A Geo-hydro-mechanical Approach to Landslide Hazard Assessment and Mitigation: a Successful Application in Southern Italy

Federica Cotecchia, Vito Tagarelli, Claudia Vitone, Francesco Cafaro, Osvaldo Bottiglieri, Simona Guglielmi, Rossella Petti,

Technical University of Bari, Bari, Italy

Francesca Santaloia, Piernicola Lollino,

Research Institute for the Geo-Hydrological Protection - National Research Council, Bari, Italy

INTRODUCTION

The Sendai Framework for Disaster Risk Reduction 2015-2030 (UNISDR, 2015) is aimed at preventing new disaster risks and mitigating the existing ones, a target which should be achieved through a tangible implementation of combined economic, social, cultural, environmental, scientific, technological, political and institutional measures. Besides reducing the hazard of several phenomena and the corresponding vulnerability of exposed elements, the resilience of the whole society should be strengthened (UNISDR, 2016).

Landslides are recognized as part of the geological hazards. They represent a variety of slope failure processes, which result in the downward movement of a soil/rock mass, as final effect of a progressive evolution of the slope equilibrium conditions. The slope failures could be predisposed by hydrological, hydrogeological and mechanical slope features. At the same time, they could be triggered by climatic events, along with earthquakes, wildfires, snowmelt and anthropogenic activities, as stated by UNISDR (2016). Landslide hazard is a function of landslide susceptibility (spatial propensity to landsliding) and time-based probability of occurrence of the landslide process. Its assessment may be carried out either with reference to vast areas (i.e. at small scale, e.g. regional), or with reference to a single slope (i.e. at large or local scale; Fell, et al, 2008 a, b; Corominas, at al, 2014; UNISDR, 2016).

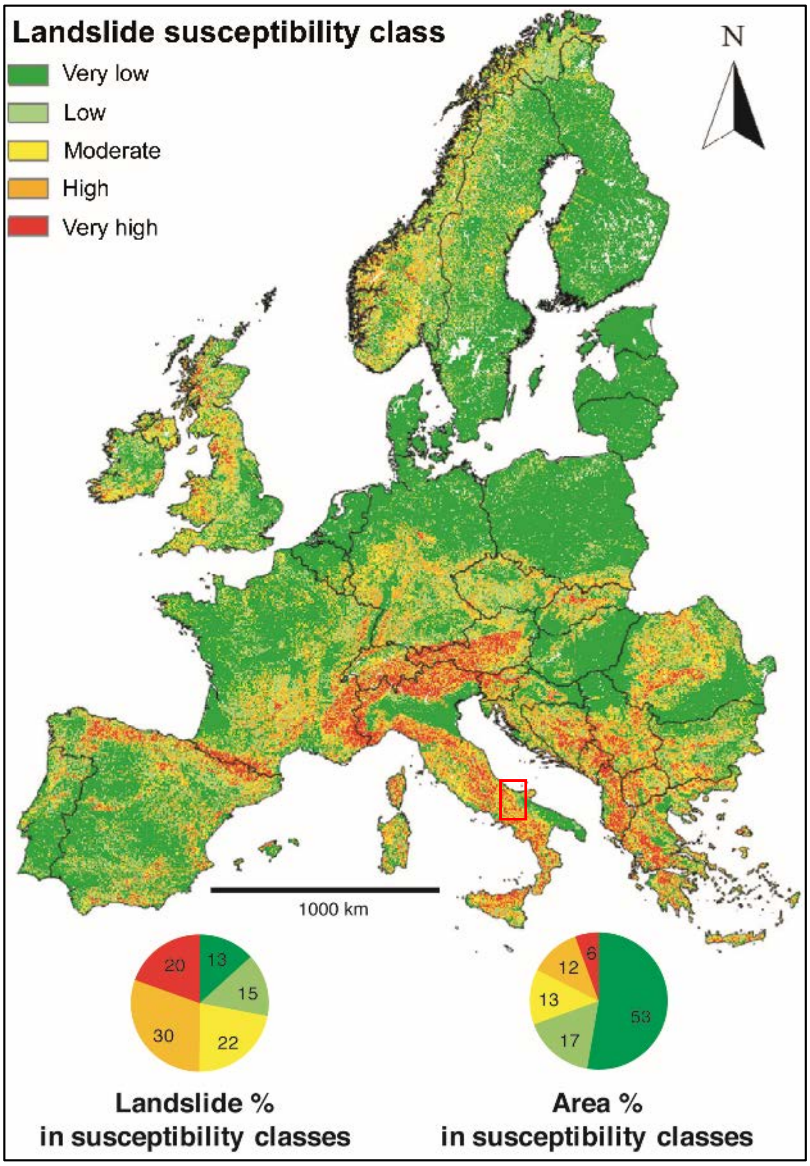
FIG. 1 shows the classified Pan-European landslide susceptibility map proposed by Günther, et al, (2014) and resulting from heuristic spatial multicriteria evaluations, which were supported by analytical hierarchy processes and validated based upon landslide inventories. The highest susceptibility (50% of landslide-affected pixels) is concentrated within hilly and mountainous areas, such as, for example, across large part of the Italian peninsula (FIG. 1).

Despite the on-going scientific and technological enhancement of both hazard and vulnerability assessment methods, as well as of risk modelling, human injuries and deaths, along with damages to structures and infrastructures caused by landsliding are still huge, not only in Europe (Haque, et al, 2016), but throughout the world (CRED Crunch, 2016). With reference to the European countries, from 1995 till 2014 a total of 1370 deaths and 784 injuries have been recorded as result of 476 landslide events (Haque et al, 2016). In this regard, it is worth pointing out that the quoted numbers may be underestimated. This is because the fatalities and damages are often consequent to landsliding caused by earthquakes and floods (UNISDR, 2015), and are associated to the landslide causes and not to the landsliding itself.

From an economic point of view, the 1995-2014 landslide events in Europe caused a total economic loss about 4.7 billion Euros per year, and Italy experienced the worst economic loss due to loss due to landslides (3.9

billion Euros; Klose, et al, 2016; Haque, et al, 2016). Moreover, an increasing trend of fatal landslides was observed both in Europe and all around the world, from 2008 to 2014; these landslides were mostly triggered by natural extreme events, earthquakes and floods (Haque, et al, 2016; CRED Crunch, 2016).

FIGURE 1. Classified Pan-European landslide susceptibility map (from Günther, et al, 2014); the studied area corresponds to the rectangular frame.



