A Study on Prediction of Geomechanical Failure-time and Rock Deformations

Azania Mufundirwa
Candidate for the Degree of Master of Engineering
Supervisor: Prof Yoshiaki FUJII
Division of Solid Waste, Resources and Geoenvironmental Engineering

Introduction

The issue of predictability of landslides, rock mass 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, rock mass and rock slopes is an important aspect to mitigate failure or accidents in the geotechnical field.

The author is proposing a failure-time prediction model based on Eq. (1) for tertiary creep of rock by Okubo and Fukui [1]. Primarily, displacements and strains are the required inputs for this failure-time prediction model. Attempts to predict failure-time (\(T_f\)) of major case histories namely, Asamushi and Vaiont landslides and other practical examples are discussed. Three methods namely, Eq. (2), Eq. (3) and inverse-velocity are used in attempts to predict \(T_f\). Different data ranges \(n_{0i}\) from an initial arbitrary time, \(t\) (beginning of tertiary creep) are used in attempts to predict \(T_f\). The reliability of predictions is also noted using regression correlation coefficient (\(R^2\)). Predictions of \(T_f\) using axial strain \(\varepsilon_a\) and circumferential strain \(\varepsilon_c\) on Shikotsu welded tuff (SWT) were done.

Lastly, a 519-day long record of monitored displacement variations with temperature of a natural rock slope, which lies adjacent to Yamada railway line, is presented. Temperature induced displacements were noted. Crack or rock mass movements due to external processes are analysed. The methods have been validated by collecting and analysing data from published literature, laboratory experiments.

Failure-time prediction model

The author is proposing a failure-time prediction model, to determine failure-time of rock mass, rock slopes and landslides based on tertiary creep behaviour prior to failure.

The analytical model is based on Eq. (1) for tertiary creep of rock, proposed by Okubo and Fukui [1].

\[
\varepsilon = -B \log(\frac{T_f}{t} - 1) + C,
\]

where \(\varepsilon\): strain, \(t\): time, \(T_f\): failure time, \(T_f - t\): life expectancy, \(B\) and \(C\): constants.

Using displacement \(u\) instead of strain \(\varepsilon\) and differentiating both sides

\[
\frac{du}{dt} = \frac{B}{T_f - t}
\]

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

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

\[
\frac{du}{dt} = T_f \frac{du}{dr} - B,
\]

\[
\frac{dt}{du} = \frac{t - T_f}{B},
\]

\(T_f\) is evaluated as the slope of \((t-\frac{du}{dr})\)-\(\frac{du}{dr}\) curve (Fig. 2b) for Eq. (3) and \(x\)-intercept of \(t-\frac{du}{dr}\) curve (Fig. 2c) for Eq. (4). The latter is called the inverse-velocity 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 (Fig. 1) predicted failure-time \(T_f\) and Eq. (3) gives earlier/safe predicted failure-time.

The data filtering method consists of using the \(n\)th observation to calculate the rate.

\[
\left(\frac{du}{dr}\right)_{i} = \frac{u_i - u_{i-n}}{t_i - t_{i-n}}, \quad (i=n+1, n+2, \ldots, m),
\]

where \(\left(\frac{du}{dr}\right)_{i}\) are the computed displacement rate points, \(t_n\) and \(u_n\) are the last time and displacement in the pre-failure range [4].

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. 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.
Landslide at Asamushi

The 100,000 m³ 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 inverse-velocity method and Eq. (2) are very large (Fig. 3b). However, the predicted life expectancy by Eq. (3) was 30 hrs whilst actual life expectancy was 80 hrs. This means that the rock slope failure could be predicted by Eq. (3), 80 hrs before the failure with 50 hrs of safe error.

Vaiont reservoir landslide disaster

The catastrophic failure of approximately 270 million m³ occurred at 23:39 on 9 October 1963 in North-eastern Italy, in the Vaiont canyon located at 680 m above sea level. 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 $T_{ip}$ 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 $n_{ip}$ increased whilst $T_i$ 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.

Creep test in Shikotsu welded tuff

Laboratory creep tests were carried out on Shikotsu welded tuff (SWT). Prediction of failure-time of rock specimens based on Eq. (3) and inverse-velocity were done. Comparison of failure-time predictions using

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 $\varepsilon_a$ and $\varepsilon_c$ respectively.

The uniaxial compressive strength ($\sigma_c = 23.30 \text{ MPa}$) of the SWT specimen was pre-measured so that the creep stress $\sigma_t$ can be reasonably selected. The rock specimens were uniaxially pre-loaded under compression to creep stress ($\sigma_t$) of 18.39 MPa. The creep stress $\sigma_t$ was kept constant in the creep test.

