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TEMPORAL PREDICTION OF LANDSLIDE OCCURRENCE: A POSSIBILITY OR A CHALLENGE?

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EXTENDED ABSTRACT

Nell'ottica di una cultura di prevenzione del rischio idrogeologico, purtroppo ancora sostanzialmente mancante, la mitigazione del rischio da frana, attraverso la previsione del tempo di occorrenza degli accadimenti franosi, è un obiettivo di straordinaria valenza sociale, economica e scientifica. La previsione di un franamento, laddove essa è possibile, consente, infatti ed anzitutto, di evitare - almeno in linea di principio - la perdita di vite umane; ed, anche, di ridurre i danni economici, di pianificare l'emergenza operativa e di porre in essere adeguate contromisure di previsione e di controllo.

Il compito è tutt'altro che semplice, dal momento che è praticamente impossibile introdurre, nella modellazione del fenomeno, la moltitudine di variabili e fattori variamente intercorrelati e non tutti definiti in termini del loro relativo contributo.

L'approccio al problema implica la comprensione del comportamento reologico dei materiali coinvolti nel potenziale movimento franoso, descritto da una curva di *creep* che correla gli spostamenti di pendio al tempo. L'applicabilità di tale approccio è, tuttavia, alquanto incerta, non essendo ancora del tutto chiara la fisica del fenomeno di *creep*. L'estensione, poi, del modello reologico ad un problema a scala reale è pressoché impossibile per un vasto insieme di ragioni, tra cui l'eterogeneità delle condizioni geologiche e della massa di terreno o di roccia ed il fatto che, nella maggior parte dei casi, le pressioni interstiziali sulla superficie di potenziale scorrimento, i parametri geomeccanici e le condizioni al contorno non possono essere definiti in modo appropriato. A ciò si aggiunge l'impossibilità pratica di prevedere i fattori esterni che possono innescare l'instabilità.

Al fine di rimuovere tali incertezze, viene comunemente impiegato un approccio empirico e fenomenologico per la predizione del tempo di possibile franamento di un pendio. Basato sull'osservazione ed interpretazione di dati di monitoraggio, l'approccio in parola definisce tale tempo attraverso una funzione empirica, ottenuta con tecniche di regressione, che descrive l'evoluzione nel tempo di spostamenti superficiali, deformazioni o attività micro-sismica del pendio.

In questo lavoro vengono presentati, per l'essenziale, alcuni metodi di questo approccio, riservando più risalto al metodo di Fukuzono, del quale vengono pure brevemente illustrate varie applicazioni sia a pendii naturali che a fronti di scavo. Questo metodo, di facile applicabilità, palesa, in generale, buona capacità predittiva a condizione che i) i dati monitorati siano di qualità ed i più rappresentativi della tendenza cinematica del pendio, ii) le fluttuazioni dei parametri in gioco non siano di breve periodo rispetto alla durata del *creep* e iii) sia applicato con cautela ed i risultati ottenuti interpretati con giudizio.

Vengono poi succintamente presentate, in forma tabellare, varie tecniche avanzate di *remote sensing*, tra cui, in primis, l'interferometria radar sia terreste che satellitare, con i loro vantaggi, limiti e performance complessiva. Rilievo è, invece, dato alla riflettometria nel dominio del tempo (TDR - Time Domain Reflectometry) ed agli assai migliorati metodi di emissione acustica (AE - Acoustic Emission): queste due tecniche presentano anche il vantaggio della possibilità di acquisizione automatica dei dati in tempo reale. Anche in modalità remota.

Da ultimo, dopo aver delineato qualitativamente il legame tra il fenomeno di *creep* e quello di rottura progressiva, viene mostrato un diagramma, che può avere utilità pratica nei casi in cui non si disponga di una serie storica di rilievi di grandezze cinematiche o deformative. Il diagramma, implementato con ulteriori dati cinematici, fornisce indicazione di probabile imminente collasso se il punto rappresentativo della situazione cinematica corrente del pendio - ottenibile con solo tre misure di spostamento, tra loro temporalmente distanziate - si situa in prossimità della retta lungo la quale sono dispersi i valori (ultimi, ovvero a rottura) di velocità di spostamento ($\dot{\eta}_f$) e di accelerazione ($\ddot{\eta}_f$) che, attinti dalla letteratura, sono relativi ad un gran numero di casi di frana con documentata evoluzione temporale degli spostamenti superficiali.

ABSTRACT

In the framework of landslide risk reduction, predicting the time of occurrence of a slope failure is a goal of major importance. The task is far from simple, since it is practically impossible to account for the large number of controlling variables and factors. For these reasons, an empirical and phenomenological approach is commonly employed in the time of slope failure prediction, given that it removes all the uncertainties involved. Based on the observation and interpretation of monitored data, this approach infers such time mainly from ground surface displacements using regression techniques based on empirical functions and neglecting rheological soil parameters. The paper presents an overview of the methods associated with this approach, with particular emphasis on Fukuzono's method accompanied by a number of its applications. Moreover, after a short account of advanced remote sensing techniques and an outline of the qualitative link between creep and progressive failure, a plot is shown which is potentially useful for early warning when historical displacement data are not available.

KEY WORDS: landslide, creep, time to failure, prediction, monitoring

INTRODUCTION

Forecasting the time of occurrence t_f of landslides is a goal of social, economic and scientific significance in the framework[1] of landslide risk mitigation, given that a reasonably accurate prediction of t_f would allow human losses to be-at least in principle-avoided, damage to property to be reduced, adequate countermeasures to be designed and operative emergencies to be planned. The task is far from simple however, since it is practically impossible to account, in the modellation of the phenomenon, for the large number of variables and factors to be considered, that are variously intercorrelated among themselves and not all clearly defined in terms of their relative contribution. The approach to the problem entails understanding the rheological behaviour of the geomaterials involved, which can be substantiated in a displacement versus time creep curve. However, the applicability of this relationship is still doubtful, given that the fundamental physics underpinning the creep phenomenon has not yet been fully elucidated (HUTCHINSON, 2001). Furthermore, extension of the relationship to the full scale problem is questionable for various reasons, among them: the heterogeneity of the soil/rock mass and the fact that, in most cases, pore pressures, mechanical parameters and boundary conditions of the problem cannot be properly defined. Moreover, it is impossible to forecast the triggering factors originating outside the sliding mass (e.g. heavy rainfall).

(1) About 50 helpful reports on assessment and quantification of landslide risk and on most appropriate risk management strategies can be found at the web site http://safeland-fp7.eu/.
Safeland was a large,integrating research project under the European Commission's 7th Framework Programme (FP7) started on 1 May 2009 and went on for 3 years, ending on 30 April 2012

For these reasons, an empirical approach, hereinafter named "phenomenological", is commonly employed, because it removes all the uncertainties involved. It determines the time of occurrence (t_f) of a landslide by means of a function, derived from the results of laboratory creep tests, that empirically describes the evolution over time of the monitored displacements/deformations or microseismic activity of a slope.

In the following, a selection of predictive methods of this approach is briefly presented to define the conditions under which they are applicable, referring a more detailed description to FEDERICO *et alii* (2012). Emphasis is given to the Fukuzono method and several examples of its application are shown. This method provides an easy tool which can be quite reliable for t_f prediction, as long as i) the monitored data are of good quality, ii) the variations of the involved parameters are not of short period in comparison to creep duration and iii) it is applied with caution and the result interpreted with care. Moreover, a short account is given of several advanced remote sensing techniques with their advantages and limits and of the possibilities offered by time domain reflectometry and improved geoacoustic methods. Then, after an outline of the qualitative link between creep and progressive failure phenomena, a plot is shown, that can be of practical usefulness when historical series of slope displacement are not available.

FIRST PREDICTIONS OF SLOPE FAILURE

Historically, the first successful time of slope failure prediction is that of the Motto (alias Monte) d'Arbino rockfall in Tessin, not far from Bellinzona (Switzerland). The rockfall occurred on October 2nd 1928, when 30 to $40x10^6$ m^3 of rock blocked the Arbedo valley, creating a small, 1.5 km long, lake (Fig. 1) (JÄGGLI, 1928; BONNARD, 2006).

Fig. 1 - View of Motto d'Arbino rockfall dam in the Arbedo valley just after the event, in 1928 (after BONNARD, 2006)