Hence, the large amount of deaths and losses caused by landsliding recorded around the world (Petley, 2012; CRED Crunch, 2016) testifies that either the landslide risk assessments, or the corresponding risk mitigation strategies, are not properly developed yet. Especially so at the small scale, where landslide hazard assessment is most often carried out by means of either heuristic or statistical methods (Fell, et al, 2008a, b; Corominas, et al, 2014), which do not entail the interpretation of the landslide processes, along with the identification of the landslide predisposing and triggering causes (Cascini, 2015; Cotecchia, et al, 2016a and b).

As agreed by the Priority Action 1 of the Sendai Framework (UNISDR, 2015), the landslide risk management should be based on the characterization of all the components of the disaster risk (i.e. hazard, exposure and vulnerability). Such characterization requires an integrated and multidisciplinary approach to landslide risk analysis, including results of social, economic, political, geological and engineering analyses. To achieve such characterization, the existing knowledge about the slope processes bringing about landsliding should be accounted for. Furthermore, foe landslide risk mitigation, the scientific and technical advancement in landslide risk mitigation design should be invoked, in order to protect social society and historical and cultural heritages (UNISDR, 2015).

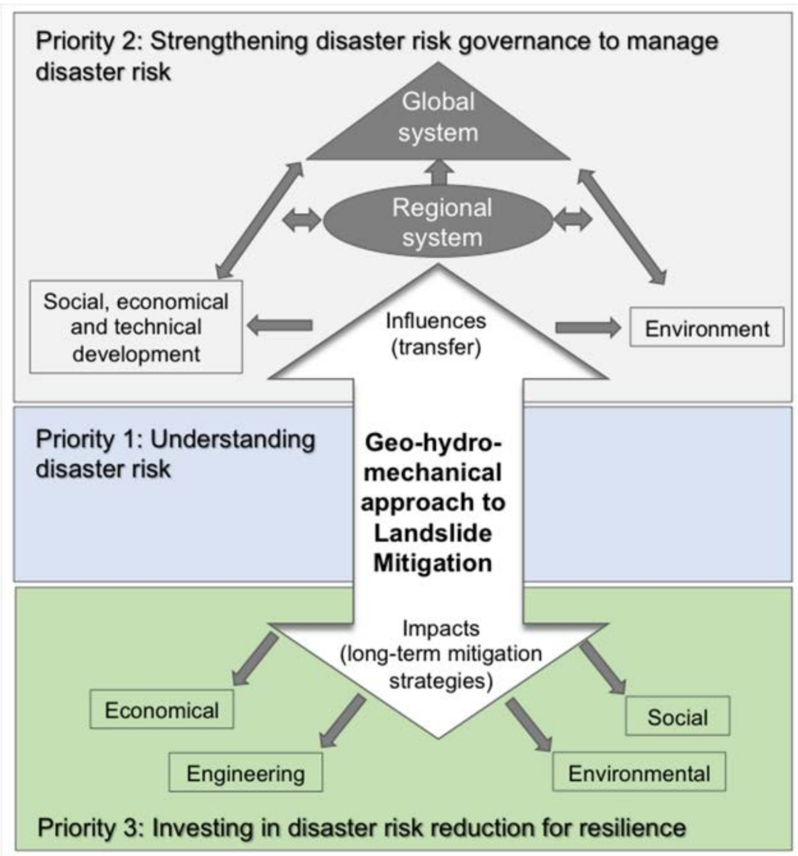
Moreover, the policies for landslide management should comply with the current availability of deterministic approaches to landslide hazard assessment, at either large or small scale (multi-scalar approaches), which allow for more objective and physically based evaluations of landslide risk, by comparison with those pursued using either heuristic, or statistical methods. Such approaches take account of the predisposing and triggering landslide causes, their spatial and temporal variability, and their role in the instability processes. Therefore, they allow for the characterization of the cause-effect relations bringing about the landsliding, by means of geo-hydro-mechanical modelling of the slopes.

Such deterministic hazard assessment methods allow to create hazard maps in which the main factors controlling the slope stability are explicitly reported, avoiding the redundancy of parameters often used within purely empirical approaches. Besides the landslide diagnosis allows to select the mitigation measure based upon the knowledge of the slope processes determining the slope failure. As a consequence, the mitigation strategy is often more sustainable and long-lasting. Despite the difficulty of adopting deterministic approaches to landslide risk assessment at the small scale, Cafaro, et al, (2017) have recently shown how such analytical strategy is applicable on the vast area.

The present paper intends to contribute to the dissemination of quantitative hazard assessment methods (Corominas, et al, 2014) at the small scale using a deterministic approach, and to show that this effort may be beneficial to improve disaster risk reduction policies in landslide prone areas. To this aim, a methodology for the quantitative assessment and mitigation of landslide hazard at small scale is presented in the paper. The proposed methodology, known as Multiscalar Method for Landslide Mitigation (recalled as MMLM hereafter; Cafaro, et al, 2017), could be applied everywhere in the world, being based on objective geo-hydro-mechanical diagnoses of the landslide processes.

Within the Priority Action 1 of the Sendai Framework (UNISDR, 2015), the MMLM starts from the understanding of the landslide mechanisms and of the relating hazard (FIG. 2), to derive a diagnosis based on a deterministic approach. Accordingly, it is capable to address the selection of the most appropriate landslide mitigation measures, using either structural, or non-structural interventions, and to enhance the resilience of the assets and environments within which landslides take place (Priority Action 3-Sendai Framework; UNISDR, 2015; FIG. 2).

FIGURE 2. Geo-hydro-mechanical approach to landslide mitigation in the spirit of the Sendai Framework: from the understanding of the processes to the social, environmental and engineering impacts and influences (after Basu, et al, 2015, modified).



The concurrent scientific advancement in the assessment and mitigation of landslide hazard, along with the compelling of a more routine transfer of knowledge from the scientific community to the institutions, industry and civil society (UNISDR, 2015), accomplishes Priority Action 2 of the Sendai Framework (FIG. 2). It strengthens the consciousness of both landslide risk and the availability of proper prediction tools (UNISDR, 2015). At the same time, it may prompt the social, technical and economic effort necessary to select the adequate mitigation measures for any critical slope condition (Cafaro, et al, 2017).

In the following, the paper describes the main actions of the MMLM and its application to a prototype region (the Daunia region, Southern Italy). Some landslide mitigation measures, designed on the basis on the MMLM application, are also reported in the paper (according to the priorities for both Actions 1 and 3; UNISDR, 2015).

GEOGRAPHYCAL CONTEXT OF REFERENCE

The MMLM was applied to the Daunia region, including 25 urban centres located in an extensively populated region of the eastern sector of the Southern Italian Apennines which displays a high to very high landslide susceptibility, as shown in the Pan-European map (FIG. 1).

