Prediction of rock mass failure-time of geo-hazards

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ABSTRACT: Can we predict failure-time of geo-hazards? Prediction of geo-hazards, for instance, rock mass failure, landslides, etc., is still a challenge to date in the rock mechanics field. Geo-hazards still pose a major threat to life and major loss in terms of economics. The focal point of our research is to predict failure-time of geo-hazards. Firstly, the authors evaluated the validity of the Inverse-velocity (INV) method to predict failure-time of rock mass and landslides. Secondly, two methods for computing predictions were also evaluated: (1) based on non-linear approximation (NLA), and (2) on the slope (gradient) to compute T_f, termed the SLO method, which will be described in detail in the paper. The concept of "safe" and "unsafe" predictions was developed to classify predictions. With this in mind, prediction of failure case histories and rock specimens in the laboratory is presented. It was realised that SLO is better than the INV method.

1 INTRODUCTION

Geo-hazards still pose a major threat to life and major loss in terms of economics. The issue of predictability of landslides and rock slope failures, which are major geo-hazards, is of great concern. In the geotechnical field, structures are monitored to ascertain their stability, but the question, "When is geomechanical failure going to occur?" is still an issue. Various monitoring equipment and devices such as Global Positioning System (GPS), Slope stability radar (SSR), extensometers, survey stations, etc. are used but somehow "failure" still occurs unanticipated. Monitoring the behaviour of landslides and rock slopes is an important aspect to mitigate failure or accidents. Previous research has been conducted in the prediction of landslides, rock mass and rock slope failures. Saito (1969) forecasted the time of slope failure using graphical method. Fukuzono (1985) used inverse-velocity to predict failure-time for sand slopes based on laboratory test. He concluded that, a linear fit through the inverse-velocity against time data provided a reasonable estimate of failure-time, shortly before failure.

Fukui & Okubo (1997) proposed Equation 1 to express strain divergence in the terminal phase of creep failure in rocks:

$$\varepsilon = -B\log(T_f - t) + C, \qquad (1)$$

where ε: strain, t: time, T_f: failure time, $T_f - t$: life expectancy, B and C: constants. Fukada et al. (1999) used two newly developed methods as well as the inverse-velocity method to show that predictions using circumferential strain ε_c tend to give smaller errors than predictions due to axial strain ε_a for creep failure of rock specimens under uniaxial compression.

The authors are comparing failure-time prediction methods. The methods are based on Equation 1, as a function that can represent strain or displacement divergence phenomenon prior to failure. Inverse-velocity (INV) method was proposed to predict failure-time of landslides, and rock failure (Fukuzono, 1985). The authors further investigated the two methods by Fukada et al. (1999) for prediction of geomechanical failure-time. The first method is based on non-linear approximation (NLA) of (du/dt)-t curve or $(d\varepsilon/dt)$-t curve (Figure 1a), and the other method is based on the slope of $t(du/dt)$-du/dt curve or $t(d\varepsilon/dt)$-$d\varepsilon/dt$ curve (SLO) as illustrated in Figure 1b. Failure-time of case histories, which includes rock mass failure, Asamushi and Vaiont landslides are predicted. Subsequently, the reliability of these methods is evaluated. With the same principles, predictions using circumferential strain ε_c on Shikotsu welded tuff (SWT) under uniaxial compression creep tests, and predictions of failure-time for Inada granite under Brazilian creep tests are presented. The general focus of this research is to attempt to predict failure-time of geo-hazards in the terminal phase of failure. It was realised that SLO is better than the INV method.

