PREDICTION OF TIME AND VOLUME OF ROCK FAILURE BY SLOPE METHOD

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Abstract: *The slope method by authors to estimate failure time of rock is described. The method was compared to the conventional inverse velocity method and it was found that the slope method was slightly better than the inverse velocity method. The method to predict volume of rock failure is also presented. The above methods are very useful since the both timing and volume of rock failure can be predicted as long as either displacement or strain is observed and analyzed in real time.*

Key words: *Prediction, Failure time, Failure volume, Displacement rate*

1. INTRODUCTION

Failure time of rock is often said to be unpredictable. Failure time however can be predicted using the slope method (SLO), which was developed by the authors [1], as well as the conventional inverse velocity method (INV) [2] as long as either strain or displacement is measured.

In this paper, the slope method is described first with a clear definition of the critical point at which prediction begins. Asamushi landslide in Japan and a rock slope failure at a Japanese limestone mine are analyzed again with the newly defined critical point and an improved smoothing. The results are represented by a slightly modified method and are compared to the results using the conventional inverse velocity method. Finally, methods to predict the failure volume are proposed.

2. THE SLOPE METHOD

Fukui & Okubo proposed the following equation for strain of rocks under tertiary creep [3].

$$\varepsilon = -B \log(t_F - t) + C \tag{1}$$

where ε is strain, t_F is failure time, t is elapsed time and, B and C are constants. Differentiating the both sides with respect to t, we get

$$t \frac{d\varepsilon}{dt} = t_F \frac{d\varepsilon}{dt} - B \tag{2}$$

where $d\varepsilon/dt$ is strain rate. Eq. (2) means that failure time can be evaluated as the slope of the regression line taking strain rate on x-axis and, the product of strain rate and elapsed time on y-axis (Fig. 1). The reduced major axis is used instead of a usual regression line since not only y data but also x data contain errors.

Strain rate is calculated by the following equations.

$$\left(\frac{d\varepsilon}{dt}\right)_{t=T} = \frac{\varepsilon_{i+n} - \varepsilon_i}{t_{i+n} - t_i} \tag{3}$$

$$T = \frac{t_{i+n} + t_i}{2} \tag{4}$$

Note that the strain rate is for $t = T$ but time of prediction is $t = t_{i+n}$.

The critical point is defined as follows.
(1) Find the earliest point (CP1) whose strain rate is bigger than any point before CP1 and less than any point after CP1.
(2) A point just before CP1 is the critical point (CP).

Predictions are made using the data from the critical point to the time of prediction. Displacement can be used instead of strain.
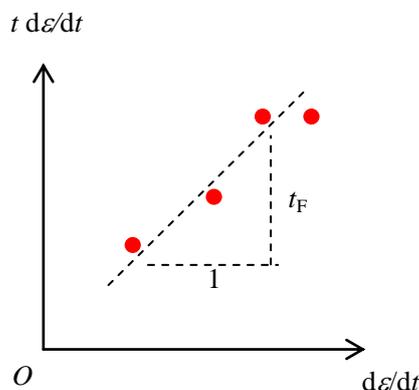

Fig. 1. Evaluation of failure time using the slope method.

3. THE INVERSE VELOCITY METHOD

Eq. (2) can be deformed as follows.

$$t = t_F - B\frac{\mathrm{d}t}{\mathrm{d}\varepsilon} \qquad (5)$$

where $\mathrm{d}t/\mathrm{d}\varepsilon$ is called inverse velocity and Eq. (5) means that failure time can be evaluated as the x-intercept of the regression line taking the elapsed time on x-axis and inverse velocity on y-axis.
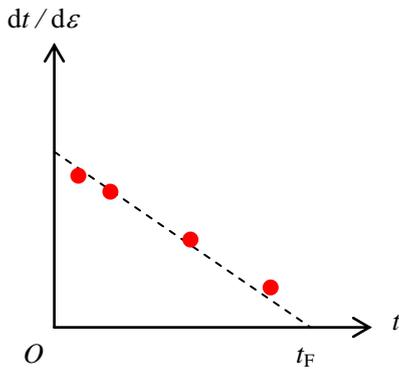

Fig. 2. Evaluation of failure time using the inverse velocity method.