The Daunia urban areas are representative for many other mountainous populated regions in Italy and more generally in Europe, whose social and urban development suffers from the fragility of the territory where they are located. Many of these urbanised territories have an extraordinary historical value (e.g. archaeological remains of Roman Age, historical monuments and churches dating back to X-XII centuries). The old part of the urban centres is generally founded on stable rock outcroppings (FIG. 3). On the contrary, the most recent urbanization, dating back to the last century, often extends over unstable slopes, where weak soil units and ancient landslides are located. This is why landsliding strongly affects these portions of the towns, causes damages to the existing structures and infrastructures and inhibits the urban expansion (Cotecchia, et al, 2010; Palmisano and Elia, 2014a, b, FIG. 4). It follows that landslide reactivations (FIG. 5) are found to contribute to the depopulation of these urban centres, despite their historical background.

Over the years, several public investments have been provided (Italian and European funds) for the landslide mitigation of these unstable slopes. Invasive retaining structures or deep large piles have been routinely used as stabilization measures, often designed disregarding the landslide mechanisms and their causes (e.g. kinematics of the slope failure, depth of the landslide bodies, cumulative rainfall or single intense rainfall events, slope undercutting and so on). As a result, these measures have been found to fail in assuring long-term stabilisation of the landslides within the clayey-rocky slopes, hence disrespecting the efficiency requested by Priority Action 3 of the Sendai Framework. The limited efficacy of such interventions is at present revealed by the monitoring of on-going landslide movements, which are often involving the above-mentioned stabilisation measures (FIG. 6).

FIGURE 3. Typical urban structure of the mountainous populated regions of the Southern Italian Apennines.

FIGURE 4. Schematic landslide maps of some of the studied urban areas (PS_119, 2006-2010).

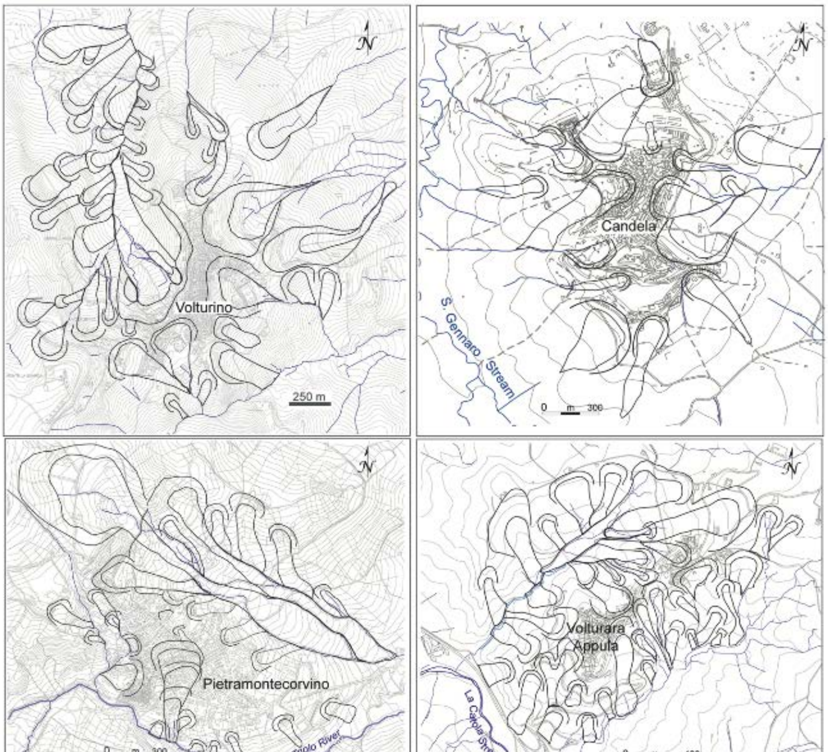


FIGURE 5. Examp… eleration of slow climate-driven l…

The MMLM resulting from studies across the Daunia region, was part of a wide multidisciplinary project aimed at the enhancement of landslide risk assessment. The Apulia Region funded this project (Framework Program for Research and Technology 2003-2005 - Strategic Projects), which is entailed academic, scientific and research entities together with private companies.

In particular, geotechnical researchers, together with geologists and hydrogeologists, were engaged into the development of the MMLM, whereas economists and town planning experts performed studies on the exposure component of risk and on the landslide susceptibility using well established statistical methods, for comparison with the hazard assessments resulting from the use of the MMLM within the same region. The statistical methods being used were multivariate and based on data processing in a geographical information system. The logistic regression was chosen to produce a susceptibility map over the studied region (FIG. 7; Mancini, et al, 2008), which implemented both morphometric and non-morphometric predisposing factors (i.e. drainage basin, land cover, lithology, distance from rivers). The landslide inventory map used for the statistical analysis corresponded to the landslide map built up during the application of the MMLM.

Structural engineering researchers were instead involved into the development of a new multi-level approach to the vulnerability assessment, which started from the damage assessment of the buildings located within the urban centres (FIG. 8; Palmisano, 2016; Palmisano, et al, 2018).

FIGURE 6. Examples of ineffective stabilisation measures realised on the unstable slopes.

FIGURE 7. Susceptibility landslide map of the Daunia region resulted from linear regression data analyses (from Mancini, et al, 2008).

