New methods for Prediction of Geomechanical Failure-time

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1. INTRODUCTION

The issue of predictability of landslides and rock slope failures, which are major geo-hazards, is of great concern in the geotechnical field. In the geotechnical field, structures are monitored to ascertain their stability, but the question, "When is failure going to occur?" is still an issue. Monitoring the behaviour of landslides, and rock slopes is an important aspect to mitigate failure or accidents in the geotechnical field.

The authors are proposing failure-time prediction methods based on Eq. (1) for tertiary creep of rock by Okubo and Fukui[1]. Inverse-velocity (INV) method was proposed to predict failure-time of landslides and rock slope failures[2]. A major merit of the method is that, it utilizes rates of displacement ($\mathrm{d}u/\mathrm{d}t$) or strain ($\mathrm{d}\varepsilon/\mathrm{d}t$) to predict actual failure-time (T_f), so the value of total displacement or strain before failure is not crucial. The authors developed two methods, which are based on non-linear approximation (NLA) of $\mathrm{d}u/\mathrm{d}t$-t curve or $\mathrm{d}\varepsilon/\mathrm{d}t$-$t$ curve, and on the slope of $t(\mathrm{d}u/\mathrm{d}t)$-$\mathrm{d}u/\mathrm{d}t$ curve or $t(\mathrm{d}\varepsilon/\mathrm{d}t)$-$\mathrm{d}\varepsilon/\mathrm{d}t$ curve (SLO), and evaluated their performance. Failure-time of major case histories namely, Asamushi, Vaiont landslides and predictions using axial strain ε_a and circumferential strain ε_c on Shikotsu welded tuff (SWT) and rock slope failure were predicted.

2. FAILURE-TIME PREDICTION METHODS

The authors are proposing failure-time prediction methods, to determine failure-time of landslides and rock slopes based on tertiary creep behaviour prior to failure. The methods are based on Eq. (1) for tertiary creep of rock, proposed by Okubo and Fukui[1].

$$\varepsilon = -B\log(T_\mathrm{f} - t) + C\,, \tag{1}$$

where ε: strain, t: time, T_f: failure time, $T_\mathrm{f} - t$: life expectancy, B and C: constants.
Using displacement u instead of strain ε and differentiating both sides

$$\frac{\mathrm{d}u}{\mathrm{d}t} = \frac{B}{T_\mathrm{f} - t}\,, \tag{2}$$

where $\frac{\mathrm{d}u}{\mathrm{d}t}$ is the displacement rate. T_f and B are evaluated by approximating $\mathrm{d}u/\mathrm{d}t$-t curve by using a non-linear least squares method (Fig. 2a).

The following equations can be derived by re-arranging Eq. (2).

$$t\frac{\mathrm{d}u}{\mathrm{d}t} = T_\mathrm{f}\frac{\mathrm{d}u}{\mathrm{d}t} - B\,, \tag{3}$$

$$\frac{\mathrm{d}t}{\mathrm{d}u} = -\frac{t - T_\mathrm{f}}{B}\,. \tag{4}$$

T_f is evaluated as the slope of $t(\mathrm{d}u/\mathrm{d}t)$-$\mathrm{d}u/\mathrm{d}t$ curve (Fig. 2b) for Eq. (3), the SLO method, and x-intercept of $\mathrm{d}t/\mathrm{d}u$-t curve (Fig. 2c) for Eq. (4). The latter is called the INV method[2].

Failure-time can be predicted from Eqs. (2), (3) and (4). Fukada et al[3]. showed that Eqs. (2) and (4) tend to give delayed or unsafe predicted failure-time T_fp and Eq. (3) gives earlier/safe predicted failure-time (Fig. 1).

The data filtering method consists of using the *n*th observation to calculate the rate.

$$\left(\frac{\mathrm{d}u}{\mathrm{d}t}\right)_i = \frac{u_i - u_{i-n}}{t_i - t_{i-n}} \quad (i=n+1, n+2, \ldots, m), \tag{5}$$

where $\left(\frac{\mathrm{d}u}{\mathrm{d}t}\right)_i$ are the computed displacement rate points, t_m and u_m are the last time and displacement in the pre-failure range[4].