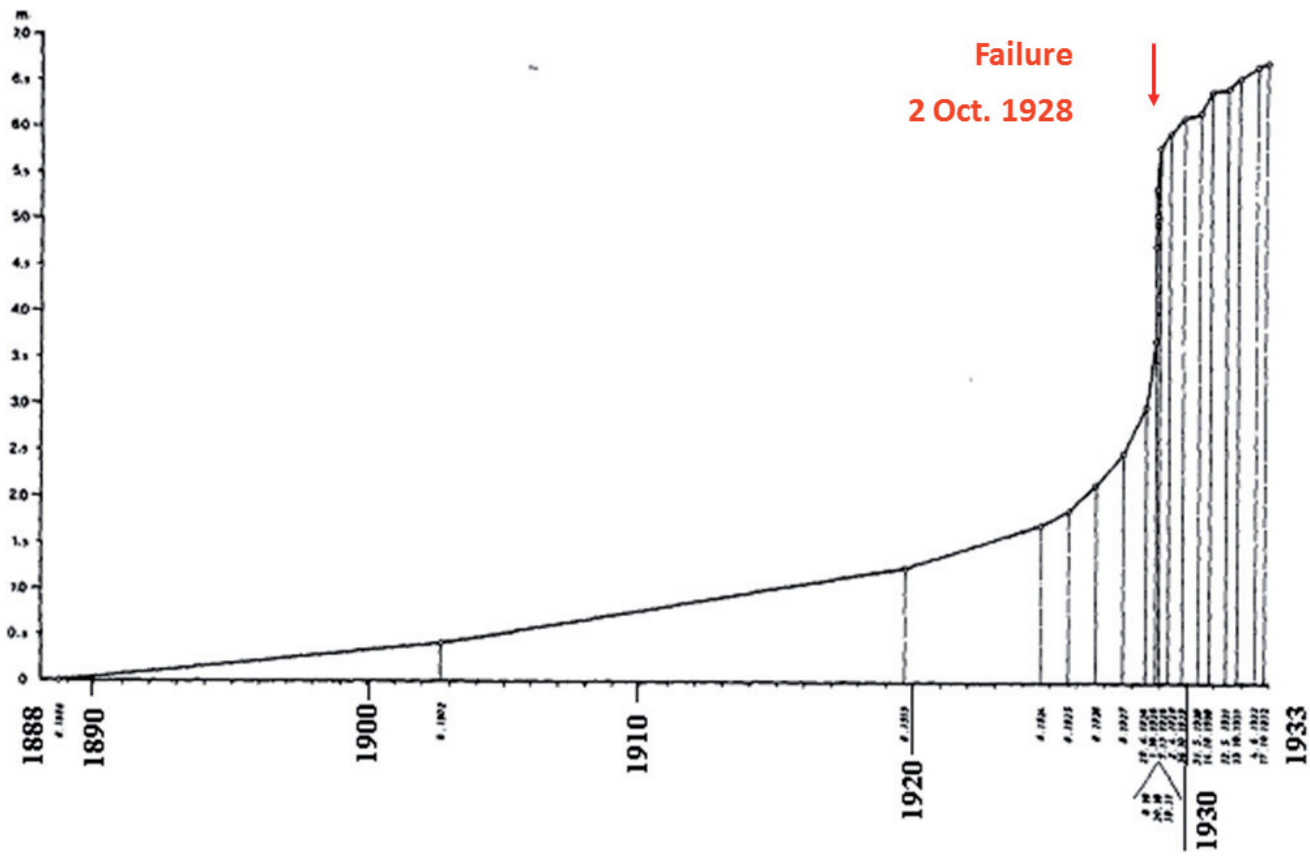

Fig. 2 - Reconstruction of movements at Motto d'Arbino from 1888 to 1933 (after Engel*, 1986, modified)*

The most interesting aspect of this case is that trigonometric surveys had been conducted by the Federal Topographic Bureau since 1888 (Heim, 1932), supplying the first scientific and duly measured evidence (Fig. 2) of the acceleration phase before the rockfall, allowing the evacuation of the 16 houses that were subsequently destroyed (Engel, 1986).

Shortly afterwards, this technique was applied by Heim (*ibid*.) to a rock slope above the town of Linthal in the Swiss Alps, for which two separate predictions of catastrophic slope failure were made, neither of which was successful. Heim reported that "lack of experience" was the reason for the inaccurate prediction.

A few decades later, a case that caught the world's attention was the slope failure forecast made for at the Chuquicamata mine in Chile (Fig. 3), five weeks before the event.

Fig. 3 - The Chuquicamata copper mine

The date of failure (February 18th, 1969) was exactly predicted by rough hand-drawn extrapolation of the displacement data of the fastest moving target on the slope surface. The prediction allowed the rockslide to be managed and worked around in such a way that production was stopped for only 65 h (Kennedy & Niermeyer, 1970; Hoek & Bray, 1977). However, as shown by Federico *et alii* (2011), the accuracy of the prediction is questionable - and the prediction rather imprudent - given that a hand-extrapolation beyond the last date of observation (January 13th, 1969) could have led to a number of other possible dates of failure, within a time span of about two months, most of them subsequent to the actual date of the event.

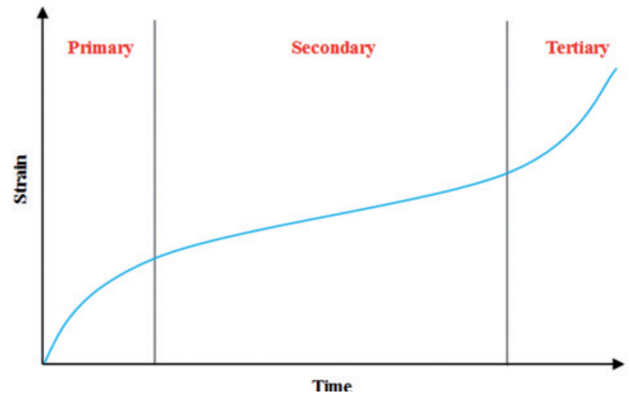

Fig. 4 - Ideal creep curve of a material

GROUND MOVEMENTS THAT PRECEDE A LANDSLIDE

As the cases of Motto d'Arbino and Chuquicamata show, displacement monitored data of a slope can be usefully analysed for the prediction of the timing of a landslide.

Indeed, significant creep[2] deformations develop in all slopes before failure occurs (Ter-Stepanian, 1980; Tavenas & Leroueil, 1981). These slope displacements against time before failure can take the form of the third stage of a creep curve (Fig. 4), i.e. of the stage of self-feeding instability, wherein accelerating slope displacements are taken as a warning of imminent failure (Eberhardt, 2008). In this regard, the diagram (Fig. 5) in Terzaghi (1950) illustrating the ground movements[3] that precede a landslide is substantially still valid.

If the slope is adequately monitored, its possible failure can be predicted, commonly using an empirical approach. It consists of defining the timing of a landslide through semi-empirical formulations that describe the evolution of the displacement versus time. Such functions usually, but not exclusively, derive from the results of laboratory creep tests and relate the prefailure monitored surface displacements to the time of slope failure. Herein this approach is named "phenomenological", to highlight that it

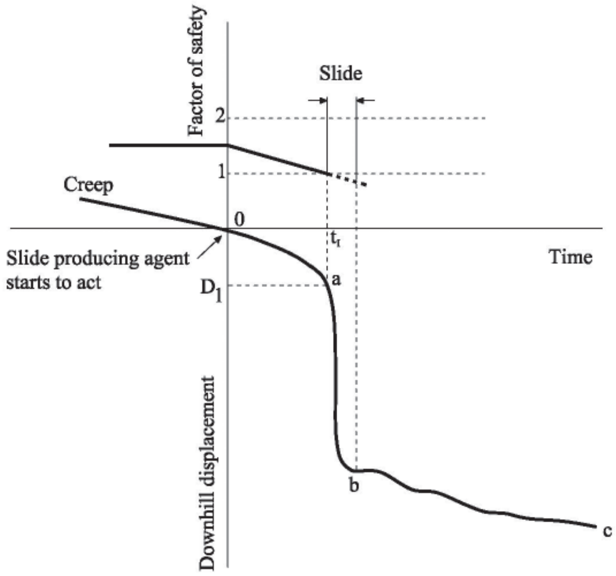

Fig. 5 - Diagram illustrating the ground movements that precede a landslide (after Terzaghi, 1950)

is based only on the available monitoring data, such as displacement /deformation versus time or acoustic emission counts of a slope and to distinguish it from other approaches based on the application of specific constitutive viscous-elastic-plastic laws implemented in numerical models.

OUTLINE OF THE PREDICTION METHODS USED IN THE PHENOMENOLOGICAL APPROACH

As already said, a phenomenological approach is commonly employed for forecasting a landslide, since it removes all the uncertainties involved.

Prediction methods based on this approach can be divided into two categories:

i) physically-consistent: the regression curve usually complies with the rheological behaviour of the rock mass;

ii) regression-only: the regression curve is not driven by the physics of the phenomenon.

Within the first category, an additional distinction can be made:

1) methods for a "critical" prediction, i.e. a prediction performed close to the failure, presumably in the tertiary creep phase;
2) methods for medium and long-term predictions, where the observations refer to a significant part of the whole creep period.

In addition to t_f - time to slope failure, the following notations are used below: η-displacement, ε-strain, t-time and t_0-initial time of the measurements or of the creep stage. The letters a, b, c and α indicate empirical parameters derived from data fitting, and are specific to each method.

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(2) A comprehensive, overview on creep of geomaterials has been presented by Varnes (1982).

(3) Terzaghi (ibid.) emphasized the role of these movements: "It has often been stated that certain slides occurred without warning. Yet no slide can take place unless the ratio between the average shear strength and the average shearing stress on the potential surface of sliding has previously decreased from an initial value greater that one to unity at the instant of the slide...(The landslides) are preceded by a gradual decrease of the ratio which, in turn, involves a progressive deformation of the slice of the material located on the potential surface of sliding and a downward movement of all point located on the surface of the slice. Hence, if a landslide comes as surprise to the eyewitness, it would be more accurate to say that the observers failed to detect the phenomena which preceded the slide... The clay slides which occurred in the spring of 1935, during the construction of the German superhighway from Munich to Saltzburg, came as a surprise to the supervising engineers, but one week before the movements started the laborers claimed that the slope becomes alive...".

Physically-consistent methods

Although philosophically seminal, the prediction technique used in the Swiss Alps remained little known and did not benefit practically from further applications and developments. Indeed, it was to be decades before research on the subject resumed.

The need for reliable methods to forecast slope failure has been a vital subject of research over the last 50 years, especially in Japan, where the second documented successful forecasting of slope failure was made (Saito & Uewaza, 1961; Saito, 1965). This was the landslide which occurred on December 14th, 1960 along the Ooigawa railway line . It was predicted (...”*forecasting was successful and railroad traffic was interrupted at 10.30 on December 13th,the day before collapse*” (Saito, *ibid.*) on the basis of comparison of slope displacement records and laboratory measurements of the strain rate during secondary creep using load-controlled triaxial tests.

CRITICAL OR SHORT TERM PREDICTION

Saito (1969) extended the mentioned method to the tertiary creep phase, obtaining:

$$(t_f - t)\dot{\varepsilon} = a \qquad (1)$$

Equation 1 indicates that the time to failure during tertiary creep is inversely proportional to the current strain rate.

Using this equation, Saito (1979) predicted the Takabayama landslide (January 1970) well in advance, while Suwa (1991) predicted the collapse of a rocky cliff-face on National Highway 327 in the village of Saigo, Japan. Thanks to the restriction of traffic following the prediction, no human life was lost.

By differentiating Equation 1, a linear relationship between the logarithm of the acceleration and the logarithm of the time to failure is obtained. Picarelli *et alii* (2000), based on the monitoring data of Pellegrino & Urciuoli (1996) on a large number of slopes monitored until failure, confirmed the validity of Equation 1.