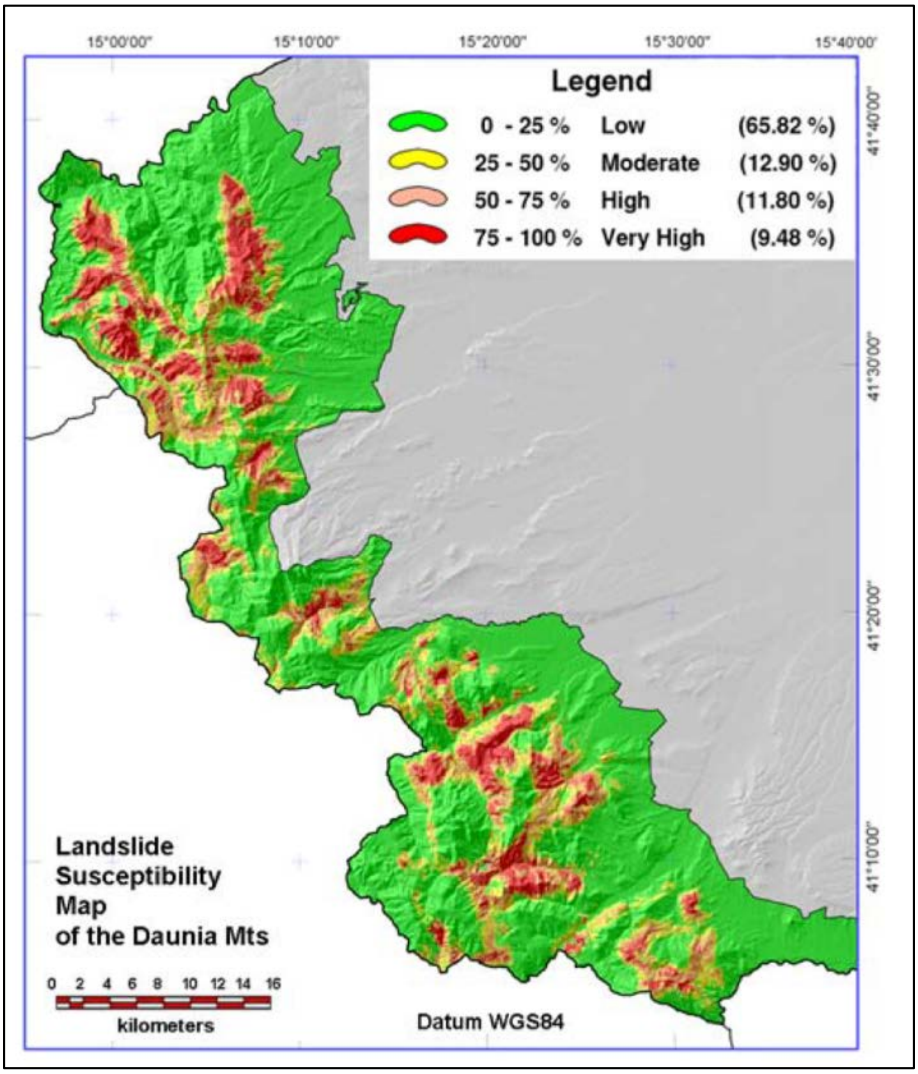
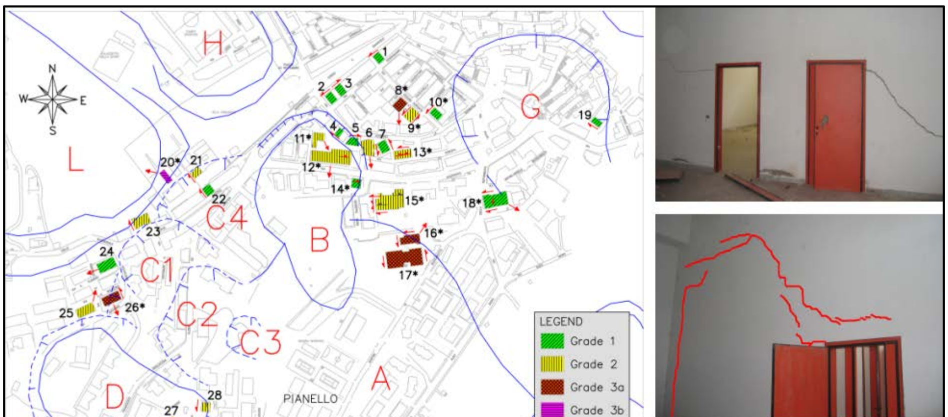


FIGURE 8. Landslide damage geotechnical chart for the town of Bovino in the Daunia region (after Palmisano et al. 2018).



THE MULTISCALAR METHOD FOR LANDSLIDE MITIGATION

Before describing the main actions of the MMLM, it is important to recall briefly the engineering definition of landslide mechanism. The landslide mechanism is the final process of a sequence of complex and coupled deformation phenomena taking place in the slope, which involve strain localisation and progressive failure (Chandler, 1974; Chandler and Skempton, 1974; Potts, et al, 1997). The landslide mechanism may be modelled through several numerical strategies, for example, through the solution of a boundary value problem which requires the simultaneous integration of equilibrium, compatibility and constitutive relationships, along with fluid mass conservation equation (Biot, 1941; Fredlund and Rahardjo, 1993; Potts, et al, 1997; Gens, 2010; Leroueil, 2001; Elia, et al, 2017).

The integration of the system refers to the boundary value problem representing the slope, characterized by the internal and the external factors (Terzaghi, 1950). The internal factors account for all the features predisposing the slope to failure (i.e. the slope geometry and geo-structural set-up, the mechanical properties of the materials, their permeability and the slope boundary conditions), while the external factors represent the actions (i.e. climate, earthquake, man-made actions etc.), which may alter the slope equilibrium conditions, being possibly triggering factor of the slope mechanism. Although the basic processes controlling the slope equilibrium and, eventually, bringing about failure, are always represented by the same set of laws (e.g. equilibrium and compatibility equations, liquid mass balance etc.), the landslide mechanisms vary with the variability of the landslide factors and boundary conditions. Hence, both the landslide factors and the boundary conditions should be investigated in order to correctly diagnose the landslide mechanism occurring within any slope, whose landslide hazard should be quantified. As previously said, this landslide diagnosis is strictly related to the Priority Action 1 of the Sendai Framework (FIG. 2; UNISDR, 2015).

The MMLM starts with the deterministic awareness of these geo-hydro-mechanical processes and the related slope factors at the slope scale and, through a reductionist approach, identifies a limited number of prototypes of slope set-ups and landslide mechanisms to be extended at smaller scales, following a bottom-up approach (FIG. 9; from the slope to the regional scale; Cascini, 2015).

FIGURE 9. Reductionist approach followed by the Multiscalar Method for Landslide Mitigation.

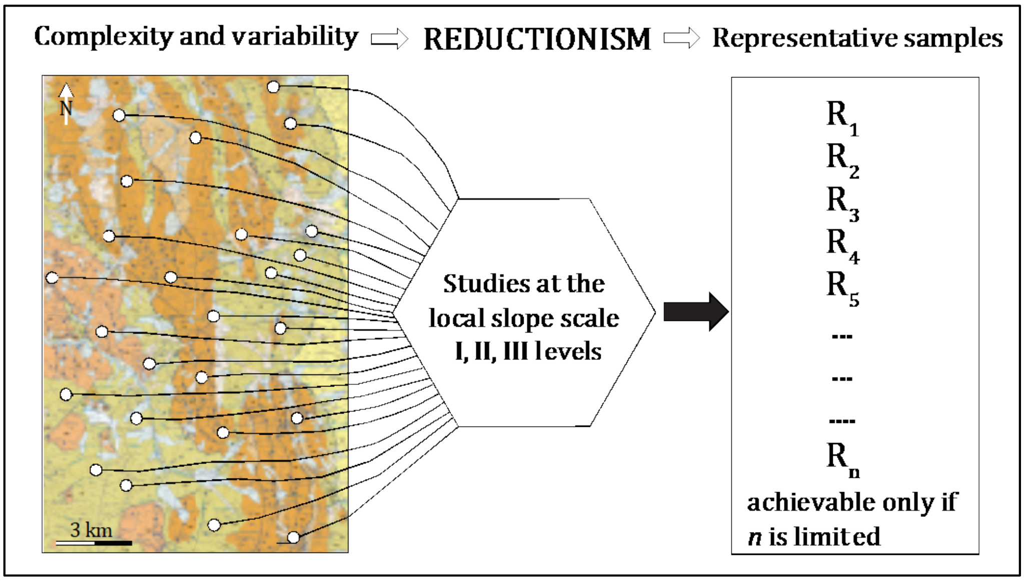
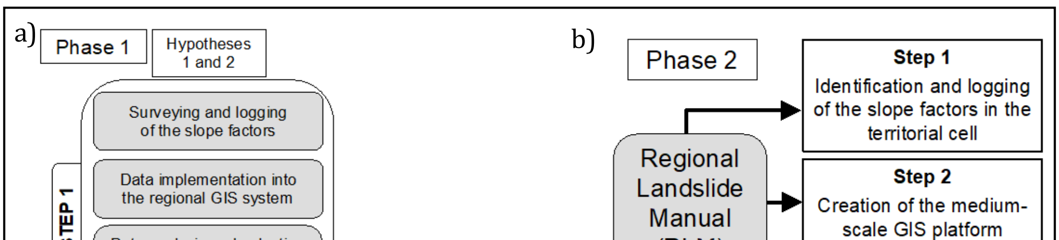