4. CASE STUDY ON ASAMUSHI LANDSLIDE

The 100,000 m^3 landslide near surface joints in liparitic tuff occurred at Asamushi, Japan in 1966, burying 80 m length of track and interrupting railroad traffic for 26 days [4].

Measured displacement is shown in Fig. 3 and displacement rate was calculated for $n = 1$, 5 and 10 (Fig. 4). The displacement rate for $n = 1$ is scattered and gave poor prediction. The best predictions were given by $n = 10$. The plot for the slope method (SLO plot) and the inverse velocity method (INV plot) are shown in Figs. 5 and 6.

The results are shown in Fig, 7. In this figure, the predicted *life expectancy* is calculated by subtracting time of prediction from the predicted failure time. The broken line shows the correct *life expectancy*. Predictions exactly on this line are correct, predictions above or below this line mean dangerous or safe predictions, and negative *life expectancy* is meaningless. The predictions using SLO and INV show safe but large error. However, SLO prediction is slightly better since its error is smaller than that of INV and it approaches the correct *life expectancy* at the last hours while INV prediction goes into meaningless region.
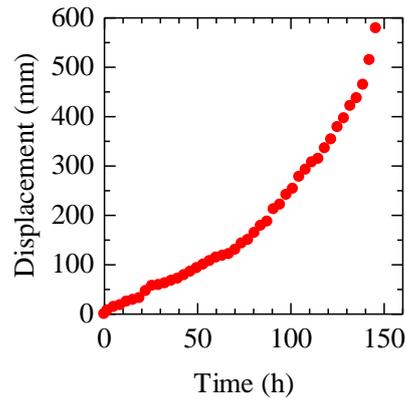

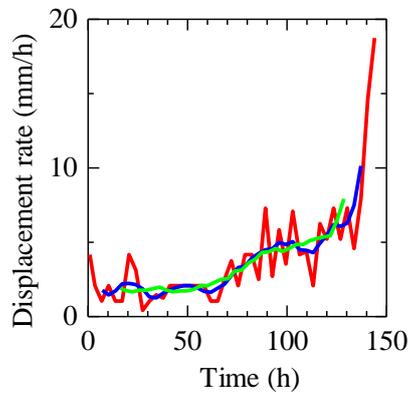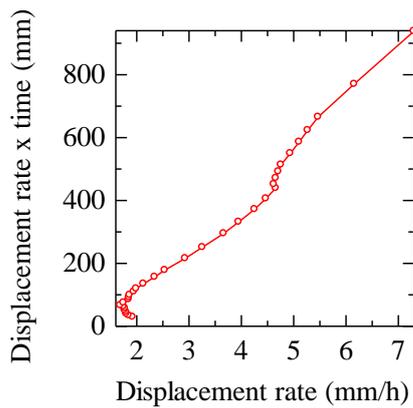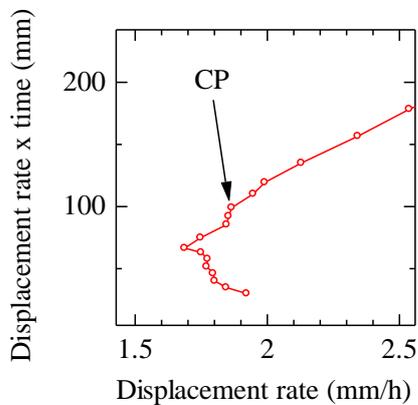**Fig. 3. Displacement vs. time for Asamushi landslide.**

Fig. 4. Displacement rate for Asamushi landslide. Red: $n = 1$, blue: $n = 5$ and green: $n = 10$.