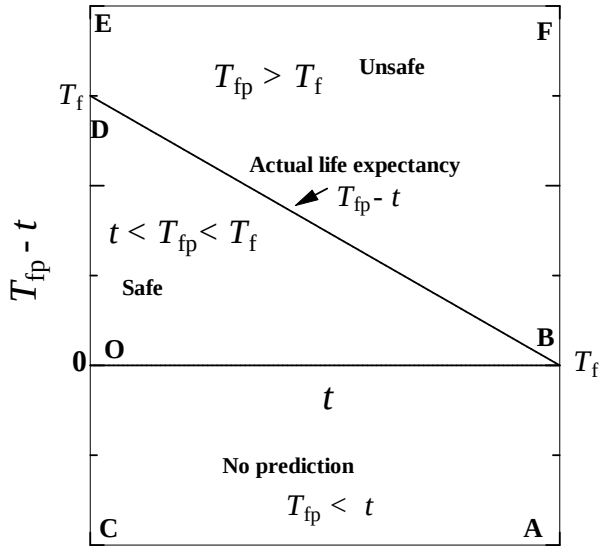


Fig. 1. Concept of "safe" and "unsafe" predictions. $T_{fp} - t$ is the predicted life expectancy. $t = t_m$ is assumed.

Concept of "safe" and "unsafe" predictions is explained in Fig. 1. T_{fp} is predicted failure-time. The line DB shows $T_{fp} = T_f$. The region OBD is the safe region ($t_m < T_{fp} < T_f$), this allows for evacuation or emergency preparedness before any "failure" occurs. Line OB, is the critical prediction line ($T_{fp} = t$), predicted time is just the same as actual time of last data used to predict T_f. The region BDEF, is the unsafe zone ($T_{fp} > T_f$). Lastly, region OCAB represents no predictions ($T_{fp} < t_m$).

3. ROCK MASS FAILURE

The rock mass failure of volume 500 m^3 occurred on 24 June 2007 at 23:33 in an open-pit limestone mine in Japan (Fig. 4). Geologically, it is comprised of clayey limestone bands of varying thickness[5].

Prediction was carried out just after displacement showed an increase, and a sufficient number of data could be used. For the initial prediction, the predicted life expectancy was very short (Fig. 3a). It is at this stage that people can be alerted of an imminent failure and hence conduct emergency procedures. This means that we could have predicted the rock mass failure 193 minutes before the failure by using the methods.

4. LANDSLIDE AT ASAMUSHI

The 100,000 m^3 landslide occurred on 27 July 1966 at 22:12 on Tohoku line interrupting railroad traffic for 26 days and burying 80 m length of track[6].

The first predictions for life expectancy using the INV method and NLA are very large (Fig. 3b). However, the predicted life expectancy using SLO was 30 hrs whilst actual life expectancy was 80 hrs. This means that the rock slope failure could be predicted using SLO, 80 hrs before the failure with 50 hrs of safe error.

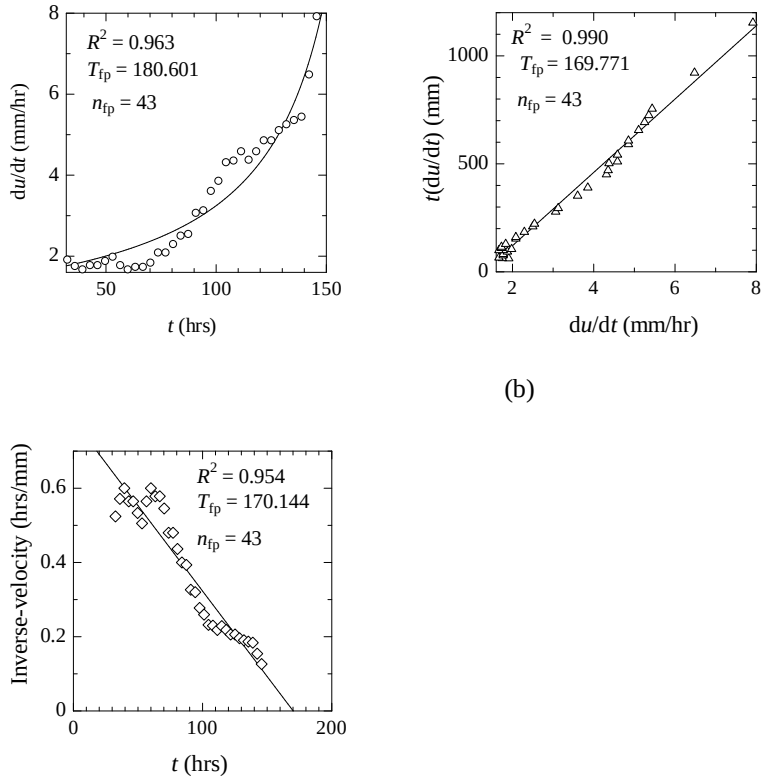


Fig. 2. Typical plots used for predictions of failure-time for Asamushi landslide using (a) NLA, (b) SLO and (c) INV method for all the data (n_{fp} = 43). n_{fp} is the number of data.