Cruden & Masoumzade (1987) used a statistical distribution method to better estimate the constants of Eq. 1, while Azimi *et alii* (1988) suggested a graphical procedure for solving such equation and estimating t_f, based on the method proposed by Asaoka (1978) for determining one-dimensional consolidation settlement. The underlying idea is to find the time for which the displacement rate tends to infinity. Equations not dissimilar to Equation 1 were derived by Yamaguchi (1978) and Hayashi *et alii* (1988a and 1988b).

Based on an experimental study of small-scale slope models run until failure under monotonically increasing load, Fukuzono (1985) found that for rapid failure the logarithm of acceleration ($\ddot{\eta}$) is proportional to the logarithm of the velocity ($\dot{\eta}$) of ground surface displacement, i.e.:

$$\ddot{\eta} = a\dot{\eta}^{\alpha} \qquad (2)$$

The *a* and *α* values may be estimated from a regression procedure. Crosta & Agliardi (2003) used a non-linear regression method to derive *a* and *α* for the assessment of the alert-velocity threshold of the Ruinon rock slide in northern Italy.

Integrating this equation for $\alpha > 1$, one obtains:

$$\dot{\eta} = \left[a(\alpha - 1)(t_f - t)\right]^{-[1/(\alpha - 1)]} \qquad (3)$$

or

$$\frac{1}{\dot{\eta}} = \left[a(\alpha - 1)(t_f - t)\right]^{[1/(\alpha - 1)]} \qquad (4)$$

The plot $1/\dot{\eta}$ *vs* t is linear for $\alpha = 2$, concave for $\alpha < 2$ and convex for $\alpha > 2$. Extrapolating this plot, its intersection with the abscissa should correspond approximately to the time of failure. The assumption of linearity ($\alpha = 2$) usually provides a reasonable estimate of t_f. The relevant procedure is shown in Fig. 6. A similar graphical procedure is available for the case when the $1/\dot{\eta}$ *vs* t is not linear. Note that Equation 4 can be rewritten as

$$(t_f - t) = \frac{\dot{\eta}^{(1-\alpha)}}{a(\alpha - 1)} \qquad (5)$$

where $(t_f - t)$ is the time interval until the slope collapse and that, for $\alpha = 2$, Equation 5 - if expressed in terms of strain ε-coincides with Equation 1 proposed by Saito (1969).

Fukuzono’s Equation 2 was manipulated and interpreted by Voight (1988a, 1988b and 1989) as a fundamental physical law governing various forms of material failure under conditions of constant stress and temperature. For the case of rock failure due to accelerated creep, the variable *η* is a characteristic deformation, e.g. strain, rotation, displacement or seismic-energy release. Moreover, drawing an analogy between failure mechanisms and volcano eruption processes, *η* can also be interpreted in terms of conventional geodetic, seismic or geochemical observations, enabling Equation 2 to provide a consistent basis for eruption prediction (Voight, 1988a and 1990; Cornelius & Voight, 1995).

MEDIUM / LONG-TERM PREDICTION

The possibility of medium/long-time prediction was dealt with by Kawamura (1985), who developed a method which accounts for the entire creep phenomenon and is therefore - in principle - applicable to medium/long-term prediction.

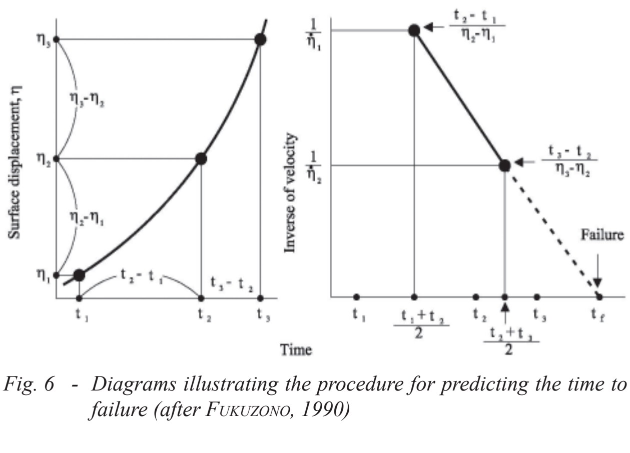

Fig. 6 - Diagrams illustrating the procedure for predicting the time to failure (after Fukuzono, 1990)

The derived relationship is:

$$\frac{1}{\dot{\eta}} = a(b-t)t \qquad (6)$$

This model is the outcome of numerical analyses based on creep theory and a large quantity of monitoring data.

FUKUZONO (1996) also introduced a creep-deformation model related to the entire creep stage which makes it possible to predict t_f at an earlier stage. The related equation is:

$$\ddot{\eta} = a(t-b)\dot{\eta}^2 \qquad (7)$$

Lastly, another physically consistent method for t_f prediction was more recently developed by MUFUNDIRWA *et alii* (2010), who claim it is also suitable for slope failures governed by processes and mechanisms not affected by creep (e.g. structural failures).

The adopted equation is that of FUKUI & OKUBO (1997), and it represents strain divergence in the terminal phase of creep failure in rocks:

$$\varepsilon = -b\log(t_f - t) + c \qquad (8)$$

where $(t_f - t)$ is the life expectancy.

REGRESSION-ONLY METHODS

There are some other predictive methods which are based only on different regression functions.

Building on a previous study by YAN (1987), LI *et alii* (1996) used the VERHULST function, which is applied to the growth of biological organisms and which is the solution of the following differential equation:

$$\dot{\eta} = a\eta - b\eta^2 \qquad (9)$$

The inverse VERHULST function-whose shape (Fig. 7) is that of a standard creep curve-is obtained as the symmetrical function with respect to $\eta = 0$ line in a η *vs* t plot.

With the initial condition $\eta = \eta_0$ at $t = t_0$, the solution of Equation 9 is:

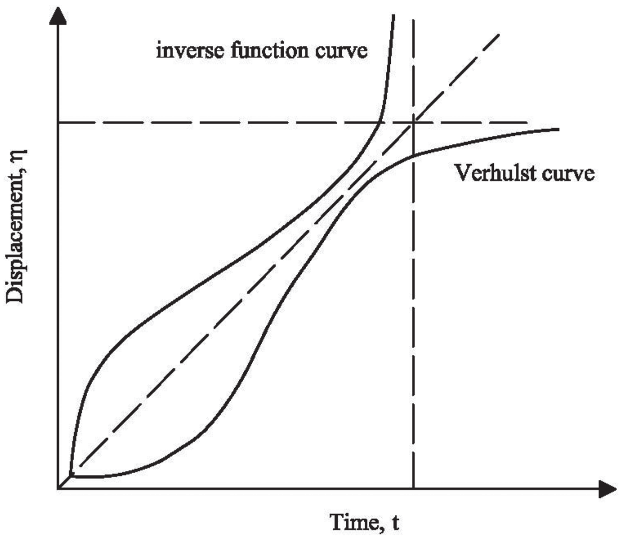

Fig. 7 - VERHULST inverse function (after LI et alii, 1996)

$$\eta = \frac{a\eta_0}{b\eta_0 + (a-\eta_0)e^{-a(t-t_0)}} \qquad (10)$$

The inverse function derived from Equation 10 is:

$$\eta = \frac{1}{a}\ln\frac{(a-bt_0)t}{(a-bt)t_0} + \eta_0 \qquad (11)$$

If $\eta \rightarrow \infty$, failure occurs. This implies, if $t_0 \neq 0$, that $(a - bt) \rightarrow 0$, i.e. $t = t_f$. The parameters *a* and *b* are provided by the best fit of the monitored data.

Li *et alii* (1996) reported two examples of this application, where the observed data were in good agreement with the predicted values of the inverse function, and claimed that the predictions based on this theory had an error ranging from 0 to 15 days.

MIAO & AI (1988) applied the "catastrophe theory" (POST & STEWART, 1978) and proposed the following governing equation, strictly limited to a purely cohesive soil:

$$\ddot{\eta} = -a(t_f - t)^{-2(\alpha+1)/3} \qquad (12)$$

By integrating Equation 12, one obtains:

$$\dot{\eta} = \frac{3a}{2\alpha-1}a(t_f - t)^{-(2\alpha-1)/3} \qquad (13)$$

$$\log(t_f - t) = \frac{3}{2\alpha-1}\log\frac{3a}{2\alpha-1} - \frac{3}{2\alpha-1}\log\dot{\eta} \qquad (14)$$

When $\alpha = 2$, Equation 13 - if expressed in terms strain ε - coincides with the Saito's equation.

CHEN & WANG (1988) applied the "Grey System Theory" ,that is a method for studying problems for which few monitored data and poor information is available. The limited knowledge of the factors controlling the creep deformation and failure of a slope and the inherent complexity of the slope system make a landslide similar to a "Grey System".

The derived solution (not reported here) is compared with the accumulated displacement and the time at which the gradient of the accumulated displacement tends to infinity is the time to failure.

In the last two decades Artificial Neural Networks (ANN) have been increasingly employed as effective tool in geotechnical engineering. They are statistical methods and take their name from the networks of nerve cells. Although they are a simplified version of biological neural networks, they retain enough of the structure observed in the brain to provide insight into how biological neural networks might operate. Like these, an ANN can learn and be trained to find a solution, recognize patterns, classify data and forecast future events (SAKELLARIOU & FERENTINOU, 2005). A peculiar feature of neural networks is that they do not require knowledge of the relationship connecting input and output variables.

This computational tool has had a number of applications in slope stability prediction (e.g. MAYORAZ *et alii*, 1996; ALEOTTI

& Chowdhury, 1999; Gao, 2008; Zhang *et alii*, 2008; Ghaffari, 2010; Kaunda *et alii*, 2010; SAFELAND Project-D1.5) A detailed description of their use for the prediction of pore pressures and slow displacement movements of slopes can be found in Mayoraz & Vulliet (2002).

CREEP AND PROGRESSIVE FAILURE

All the prediction methods so far outlined account for the creep phenomenon and do not mention the progressive failure phenomenon. In reality, these two phenomena are strongly connected and hypotheses about the relationship between them have been circulating for several decades (e.g. Nelson & Thompson, 1977; Puzrin & Schimd, 2011). However a definitive theory encompassing creep and progressive failure is not yet available, and the following comments are offered as a schematic introduction to this problem.