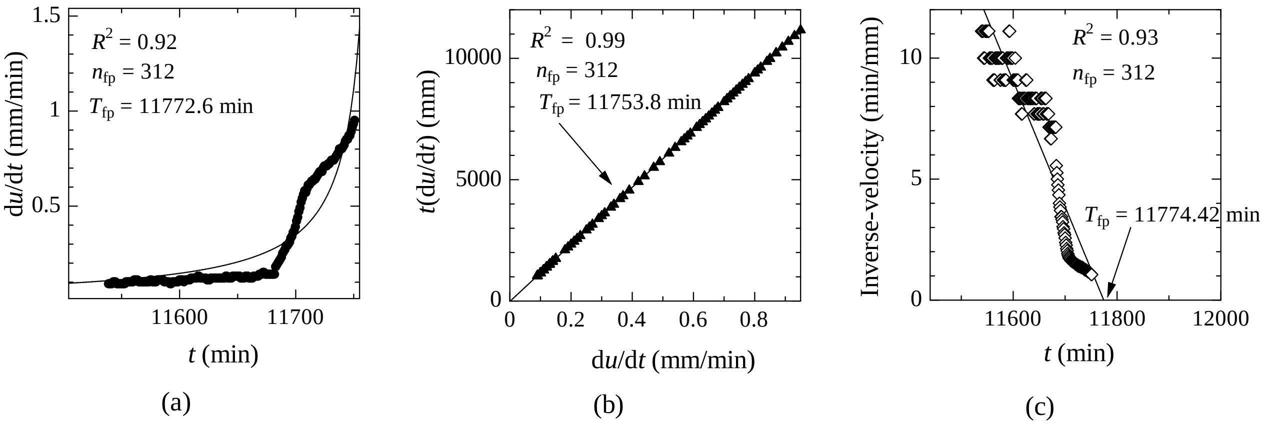


Figure 1. Typical plots used for predictions of Rock mass failure using (a) NLA, (b) SLO and (c) INV methods using all last data in the pre-failure range (n_{fp} = 312). n_{fp} is the number of data.

2 PREDICTION METHODS

Using displacement u instead of strain ε and differentiating both sides of Equation 1 with respect to time t:

$$\frac{du}{dt} = \frac{B}{T_f - t}, \tag{2}$$

where (du/dt) is the displacement rate. T_f and B are evaluated by approximating (du/dt)-t curve by using a non-linear least squares method (Figure 1a). The following equations can be derived by re-arranging Equation 2:

$$t\frac{du}{dt} = T_f\frac{du}{dt} - B, \tag{3}$$

$$\frac{dt}{du} = -\frac{t - T_f}{B}. \tag{4}$$

T_f is evaluated as the slope of t(du/dt)-du/dt curve (Figure 1b) for Equation 3, termed the SLO method, and x-intercept of (dt/du)-t curve (Figure 1c) for Equation 4. The latter is called the INV method (Fukuzono, 1985).

Failure-time T_f can be predicted from Equations 2–4). Fukada et al. (1999) including one of the authors showed that Equations 2 and 4 tend to give delayed or unsafe predicted failure-time T_{fp} and Equation 3 gives earlier/safe predicted failure-time (Figure 2).

The data filtering method consists of using the nth observation (sampling value) to calculate the rate:

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

where (du/dt)$_i$ are the computed displacement rate points, t_m and u_m are the last time and displacement in the pre-failure range, respectively. Samplingvalue, n, was selected so as to yield positive rates of displacement or strain only.

2.1 *Concept of "safe" and "unsafe" predictions*

Figure 2 shows an annotated diagram for the concept of "safe" and "unsafe" predictions. T_{fp} is the 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 failure-time is just the same as actual time of last data (real-time) used to predict T_f in the pre-failure range. The region BDEF is the unsafe region ($T_{fp} > T_f$). Lastly, region OCAB represents no predictions ($T_{fp} < t_m$).

3 PREDICTING USING FIELD DATA

3.1 *Rock mass failure in open-pit mine*

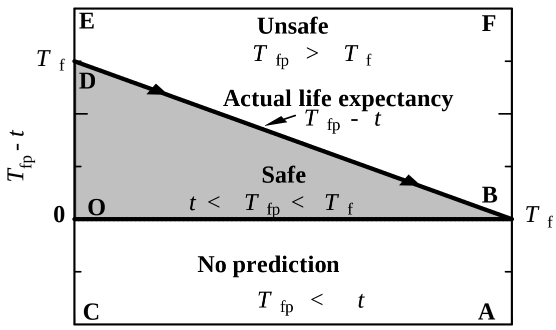
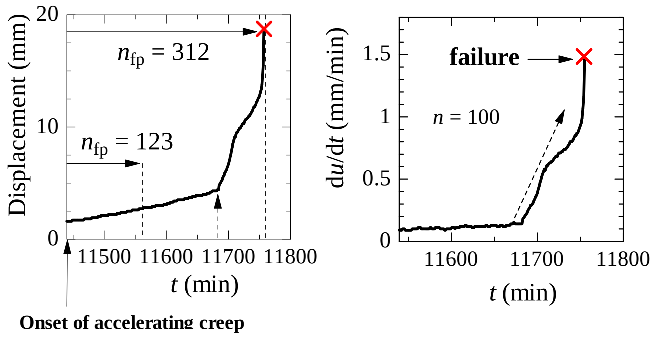


Figure 2. Concept of "safe" and "unsafe" predictions. $T_{fp} - t$ is the predicted life expectancy. $t = t_m$ is assumed.