FIG. 10 shows the sequence of actions required to derive landslide hazard assessments according to the MMLM (Cotecchia, et al, 2010, 2016b; Cafaro, et al, 2017). The actions are comprised in two subsequent phases. The first one is addressed to the sorting out of the landslide mechanisms representative for the region under analysis (FIG. 10a) through the above-mentioned reductionist approach. The second phase concerns the assessment of the landslide hazard for a given territorial cell of the region (FIG. 10b).

FIGURE 10. Flow chart of the MMLM (from Cotecchia, et al, 2016a, b): a) Phase 1: characterization of the landslide mechanism at the regional scale; b) Phase 2: landslide hazard assessment in a given territorial cell.



The proposed methodology assumes that a limited number of geo-hydro-mechanical set-ups, GMi (which are setting of slopes having similar lithology, mechanical behaviour and hydraulic properties at the slope scale), can be identified in any sufficiently limited region (hypothesis 1 in FIG. 10a), despite the variability of the geological landscape. This assumption is valid if soil/rock mechanics is used to characterize the slopes, since the mechanical properties of the soils vary among geological formations less than the corresponding geological features. A limited number of GMi implies a limited number of landslide mechanisms, Mi, as the laws controlling the slope equilibrium conditions are always the same (e.g. equilibrium, compatibility and liquid mass balance), and, once for a given set of slope factors, similar landslide mechanisms should be expected (hypothesis 2 in FIG. 10a). Therefore, the MMLM may be applied in any geo-mechanically homogeneous region where the environment could be categorised in few GMi and Mi, according to the geo-hydro-mechanical features of the natural assets. For instance, a national territory could be discretised in different sub-territories, each of them with representative GMi and Mi (e.g. volcanic environment with rapid-very rapid flows; rocky territories with rock mass movements; etc.).

Once the hypotheses 1 and 2 are assumed, the MMLM entails Step 1 of Phase 1 (FIG. 10a), which deals with the creation of an analytical database of both the internal and external slope factors across the region. The generation of such database requires the analysis of the geo-hydro-mechanical factors for several slopes across the region. The analysis of all the data acquired during the first step of Phase 1 (FIG. 10) will allow for the identification of the geo-hydro-mechanical classes, GMi, representative for the region.

The following Step 2 of Phase 1 (FIG. 10a) entails the recognition of the connections between the internal factors, characterising the GMi classes, the external factors and the failure processes recurrent in the slopes of the region. Therefore, this step concerns the interpretation of the landslide mechanisms, that is developed through three different stages of diagnosis: I, phenomenological, II, using the limit equilibrium method, and III, with finite element (FE) numerical analyses. The first stage deals with a phenomenological interpretation of the slope factors and of the either possible or active failure mechanisms at several sites in the region. At this stage, field surveys, aerial photointerpretation, studies of historical evolution of the landforms and analyses of pre-existing slope data (geological, geotechnical, hydraulic and monitoring data) are performed extensively across the region. During this stage, the database is also enlarged to include several landslide maps (e.g. landslide inventory, event and multi-temporal maps).

Afterwards, limit equilibrium and numerical analyses are carried out for some of the slopes characterised through the previous phenomenological studies. Parametric limit equilibrium analyses, implementing the results of the previous stage, are then performed for several slopes, in order to verify the phenomenological interpretation of the landslide mechanisms. These analyses are also aimed at improving the knowledge of both the landslide activity and the hydro-mechanical behaviour of the slopes, along with the slope failure causes. The numerical analyses, instead, are conducted only for few unstable slopes whose landslide mechanisms are the most representative across the region. Designed on the basis of the results of the I and II stage-studies, these analyses are aimed at solving the boundary value problem, through the implementation of the algorithms that simulate the relevant processes active within the modelled slope. These analyses should provide further interpretation of the landslide mechanism, allowing to characterize the predisposing and triggering causes of failure, along with its expected progression with time. As a consequence, the quantitative modelling of the hydro-mechanical processes that cause landsliding allows to update the knowledge about the landslide mechanisms in different slope scenarios, improving the landslide hazard assessment for the region under study. After Step 2, the most relevant slope factors and processes are deduced.

Step 3 of Phase 1 (FIG. 10a) then deals with the classification of the representative landslide mechanisms of the region, Mi, and is carried out through a screening of all the mechanisms recognized in the previous step. The predisposing and triggering causes of the Mi are to be defined, together with their possible timing and magnitude.

All the knowledge acquired during Phase 1, along with the methodological steps to be applied for the assessment of the landslide hazard in a given specific territorial cell of interest for the operator in the region, has to be collected in a Regional Landslide Manual (RLM, FIG. 10a) and framed within a GIS platform-database (Mancini, et al, 2008; Cotecchia, et al, 2012; Santaloia, et al, 2012a, b). In such a way, the mapping of landslide hazard would be based on the geo-hydro-mechanical diagnosis of the slope processes as resulted from the RLM, hence overcoming the landslide hazard mapping based on heuristic and/or statistical analyses (Reichenbach, et al, 2018; Corominas, et al, 2014; Norwegian Geotechnical Institute, 2010).

The RLM is meant to be also the handbook gathering the geo-hydro-mechanical knowledge about the slopes across the region, of reference for all the operators involved either in land use planning or in mitigation design for the unstable slopes of the region. Therefore, the RML should be in continuous upgrading in any region. At the same time, the RLM could be useful for strengthen the disaster risk governance, in agreement with a phase of knowledge-transfer that is the core of Priority Action 2 (FIG. 2) in the Sendai Framework.