Typical curves from creep tests are shown in Fig. 8. The early part of these curves indicates a decreasing strain rate (primary creep), reaching a minimum value that may be sustained for time periods representing sizable strain (secondary creep). Eventually, this prolonged straining leads to accelerated creep culminating in failure of the specimen (tertiary creep).

As pointed out by Nelson & Thompson (1977), the accumulation of plastic strains during primary and secondary creep stages results in continuous deterioration of the soil's internal bonds. On the basis of published creep data (e.g. Campanella & Vaid, 1974; Murayama & Shibata, 1961) there is evidence that a critical threshold of accumulated strains exists - specific to each type of soil - at which all the variable components of strength have been destroyed or overcome, causing the reduction of the shear strength of the soil to its residual value. Then, if the locally applied stress τ is greater than the residual strength τ_r, equilibrium is no longer maintained and, as a result, progressive failure and stress redistribution begin. On the other hand, if the applied stress is lower than the residual strength, the system remains in equilibrium and progressive failure will not be triggered. However, as shown in Fig. 8, creep will continue at its slow rate. Obviously, from a physical point of view, even this low strain rate can eventually lead to the onset of progressive failure, depending on the τ/τ_r ratio.

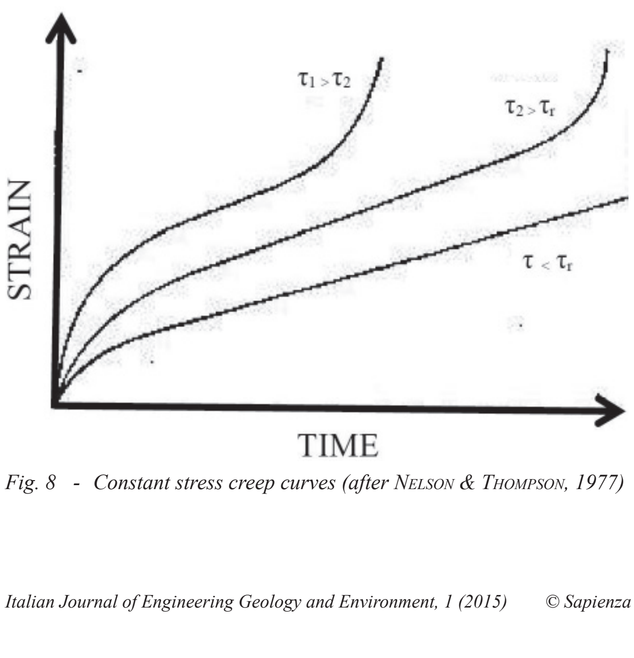

Fig. 8 - Constant stress creep curves (after Nelson & Thompson, 1977)

From a mathematical point of view, modelling tertiary creep requires a time dependent constitutive model (i.e. a viscosity model) that is able to capture strain localization in a shear band during progressive failure. As it is well known, local softening plasticity is associated with strong mesh dependency and serious problems of convergence as soon as strain localization occurs. In order to avoid these problems, viscoplastic constitutive models or higher-order continuum theories can be employed. Elasto-viscoplastic constitutive models seem to be particularly suitable, as experimental evidence shows that the mechanical behaviour of all geomaterials is time-dependent (Di Prisco & Imposimato, 1996).

One regularization technique applied with success in the last few years (Di Prisco & Imposimato, 2003; Troncone, 2005; Conte *et alii*, 2010; Murianni, 2011) is the non-local elasto-viscoplastic approach. The viscosity accounts for the time-dependent behaviour of the soil thanks to the introduction of two viscous parameters [calibrated on the basis of creep tests or parametric analysis (Murianni, *ibid.*)], while the non-local approach makes it possible to overcome the numerical problems of the softening laws.

However, a great deal of research is necessary to render this approach suitable for the analysis of slope stability.

A SHORT ACCOUNT OF ADVANCED MONITORING TECHNIQUES FOR PREDICTING TIME TO SLOPE FAILURE

The t_f prediction methods outlined above are based exclusively on the measurement of displacement or deformation.

During the past 10 years there has been a rapid development of remote sensing methods for monitoring slope displacement or deformation, enabling automated high -precision surveys. Table 1 lists the main remote sensing methods and their (multiple) acronyms along with their performance when applied to slopes instabilities. The advantages and limitations of such methods are compared in Table 2,while the rating of their mean features is shown in Table 3.

However, measurements can also be made of acoustic emissions and time domain reflectometry.

Geoacoustic methods were first developed mainly to obtain warnings of the occurrence of rockburst in mines (e.g. Obert & Duvall, 1945, *apud* Hutchinson, 1983). Application of these methods to rock slope stability problems came later (e.g. Cadman & Goodman, 1967; Kennedy, 1972; McCauley, 1975; Novosad *et alii*, 1977) when the Acoustic Emission (AE) count rate was recognized as an early indicator of slope instability.

In Fig. 9 the extensometer data are compared to the accumulated AE count measured during a slope-failure experiment carried out by Fujiwara *et alii* (1999). The similarity of the two curves is apparent

REMOTE MONITORING METHOD	*ACRONYM(S)*	*PERFORMANCE*
Terrestrial/Airborne Laser Scanning *also referred to as* Terrestrial/Airborne Light Detection and Ranging	TLS/ALS Terrestrial/Airborne LiDAR	High
Terrestrial Interfermetric Synthetic Aperture Radar *also referred to as* Ground Based Interfermetric Synthetic Aperture Radar	TInSAR GBInSAR	Extremely high
Satellite Interfermetric Synthetic Aperture Radar *also referred to as* Differential Interfermetric Synthetic Aperture Radar	SInSAR DInSAR	Medium
Permanent Scatterers Interfermetric Synthetic Aperture Radar	PSInSAR	Medium-High
Robotic Total Station *also referred to as* Automatic Total Station *or* Automated Motorized Total Station	RTS ATS AMTS	High
Reflectorless Robotic Total Station	RRTS	Medium
Digital Photogrammetry	DP	Medium
Differential Global Positioning Systems	D-GPS	Low-Medium

Tab. 1 - Main remote sensing methods

	ADVANTAGES	LIMITATIONS
TLS	• High density of information • Good view of results thanks to the 3D models • Long distance measurements	• Low accuracy • Difficult data management • Not effective in rainy and cloudy weather
ALS	• High density of information • Wide-area coverage (up to regional scale • Can obtain results also in vegetated areas	• Low measurement precisions (cm-dcm) • Generally too expensive for repeat surveys • Not effective in rainy and cloudy weather
TInSAR	• High density of information • High accuracy and precision • Effective in any weather conditions	• Difficult data processing • Unidirectional measurement of deformation • Phase ambiguity
SInSAR	• Monitoring at regional scale (large areas) • Analysis of historical deformation (since 1992) • High information density	• Low temporal frequency • Unidirectional measurement of deformation • Low spatial resolution
PSInSAR	• Monitoring at regional scale (large areas) • Analysis of historical deformation (since 1992) • High information density under favourable conditions	• Sensitivity to land cover conditions • Unidirectional measurement of deformation • Limitations on detectable displacement velocity
RTS	• High accuracy and precision • 3D monitoring • Easy to use	• Interaction with ground/structure (target required) • Not effective in some lighting and weather conditions (fog, rain, etc.) • Low accuracy at large distances
RRST	• Cost effective • 3D monitoring • Easy to use	• Limited range and incidence angle • Not effective in some lighting and weather conditions (fog, rain, etc.) • Limited number of investigated points
DP	• Simultaneous monitoring of large areas • Cost effective • Analysis of historical deformation	• Low accuracy and precision • Not effective in some lighting and weather conditions (fog, rain, etc.) • Low temporal frequency
D-GPS	• Monitoring of deformation along the three main directions • Effective in any weather conditions • Easy to use	• Strong interaction with ground/structure • Low precision in the short term analysis • Low information density

Tab. 2 - Advantages and limitations of the methods for remote monitoring of displacement or deformation (after MAZZANTI, 2012, modified)

Tab. 3 - Remote sensing methods: qualitative rating of the main relevant features (after Mazzanti*, 2012, modified)*

	Precision	Temporal resolution	Spatial resolution	Density	Deformation geometry	Interaction	[illegible] monitored area	Operability range	Data reliability	Atmospheric noise	Costs
TLS	Medium	Medium	High	Ext. High	Medium	Ext. High	High	Medium	High	Ext. Low	Ext. Low
ALS	Low	Ext. Low	Medium	Ext. High	Ext. Low	Ext. High	Ext. High	High	High	High	High
TInSAR	Ext. High	Ext. High	Medium	High	Ext. Low	Ext. High	High	High	High	High	Ext. Low
SInSAR	Medium	Ext. Low	Ext. Low	Medium	Ext. Low	Ext. High	Ext. High	Ext. High	Medium	Ext. Low	Ext. Low
PSInSAR	High	Medium	High	Medium	Low	Ext. High	Ext. High	Ext. High	Medium	Ext. Low	Low
RTS	Ext. High	High	High	Medium	Ext. High	Medium	Medium	Medium	High	Medium	Medium
RRST	High	High	High	Medium	Ext. High	Ext. High	Ext. Low	Ext. Low	Medium	Ext. Low	High
DP	Ext. Low	Medium	Medium	High	Medium	Ext. High	High	High	Ext. Low	Ext. Low	Ext. High
D-GPS	High	High	Ext. Low	Ext. Low	Ext. High	Ext. Low	High	Ext. High	High	High	Medium

