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A field experiment for calibrating landslide time-of-failure prediction functions

Bozzano Francesca[a,b,c], Cipriani Ivan[a], Mazzanti Paolo[a,c,*], Prestininzi Alberto[a,b]

[a] Dipartimento di Scienze della Terra, “Sapienza” Università di Roma, P.le Aldo Moro 5, 00185 Rome, Italy
[b] CERI, Research Centre on Prevention, Prediction and Control of Geological Risks, P.zza U. Pilozzi 9, 00038 Valmontone, Italy
[c] NHAZCA S.r.l., spin-off “Sapienza” Università di Roma, Via Cori snc, 00177 Rome, Italy

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ABSTRACT

Over the last decades, time-of-failure semi-empirical prediction functions have been developed and applied to different landslides with mixed results. In this study, a field experiment was carried out to calibrate these functions with the simultaneous consideration of small-size landslides and landslides that occur on slopes modified by human activities. Four years of continuous monitoring using an integrated platform consisting of both traditional sensors (i.e., inclinometers, piezometers, load cells, topographic measurement) and innovative remote-sensing equipment (i.e., Terrestrial SAR Interferometer) resulted in the collection of a notably large amount of data. Several landslides affecting different slopes (i.e., cut slopes, cut slopes covered by spritz-beton and slopes stabilised by anchored bulkheads) were observed as part of the experiment, thus facilitating the inference of detailed information for the pre-failure behaviour. Nine landslides were back-analysed, thus allowing for calibration of the failure prediction functions for different types of slopes. From these observations, it was found that events occurring on slopes modified by human interventions could be effectively predicted using the Voight function if suitable parameters are used. As a general remark, the landslides that originate from cut slopes in natural terrain behave similar to large landslides reported in the literature (similar values of A and α) while landslides that originate from cut slopes covered by spritz beton and slopes stabilised by anchored bulkheads show α values that are significantly lower and A values that are significantly higher than those of landslides on natural terrains.

1. Introduction

Predicting the short- and long-term evolution of a slope presents a fundamental challenge for studies of the interaction of landslides with large infrastructures. Landslide behaviour has been extensively investigated in the scientific community since the beginning of the 20th century [1,2]. However, only from the 1960s have some authors attempted to define semi-empirical approaches for predicting the time of failure (t_f) using instrumental monitoring of slope displacement [3–6]. The first attempts to predict the t_f of unstable slopes based on displacement time evolution date to the early 1960s [3,7,8]. By analysing the rupture of eighty samples in tri-axial compression lab tests, Saito observed that displacement was the most useful parameter for prediction of t_f. Hence, Saito and Uezawa [7] developed a method to obtain the time to failure using the slope displacement data. The Saito method was based on the “slope creep” theory [2,9] and provided a good fit to the steady strain rate phase (i.e., secondary creep). Next, relevant improvements to the Saito′s slope creep theory were accomplished [4,10–12]. Based on large-scale experiments, Fukuzono showed that the logarithm of the velocity of the surface displacement is proportional to the logarithm of the acceleration. In other words, under invariant loading conditions, the pre-failure behaviour can be described by a power law equation in the following form:

$$\frac{d^2x}{dt^2} = A\left(\frac{dx}{dt}\right)^{\alpha} \text{ or } \ddot{\Omega} = A(\dot{\Omega})^{\alpha} \qquad (1)$$

where x is the downward surface displacement along the slope, t is the time, $\dot{\Omega}$ is the velocity, $\ddot{\Omega}$ is the acceleration, and A and α are constants. According to the results of Fukuzono [4] and studies by Varnes [13] and Yoshida and Yachi [14], the α value for natural landslides ranges from 1.5 to 2.2. Specifically, α is larger than 1 for approximately 80% of the available landslide dataset, and is equal to 2 for approximately 50% of those measurements.

Hence, the following equation has been suggested for the prediction of t_f.

$$v^{-1} = [A(\alpha - 1)(t_f - t)]^{-1/(\alpha - 1)} \qquad (2)$$

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* Corresponding author at: Dipartimento di Scienze della Terra, “Sapienza” Università di Roma, P.le Aldo Moro 5, 00185 Rome, Italy. Tel.: +39 064 991 4835.
E-mail addresses: paolo.mazzanti@uniroma1.it, paolo.mazzanti@nhazca.com (P. Mazzanti).

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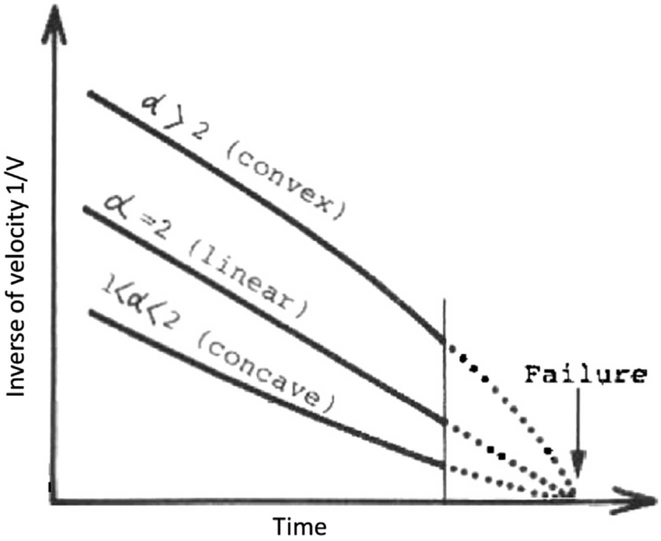

Fig. 1. Typical trends of the changes in the inverse of the displacement velocity before failure (modified from [4]).

where v is the surface displacement velocity. The inverse velocity vs. time curve is linear for $\alpha=2$, convex for $\alpha>2$ and concave for $1>\alpha<2$. Hence, in the case of $\alpha=2$, the failure time can be simply computed using the following equation:

$$t_f=\frac{(t_2/v_1)-(t_1/v_2)}{(1/v_1)-(1/v_2)} \tag{3}$$

Also, t_f corresponds to the intercept of the straight line of the inverse velocity vs. time plot with the x-axis (time axis, Fig. 1).

