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Discontinuum modelling of slope instability as a support tool for risk management

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ABSTRACT: The definition of threshold values within an early warning system for monitoring of an instability phenomenon in nearly real time represents a key step. Several approaches exist in literature, among which numerical modelling for the simulation of instability scenarios is the least common. The present paper illustrates how discontinuum numerical modelling can be used as a support tool for risk management with reference to a slope instability case study. The aim is to investigate the displacement rate that can anticipate the instability phenomena. To highlight the reliability of the models, back-analysis of a past instability event is carried out and a time-scaling coefficient is defined, and eventually validated, to match numerical results and monitored data. Based on such results, that reproduce the slope displacement trends from triggering to collapse, thresholds and related timespans to be adopted within the existing monitoring system are suggested.

Keywords: Slope Stability, Discontinuum Modelling, Risk Management, Thresholds.

1 PROBLEM FRAMEWORK

Landslide risk management relies increasingly on the prompt protection against damages of the elements exposed to risk, such as buildings, infrastructures, industrial plants. In this framework, Early Warning Systems (EWS) and adoption of procedures are efficient tools that can be used to mitigate this risk by keeping away people from dangerous areas with a sufficient lead time in case of expectation of an imminent collapse. A reliable forecast of the collapse of landslides is however problematic since large rock slope deformations are very often characterized by a non-linear behavior. Not all rock slope instabilities obviously lead to rapid and catastrophic failures according to the classical evolutionary creep theory of landslides (Saito 1969, Varnes 1982, Cruden & Masoumzadeh 1987) but many of these diverge from the theoretical trend and remain characterized by slow or extremely slow continuous movements while still others can show intermittent behavior over long periods with acceleration and deceleration phases. Data collected by monitoring networks, in terms of displacement, velocity and acceleration can therefore provide useful indications about the short-term prediction of a slope failure (Rose & Hungr 2007) but, to manage and mitigate the risk for the exposed elements, a critical element needed is the definition of specific thresholds for relevant monitored quantities able to anticipate the occurrence of such phenomena.

In literature (Fukuzono 1985, Cruden & Masoumzadeh 1987, Crosta & Agliardi 2003, Voight 1988, 1989) different approaches have been used for the definition of these thresholds, among which: site-specific empirical or semi-empirical correlations between different measured quantities, analysis of monitoring data with regard to previous collapse events, general correlation laws such as the inverse velocity method and rainfall intensity-duration, probabilistic models such as the discriminant analysis of rain events, advanced numerical modeling and expert judgment.

In this paper, a new methodology based on numerical modelling was used to identify the displacement rate of specific monitored points along the slope that can anticipate the collapse thus defining a set of velocity thresholds to be used in the EWS.

2 SCOPE AND METHODOLOGY

To define thresholds in terms of velocities discontinuum numerical modelling was adopted to investigate the displacement rate that can anticipate the instability phenomena.

The methodology adopted is described in the flow chart shown in Figure 1. The starting action is the extensive geological and geotechnical characterization of the site, including stress and hydraulic state assessment to build a simplified conceptual representation of the reality, i.e. the representative geotechnical model. Based on this information, which also include the most reliable geometry and characteristics of the slope, a representative numerical model can be built. As anticipated, in this case the Distinct Element Method (DEM) was used. The numerical model is used to study instability and different possible triggering conditions of the slope, i.e. due to hydraulic, seismic, gravitational and/or rheological forces and produce different scenario analyses aimed at identifying the displacement rates that can anticipate the development of instability phenomena.

The availability of reliable monitoring data is of paramount importance to validate (or calibrate) the numerical model. If possible, a back-analysis of a past instability event can be carried out with the discontinuum numerical model to assess the reliability of the numerical assumptions and the capability of the model to properly reproduce the observed phenomenon.

In the case under investigation, based on the comparison with monitoring data, a time-scaling coefficient is defined, and eventually validated, to match numerical results and monitored data. Based on such results, that reproduce the slope displacement trends from triggering to collapse, warning, alert, pre-alarm and alarm thresholds, to be adopted within the existing monitoring system, are finally identified to be used with the monitoring system at the site.

Through the present work we therefore propose a method to move from the definition of the thresholds based on the mere observation of the phenomenon to that also allowed by the analysis and modeling of the mechanical behavior of the slope, to broaden the confidence both with respect to the threshold values and with respect to the early warning and deceleration times adopted today.

