*5th Italian Workshop on Landslides (IWL 2018)*
28 - 30 May 2018, Napoli, Italy

# SHALLOW TO DEEP MOVEMENTS IN CLAYEY SLOPES RELATING TO CLIMATE: FIELD EVIDENCE AND MODELING FOR EARLY WARNING

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The evolution and the reactivation of landsliding in the south of Italy Apennines has been found often prompted by the slope-atmosphere interaction, as recognized through several phenomenological diagnoses (Picarelli et al. 2005, Cotecchia et al. 2014). This interaction has been identified as the triggering cause of the activity of shallow failure mechanisms, as well as the acceleration of deep slow landslide bodies (Cotecchia et al. 2014 and 2015). The latter is the case in particular for slopes formed of structurally complex clay formation (i.e. clayey turbidites) or of slopes location of preexisting landslide bodies. The climate impact has been detected within fissured clay slopes even at large depths (Pedone, 2014). In these contexts, the soil-atmosphere interaction in the very top soil layers has been found to cause transient seepage, which results quite immediate in significant seasonal variation of pore water pressures at very shallow depths, and at larger depth, below the water table (D'Elia et al., 1998; Cotecchia et al. 2014); in this regard case studies have been reported in the Italian Southern Apennines, (Di Maio et al., 2010).

This abstract reports briefly about the results of a broad research concerning the slope phenomena cited above. As first, the studies have pursued the phenomenological diagnosis of the landslide activity relating to climate through i) the monitoring of the climatic variables, of the piezometric heads and the displacement rates across the slope; ii) the modeling of the slope-atmosphere interaction, in terms of effects on the piezometric heads across the slope and on the safety factor of landslide bodies at different depths. Such diagnosis guides the identification of the values of the climatic variables (precursors), and of the pore water pressures (indicators) representing the threshold for the loss of stability (herein threshold values) at different depths in the slope. The research results, therefore, provide a methodological contribution for the design of early warning systems for the mitigation of landslide risk caused by climate. Field evidences of the climate effects on the slope stability are presented with reference to three case studies, the Pisciolo landslide, the Pianello landslide and the Petacciato landslide. Both the Pisciolo and the Pianello landslides involve clayey turbidites (Cotecchia et al. 2014, 2015) and are phenomenologically representative of several landslides south-eastern Apennines. The Petacciato occurs in a different geo-hydro-mechanical scenario and represents an example of deep landslides in clays whose activity is connected to climate. This contribution reports also briefly about the numerical investigation of the pore water pressure variations with time across a representative slope, in relation to representative weather conditions, and hydro-mechanical settings. Numerical FE analyses have been carried out to identify the threshold weather variables to be of reference in early warning systems designed to mitigate landslide risk. The obtained variation in time of the safety factor of landslide bodies of different depth brings into evidence the variability of the alert thresholds with the type of landslide mechanism and the relationships between the alert values and the slope hydro-mechanical features.

The Pisciolo slope is located on the right side of the Ofanto River Valley. It is mainly formed of fissured clays including isolated fractured rocks. This formation overlies the scaly clays of the Red Flysch. Several slow landslides involve both the clays. These have developed since the seventies, according to temporal analyses, and involve materials of physical and mechanical properties thoroughly discussed in Cotecchia et al. (2014, 2015) and in Pedone (2014). Landsliding has maximum rate about decimetres per year (Cotecchia et al. 2014) and causes damage to both the Apulian Aqueduct pipeline and a road located at the base of the slope, where the common toe of the landslides C9, C and A is located. This toe is intercepted by an inclinometer, whose monitoring has given evidence to a shear band at about 17 m depth. The displacement rates have been monitored along this shear band and at ground surface. The piezometric fluctuations as well as the displacement rates at present, which represent reactivation rates, are characterized by a seasonal trend of variation (180-day period); the maximum values occur at the end of winter - early spring whereas the minimum values at the end of summer. The piezometric fluctuations are synchronous with the 180 – day cumulated rainfalls (Cotecchia et al., 2014; Pedone, 2014). Therefore, the piezometric regime and the current landslide activity in the slope is controlled by the seasonal climate changes.