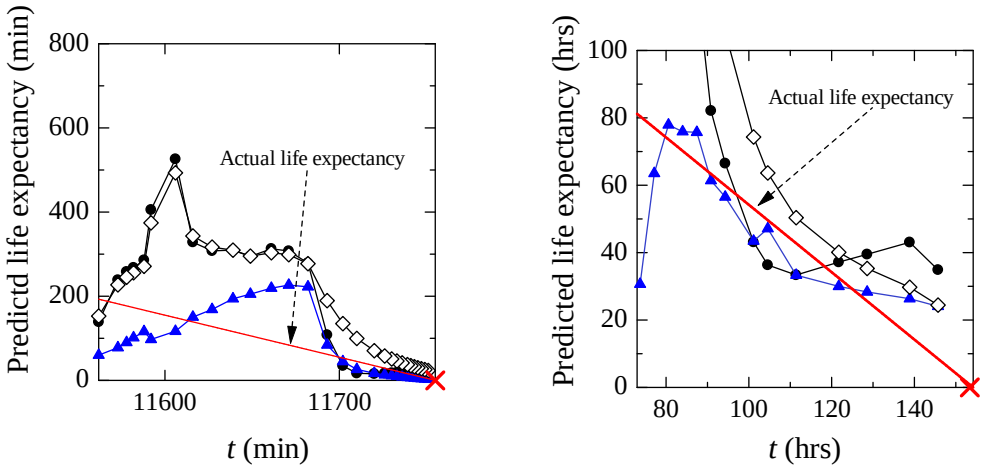
5. VAIONT RESERVOIR LANDSLIDE DISASTER

The catastrophic failure of approximately 270 million m^3 occurred at 23:39 on 9 October 1963 in North-eastern Italy, in the Vaiont canyon located at 680 m above sea level (Fig. 5). The flood caused by the failure killed more than 2000 people. There was evidence of creep activity on the southern side of the canyon and it increased as the level of reservoir rose[4].

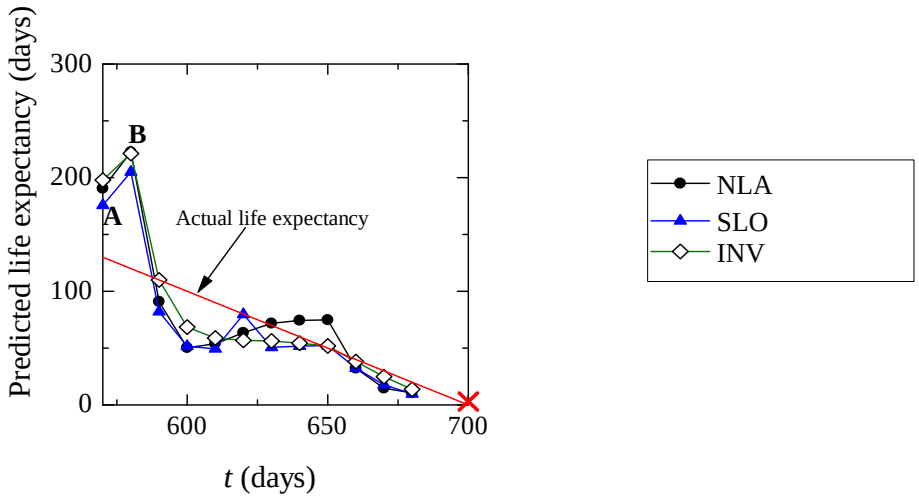
All three methods have predictions with a similar trend but with slight variations (Fig. 3c). Small data ranges were used to predict T_{fp} at points A and B and gave life expectancies that were in the unsafe error zone but gradually shifted to the safe error zone as data range n_{fp} increased whilst T_f was approached.

Failure was predicted 130 days before actual failure with point A having 45 to 68 days of unsafe error. Then, for example predicted life expectancy becomes less than 10 days on 20 days before failure. Government and responsible authorities should have adequate time to alert people to evacuate to safe

places before the landslide.