Ext. Low | Low | Medium | High | Ext. High

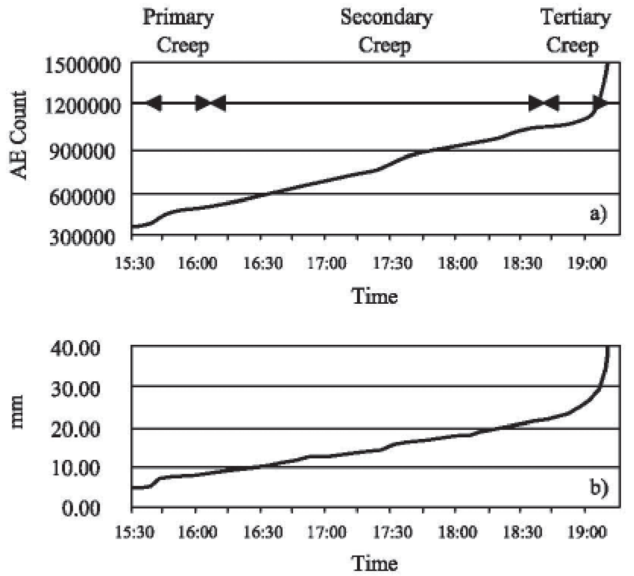

Fig. 9 - Comparison of extensometer results and accumulated AE count (after Fujiwara *et alii, 1999)*

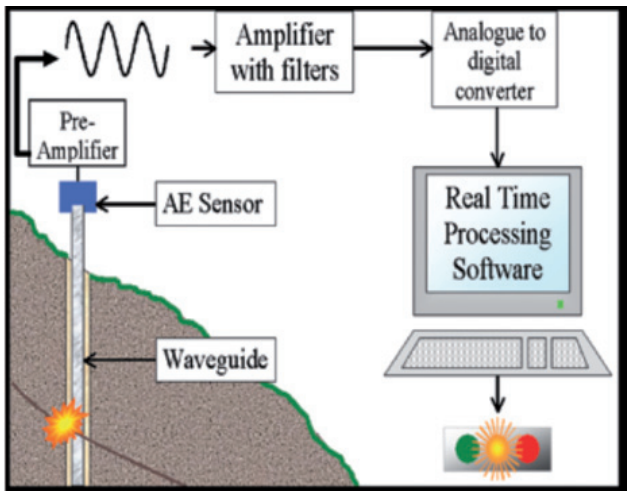

Fig. 10 - Schematic of the AE monitoring system, including active waveguide (after Dixon *et alii, 2003 b)*

and both resemble a typical displacement-time creep curve. Application of rate process theory to AE activity gives better results than techniques based on graphical analysis (Shiotani & Ohtsu, 1999).

However, the technique has two shortcomings: the levels of AE in fine-grained soils during shearing are very low (Koerner *et alii*, 1981) and even in relatively noisy soils (i.e. coarse-grained soils) attenuation may be high as a consequence of local energy losses when AE is transferred from one particle to another. To improve the detection of AE when dealing with deep soil strata, Kousteni (2002) and Dixon *et alii* (2003a) proposed using of active waveguides which consist of a steel tube installed in a pre-drilled borehole with a coarse-soil backfill placed around it. The steel of the waveguide transmits the signal generated by the soil deformation with low attenuation to a sensor at the ground surface (Fig. 10).

This technique is very promising and, being very sensitive to small pre-failure slope deformations, can be used specifically as an early-warning system. Based on the analysis of Lamb wave arrival times, Dixon *et alii* (2003b) developed a method to locate the AE sources along the waveguide; once the loci of these sources are identified, a developing or existing reactivated shear surface can be located. The technique has been further improved to quantify the displacement rate and to locate a developing or existing reactivated shear surface (Spriggs, 2005; Dixon & Spriggs, 2007).

Originally developed to locate breaks and faults in communi-

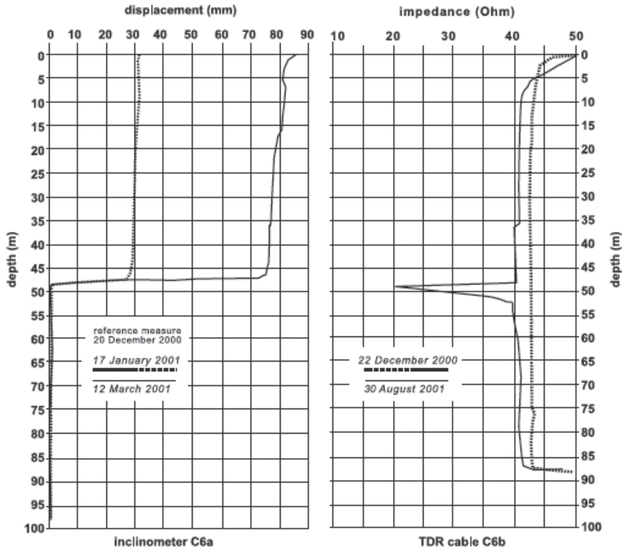

Fig. 11 - Comparison of inclinometer and TDR measurements (after CORSINI *et alii, 2005)*

cation and power lines, Time Domain Reflectometry (TDR) has been extended to the monitoring of slope movements (KANE & BECK, 1994; MIKKELSEN, 1996; O'CONNOR & DOWDING, 1999). The technique consists of logging the impedance to a pulsing electronic signal along a coaxial cable. The impedance changes are correlated with the distortions of the cable, such as crimping or shearing due to rock deformations. Therefore, by installing either vertical or horizontal cables in slopes, movements of slip planes, shear zones and tension cracks can be easily detected. The location of the TDR cable spikes correlates with the zone of movement and the rate of spike growth correlates with the rate of slope movement (Fig. 11).

TDR cables have longer time efficiency than inclinometers and their functionality is rarely compromised. A significant advantage of TDR, as well as of AE, is automatic data acquisition, even remotely.

PREDICTION IN THE ABSENCE OF HISTORICAL SERIES OF MONITORED DATA

The use of the above-described predictive approaches requires long-term measurements of slope displacement or deformation. However, sometimes it is necessary to evaluate the behaviour of an unstable slope even when long-term measurements are not available.

A number of case histories of landslides, with well documented temporal evolutions of recorded displacements, are reported in the literature. In this study, the last monitored values of acceleration $(\ddot{\eta}_f)$ and velocity $(\dot{\eta}_f)$ before failure were derived from the displacement time histories of different case studies. The obtained values, reported in a log-log plot, were found to be scattered along a straight line (Fig. 12) whose equation

$$\ddot{\eta}_f = 0.048\dot{\eta}_f^{1.54} \tag{15}$$

is formally equal to Equation 2 from FUKUZONO (1985) and similar to the equation derived by FUKUZONO & TERASHIMA (1982) from tests on small-scale models.

This plot can be of practical use when historical series of slope displacements are not available: indeed, it indicates a probable imminent collapse if the representative point of the current slope's kinematic situation - which can be obtained using just three temporally spaced measurements - is close to the straight line.

EXAMPLES OF APPLICATION OF THE FUKUZONO METHOD

The formulation by FUKUZONO (1985, 1989 and 1990), implemented by Voight, is universally known as the FUKUZONO's method or the "*inverse velocity method*". It is the most commonly applied predictive method and is based on the consideration that when the mean velocity of slope surface displacements becomes high, its inverse tends to zero. Therefore, the intersection of the curve $1/\dot{\eta}$ with the abscissa represents the time of maximum velocity, that is the time t_f of the slope collapse.

The analysis of slope surface displacements on different time windows along with the use of straightforward statistical methods can further increase the potential of the Fukuzono method (ALLASIA *et alii*, 2013; MANCINI & GIORDAN, 2014).

In the following, several applications of this method will be briefly described.

SUCCESSFUL PREDICTIONS

A well known example of "post-factum" or backward prediction (an oxymoron) using the Fukuzono method is the Vajont landslide (Fig. 13).

Figure 14a illustrates the monotonic curve of increasing slide velocity for the last phase of pre-failure movement at Vajont. In this, the displacement velocities for survey points 5 and 63 for the last 68 days before the failure are plotted versus time.

The same data are replotted as the reciprocal of the displacement velocity versus time in Fig. 14b, where, even the simplest extrapolation technique indicates, with the benefit of hindsight, that the catastrophic Vajont failure of 9th October, 1963 could have been forecast more than a month and a half before this date. As is well known, the slide created a surge of water in the reservoir, overtopping the dam and killing more than 2000 people.

The comparison of figures 14a and 14b shows the clear predictive advantage of plotting the reciprocal of displacement velocity against time instead of using the hyperbolic curve of displacement velocity against time (HUTCHINSON, 2001).

Anyway, this method has had a number of successful and useful applications with both natural and man-made slopes.

The case of a coal mine waste dump failure prediction is reported by HUNGR & KENT (1995): the dump failure, monitored by

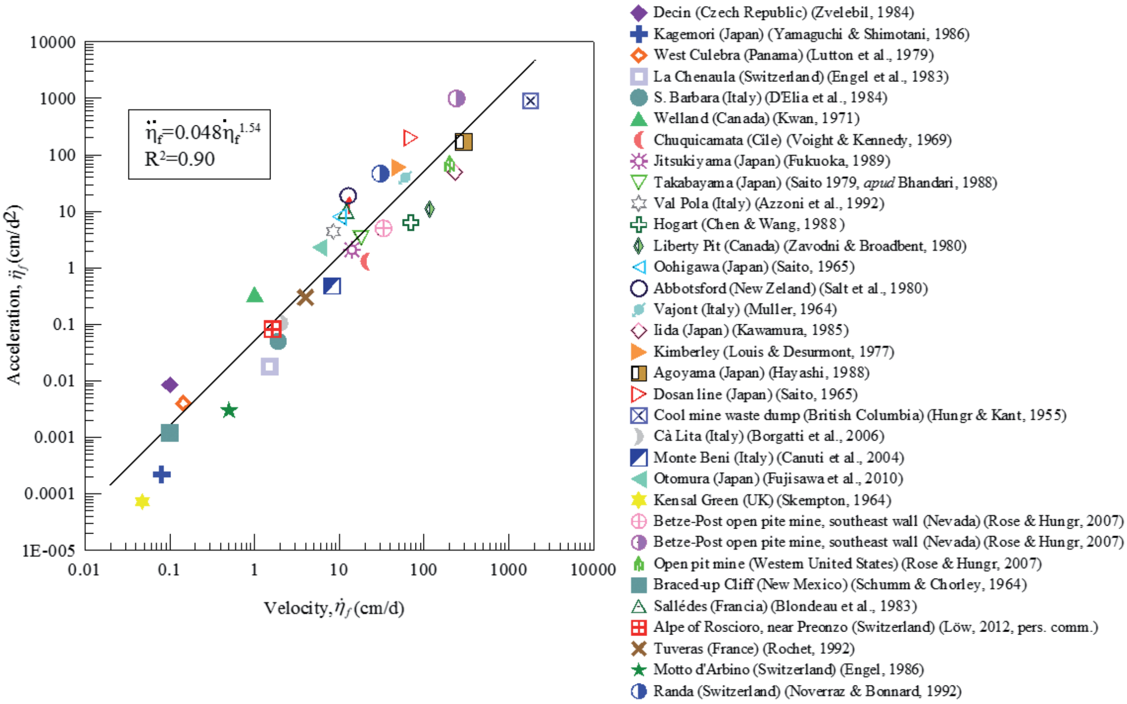

Fig. 12 - Slope velocity ($\dot{\eta}_f$) against acceleration ($\ddot{\eta}_f$) before failure for a number of landslides