Since its construction in the 70’s the Pianello area, in the Bovino (FG) municipality, have been suffering landsliding. A field monitoring campaign since 1991 has characterized a seasonal activity of an ancient deep landside body, A. The slip surfaces of the sliding body in the Pianello slope has been reconstructed based upon inclinometric monitoring data and analysis of the disturbance degree of the borehole corings. The material involved in this instability mechanism is mainly the Faeto Flysch, a not fissured clay turbidites. Based on historical data, the ancient landslide A is recognized to have been probably caused by river erosion and tectonic uplifting in the Quaternary. Therefore, the recent slope movements represent an evolution of pre-existing slope failure. Since 1984, the landslide activity has been going on, as recognized through the analysis of inclinometer monitoring data referring to 1991 and 2008-2014. Landslide A is moving very slowly (Cruden & Varnes, 1996). The current activity is also confirmed by the monitoring of the damages affecting buildings located about the rear scarps and along the lateral borders (Palmisano & Elia 2014).

Monitoring data give evidence of the seasonality of both the current slope displacement rate variations and the piezometric head fluctuations, since they reach their maximum values about the end of winter-early spring and minimum values by the end of summer (Cotecchia et al. 2014). Besides, the seasonal trend of the piezometric head fluctuations corresponds to that of the 180-day cumulated rainfalls. The piezometric levels recorded within the slope are only few metres b.g.l., becoming higher before the accelerating phases of the landslides. Therefore, they represent a predisposing factor of landsliding. Furthermore, all the monitoring data suggest that the feeding of the underground seepage domain down to large depths, generated by the seasonal infiltration of rainfalls, represents the current triggering factor of the landslide activity.

In a different geo-hydro-mechanical context with respect to the two case studies already presented, the Petacciato large landslide basin occurs on a slope located along the Adriatic coastline, just below the town of Petacciato (CB). This area has been object of a detailed field campaign, with boreholes equipped with either piezometers, down to 119 m depth, or inclinometers and monitoring was on from 1982 to 2004 (Cotecchia et al., 2008). Laboratory testing was carried on undisturbed samples. Stiff Sub-Apennine Blue Clays has been identified as the material mainly composing the slope. Landslide bodies of medium to large depth occur at the slope toe (displacement rate lower than 3 mm/month), which are in turn nested in a far larger and very deep (≅ 100 m) body A. Given the slope gradient and the strength of the clays when undisturbed, the mobilisation of such bodies is possible only if the operational strength along the reconstructed slip surfaces is about residual, according to LE back-analyses. This finding suggests that instability at Petacciato is effect of a reactivation of an ancient landslide. Piezometric monitoring has given evidence to very large piezometric levels at large depths in the slope, higher that those measured at shallow depths. As such, the piezometric heads in the slope are recognised to be a factor impoverishing the strengths available at large depth and predisposing the slope to deep sliding. Similarly, to the previous case histories, this leads to conclude that the seasonal reactivation of the main landslide body A is caused by the climate and its interaction with the slope.

The early warning system to be designed in order to mitigate the risk associated to these type of landslides, i.e. to alert before the onset of the acceleration of pre-existing landslide bodies requires analyses of the coupled hydro-mechanical phenomena bringing about the acceleration.

As first, the modelling of the variations in the slope of the pore water pressures during the year, due to rainfall infiltration, is presented. The pore water pressures represent the indicators of the reach of instability, whereas the rainfalls and the evapotranspiration flows represent the external cause of instability. Different numerical approaches are available to compute the evolution of the pore water pressures with time, and consequently the stability level of the landslide with time (Elia et al. 2017). It is necessary to carry out an analysis, able to predict the timing of the reach of the threshold values during the year, given the climatic context. To this aim, in the modeling of the transient seepage, the soil properties and state have been set to configure the behaviour of the soils when either above the water table, or when saturated. Also, the modelling has implemented real boundary hydrological conditions of the slopes, and at the ground surface, the estimation of rainfall infiltration, as result of the total rainfall, the evapotranspiration at the hydrological processes. The results of the modelling guide the design of an early warning system with reference to landsliding form minor to large depths shallow to depth.

*Keywords: slope-atmosphere interaction, seasonal re-acceleration, early warning system, field monitoring, transient seepage modeling.*

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