PREDICTION OF TIME OF CREEP RUPTURE FAILURE
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SYNOPSIS: Saito's methods for predicting the time of creep-rupture failure are reviewed and applied to landslide case histories. Doubts are raised about the appropriateness of Saito's field measurements for his secondary creep method. Saito's tertiary method is found to give satisfactory results. An improvement is proposed for predicting failure time.

INTRODUCTION

When slope failure is likely, accurate predictions regarding the time of failure are desirable, especially if the slide affects a critical transportation facility or if salvage or rescue efforts will be necessary. Saito (1965, 1969, 1970, and 1980; Saito and Uezawa 1961; Saito and Yamada 1973) and others (described in Fukuzono 1990) have developed methods to predict the time of failure for creep-rupture failures. Saito's methods are attractive because they are intuitively obvious and because he has successfully applied them to a few actual slides. Although Saito's methods have been mentioned by others, e.g., Pilot (1984) and Fukuzono (1990), none have apparently critically reviewed his methods or tested them by systematic application to a series of case studies.

Based on a study of creep rupture characteristics of soils, Saito proposed two methods for predicting the time of occurrence of slope failures. He concluded that a rough prediction may be made by analyzing secondary creep movements and improved measurements could be obtained by analyzing tertiary creep movements. This paper summarizes a study that reviewed Saito's methods and applied them to landslide case histories (Wu, 1992).

PREDICTION BASED ON SECONDARY CREEP

Saito (1961, 1965) reviewed the results of laboratory tests and detected a relationship between the rate of shear strain during the secondary creep stage and the time to failure. He presumed that the same relationship applied to full scale landslides and he used this to develop a prediction model. The triaxial and unconfined compression tests were performed on undisturbed samples of loam, clay, and silt. The compressive stress was adjusted to provide the desired strain rate, and the time to failure was noted. Thirty four of the 80 samples tested produced creep curves; the remaining samples failed suddenly.

Saito combined his test results with others found in the literature. When $\log_{10} t_r$ was plotted against $\log_{10} \dot{\varepsilon}$, the results tended to scatter along a straight line. Ninety five percent of the points fell within the bounds of:

$$\log_{10} t_r = 2.33 - 0.916 \log_{10} \dot{\varepsilon} \pm 0.59 \qquad (1)$$

where t_r = time of rupture in minutes and $\dot{\varepsilon}$ = constant strain rate in microstrain per minute (10^{-4} ε/min).

Saito (1965) used the following procedure to predict the time of occurrence of landslides: 1) Measurement of surface relative displacements by optical surveying techniques or by strain/meters straddling tension cracks. 2) Identification of the secondary creep stage by examining the relative displacement vs. time relationship. 3) Calculation of the surface strain rate. 4) Estimation of the time of failure using Eq. 1.

No information was given about how the surface strain rate should be calculated or what the relationship is between the surface strain rate and the shear strain rate.

Review of the Secondary Creep Method

What baseline length (l) did Saito use for calculating $\varepsilon = \Delta l/l$? To calculate shear strain, l should be the thickness of the shear band, if one exists. Saito's plots provide enough information to backcalculate l from $\Delta l/\varepsilon$. Wu (1992) reviewed the Ooigawa, Dosan, and Soya case histories (Saito, 1965) and performed this backcalculation. In general the baseline lengths appear to be reasonable for strain meters and survey baselines. If this is true, it is difficult for us to imagine how strain measurements based on these baseline lengths could be used as input for a prediction method that is based on shear strain, especially if shear deformation is concentrated in a shear band. However, Saito (1965) reported reasonable predictions from his method. Perhaps the measurements were arranged to provide an equivalent shear strain, although this is not given in his paper. Alternatively, perhaps the lengths of the base lines matched the width of the shear band in each case, or possibly the match between the predictions and the actual events was purely coincidental.

PREDICTION DURING TERTIARY CREEP STAGE

By modifying Eq. 1, Saito (1969) obtained:

$$\Delta l = a \log_{10} \frac{t_r - t_o}{t_r - t} \quad (2)$$

where Δl = relative displacement, a = a constant, t_r = time of rupture, t_o = initial time, and t = time of observations. A linear relationship exists between Δl and $\log_{10} t_r\text{-}t$. However, since a is unknown, a trial and error method is used to identify t_r. The procedure is as follows: 1) Assume several values for t_r and for each value, plot Δl vs. $t_r\text{-}t$ on semi-logarithmic paper (Fig. 1). 2) Select the value of t_r that yields the straightest line during the tertiary creep stage. Saito indicated that some lines will curve concave upwards and some downwards. The straightest line is in between. Obviously, judgment is required to select the straightest line. A method will be proposed herein to quantify the process for selecting the straightest line.