Fig. 13 - The Vajont landslide (Italy) (courtesy of Prof. Paronuzzi)

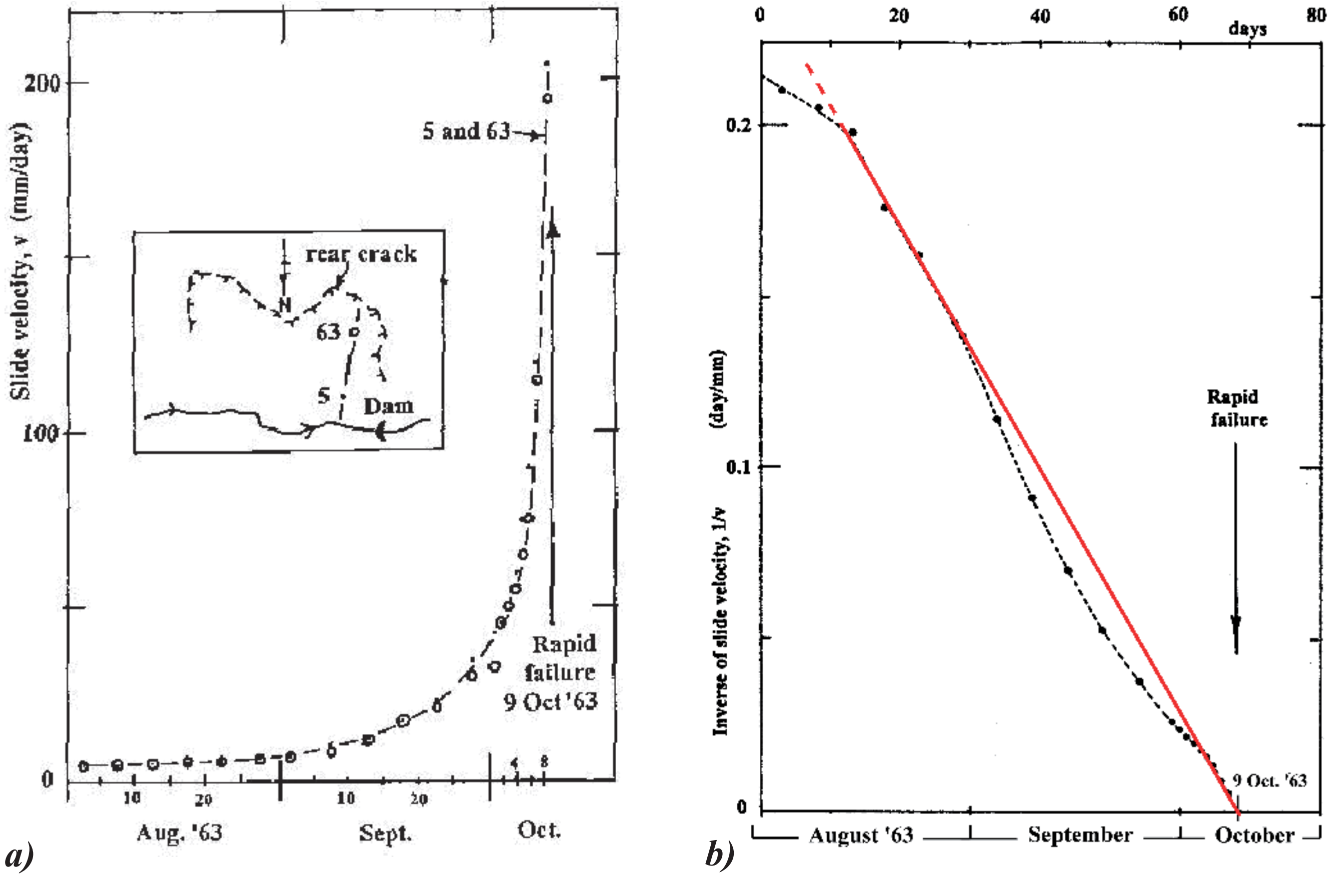

Fig. 14 - "Post-factum" (after-fact) prediction of the Vajont landslide.
a) Displacement velocity versus time (after Leonards*, 1987, modified apud* Hutchinson*, 2001)*
b) Application of Fukuzono*'s method (after* Hutchinson*, ibid., modified)*

Fig. 15 - The Mount Beni landslide (courtesy of Prof. Casagli)

means of simple wire extensometers, involved 3 million cubic meters of mine waste material.

A prediction was carried out on Mt. Beni (near Florence, Italy) relative to a landslide that occurred on its eastern flank on December 28th, 2002 (Fig 15) (Gigli *et alii*, 2011).

The collapse was preceded by several forewarning signals. An automatic monitoring system was immediately put in place. Due to the fast movements, most of the rockslide body was not accessible for the installation of benchmarks, with the exception of the upper area. For this reason, it was decided to employ a remote sensing technique based on radar interferometry (in particular, the GBInSAR technique), which allowed the highly precise definition of the boundaries of the moving mass and the evolution of the movement in space and time, as well as the magnitude, failure mechanism and the runout distance of the rockslide.

The monitoring system at Mt. Beni started in April 2002 and was carried out until December 19, 2002, just nine days before the main event, when it was ceased for safety reason and benchmark damage. It allowed an accurate forecast of the time of failure (Fig. 16), providing public authorities with all the necessary information to plan suitable measures for risk management and reduction.

Rose & Hungr (2007) presented three case histories of open cast mines in the United States, monitored during mining operations with manual and robotic total station surveys and wireless extensometers, where t_f was forecast . Moreover, the same authors

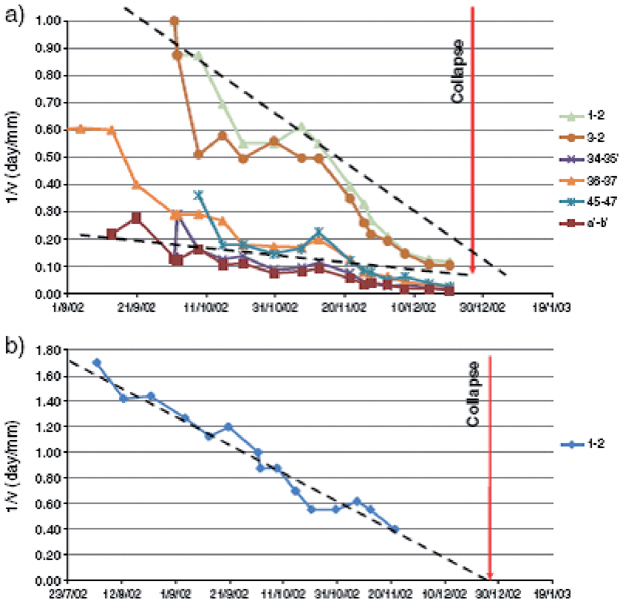

Fig. 16 - Time of failure forecast for Mount Beni landslide: a): most sensitive baselines; b): distometric base 1-2 (after Gigli *et alii, 2011)*

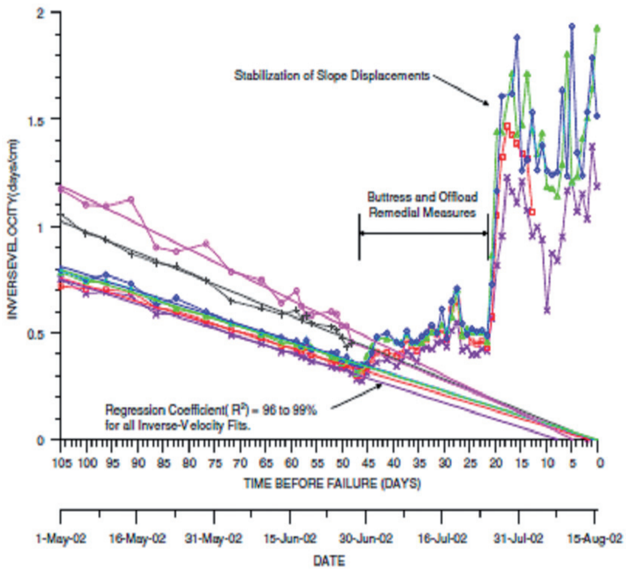

Fig. 17 - Plot of inverse velocity versus time for six targets located on the upper slope of Betze-Post (Nevada) open pit mine (after Rose *&* Hungr*, 2007)*

presented a set of useful general rules for the use of the Fukuzono method, together with an example of the method's usefulness in planning remedial countermeasures for an unstable rock slope, using threshold velocity values based on the predicted t_f. This example concerns the instability of 3-10 Mm^3 of rock on the north-east wall of the Betze-Post (Nevada) open pit mine. From early May to late June 2002, slope movements within the Midnight/Pats complex wedge exhibited accelerations. Fig. 17 shows the plot of inverse velocity versus time for six targets located on the upper slope, where a consistent linear trend is clear and indicates a possible failure time of early to mid August 2007.

On the basis of this observation, it was decided to stabilize the slide by unloading the active part and loading the foot of the complex wedge.