(a) Whole plot

(b) Magnified plot
Fig. 5. SLO plot for Asamushi landslide ($n = 10$).
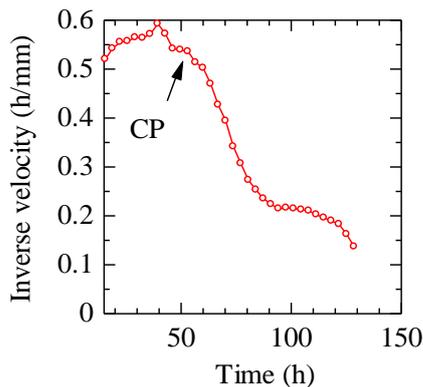

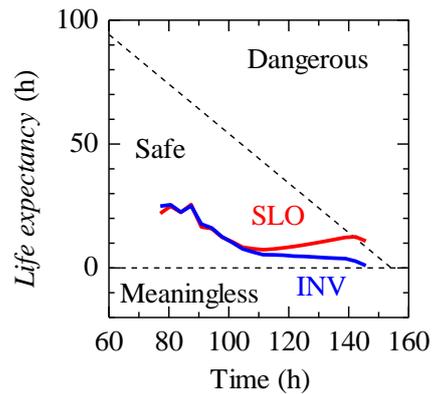**Fig. 6. INV plot for Asamushi lanslide ($n = 10$).**

Fig. 7. Predictions by SLO and INV ($n = 10$) for Asamushi landslide.

5. CASE STUDY ON ROCK SLOPE FAILURE [1]

A 500 m^3 rock mass failure occurred in a Japanese limestone mine in 2007. Displacement shows a significant increase from approx. a day before failure (Fig. 8). The displacement rate for $n = 1$ shows large scatter (Fig. 9a) and that for $n = 10$ (Fig. 9b) is used for the analysis. The displacement rate increased, decreased and increased again to the failure (Fig. 9b).

The predictions are in the meaningless region (Fig. 10). This is because the decrease in the displacement. However, using only the data after the decrease (Fig. 11), the life expectancy was able to be predicted (Fig. 12). The predictions contained large dangerous error. However, the prediction by SLO is slightly better than that by INV since the error in SLO prediction is smaller than that in INV prediction although SLO prediction goes into the meaningless region at the last minutes.
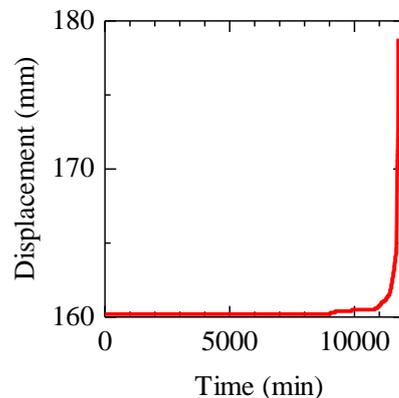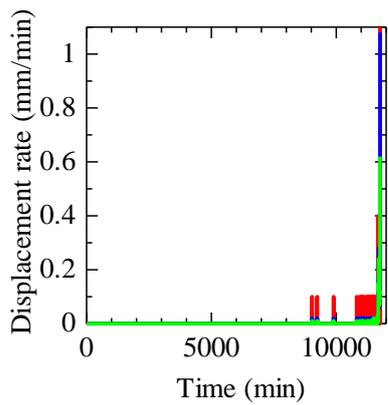

Fig. 8. Displacement vs. time for rock slope failure.