Saito also developed an alternate graphical method that provided a prediction of failure time by examining three points on the time vs. relative displacement relationship. However, we found that the trial and error method was expedient because of the availability of integrated spreadsheet and graphing programs.

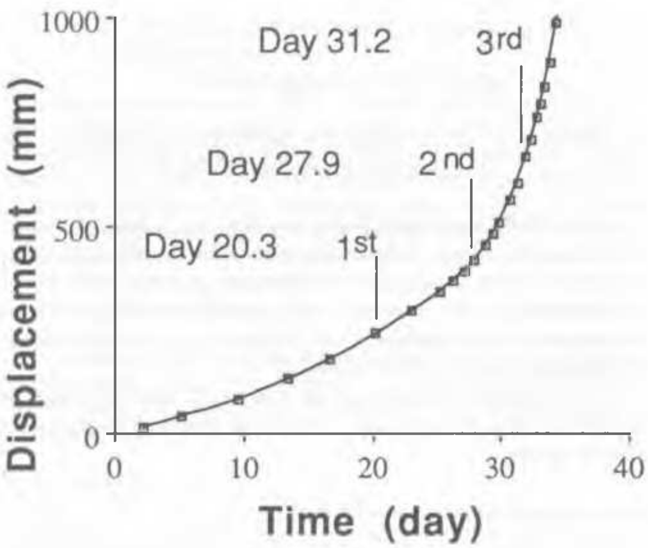

Figure 1. Displacement vs. Time History of the Vajont Slide.

Application of the Tertiary Creep Method

A literature search was conducted to find published case histories which could be used to check Saito's tertiary prediction method. When slope movements are observed, remedial action is usually taken to prevent failure. Although it is difficult to find case histories that include failures, 20 were found. Of these, eight were not considered because they were sudden failures or slip stick failures that could not be predicted using Saito's methods. The remaining 12 case histories are listed in Table 1. No. 12's graphs were too small to analyze, and Nos. 10 and 11 had been previously analyzed by Saito. He found that the tertiary method was satisfactory for these. History 8 was interrupted by remedial efforts. Our analysis of the six remaining histories is presented in this paper. (Although Saito authored Histories 4, 5, 7, and 9, he used the previously mentioned alternate graphical analysis). The first six

Table 1. Results of Case History Search

Case History	Material	Reference
1. Vajont Slide	Stratified Dolomite	Nonveiller (1987)
2. Ruahihi Slide	Schist?	Salt (1985, 1988)
3. East Abbotsford Slide	Schist?	Salt (1985, 1988)
4. Takabayama Slide	Mudstone/Sandstone layers	Saito (1973)
5. Dosan Slope Failure	Crystalline Schist	Saito (1965, 1969)
6. Kensal Green Wall Failure	London clay	Skempton (1964)
7. Ooigawa Collapse	(not stated)	Saito (1965, 1969)
8. Soya Slide	(not stated)	Saito (1965, 1969)
9. Asamushi Slide	Tuff	Saito (1969)
10. Hiketa Slide	Tuffaceous Sandstone	Saito (1980)
11. Agoyama Slide	Sandstone	Saito (1980)
12. Induced Failure	Clay	Mitchell and Williams (1981)

case histories provide a variety of materials, and a range of elapsed times between the start of movements and the time of failure. They are analyzed here.

Similar questions regarding the appropriateness of field measurements for secondary creep predictions also apply to tertiary creep predictions. The tertiary method assumes that changes in the rate of strain may be used to predict the time of failure (i.e., the time that the rate of strain reaches infinity). Suppose that the selected baseline length for strain measurements (l_o) is not equal to the thickness of the shear band. Will that compromise the accuracy of the predictions? The answer is no, if the measurement for Δl is proportional to shear strain. For this paper, we have assumed that the relative displacements in the six case histories were proportional to the shear strain.

For the prediction to be useful, the time of failure must be predicted before the time vs. displacement history is complete. It is expected that the quality of the prediction would improve as the time of failure is approached. To check this expectation, three predictions are provided for each case history. A linear regression analysis is obtained for each plot of Δl vs. $\log_{10} t_r\text{-}t$, and the plot with the highest correlation coefficient is selected. For each case history, the end of the record or the case history author's opinion is designated as the time of failure.

The beginning of the tertiary creep period is not well defined. However, the method is not very sensitive to differences regarding this item. If secondary creep data is also included in the analysis, all of the log $t_r\text{-}t$ vs. Δl lines will be concave downwards while they are in the secondary creep period. Thus, the analyst can easily adjust the start of the tertiary creep after visually reviewing the graphs.