A threshold movement rate ($\dot{\eta} = 2.5$ cm/d or $1/\dot{\eta} = 0.4$ d/cm) was selected for remediation activities to ensure that construction and operation would be completed with a two-week buffer period prior to failure, if it were to occur. As the graph shows (Fig. 17), approximately 3 days after construction started, a significant shift in the trend could be detected, as the slope began decelerating. Remediation activities were carried out without causing significant disruption to the mine and continued over a period of about 3 weeks, until slope displacement rates stabilized to acceptable levels.

The case of the Otomura landslide (Japan) (Fig. 18a) (Fujisawa *et alii*, 2010) is a textbook example of operative emergency planning. In January 2004, cracks were found in retaining walls along national highway 168 near Otomura village in Nara Prefecture (Japan). Given the strategic role played by this road as a long distance route for passenger vehicles and trucks, field and aerial surveys of the site were carried out soon after appearance of the first geomorphologic evidence of landslide movements and surveying and monitoring systems were immediately activated in order to guarantee safe transit to vehicles. The monitoring system consisted of a warning device based on extensometers (alarm threshold of 2 mm/h for two continuous hours) and real time automatic data acquisition system capable of managing possible alert situations, thus allowing vehicle circulation to be blocked and evacuation of the population from the areas at risk. A road was constructed on the opposite bank as a diversion for the worst case scenario of the landslide actually occurring and was opened on August 9th. On August 10th a large typhoon-triggered landslide occurred with a forecast of the collapse some hours in advance (Fig. 18b). Thus, no people were affected and damage was kept to minimum. The time of failure was quite precisely predicted using the data recorded by the installed extensometers.

It is interesting to note that, besides the Fukuzono method, the prediction was also carried out using the Saito relationship (eq. 1) between strain rate in the tertiary creep phase and the residual time to failure with almost the same precision.

More recent prediction examples regard the Preonzo (Swiss Alps) landslide (Loew, 2012, pers. comm.) and a landslide in the Copper Bingham Canyon Mine[4] (southeast of Salt Lake City, Utah, USA) landslide (Fig. 19), occurred on May 15th, 2012 at 11:30 am and on April 10th, 2013 at 9.30 pm, respectively.

[(4)] *Known also as Kennecott Copper mine, it is the largest man-made excavation in the world. It has been in production since 1906, and features a pit almost 1 km deep and 4 km wide*

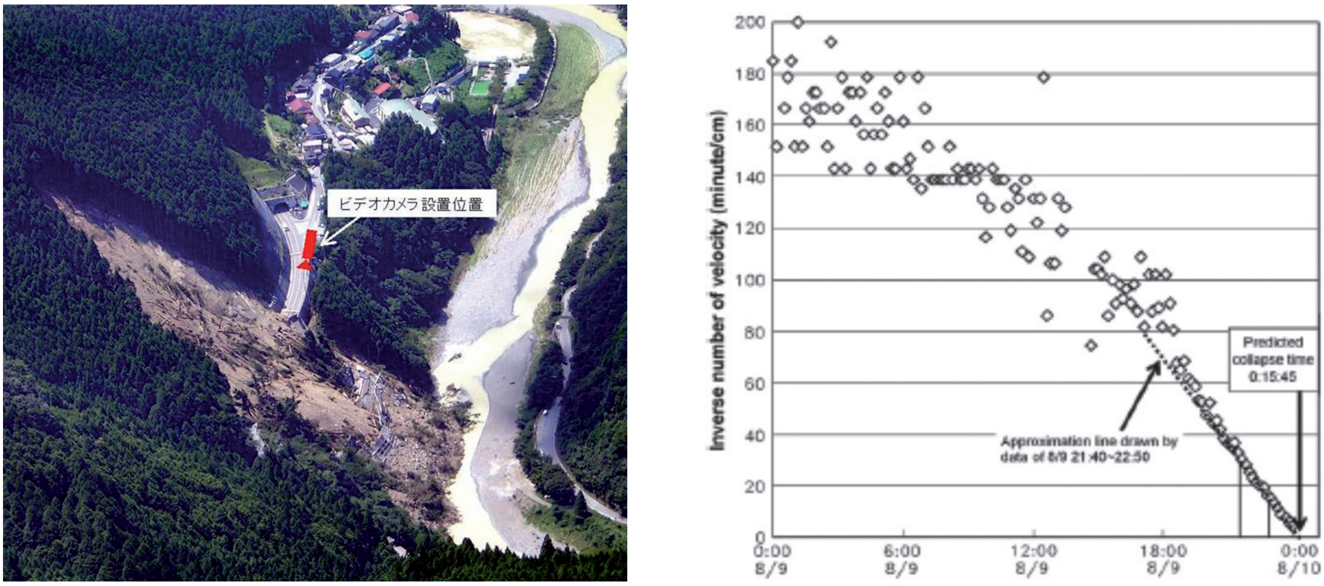

Fig. 18 - a) Otomura landslide (courtesy of Dr Pasuto); b) Plot of inverse velocity versus time for Otomura landslide (after Fujisawa *et alii, 2010)*

Fig. 19 - Copper Bingham Canyon Mine (USA) landslide (after news. yahoo.co)

The above case histories are characterized by a pattern of surface displacement that is continuous in its evolution and is described by a smooth concave curve, typical of an accelerating creep phase, essentially due to a ductile failure of the affected rocks and soils. When the slope failure has a brittle character, especially if it involves strong rock masses, the displacement records may have a step-like shape, characterized by instantaneous and abrupt jumps in short time intervals and nearly constant values over long periods. In those cases, the inverse-velocity method for the t_f prediction is harder to apply (Rose & Hungr 2007), even though the displacement-time diagram can give indications of the probable overall trend.

(POSSIBLE) UNSUCCESSFUL PREDICTIONS

As already said, given the empiric and phenomenological character of the Fukuzono method, its application does not require a detailed analysis of the factors which contribute to the evolution of deformations until the collapse. Nevertheless, as pointed out by Hutchinson (2001),failures may exhibit quite irregular pre-failure movements, particularly when further variables are introduced by changes in internal or external conditions. For these reasons, as several examples show, its use can result in greatly inaccurate predictions. The first example refers to the already described Vajont landslide, where, as thoroughly documented by Hutchinson (*ibid*.) "*...increases of slide velocity with time, somewhat similar to those of October 1963, occurred in the autumn 1960 and in late 1962,but in neither case leading to rapid failure. Had anyone been plotting data such as those prior to the 9th October 1963, they may have been influenced by these earlier records into thinking that the rate of movement would again diminish without failure being reached.*".

A second and equally impressive example of an unpredicted trend break in the evolution of a landslide is given by the unusual kinematic behavior of the la Clapière landslide (Maritimes Alps, France) (Fig. 20), which is probably the biggest active landslide in Europe. Its surface displacements have been monitored since 1982.

As Fig. 21 shows, to a long phase of increasing of displacement velocity peaked at more than 80 mm/d in 1987, an unexpected trend reversal followed, with a slow return to a more reassuring velocity of 20 mm/d in 1988. Currently, the most active part of the rockslide shows a movement of about 0.4 m/y, slower than the rate of several m/y recorded during the late 1980's (El Bedoui *et alii*, 2009).

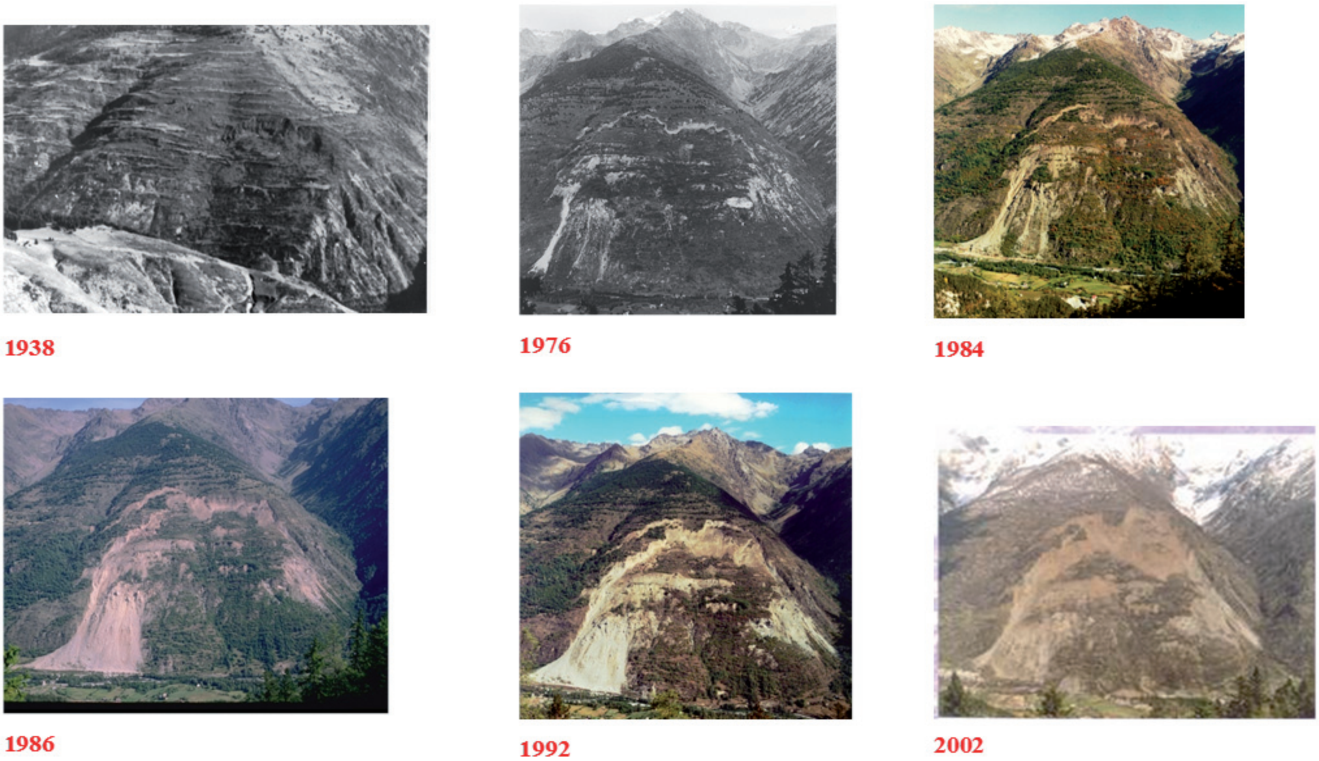

Fig. 20 - Development of La Clapière landslide since 1938 (courtesy of Prof. Marinos)