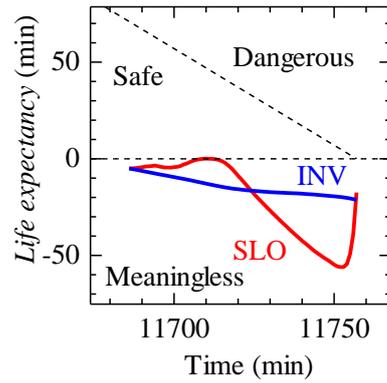(a) Whole plot. Red: *n* = 1, blue: *n* = 5 and green: *n* = 10.
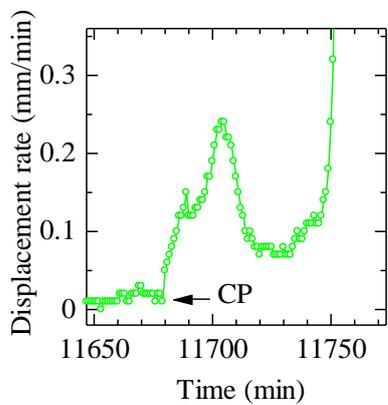
(b) Moderately magnified plot for *n* = 10.
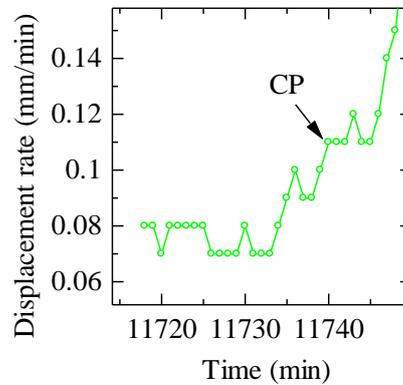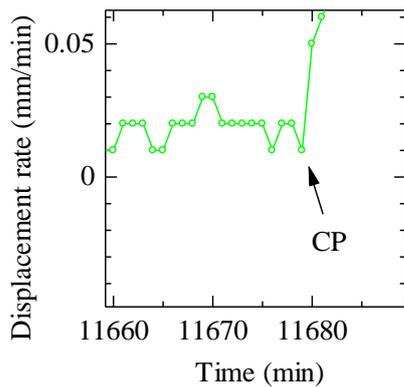
(c) Fully magnified plot for *n* = 10.
Fig. 9. Displacement rate for rock slope failure.

Fig. 10. Predictions by SLO and INV (*n* = 10) for rock slope failure.
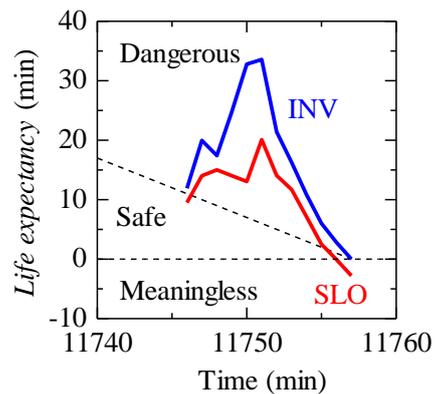

Fig. 11. Displacement rate for rock slope failure.

Fig. 12. Predictions by SLO and INV (*n* = 10) for rock slope failure.

6. PREDICTION OF THE FAILURE VOLUME

Prediction of failure volume is possible using the following equations (Figs. 13 and 14) which summarize the data in Mufundirwa et al. [1] with correlation coefficients of 0.98 and 0.95, respectively.

$$V = 3.02 \times 10^{-11} \delta t^{2.80} \qquad (6)$$

$$V = 3.09 \times 10^{5} \dot{u}_{C}^{1.902} \qquad (7)$$

where V (m^3) is the failure volume, δt (s) is the time from the critical point to failure and $\dot{u}_{C}$ (mm/min) is the displacement rate at the critical point. Data by other researchers [5-8] are located around the regression line (Fig. 14) implying the validity of Eq. (7).

Plotting the critical displacement and the time from the critical point to failure, we get the following equation.

$$\delta t = 3.71 \times 10^{5} \dot{u}_{C}^{0.623} \qquad (8)$$

The time from the critical point to failure can be roughly estimated only from the critical displacement rate. Eq. (8) is very convenient to obtain the first rough prediction of failure time.