During Phase 2 (FIG. 10b), the RLM becomes a guideline for the operator in the assessment of the landslide hazard within the given territorial cell of interest. As first, the slope factors within the territorial cell of interest are identified and logged, following the procedures reported in the RLM (Step 1, FIG. 10b). Step 2 (FIG. 10b) entails the creation of a medium-scale analytical database, more detailed than that of Phase 1. It will include data representing the landslide factors at the site of interest, with particular emphasis on those recognised to be predisposing the landslide reactivations in the first phase, and data about the slope movements (e.g. topographic, interferometric, inclinometer monitoring data and structure damage data). The joined consultation of the local GIS database and of the RLM (Step 3) should lead to the recognition of both the class of geo-hydro-mechanical set-up (GMi) and the class of failure scenario (Mi) that are likely to occur in the territorial cell of interest. At the same time, the RLM should also indicate how to carry out either limit equilibrium or numerical analyses of the slope conditions for the given expected failure scenario, to validate the hazard assessment derived on the basis of the RLM indications.

APPLICATION OF THE MMLM TO THE EASTERN SECTOR OF THE ITALIAN SOUTHERN APENNINES

The application described in the following represents an example that, however, can be extensively replicated in other geological contexts. According to FIG. 2, it starts from the understanding - driven by a geo-mechanical approach - of the slope scale contexts (Priority 1 of Sendai Framework), in order to find out both the representative slope models to be applied at regional scale and the factors that control the spatial-temporal dynamics of the processes. Such a deterministic-based knowledge is found to impact on the selection of the mitigation strategies (Priority 3; FIG. 2), in order to guarantee their long-term efficacy.

According to Phase 1 of the MMLM (FIG. 10a), a widespread survey of the slopes within the urbanized territories of the eastern sector of the Southern Apennines was carried out; in the frame of the I stage analyses (FIG. 10a). The information concerning: the topographic, lithological and geo-structural features of the slopes, as well as the hydraulic and mechanical properties of the slope materials, were collected and implemented in a GIS platform database (Palmisano, 2016; Cotecchia, et al, 2012; Lollino, et al, 2012a, b; Santaloia, et al, 2012a, b).

A schematic geological map of the Apennine sector under study is shown in FIG. 11. This region is made up of geological formations that include mainly clayey marls, clays and silty clays, interbedding either limestone or sandstone strata (often as floating blocks within the clayey matrix). At places, also sands and conglomerates outcrop. Tectonics largely caused fissuring and disturbance of the soils. As a consequence, the clays are largely fissured and the rocks are fractured (Santaloia, et al, 2012 a, b; Cotecchia, et al, 2015).

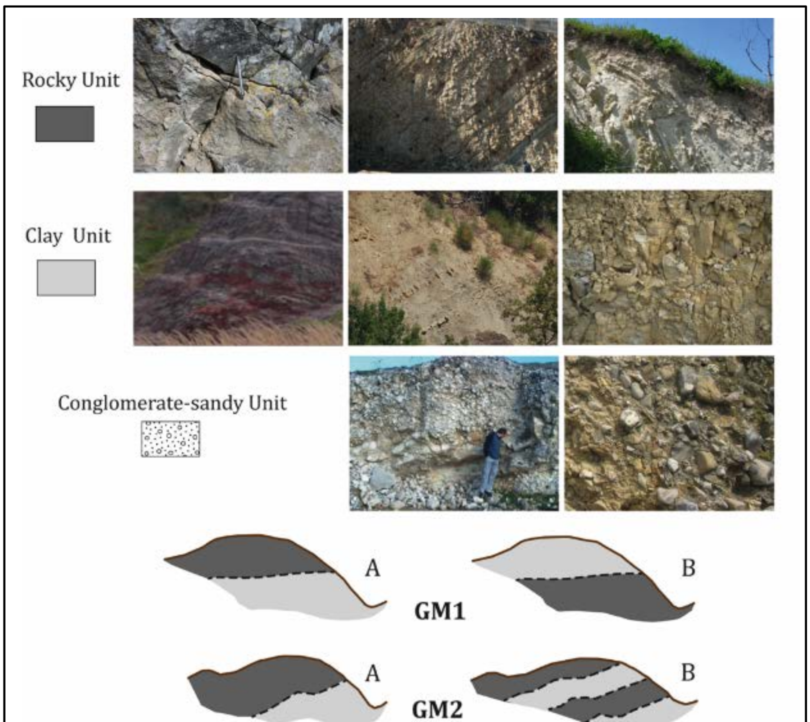
Based on the lithological and the meso-structural features of the geo-materials (Vitone and Cotecchia, 2011; Vitone, et al, 2018; Cotecchia. et al, 2007; Silvestri, et al, 2007), as well as on their mechanical behaviour, three main geo-mechanical units were distinguished: rocky, conglomerate-sandy, and clay units (FIG. 12).

According to the spatial distribution of the geo-mechanical units within the region under study, four main geo-mechanical set-ups were identified at the slope scale. They were selected to be the representative set-ups of the slopes in the region: GM1-GM4 in FIG. 12. These GMi mainly differ for the trend of the contact between the units; this contact may be either stratigraphic or tectonic (FIG. 12). In general, all the GMi in the region appear to host seepage domains having shallow water table (no more than 4-5 m below ground level). High piezometric heads are recorded down to large depths.

FIGURE 11. (a) Schematic structural map of Italy; the studied area is in the rectangular frame. (b) Simplified geological map of the Apennine sector where the studied area is located (modified from Patacca and Scandone, 2007). Key: 1) continental, marine, volcanite and volcanoclastic deposits (middle Pliocene-Holocene); 2) Pliocene and uppermost Messinian deposits; 3) uppermost Tortonian-Messinian terrigeneous deposits unconformably overlying the Apenninic Units; 4) Apenninic Units (Lagonegro, Sannio, Fortore, Serra Palazzo, Daunia Units, middle Triassic-Messinian); 5) geological contacts (a-stratigraphic, b-fault, c-synclinal axis, d-thrust); 6) areas of detailed studies; 7) urban centres out of the studied territories; 8) altitude points.

Based on the data collected in the regional database, phenomenological analyses and interpretations of the slope stability conditions were carried out for several slopes throughout the studied area. Through the comparative phenomenological analyses, five main categories of representative landslide mechanisms, M1-M5, were selected, with two additional secondary classes: M6-M7.