**Predictions using Eq. (3)**

Predictions for failure-time of SWT using axial strain $\varepsilon_a$ and circumferential strain $\varepsilon_c$ were done. Substituting $u$ by $\varepsilon_a$ and $\varepsilon_c$ in Eq. (3), $T_{fp}$ is evaluated as the slope of $t(d\varepsilon_a/dt)-d\varepsilon_a/dt$ curve (Fig. 4a) and slope of $t(d\varepsilon_c/dt)-d\varepsilon_c/dt$ curve (Fig. 4b).

![Fig. 4. Typical Eq. (3) plots used for predictions of failure-time of SWT using (a) axial strain $\varepsilon_a$ data (b) circumferential strain $\varepsilon_c$ data.](image)

**Predictions using inverse-velocity method**

Predictions for failure-time of SWT using axial strain $\varepsilon_a$ and circumferential strain $\varepsilon_c$ were done. Substituting $u$ by $\varepsilon_a$ and $\varepsilon_c$ in Eq. (4), $T_{fp}$ is evaluated as the $x$-intercepts of $t-d\varepsilon_a/dt$ curve (Fig. 5a) and slope of $t-d\varepsilon_c/dt$ curve (Fig. 5b).

![Fig. 5. Typical inverse-velocity plots used for predictions of failure-time of SWT using (a) axial strain $\varepsilon_a$ data (b) circumferential strain $\varepsilon_c$ data.](image)

**Discussion**

Two methods, namely Eq. (3) and Inverse-velocity method were used to predict $T_t$ of SWT using $\varepsilon_a$ and $\varepsilon_c$ data. It is deduced that,

- Predictions using $\varepsilon_a$ data gave unsafe errors in both methods namely, Eq. (3) and inverse-velocity, respectively (Fig. 6a and b).
- Eq. (3) gave better predictions than inverse-velocity using $\varepsilon_c$ data.
- Predictions using $\varepsilon_a$ data gave late initial predictions (points A and C) as compared to predictions using $\varepsilon_c$ data (points B and D in Fig. 6a and b).
- Predictions using circumferential strain $\varepsilon_c$ data gave safer and more precise predictions than predictions using $\varepsilon_a$ data (Fig. 6a and b).

**Deformation of natural rock slope**

Potential rock slope failures are major threats if they are located near a roadway or a railway. Attempt to predict failure of a natural rock slope near Yamada railway is presented. Six surface crack displacement sensors are installed on the surface of natural rock slope at different locations.

Geologically, it consists of a chert block with some slates. Weather conditions were recorded as displacement was monitored from 8 November 2006 to 10 April 2008. Displacement and temperature variations are mainly considered.

**Effects of temperature**

To minimise displacements due to thermal expansion or contraction of crack surface displacement sensors, Eq. (6) was used.

$$ u' = u \pm AT_a $$

where $u'$ is the corrected displacement, $u$ is observed displacement (moving averaged), $A$ is correction coefficient, $T_a$ is air temperature (moving averaged).
For ch1, at \( t = 4 \times 10^3 \) minutes, equivalent to 23:00 August 21, 2007, a steep increase in displacement from -0.04-0.17 mm was observed (ch1 in Fig.7). The overall displacement was 0.21 mm. This may possibly be due to crack or rock mass movement.

The value of \( A \) was selected so that displacement amplitude becomes minimum. Correction coefficients range was +0.005-0.007, except for ch2 with \( A = -0.003 \). This may possibly be due to difference in rock mass and installation conditions.

- Inverse-velocity method gave initial unsafe predictions in most cases. This is possibly due to the initial convex nature of the inverse-velocity plots.
- Circumferential strain \( \varepsilon_c \) gave earlier and safer predictions than predictions using axial strain \( \varepsilon_a \).
- Predictions from Eq. (3) using \( \varepsilon_c \) were the best in prediction of failure-time for SWT.

Eq. (3) is a reliable method that proved consistent and was validated in all the cases.

Lastly, a 519-day long record of displacement and temperature variations for a natural rock slope, which lies adjacent to Yamada railway, was monitored. Channel 1, ch1 gave a clear crack or rock mass movement. For ch2 and ch6, crack was generally closing (Fig.8).

Further Study

The authors wish to investigate more case studies, to attempt to predict \( T_f \). It is expected that this method to predict \( T_f \) would be applied to any monitored deformations or strains at rock slopes, rock openings etc. Uniaxial and triaxial compression creep test for different rocks will be carried out, for prediction of failure-time of rock under compression. Brazilian creep tests will also be carried out for prediction of failure-time of rock in tension. Prediction for triaxial and tension tests would be the first attempt in the world. Attempts to predict pillar failure in underground mines will be done. The author will continue to monitor the natural rock slope do numerical analysis on thermal displacement and thermal stress.

References