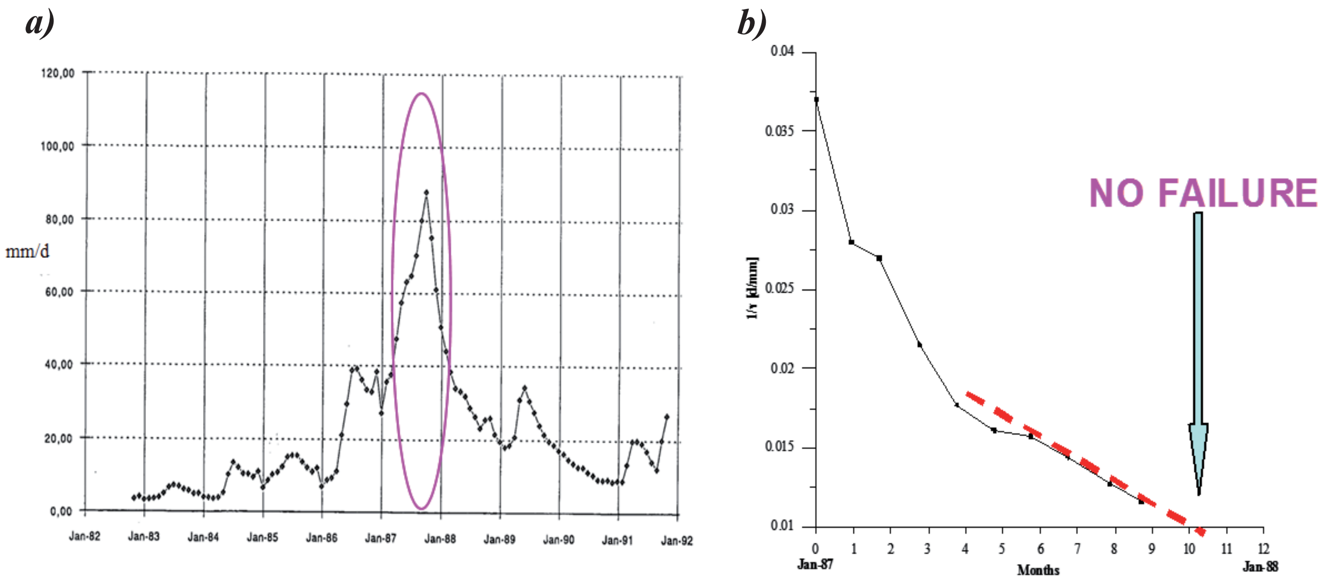

Fig. 21 - a) Displacement velocity versus time (after Rochet*, 1992, modified); b) Inverse of displacement velocity versus time in the period january 1987-January 1988*

Theoretical speculations (Helmstetter *et alii*, 2003), based on a friction law function of velocity, seem to account for the singular behavior of this landslide as well as of the catastrophic outcome of the Vajont landslide on October 9th, 1963. The theoretical interpretations of Kilburn & Petley (2003) are also important in this regard.. Anyway, the trend to self-stabilization of the la Clapière landslide

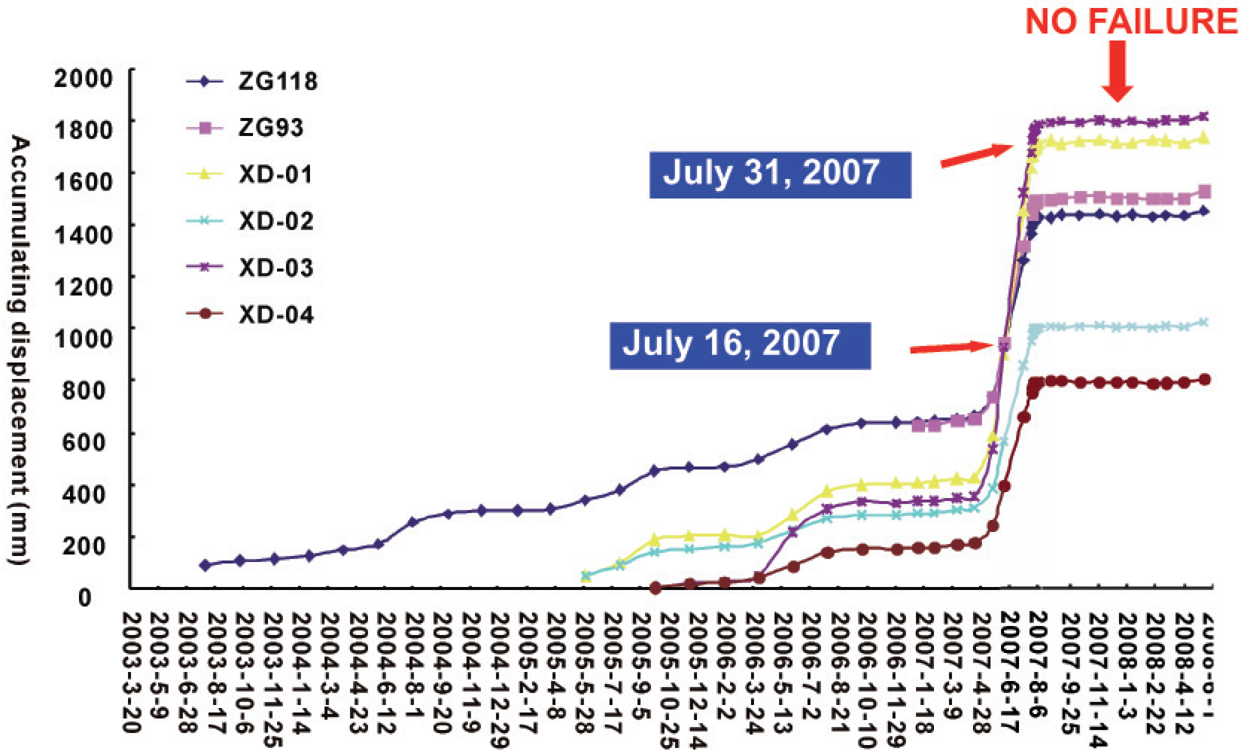

Fig. 22 - Cumulative slope displacement versus time of Baishuihe landslide (courtesy of Prof. K. Yin)

may be, more simply, the effect of the displacements themselves[5] as well as of the soil masses deposited by the constantly collapsing toe of the slide which assist the stability (Nieuwenhuis, 2002).

Equally surprising is the trend breaking (Fig. 22) of displacements - due to the combined effects of rain and drawdown - of the Baishuhe landslide (China), 56 km uphill of Three Gorges dam along the Yangtze river (Li *et alii*, 2010).

The application to these cases of any one of the prediction methods would have resulted in a mistaken disaster prediction.

DISCUSSION AND CONCLUDING REMARKS

There is a rich technical literature on the prediction of the time of failure t_f of a slope and a general framework for the prediction of t_f has been herein presented.

The methods for forecasting impending slope failure, briefly discussed in this paper, are empirical and phenomenological, generally relying on surface-based point measurements of displacement/deformation monitored overtime. Inherently, this approach is "holistic" (Eberhardt *et alii*, 2008), disregarding the mechanical behaviour of the soil and the influence it has on the development of the landslide, the actual boundary conditions and details pertaining to the underlying slope failure mechanism.

The lack of any direct relation to the physics of the phenomenon means that the results of these methods would be mainly of academic interest, especially when the parameters involved have a limited period of variation in comparison to creep duration. In such cases, the inverse-velocity method should be applied with caution, extrapolating the recorded data over varying time intervals where the trend looks consistent, thus avoiding long-term predictions (Rose & Hungr, 2007).

Regardless of the technique used for extrapolating the time to failure, the quality of the prediction clearly depends on the quality of the data, and correct identification of the critical points or parameters selected for the monitoring is thus essential in order to produce a reliable prediction. This implies the need for more progress in understanding pre-failure deformations and other precursory signs of various landslide mechanisms (Fell *et alii*, 2000). To this aim, the help offered by advanced remote sensing methods can be considerable.

(5) Verruijt (1995) drew attention to the stabilizing effect of the downslope movement of slides along circular surfaces. He considered the Bishop's method and added a new formula for a slide displaced over an angle of rotation β (measured at the centre of the slip circle). Nieuwenhuis (ibid.) considered the last 8 m of the monitored 40 m of displacement, representing the displacements of the second half of 1987. This displacement implies β=1°. A crude application of the Verruijt analysis shows that the factor of safety varies from F=1.010 to F= 1.029, with an increase of 1.9%.The stabilizing effect described by Verruijt is strong enough to break the trend and slow down the la Clapière slide in its 1987 condition

Emphasis has been placed on Acoustic Emission and Time Domain Reflectometry because they appear particularly promising.

In several methods the frequency of the observations as well as the time span of data collection affect the reliability of the prediction.

In addition to the displacements, the observations would need to be extended to other parameters such as pore pressure and crack aperture.

All the methods reviewed in this paper neglect small variations in the influencing factors. This leads to a serious limitation when dealing with predictions in the long-term. Chaos theory was applied by Qin *et alii* (2001) to determine the time scale for which the prediction is reasonable and to refine the prediction within a specific time scale with its relative error. According to these authors, long-term predictions are strongly influenced by chaos and therefore cannot be accurate. Medium-term prediction can be accomplished by means of deterministic methods but nevertheless they introduce uncertainty. Critical prediction, performed close to failure when there is strong instability, is relatively accurate, given that the influence of chaos is minimized.

Expert visual examination of the plots of the monitored data makes it possible to roughly assess the current creep stage of a slope. If this stage is tertiary creep, the slope is in a critical condition, close to failure, and the confidence of the prediction should be high, because of the reduced impact of factors causing unpredictability.

In this respect, within the above mentioned limits, the plot in Fig. 12 could have practical usefulness.

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