FIGURE 12. Some examples of the geo-mechanical units recognised in the studied region together with the geo-hydro-mechanical set-ups, GMi, recurrent in the same territory (after Cafaro et al, 2017, modified).



According to the landslide classification proposed by Cruden and Varnes (1996), the mechanism classified as M1 includes compound, or roto-translational slides, usually deeper than 30 m (M1, FIG. 13). The M2 mechanisms correspond to clay slides (or mudslide according to Hutchinson, 1988), with one or more source areas and an elongate or lobate body (FIG. 13). Thick shear bands, located at medium to high depth, bound these slides. The thickness of these shear bands may reach even several meters. The third category, M3, includes flow-like landslides, defined as earthflows by Hungr, et al, (2014). They extend over few kilometres and their depth is generally either about or higher than 15 m (Cotecchia, et al, 2009). M4 category represents a composite and complex landslide: a deep (more than 30 m) rotational landslide evolving into a shallow earthflow downslope (less than 10 m deep; FIG. 13). Finally, shallow soil slips (M5), slumps or shallow rotational slides (M6), and rock falls or toppling (M7) are other failure mechanisms identified in the studied territories.

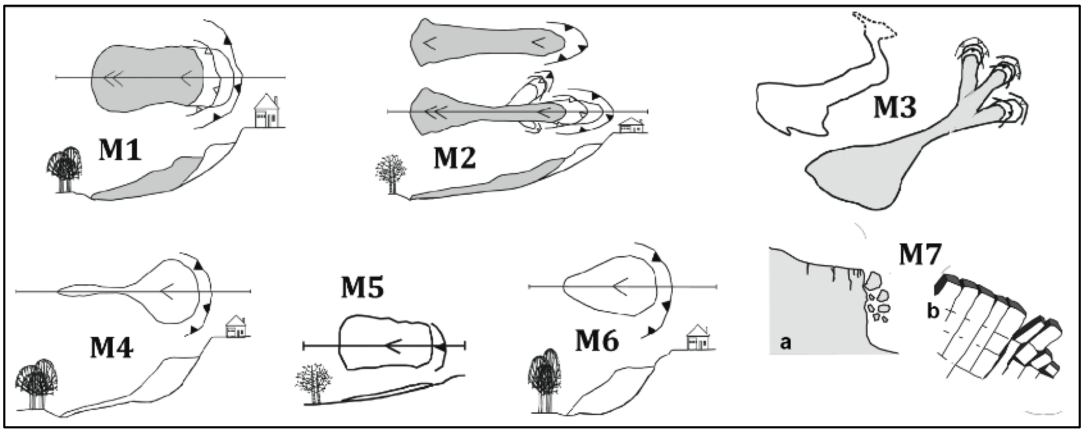
These landslides mechanisms were validated by the II and III stages of diagnosis performed for some of the slopes studied during the first stage as requested by the MMLM.

With reference to the studied slopes, M2 is the most largely present landslide mechanism, followed, in decreasing order, by M1, M5, M3 and M4. The others, M6 and M7, occur locally in steeper slopes.

Based on the I and II stages results, most of the M1-M4 landslides involve slopes location of ancient failures, which are at least in part reactivated at present. The current landsliding is slow to very slow, of rates $v<5x10^{-5}$ mm/s (Cruden and Varnes, 1996).

The reactivation of M1, M2 and M4 landslides occurs with operational strengths between peak and residual, as deduced by means of limit equilibrium back-analyses of the landslide bodies. Ground surveying and inclinometer monitoring have given evidence to the recurrence of movement accelerations, for M1, M2 and M4, from the end of winter to mid-spring. These landslide accelerations occur in a region whose climate is generally quite dry in summer and the wettest from mid-winter to mid-spring (Cotecchia, et al, 2016c, d).

FIGURE 13. Landslide mechanisms (after Cafaro, et al, 2017 modified): M1) compound or roto-translational landslide; M2) clayslide or mudslide; M3) earthflow; M4) slump-earthflows or slump-mudflow; M5) soil slip; M6) rotational landslide; M7) fall (a) or toppling (b).

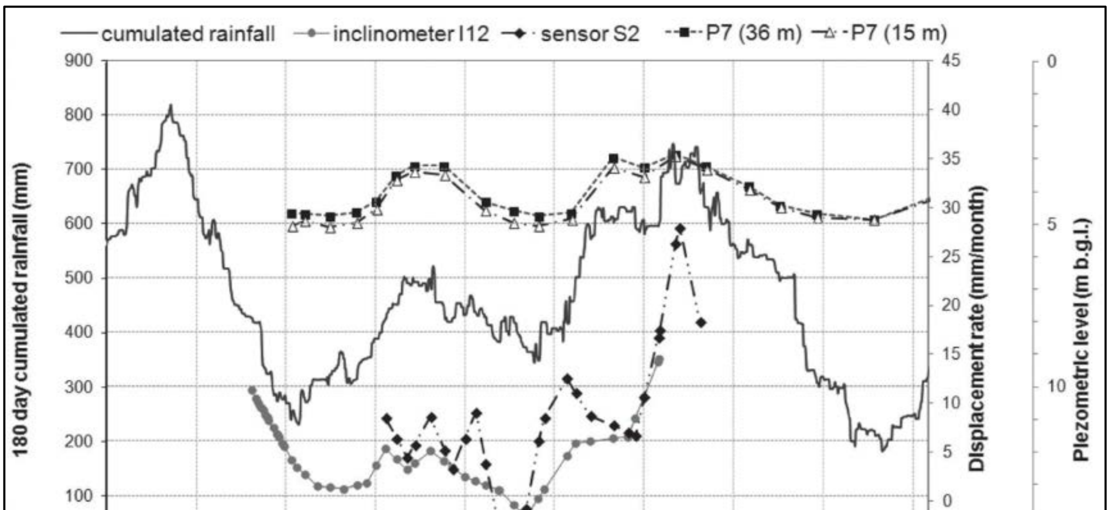


In general, for any landslide typology involving clays or clays with fractured rocky levels, from M1 to M6 (excluding the rock-falls M7), the weakness of the tectonised slope clays represents an internal cause of the slope failure, in the whole region. In particular, for M1, M2, or M4 landslides, limit equilibrium analyses have shown that, given the strengths available in the slopes, the stability factor (FS) decreases with increasing depth (Cotecchia, et al, 2009). This decrease in FS justifies the recurrent observation of deep sliding in the region. Furthermore, the deepest M1 and M2 landslide mechanisms often involve slopes where the soil plasticity index increases with depth, inducing a consequent decrease of the intrinsic strength of the soil with depth (Lollino, et al, 2010), that is detrimental for the slope stability. Besides, the high piezometric heads recorded down to large depths are also recognised as predisposing factor of failure for the landslide classes M1, M2 and M4 (Cotecchia, et al, 2016b).