(a) (b)



(c)

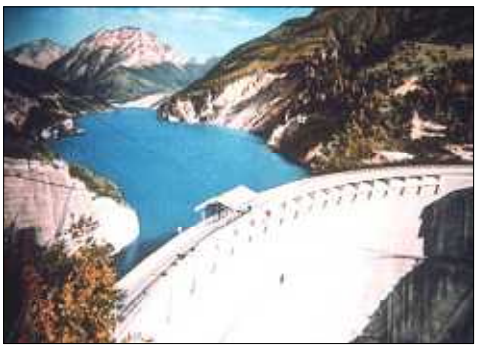
Fig. 3. Predicted life expectancy against time *t* (a) Rock mass failure (b) Asamushi landslide (c) Vaiont landslide reservoir. × depicts “failure”.

(a)

(b)

(c)

Fig. 4. Rock mass failure (a) side view (b) front view (c) plan view. □ denotes the region of rock mass failure. Arrow indicates the downward direction of movement of rock mass failure.



(a)

(b)

Fig. 5. Vaiont reservoir landslide disaster (a) before landslide failure, (b) The town of Longarone, located downstream of the Vaiont dam, before the Mount Toc failure in October 1963 and (Upper right), The remains of the town of Longarone after the flood that caused overtopping of the Vaiont dam wall as a result of Mount Toc failure. More than 2000 persons were killed in this flood (pictures[7]).

6. CREEP TEST IN SHIKOTSU WELDED TUFF

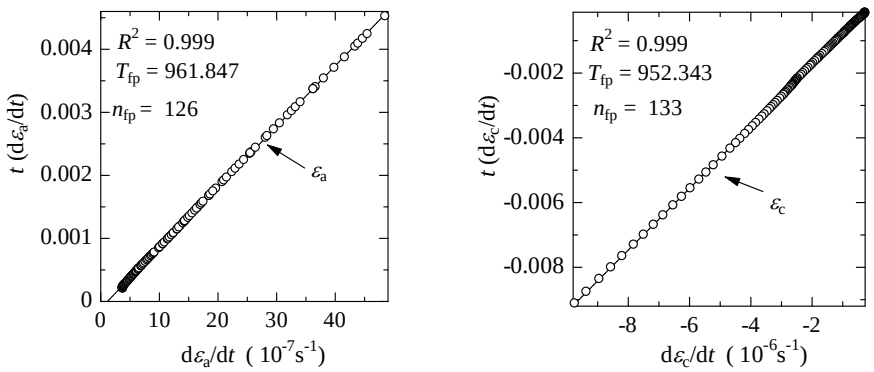
Laboratory creep test was carried out on Shikotsu welded tuff (SWT). Prediction of failure-time of rock specimen based on SLO and INV methods were done. Comparison of failure-time predictions using axial strain (ε_a) and circumferential strain (ε_c) were carried out.

6.1 Experimental program

The tests were performed on cylindrical specimens for SWT of 60 mm length and 30 mm diameter, which were dried at 80°C for 24 hrs. The cylindrical specimens were kept in the laboratory for several days at 21.5°C and tested. Loading was carried out using an Instron 5586 loading frame (300 kN) through spherical seating. In order to monitor strains, two displacement sensors, a clip-type and chain-type sensors were attached on the surface of the specimens to measure ε_a and ε_c, respectively. The uniaxial compressive strength (σ_c = 23.3 MPa) of the SWT specimen was pre-measured so that the creep stress σ_1 can be reasonably selected. The rock specimens were uniaxially pre-loaded under compression to creep stress (σ_1) of 18.4 MPa. The creep stress σ_1 was kept constant in the creep test.

6.2 Predictions using SLO method

Predictions for failure-time of SWT using axial strain ε_a and circumferential strain ε_c were done. Substituting u by ε_a and ε_c in Eq. (3), T_{fp} is evaluated as the slope of $t(d\varepsilon_a/dt)$-$d\varepsilon_a/dt$ curve (Fig. 6a) and slope of $t(d\varepsilon_c/dt)$-$d\varepsilon_c/dt$ curve (Fig. 6b).



(a) (b)

Fig. 6. Typical SLO plots used for predictions of failure-time of SWT using (a) axial strain ε_a data (b) circumferential strain ε_c data. n_{fp} is the number of data.