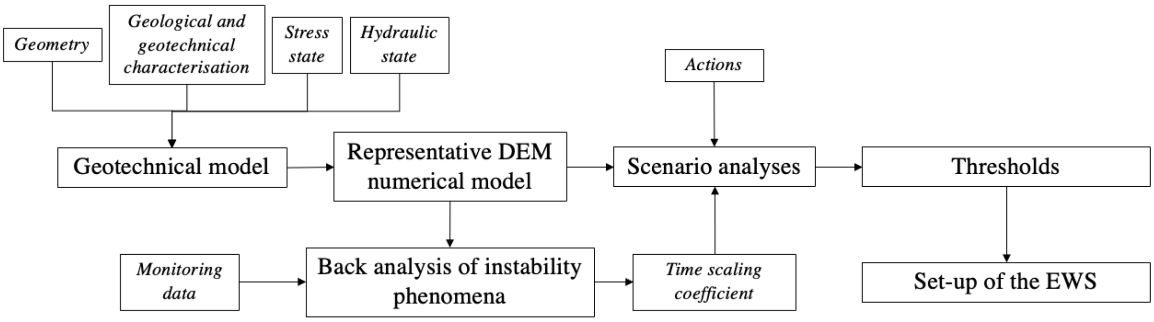
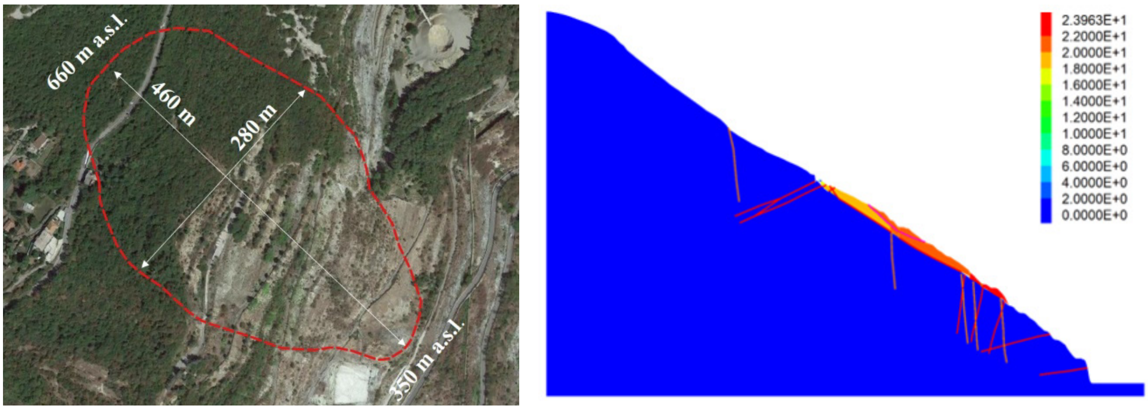


Figure 1. Flow chart describing the methodological approach proposed.

3 DESCRIPTION OF THE CASE STUDY

The case study is represented by an active rockslide that originated on a steep depleted quarry face. The rock mass in the area is constituted by medium to thin stratified limestones and marly limestones with marls interlayers. From a structural point of view, the rock mass is blocky i.e., characterized by the presence of two different discontinuity families (K1 and K2), the bedding planes (ST), and a set cleavage surfaces (CV). The extensive monitoring system as well as the in situ geomorphological and geotechnical surveys carried out have allowed the identification of the landslide boundaries both on the surface and at depth. Figure 2a shows the approximate extension of the unstable slope sector (100,000 m^2) which moves along a well-defined sliding surface, corresponding to an inclined bedding plane (on average 30°) located between 10 to 55 m from the surface. The mean thickness of the sliding mass is about 22 m while its estimated volume is about 2.1 Mm^3. In the middle-upper slope sector, the groundwater is generally absent inside the rock mass. Only in the basal portion of the slope (350-360 m a.s.l.) it is possible to infer the presence of saturated but discontinuous rock mass horizons developed above impervious marly-clayey interlayers due to the presence of some intermittent springs characterized by a limited discharge.



a) b)

Figure 2. a) View of the depleted quarry face with the localization of the 2.1 Mm^3 rockslide and b) total displacements (in meters) obtained at the end of the analyses with hydraulic triggering.