To illustrate our procedure, application of the method to predict the time of failure of the Vajont Landslide will be given. The time vs. displacement relationship for the Vajont Slide is shown in Fig. 1. It was scaled from a plot provided by Nonveiller (1987). Predictions were made starting at Day 20.3, 27.9 and 31.2. Failure occurred on Day 35. Figure 2 gives the plots of Δl vs. $t_r\text{-}t$. Consider these two questions: 1) How much information is available at the time of each prediction? 2) How does the quality of the prediction change with time? The amount of information that is available for each prediction is marked on Figures 1 and 2. Prior to Day 20.3, there is not a curve on Figure 2 that is clearly concave upwards. By Day 31.2, the topmost

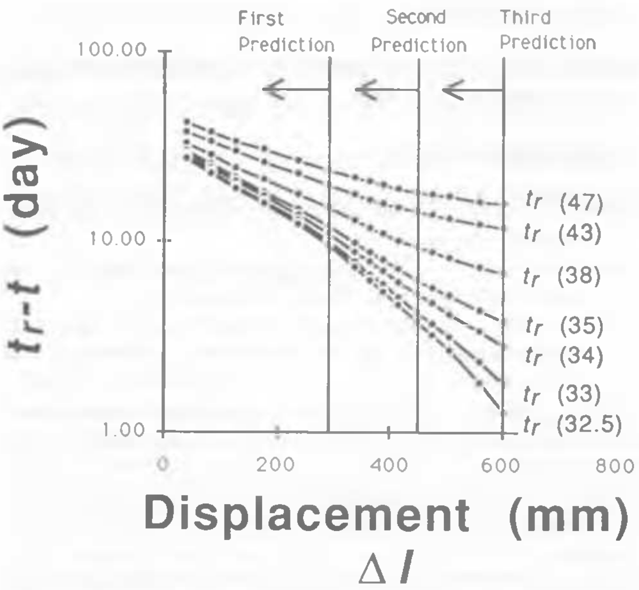

Figure 2. Prediction for the Vajont Slide

curve (the one that corresponds to t_r = Day 47) is concave upwards. This indicates that the failure would occur before Day 47. A plot of the correlation coefficient vs. the assumed failure time for each of the prediction trials is shown in Fig. 3. Although the highest value for the correlation coefficients may be selected by consulting the spreadsheet that was used to generate the plots, little difference is shown on the graph. If the several assumed failure times have similar correlation coefficients, one failure time is not clearly preferred over another. In that case, a prudent analyst should consider choosing an earlier date for the failure prediction, especially if life safety issues are involved.

The results of our study of the six case histories demonstrate the usefulness of Saito's method for predicting the time of creep rupture failures (Table 2). Sixteen out of eighteen predictions were on or before the failure date. The last prediction was closer to the failure time than the first prediction for four out of six case of the histories. On one case (Takabayama Slide) the third prediction was for Day 35, or substantially later than the failure date of Day 22; however, the quality of the previous predictions are better. For the third prediction the correlation coefficient for Day 36 is only slightly higher than that for Day 26. (Fig. 4). Thus Day 26 should also receive consideration as a possible failure date. There is a deviation in the time vs. relative displacement relationship in the area of Day 20 that causes the late prediction (Figs. 5 and 6). Thus expert review of the results and a reliance on more than one prediction are required.

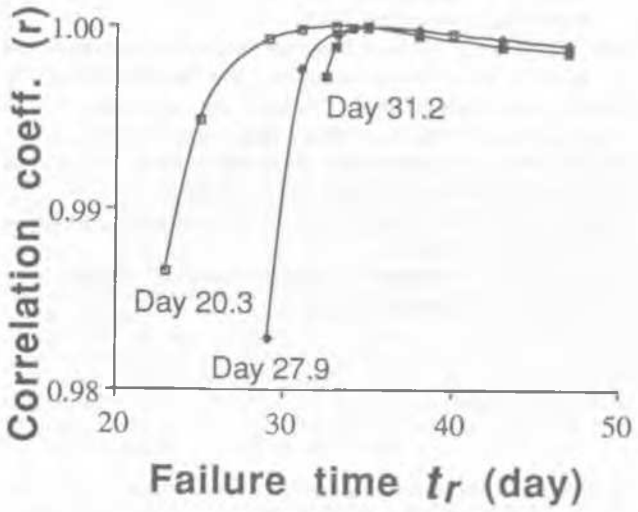

Figure 3. Comparison of Predictions for the Vajont Slide.