In this case study, rock mass failure (500 m^3) occurred on a rock slope at a limestone mine in Japan. Fortunately, no injuries or damage to property were reported. Geologically, it comprised of clayey limestone bands of varying thickness. Precise recording



(a) (b)

Figure 3. (a) Displacement as a function of time t, 5.25 hours before rock mass failure at an open-pit limestone mine, Japan (b) displacement rate (velocity) as a function of t using n = 100 (100 min) in Eq. (5).

of displacement was done at 3.26 days (11,755 min) before failure at a sampling rate of 1 min. Figure. 3a shows displacement during the last stages of failure (June 2007). Prediction was carried out just after displacement showed an increase, and after a sufficient number of data could be used from an arbitrary time, t = 11,440 min (u = 1.6 mm), assumed to be the onset of accelerating creep (Figure 3a). At t = 11,682 min (u = 4.4 mm), displacement steeply increased towards failure, T_f = 11,755 min (u = 18.6 mm), (Figure 3a). Three methods were used to predict failure-time namely, NLA, SLO and INV. From an arbitrary time, t = 11,440 min (assumed onset of accelerating creep) as illustrated Figure 3a; different data ranges (n_{fp}) were used to compute failure-time predictions T_{fp} using the above-mentioned three methods. A sufficient quantity of data was used to compute predictions starting from n_{fp} = 123 to 312, prior to failure.

Using NLA, T_{fp} for the rock mass failure was evaluated by approximating (du/dt)-t curve by using a non-linear least squares method (Figure 1a). Point A (Figure 4a) denotes initial prediction (n_{fp} = 123 at

For INV, the x-intercept (T_f) depends much more on large inverse-velocities, that is, small velocities. On the other hand, in SLO, the slope (T_f) depends more on the large velocities. This is the main cause why SLO gives better prediction although SLO and INV are based on the same equation.

3.2 *Asamushi landslide*

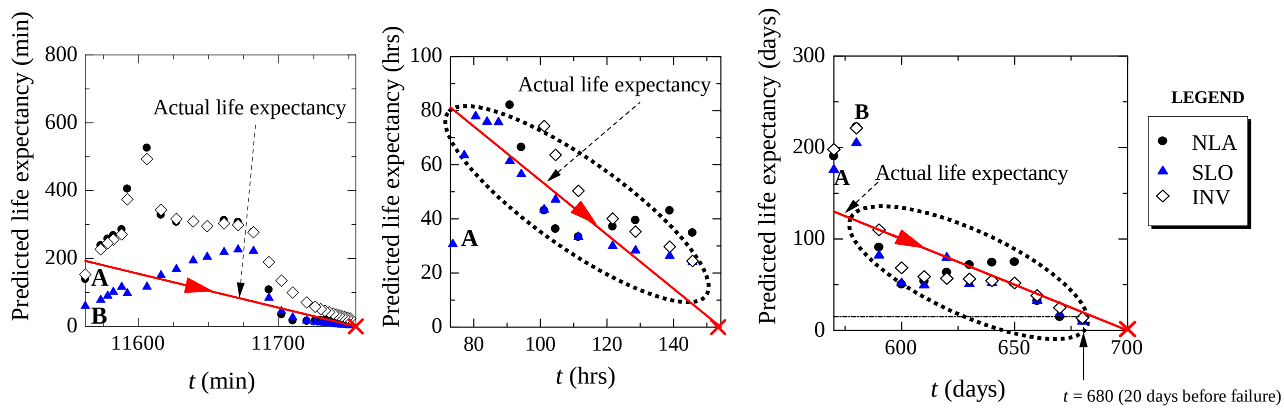
The 100,000 m^3 landslide occurred at Asamushi at 22:12 in July 1966, on the Tohoku line, Japan, interrupting railroad traffic for 26 days and burying 80 m length of track (Saito, 1969).