4 NUMERICAL STUDY OF THE SLOPE BEHAVIOUR

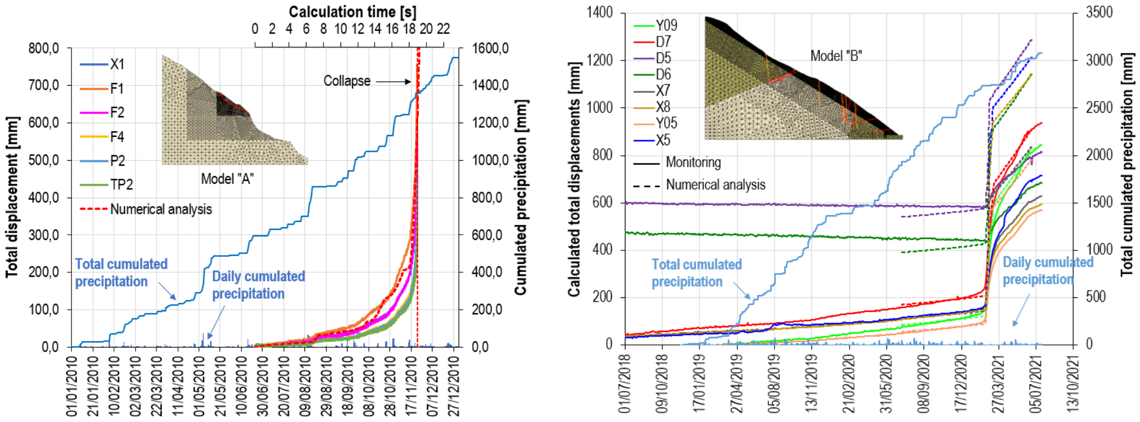
In this chapter the results of the numerical analyses carried out, in the framework of the methodological approach described in Chapter 2, will be illustrated with the aim to understand the slope behavior and to infer useful information for the definition of the thresholds and the timespans for the early warning system discussed in Chapter 5.

4.1 Back analysis of a past instability event and definition of a time-scaling coefficient

Before studying the possible triggering conditions of the slope, a two-dimensional model of a representative section of a past instability phenomenon (model “A”), observed at the site, was created according to the discontinuous approach (DEM) using the UDEC software (Itasca Consulting Group, 2019a). Based on the displacement data recorded by six optical targets and on the cumulative daily and total precipitation (see Figure 3a), it can be observed that an unstable block had an almost constant speed up to a certain date after which, due to the intense and prolonged precipitations, it accelerated suddenly and then settled back to the initial speed. Eventually, almost one month later, its speed increased to inexorably higher levels until the collapse.

In light of these observations, the numerical model was aimed at back-analyzing the commented data. First, the quarrying of the slope was simulated and the block resulted in equilibrium. Then, cohesion was reduced to try to reproduce the first phase of the phenomenon observed on site. In correspondence of sudden speed changes, a specific groundwater level determined with a trial-and-error procedure was introduced and then removed. The result obtained in terms of total displacement as a function of calculation time is shown in Figure 3a. However, it is worth pointing out that the calculation time in the static analyses of codes with a discontinuous approach does not coincide with real time (Itasca Consulting Group, 2019b). In fact, in order to increase the timestep and reduce the computational time, the resolution algorithm applies fictitious damping without which, not only would the computation time greatly increase, but it would be difficult to even reach a stationary solution.

Given the unrepresentativeness of time in the obtained numerical results and in order to be able to perform an appropriate comparison with the monitoring data, the calculation time was artificially amplified by means of a specially calibrated time scale coefficient equal to 700 000, i.e. about 8.1 times the seconds in one day. The comparison between the displacements calculated with the amplified time by means of the aforementioned scale coefficient and those measured by the monitoring system is reported in Figure 3a. The overlap between monitored data and calculated displacements appears very satisfactory.



a) b)

Figure 3. Monitored displacement data, total and daily cumulated precipitation and calculated total displacement as a function of numerical time and of scaled time for a) a past instability event and b) a recent instability event observed at the site.

4.2 Validation on a recent instability event and collapse scenarios

The time-scaling coefficient evaluated on the past instability event was validated considering a more recent instability event occurred to check its uniqueness. The instability triggering factor considered is of hydraulic type. A new DEM numerical model was built for the section under study and, as before, the quarrying of the slope was simulated in order to obtain the initial stress-strain state (model "B"). The optical targets measurements showed an approximately constant velocity trend. Therefore, after some attempts, the cohesion was degraded from 36 kPa to 30 and 29 kPa in the calculation model. With such values it was possible to reproduce the phase before the instability in a sufficiently precise way. Later, a specific groundwater level was included in the analysis, which after a predefined number of calculation steps was gradually lowered until it was completely cancelled.

