they arrived at the distance of 150 m to the site, they stared the slope just failing

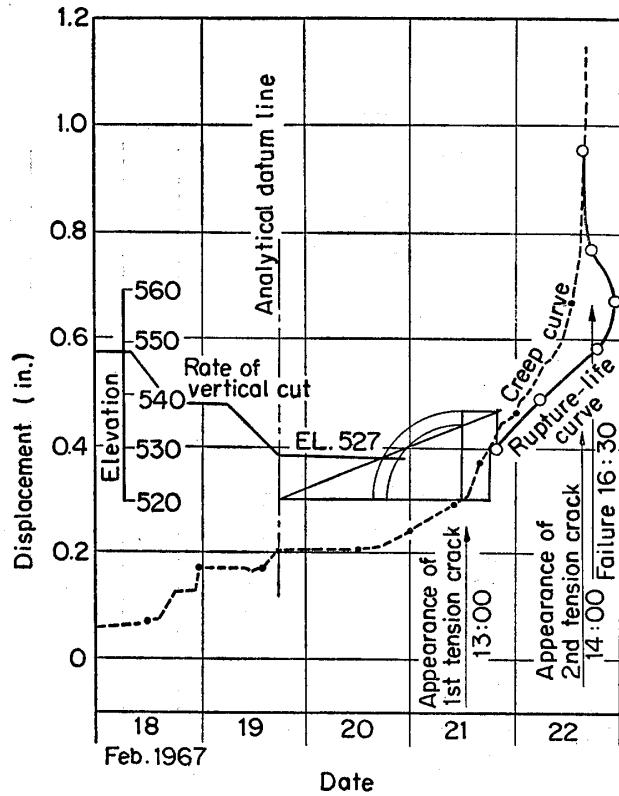


Fig.32 Graphical analysis for forecasting failure time, Welland, Canada

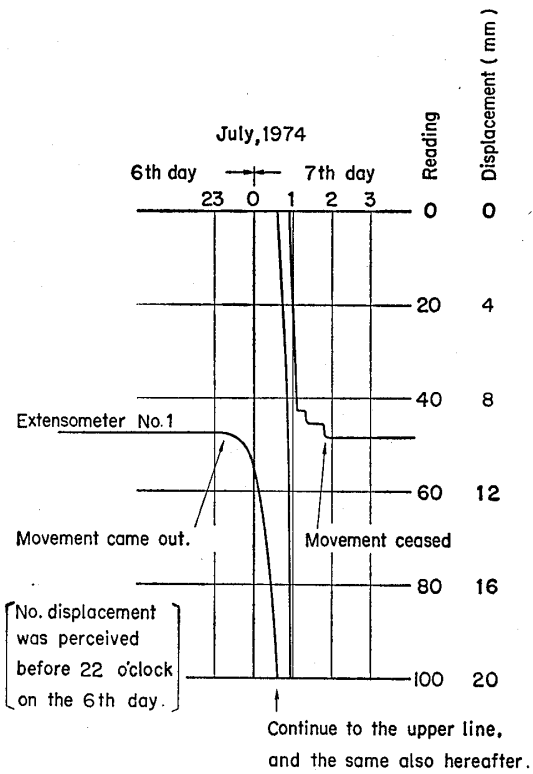


Fig.33 Progress of displacement, Hiketa Landslide

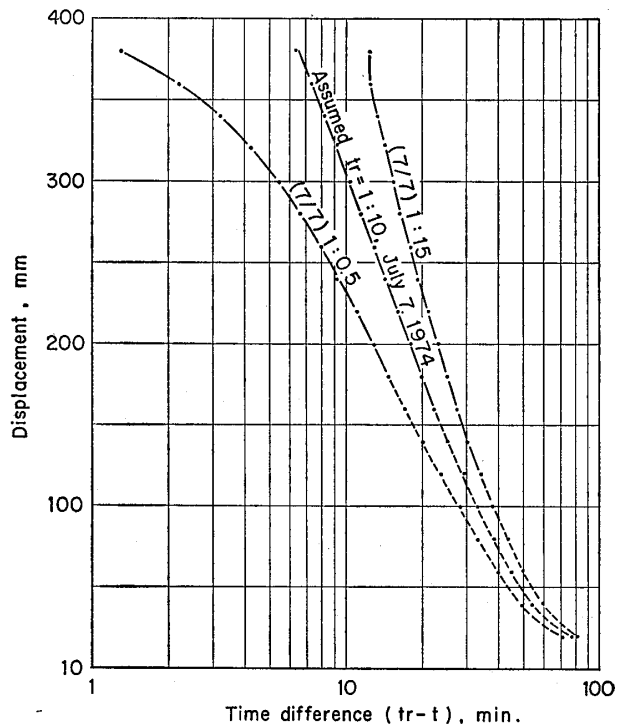


Fig.34 Forecasting failure time based on linearity on semi-logarithmic coordinates, Hiketa Landslide

under illuminating equipments. If they had arrived there one or two minutes earlier, or if the slope failure had occurred one or two minutes later, all the guardmen would have been endangered to be buried under huge moved debris.

A record of an extensometer is shown in Fig. 33. It is supposed that mechanism of sliding movement in case of slope failure caused by rainfall is not the same with that of usual landslide, because the condition of circumstances are changing every moment. Neither forecasting method using transient strain rate nor graphical analysis in the tertiary creep range is adaptable to this case.