For NLA method, 21.4% (3 out of 14 predictions) were safe predictions. In SLO method, 57.1% were safe predictions. Point A (Figure 4b) denotes initial prediction (n_{fp} = 22 at t = 73.71 hrs). This means we could have managed to predict failure at 80.49 hrs before actual failure. INV method gave no safe predictions. It is also interesting to note that, although all the three methods had T_{fp}s scattered around the actual life expectancy curve (T_{fp} = T_f), SLO had majority of predictions more close or along the actual life expectancy path (Figure 4b). These T_{fp}s (encircled, Figure 4b) could be used to extrapolate a reasonable T_f under linear fits.

3.3 *Vaiont reservoir landslide disaster*

The catastrophic failure of approximately 270 million m^3 occurred at 23:39 on 9 October 1963 in northeastern Italy (Rose & Hungr, 2007).

All three methods have predictions with a similar trend



(a) (b) (c)

Figure 4. Predicted life expectancy against time t (a) Rock mass failure (b) Asamushi landslide (c) Vaiont landslide reservoir. Symbol × depicts “failure”.

t = 11,562 min), this means we could have managed to predict failure at 193 min (T_f – 11,562) before failure and 22.6% (7 out of 31 predictions) were safe predictions. This physically means there is time to evacuate in the case of a geo-hazard.

In SLO method, 74.2% (23 out of 31 predictions) were safe predictions. Lastly, using INV method, 3.2% (1 out of 31 predictions) were safe predictions.

but with slight variations (Figure 4c). Failure was predicted 130 days before actual failure with point A having 45–68 days of unsafe error (Figure 4c). Then, for example predicted life expectancy becomes less than 10 days on 20 days before failure using all three methods (Figure 4c). Government and responsible authorities should have adequate time to alert people to evacuate to safe places before the landslide. These T_{fp}s (encircled, Figure 4c) could be used to extrapolate a reasonable T_f under linear fits.

4 PREDICTION USING LABORATORY DATA

4.1 *Shikotsu welded tuff under uniaxial compression creep test*

Laboratory uniaxial compression creep tests were carried out on Shikotsu welded tuff (SWT). Prediction of failure-time using circumferential strain ε_c for rock specimens based on SLO and INV methods was done and the results

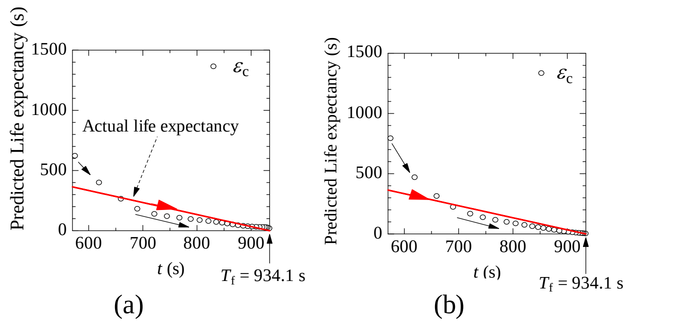


Figure 5. Predicted life expectancy against *t* using (a) SLO (b) INV methods.

are shown in Figure 5. Failure was predicted 359 sec before T_f using both methods. Generally speaking, both methods had predictions that followed a nearly consistent concave path towards failure (Figure 5).

4.2 *Inada granite under brazilian creep test*

Laboratory Brazilian creep tests were carried out on dry Inada granite (30 mm diameter, 30 mm height) to explore the ability to predict extensile failure-time for rock specimens. Predictions were done and we found out that given the dominant brittle tensile failure of the small Inada granite specimens the methods seem to have limited reliability (Figure 6).

5 CONCLUDING REMARKS

Attempts to predict failure-time T_f of rock mass failure, Asamushi landslide, Vaiont reservoir landslide, Shikotsu welded tuff (SWT), and Inada granite were done. SLO gave much safer predictions in all the case studies. It was also found that given the dominant brittle tensile failure of the

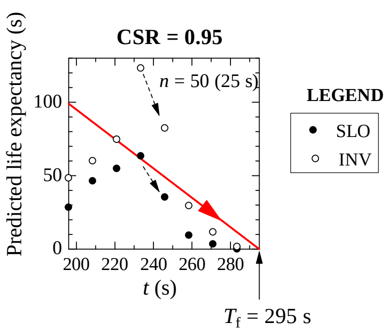


Figure 6. Predicted life expectancy against time *t* for Inada granite at creep stress ratio, CSR = 0.95.

small Inada granite specimens, the prediction methods seem to have limited reliability. However, SLO method further investigated in this research is a reliable method that proved consistent and was validated in most 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. SLO is a simple, quick and easy-to-use analytical method that can find use in planning and disaster management in the geotechnical field.

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