Figure 3b shows the result obtained from the computation. The result of the monitoring (continuous line) and the computation (dashed lines) are compared with the same colors. The cumulative daily and total precipitation are also superimposed for a better reading. Despite some slight inconsistencies, the comparison is quite good and it is believed that the time-scaling coefficient adopted is sufficiently reliable and can be reasonably used for defining the thresholds and the related timespans.

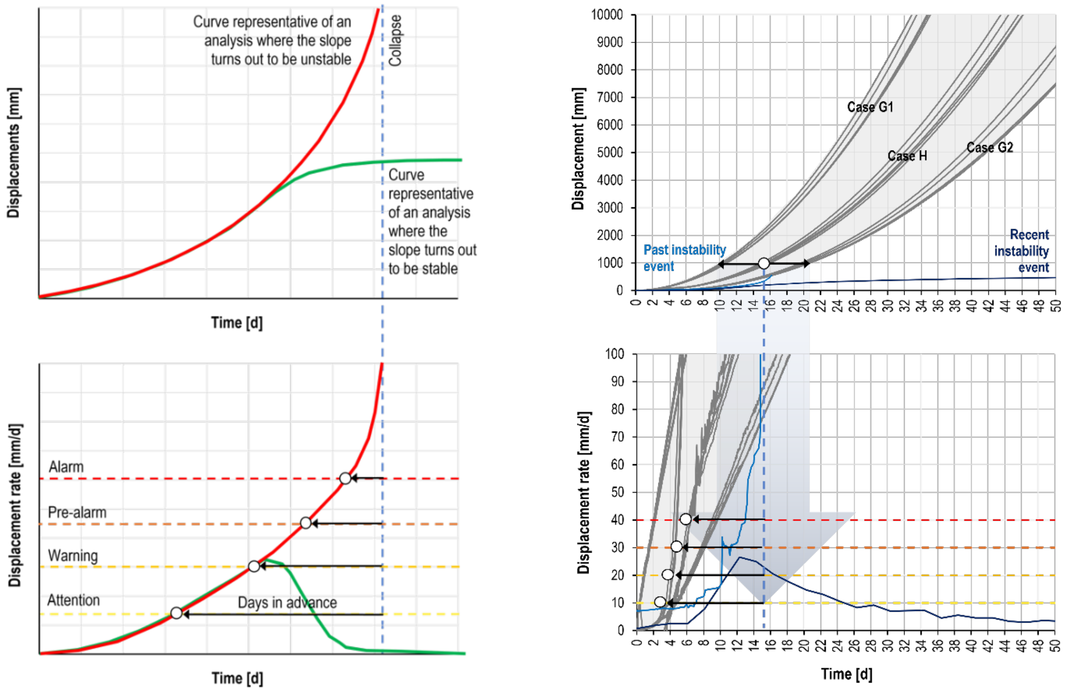
Starting from the stress-strain state obtained at the end of the discontinuous 2D analysis of model "B" in the presence of a slip surface and absence of water, some hydraulic (H) and gravitational (G) triggering elements were considered to evaluate the slope stability conditions. About the former (hydraulic triggering), a high level of groundwater was inserted and maintained to study the stability of the deep landslide (case H). About the latter (gravitational triggering), the strength parameters of the landslide were nulled (case G1) or progressively reduced (case G2) until a factor of safety of 1.2 over one-week time (intended as real time).

The results expressed in terms of displacements at the end of the analyses characterized by a hydraulic triggering are shown in Figure 2b by way of example. As expected, in the first case the instability involves the entire active landslide. In the second case, only a part of the potentially unstable volume delimited upstream by a subvertical joint is mobilized.

5 DEFINITION OF THRESHOLDS FOR RISK MANAGEMENT

The final step is to synthesize the results gained from the scenario analyses into information to build a reliable EWS. Typically, the EWS management scheme provides the adoption of a certain number of different levels of criticality corresponding to specific risk scenarios, separated by specific threshold values. In this study five levels were taken into account: ordinary, attention, warning, pre-alarm and alarm.