However, the experimental formula in the tertiary creep range

$$\varepsilon - \varepsilon_0 = A \log \frac{t_r - t_0}{t_r - t}$$

indicates the other forecasting method, that plots of measured values will form a straight line on a semi-logarithmic graph, measured value on normal scale and  $(t_r - t)$  on log-scale, if rupture life  $t_r$  could be chosen adequately. The result of this method is shown as Fig. 34. From the process of choosing temporary rupture life, failure time is about 10 minutes past one o'clock of the 7th day. This estimation would have been very effective, if this procedure had been applied in this case. Thus, forecasting of failure time directly caused by rainfall is also applicable with semi-logarithmic representation.

## 5 FINAL REMARKS.

Considered from several case studies explained above, it can be said that the method of forecasting failure time based on creep-rupture characteristics, that is to say, rough estimation of failure time based on steady-state strain rate in the secondary creep range, close estimation through calculation or graphical analysis using substituted logarithmic formula and final precise estimation based on linearity on a semi-logarithmic graph assuming temporary rupture life, is effective and reliable. As for reliability, it can be indicated with unit of day, if forecasting is made before several days, and with the unit of hour, or even with order of 10 minutes, if on the previous day.

## 6 ACKNOWLEDGEMENT.

Most of field investigations of slope failure were carried out with no relation to me, but these data resulted immediately to demonstrate the reliability of the forecasting method. I appreciate it very much that I was provided such opportunities to make practical use of them.

I would like to express cordial gratitude to Prof. Dr. Techn. Sc. G. I. Ter-Stepanian, who kindly gave me an approval of reproducing this paper in "OYO Technical Report" of OYO Corporation.

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#### Additional Remark

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## 斜面崩壊の発生予測の実証的研究

齊藤 迪孝

### 概 要

崩壊発生の予測には、少なくとも発生する場所、発生の時期、発生する現象の規模と形態の3つの要素が明らかにされなければならないが、ここで予測と言うのは、特定斜面の崩壊時間の予測に限るものとする。

予測に役立つ因子を見出すには、斜面崩壊実験を行なって、どの因子がもっとも鋭敏に、また早期に変動を示すかを調べるのが一番の近道である。この目的で1949年北陸本線能生一箇石間で実施した人工降雨による大型斜面崩壊実験では、斜面の表面ヒズミの測定が予知因子として最も有効であることがわかった。そこで今度は室内で土のクリープ破壊試験を行ない、第2次クリープ領域の定常ヒズミ速度とクリープ破壊時間とが逆比例することを見出した。

この関係を実斜面の崩壊記録で検討した結果、崩壊時間の予測に有効であることがわかり、さらにこの逆比例の法則は第3次クリープ領域においても若干の修正により適用できることがわかった。それ故、斜面崩壊の発生予測としては、通常つぎの2つが用いられる。

- (1) 第2次クリープ領域における定常ヒズミ速度に基づく概略予測
- (2) 第3次クリープ領域における置換対数曲線式を用い、計算または図解による近接予測

クリープ破壊の最初の論文を海外に発表したのが1961年であったが、その後国内国外いずれにおいても多くの論文が発表され、クリープ速度が一定の時期はなく、最小値を経過してから急増に転じるという主張が幅をきかせているようであるが、これは対数目盛を使って微小部分を拡大して初めて言えることであって、通常目盛で表現する場合は依然定常ヒズミ速度の範囲がクリープ破壊に至るまでの大部分を占めているし、Campanella (1974) のように本質的には最小ヒズミ速度と定常ヒズミ速度とはほとんど変わらないとする研究者もいるので、これを同じものとして今までの内外のデータを図示したのが図-15であって、これをみると大部分の点が最初に発表し

た95%の信頼幅の中に入っており、今でもこの関係が有効なことがわかる。

また、第3次クリープ領域の関係式について、Singh と Mitchell (1969) や Vyalov その他 (1977) などの実験式や理論式が出されているが、何れも有限時間内にヒズミが無限大にはならないので、崩壊時間の予測には適さない。これに対して私の実験式は、有限時間内に無限大のヒズミが得られるので、崩壊時間の予測に確定値で得られ、はるかに現実即していると言えよう。

崩壊予測の事例はつぎの4つに区分した。

- (1) 長時間のクリープ変形の後崩壊した地すべり
- (2) 崩壊せずに遂には停止した地すべり
- (3) 割裂性の崩壊
- (4) 降雨が直接の原因となった斜面崩壊

飯山線高場山トンネルの地すべりは、1970年1月22日に崩壊したが、前日の午後5時に公表した予測では、崩壊時刻は翌日の午前1時30分とのことだったが、実崩壊は1時24分で、その差はわずかに6分であり、適中度は正に神わざではないかと言われた。

福井市安居(あご)山の地すべりは、動き始めから地元でさわがれ、今にも大きくすべり出すかと思われていたが、実際は約2ヶ月後に動き出し、予測より5時間ばかりおそく生じたが、この相違は最後には滑動土塊の1/3程度だけがすべりおちたことから、滑動機構が変わったためと思われる。

動きを生じたが遂には停止した例としては、西名阪道路柏原インターの地すべり、中央自動車道岩殿山地すべりの例をあげ、割裂性のものはカナダのWellandの実験例をあげた。

また、高徳線引田の地すべりでは、降雨による崩壊にも拘らず、前もって計器を設置してあったので、1時間半前に動きをとらえ、現地に急行した警戒職員があやうく生き埋になる程の正確な予測が得られた。

以上の事例からみても、このクリープ破壊特性に基づく崩壊時間の予測方法は有効であり、信頼し得ると言えよう。