Those data in the previous researches should be examined again in future since the critical point was not strictly defined although there will not be big differences in the critical displacement rates.

7. CONCLUDING REMARKS

The slope method to estimate failure time of rock was described. The method was compared to the conventional inverse velocity method and the slope method was slightly better than the inverse velocity method.

The method to predict the volume of rock failure was also presented. The timing and volume of rock failure can be predicted by the above methods as long as displacement or strain is observed and analyzed in real time.

However, necessary reinforcements are carried out for dangerous slopes and it is rare that a slope collapse occurs at a rock slope under observation. The slope method can be used even for this kind of rock slopes to confirm the effectiveness of the reinforcements and that an imminent failure has gone.

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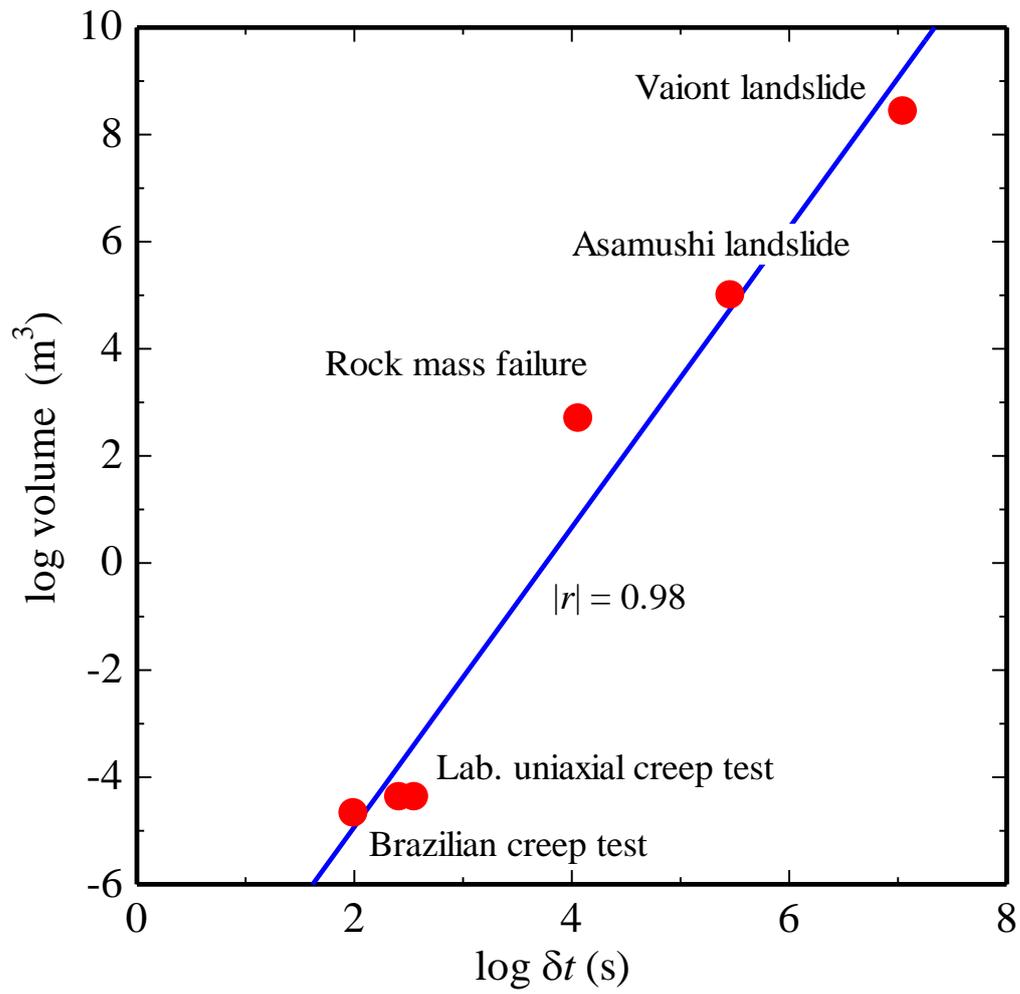
Fig. 13. Relationship between the volume of rock failure and time from critical point to failure.
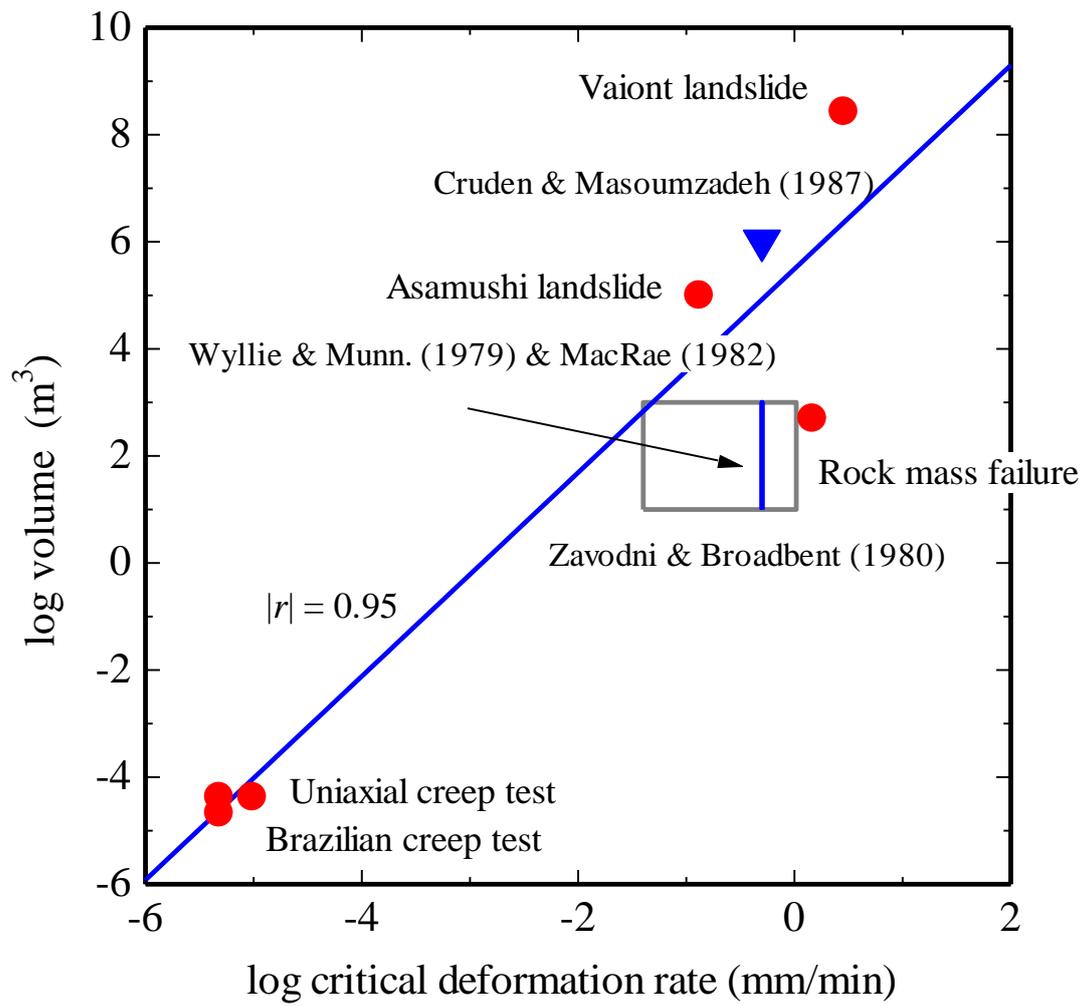
Fig. 14. Relationship between the volume of rock failure and deformation rate at the critical point.
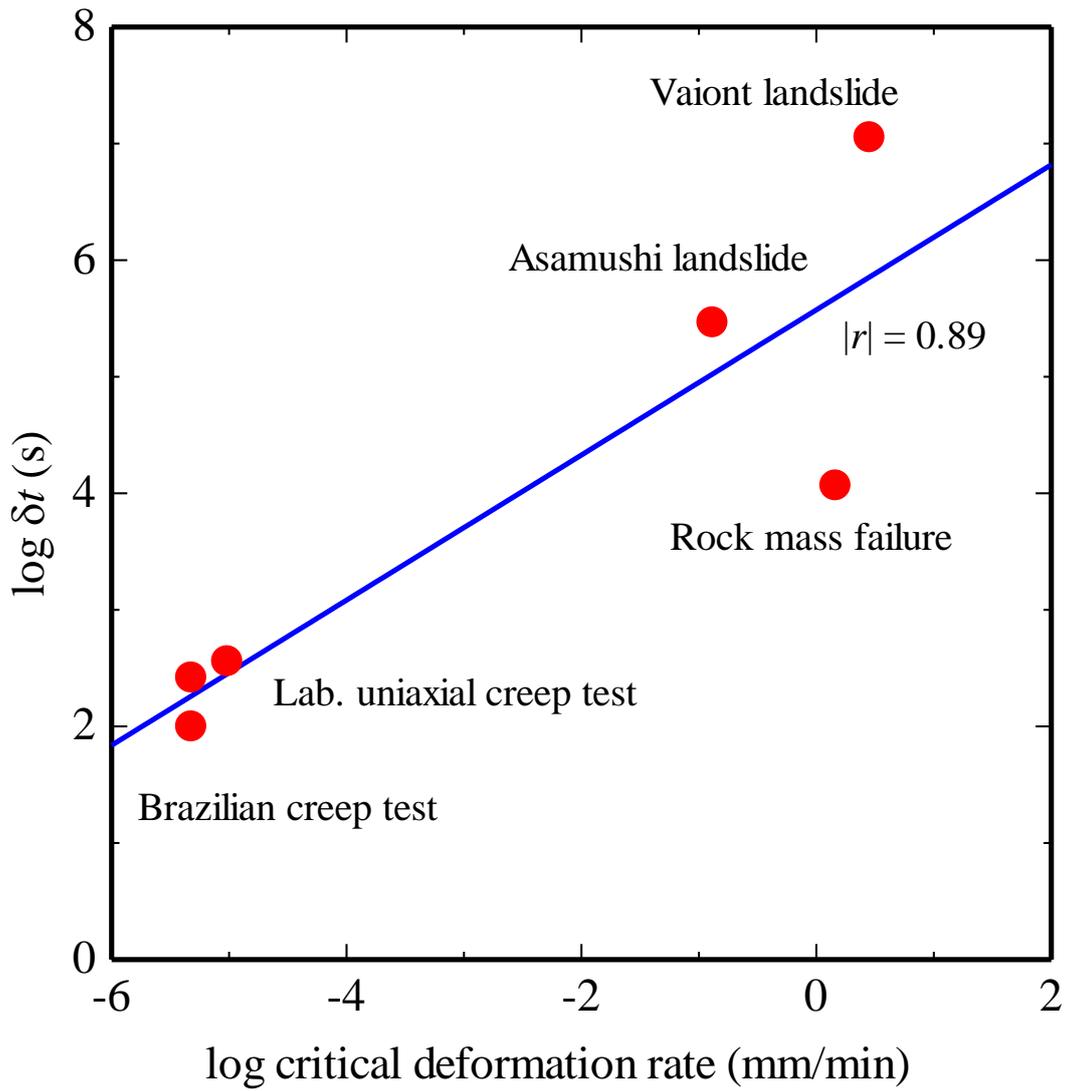
Fig. 15. Relationship between the critical deformation rate and time from critical point to failure.