For the application of the EWS system management model, it is necessary to define four speed thresholds expressed in mm/day. The choice of the thresholds and the estimate of the timespans from the exceeding of the different thresholds to the potential collapse of the slope was made by referring to the numerical analyses described in Chapter 4.



a) b)

Figure 4. a) Schematic description of the methodology used to identify the timespans corresponding to different thresholds and b) application to the case study on the basis of the results of the numerical analyses.

Figure 4a schematically depicts the methodology used to determine the alarm times for each threshold. Following a triggering cause, the slope can react either by manifesting a finite permanent displacement (green curve in Figure 4a, top) or by an infinite displacement, i.e. a collapse (red curve in Figure 4a, top). By calculating the displacement rate, the velocity first increases up to a maximum value and then goes back to zero in the first case, whereas it increases continuously in the second case. Having defined a displacement value that we refer to conventionally as representing the collapse, the time (expressed in terms of number of days) when the collapse occurs is known. Hence, moving to the displacement rate chart, the number of days before the collapse can be defined for each specific displacement rate threshold.

Figure 4b shows how the above methodology was applied to the case study herein described. In Figure 4b (top) all the displacement curves obtained numerically following the triggering causes described in Chapter 4.2 are reported, together with their envelope. In all cases the slope reacts with a collapse-like scenario. The achievement of a displacement greater than 1 m was conservatively considered as the instant of collapse, yielding a number of days from the beginning of the instability to collapse of around 16 on average (between 10 and 22 considering the whole envelope). Based on the calculated displacement rate curves, on the value set for the collapse and on the threshold of 10, 20, 30 and 40 mm/d set, it was possible to infer the timespans existing from the attainment of each threshold to the collapse. As anticipated, these times differ in the various analyses performed. The thresholds were identified in such a way as to guarantee the time needed to implement the civil protection actions envisaged at the various levels of criticality.

6 CONCLUSIONS

This paper has illustrated how discontinuum numerical modelling can be used as a support tool for risk management of slope instability. The methodology adopted, starting from an extensive geological and geotechnical characterization of the site, requires the development of a numerical model to study instability and triggering conditions of the slope due to hydraulic, seismic, gravitational and/or rheological forces and produce different scenario analyses to identify the displacement rates that can anticipate the development of instability phenomena.

In the investigated case, the availability of reliable monitoring data was indeed relevant to allow for the validation of the numerical model and assess the capability of the model to properly reproduce the observed phenomenon.

The time-scaling coefficient, defined on the basis of the comparison between monitoring data and computed results, was then used to define warning, alert, pre-alarm and alarm thresholds, to be adopted within the existing monitoring system in an early warning approach.

Through the present work we therefore propose a method to improve the definition of the thresholds based on the mere observation of the phenomenon to that obtained by the analysis and modeling of the mechanical behavior of the slope.

REFERENCES

Crosta, G.B., Agliardi, F., 2003. Failure forecast for large rock slides by surface displacement measurements. *Can. Geotech. J.* 40 (1), 176–191.

Cruden, D.M., Masoumzadeh, S., 1987. Accelerating creep of the slopes of a coal mine. *Rock Mech. Rock. Eng*. 20, 123–135.

Fukuzono, T., 1985. A new method for predicting the failure time of a slope failure. In: *Proceedings of the 4th International Conference and Field Workshop on Landslides*, Tokyo (Japan), pp. 145–150.

Itasca Consulting Group, Inc. 2019a. UDEC Ver. 7.0. Minneapolis, USA.

Itasca Consulting Group, Inc. 2019b. User's Guide. Problem solving with UDEC. Minneapolis, USA.

Rose, N.D., Hungr, O., 2007. Forecasting potential rock slope failure in open pit mines using the inverse velocity method. *Int. J. Rock Mech. Min. Sci*. 44 (2), 308–320.

Saito, M., 1969. Forecasting Time of Slope failure by Tertiary Creep. In: *Proceedings of the 7th International Conference on Soil Mechanics and Foundation Engineering*, Mexico City. vol. 2. pp. 677–683.

Varnes, D.J., 1982. Time-deformation relations in creep to failure of earth materials. In: *Proceedings of the 7th Southeast Asia Geotechnical Conference*, Hong Kong, pp.107–130.

Voight, B., 1988. A method for prediction of volcanic eruption. *Nature* 332, 125–130.

Voight, B., 1989. A relation to describe rate-dependent material failure. *Science* 243, 200–203.