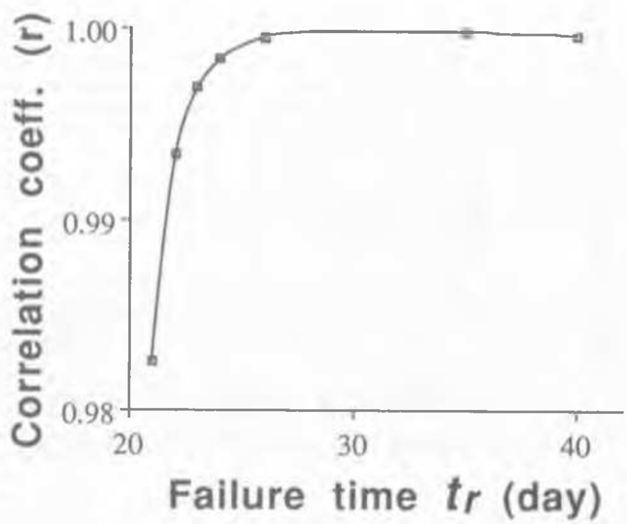

Figure 4. Regression Analysis, Day 20, Takabayama Slide.

Table 2. Results of Case History Studies

Trial for Prediction

Failure	Unit of Time	First Prediction*	Second Prediction*	Third Prediction*	Actual Failure Time
Vajont Slide	day	33 (31.2)	35 (28.0)	35 (20.3)	day 35
Ruahihi Slide	day	17 (13.8)	18.5 (16.4)	21 (18.1)	day 20
East Abbotsford Slide	day	50 (36.0)	48 (41.9)	49 (45.8)	day 50
Takabayama Slide	day	17 (14.0)	20 (17.0)	35 (20.0)	day 22
Dosan Slope Failure	hour	70 (38)	50 (42)	60 (54)	hour 62
Kensal Green Wall Failure	year	11.5 (10.3)	11.0 (12)	12 (11.4)	year 12

* Note: The first number of each entry is the predicted time of failure. The second number is the time that it was assumed that the analysis was conducted.

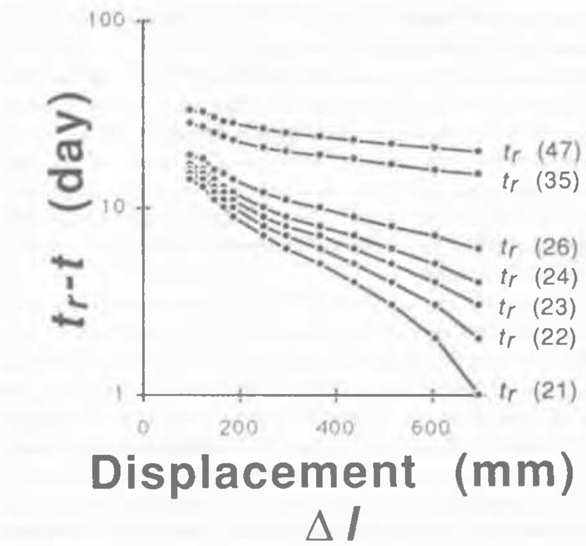

Figure 5. Prediction for the Takabayama Slide.

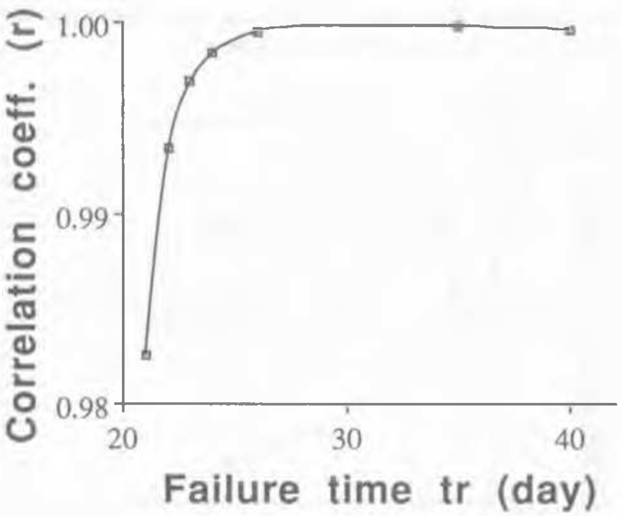

Figure 6. Displacement vs. Time History of the Takabayama Slide.

CONCLUSIONS

Empirical evidence suggests that Saito's tertiary creep method can, under the right circumstances, produce satisfactory predictions of when creep rupture failure will occur. The predicted time of failure may be selected from the series of plots by calculating the correlation coefficient for a linear regression analysis of Δl vs. $\log_{10} t_r - t$ for each assumed failure time and selecting the plot with the highest correlation coefficient. The method should be applied with considerable caution. Several predictions should be made and trends should be observed before a predicted time of failure is selected. Differences between the correlation coefficients for different predictions should be examined and consideration should be given to selecting an earlier date if the difference is small. It should also be noted that Saito's method is not appropriate for sudden and slip stick failures.

For predictions based on the secondary creep stage only, it is necessary to obtain the shear strain rate that is required by Saito's secondary method. If the thickness of the shear band is known, in many cases the shear strain rate may be calculated if the surface displacement rate is known.

ACKNOWLEDGMENT

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