The efficacy of this method for predicting landslides (t_f) has been demonstrated by several authors [12,15–23]. However, a generalized expression and additional calibration are urgently required [24], particularly for man-made slopes and natural slopes affected by human activities.

Over the last four years, the authors of this paper have had the opportunity to continuously monitor the displacement of a large slope affected by human activities (i.e., a tunnel excavation) using Terrestrial SAR Interferometry [25–26]. This long-term continuous monitoring allowed collecting a large set of interesting data on the pre-failure displacement of different types of landslides. This “field” laboratory provides the foundation for the study presented in this work, which aims to assess the most common α and A parameters of the Fukuzono and Voight equations (Eq. (1)).

2. The experimental setting and collected data

The experimental setting consists of a natural slope affected by anthropic activities associated with the excavation of a tunnel. Following a destructive landslide (with a volume of approximately 10^4 m^3) on March 2007, the slope was instrumented for continuous and real-time monitoring to control the safety conditions during the subsequent stabilisation activities and tunnelling excavations. The instrumental setting consisted of the following equipment (Figs. 2 and 3): (i) An integrated remote platform, including a Terrestrial SAR Interferometer (TInSAR) model IBIS-L (by IDS S.p.A.), a weather station and an automatic photo camera installed on the frontal slope (with respect to the landslide [26]) at a distance ranging from 700 to 900 m (active from November 2007); (ii) three inclinometers with a variable length between 45 and 75 m, one full-screen piezometer installed at a depth of 16 m and one ‘Casagrande’ piezometer installed at a depth of 48 m (active from June 2007); (iii) monitoring via a topographic station of prisms installed on the bulkheads (active from September 2008); (iv) three load cells for monitoring the anchors installed on the bulkheads (active from September 2008) and (v) convergence monitoring of the tunnel (active from November 2009).

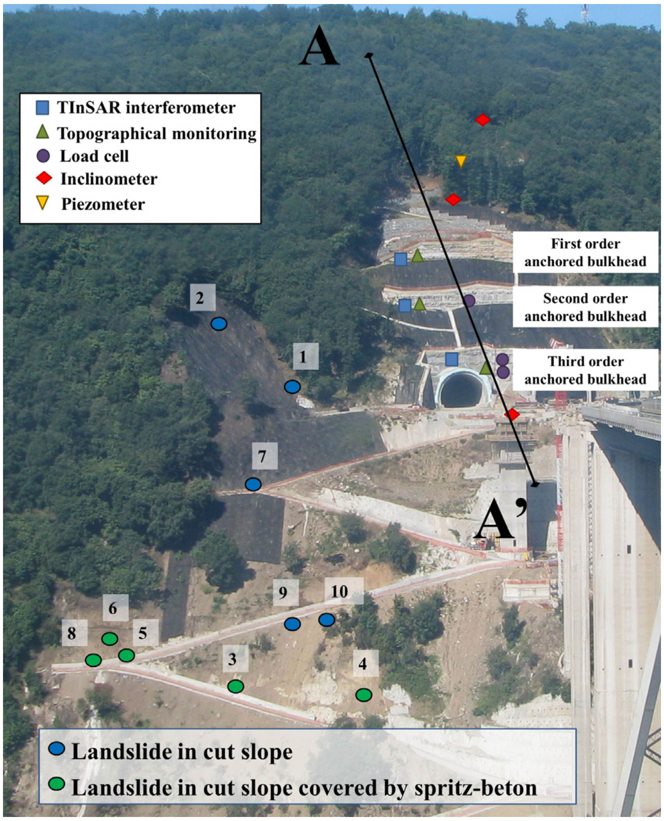

Fig. 2. Picture of the slope showing the monitoring sensors, the ten small-size landslides (Figs. 5 and 6) and the location of the engineering-geological section (Fig. 3).

The continuous monitoring of the slope from the middle of 2007 to the end of 2011 allowed collecting a large set of displacement data for the overall slope following various work phases conducted on the slope. Specifically, the following data are available: approximately 20,000 photos, 250,000 measurements of weather data, 400,000 SAR images collected from the same position, 160 inclinometric measurement 160 piezometric measurements, 160 topographic measurements, and, finally, 85 load cell measurements.

2.1. Engineering geological features of the slope

During the experimental period, the slope was investigated in detail using (1) field geomorphological, geological, geomechanical and seismic surveys and (2) boreholes and laboratory tests of samples, thus enabling a detailed engineering geological model to be derived [21,26]. The steep relief of the slope consists of jointed and weathered metamorphic rocks overlaid by Pliocene and Pleistocene sandy marine deposits. Sandy colluvial deposits a few meters thick constitute an irregular blanket along the slope. Furthermore, geological and geomorphological features show evidence of an old and deep roto-translational slide whose total volume was on the order of 1×10^6 m^3 that affected the jointed gneiss and the overlying Pliocene and Pleistocene sands. The main sliding surface (up to 50 m deep) and many secondary surfaces were reconstructed using geomorphological surveys, stratigraphic logs, interpretations of the surface displacements (derived from TInSAR and topographical data) and deep displacements (derived