6.3 Predictions using INV method

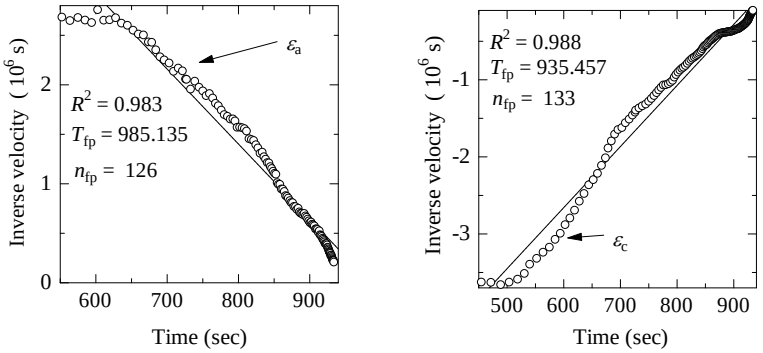
Predictions for failure-time of SWT using axial strain ε_a and circumferential strain ε_c were done. Substituting u by ε_a and ε_c in Eq. (4), T_{fp} is evaluated as the x-intercepts of $dt/d\varepsilon_a$-t curve (Fig. 7a) and slope of $dt/d\varepsilon_c$-t curve (Fig. 7b).

6.4 Discussion

Two methods, namely SLO and INV method were used to predict T_f of SWT using ε_a and ε_c data. It is deduced that,

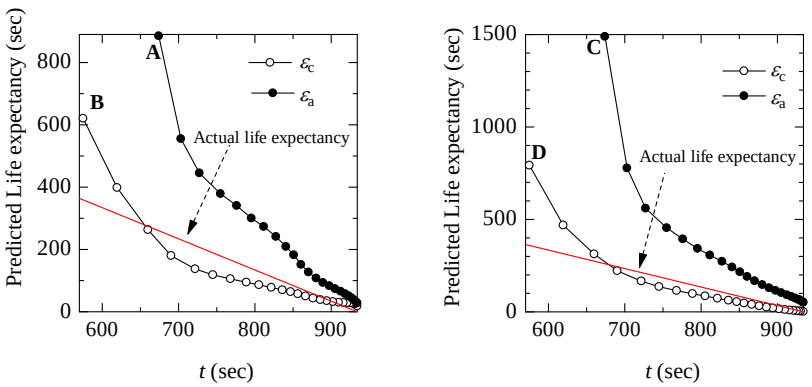
- Predictions using ε_a data gave unsafe errors in both methods namely, SLO and INV, respectively (Fig. 8a and b).
- SLO method gave better unsafe predictions with fewer errors than INV method using ε_a data.
- Predictions using ε_a data gave late initial predictions (points A and C) as compared to predictions using ε_c data (points B and D in Fig. 8a and b).

Predictions using circumferential strain ε_c data gave safer and more precise predictions than predictions using ε_a data (Fig. 8a and b).



(a) (b)

Fig. 7. Typical INV plots used for predictions of failure-time of SWT using (a) axial strain ε_a data (b) circumferential strain ε_c data.



(a) (b)

Fig. 8. Predicted life expectancy against *t* using (a) SLO (b) INV method.

7. CONCLUSION

Attempts to predict failure-time T_f of rock mass failure, Asamushi landslide, Vaiont reservoir landslide and Shikotsu welded tuff (SWT) were done. Monitored displacements or strains were used to compute T_{fp} using NLA, SLO and INV method. Predicted life expectancies from the three methods were compared focusing mainly on the safe and unsafe errors. It is conclude that,

- NLA is a time consuming and tedious method that needs initial precise value. Predictions were unsafe in most cases, despite high values of R^2.
- SLO gave early and much safer predictions in all the case studies.
- INV method gave initial unsafe predictions in most cases. This is possibly due to the initial convex nature of the INV plots.
- Circumferential strain ε_c gave earlier and safer predictions than predictions using axial strain ε_a.
- Predictions from SLO using ε_c were the best in prediction of failure-time for SWT.

The SLO method developed in this research, is a reliable method that proved consistent and was validated in all the cases. SLO seems indispensable for different time scales from seconds in SWT, minutes in Rock mass failure, hours in Asamushi landslide, and lastly, days in Vaiont landslide. SLO also proved useful under different scales of failure from small scale laboratory creep tests to real-life large failures, such as the 500 m^3 of rock mass failure, 100,000 m^3 for Asamushi landslide and the 270 million m^3 for Vaiont reservoir landslide.

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