Referring to the triggering factors, the rainfall input plays an important role into the change of the current slope equilibrium within the studied region. The current activity of the shallow soil slips (mechanism M5) is influenced by single intense and prolonged rainfall events (Sorbino and Cotecchia, 2012). Conversely, the current activity of M1, M2 and M4 landslides is largely affected by the reach of the maximum piezometric heads in the slopes, as result of the seasonal recharge of the seepage domain, given the regional climatic conditions. A very similar seasonal trend of displacement accelerations, piezometric head fluctuations and 180-day cumulative rainfalls has been recorded in slopes location of M1, M2 and M4 mechanisms. FIG. 14 shows an example of the seasonal activity of these deep slow-moving landslides in the clayey-rocky slopes in Daunia (e.g. Pisciolo slope: M2 landslide mechanism within a GM3A slope; Cotecchia, et al, 2014; FIG. 12). The figure gives evidence to piezometric level excursions (P7 electric piezometers in the figure) with time, which recur with the variations with time of the 180-day cumulative rainfalls. Furthermore, FIG. 14 reports the rates of sliding of the M2 landslide recorded, by means of inclinometer monitoring (I12 monitoring), at the base of the body, very close to the piezometric cells. The rates of movement logged at the ground surface by means of a GPS sensor (S2) are also shown. On the whole, the data indicate that piezometric heads and the landslide displacement rates follow a seasonal trend, in accordance with the trend followed by the 180-day cumulative rainfalls: the maximum rate values occur between the end of winter and mid-spring, when also the peak values of the piezometric heads and of the 180-day cumulative rainfalls are reached. The same trend is recorded in several other hill-slopes location of landsliding within the whole Southern Apennines (Cotecchia, et al, 2009; 2011a; 2015; 2016c, d).

The III stage modelling has validated the interpretation that the current activity of most of the M1, M2 and M4 landslides is related to the seasonal slope-atmosphere interaction. In particular, the finite-element analyses of the yearly transient seepage in the slope, with the daily rainfalls and the evapotranspiration implemented at the ground surface of the slope (as top boundary condition of the slope model), have confirmed that the combination of the regional climate with the hydro-mechanical properties of the slope soils allows for seasonal fluctuations of the piezometric heads down to large depths (Pedone, 2014; Tagarelli, 2019). These seasonal piezometric cycles bring about variations of the available strengths and, hence, of the slope stability factor, that range from 20 to 8% for slip surfaces of maximum depth ranging from 20 to 40 m, respectively (Cotecchia, et al, 2014; 2018).

FIGURE 14. Pisciolo slope: displacement rates at 17-19 m depth down inclinometer I12 and at ground surface (GPS sensor S2); piezometric levels at 15 m and 36 m b.g.l. down borehole P7 and 180-day cumulative rainfall (from Cotecchia, et al, 2014).



As concerns the M3 landslides, the landslide activity appears not to be controlled by the seasonal climate in the way recognized for the landslides M1, M2 and M4. The hydraulics of the slopes, location of landslides of M3-type appears to be more complex, hence the reactivations of these landslides should be analysed within the geomorphological evolution of the slope affected by this type of landslide mechanism.

The recognition that the reactivation of landsliding for several of the slopes of the region is climate driven has prompted studies of the measures capable of mitigating the effects of climate on the seepage within the slopes of the region, as discussed in the following. This approach to landslide risk mitigation, result of the application of the MMLM, represents a significant change with respect to the routine management of the landslides for the region under study, where structural interventions are the most used stabilization measures, as previously described.

MITIGATION MEASURES RESULTING FROM THE APPLICATION OF THE MMLM TO THE APENNINE SLOPES

As anticipated, the diagnosis of the landslide mechanisms representative for the studied region advises the design of the measures to be adopted for the risk mitigation, following the recognition of the recurrent inefficiency of the structural stabilizations. In this way, the public and private funds could be invested into stabilization measures addressed by a deterministic landslide diagnosis and, therefore, that would be more effective to increase the system resilience (i.e. that of the society exposed to the specific environmental risk; FIG. 2).

Therefore, the research has also entailed the design of measures to mitigate the causes of the climate driven landslide activity that has been found to be so diffuse in the region.

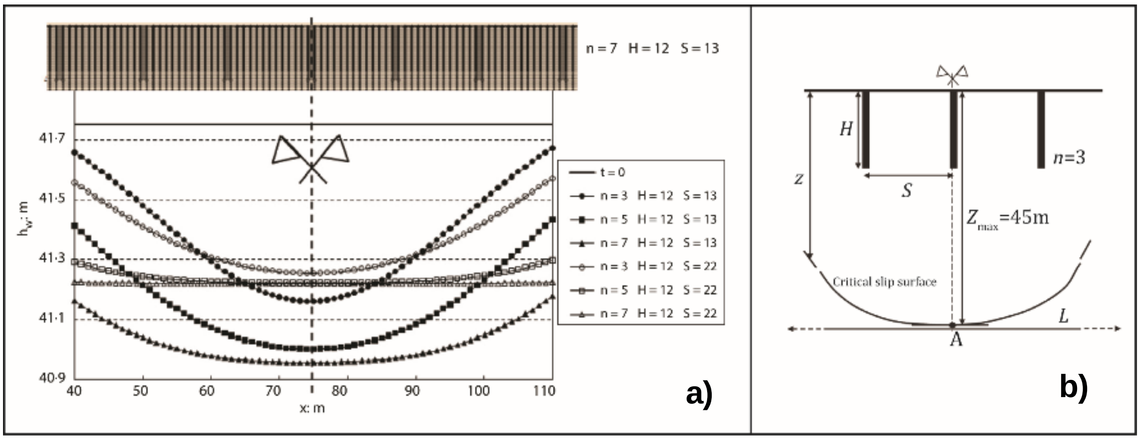
For the shallow (M5) to deep landslides exhibiting a climate driven activity (M1, M2, M4; Cotecchia, et al, 2014; 2016a; 2018), mitigation strategies aimed at the reduction of the piezometric heads are under investigation. Some preliminary results of this research are briefly discussed in the following.

In particular, the efficacy of either drainage trenches (Cotecchia, et al, 2011b; 2016c) or highly transpiring vegetation, is under study, since these measures are not only capable, in principle, of increasing the available soil strength from small to large depths in the slope but are also the least expensive and invasive. Hence, these interventions are expected to be relatively efficient. Moreover, in line with the definition provided by Basu, et al, (2015), they are considered to be highly sustainable, so as to survive and retain their functionality over the time. The stabilizing effect of systems formed by medium depth to deep drainage trenches was investigated through the combination of finite element modelling of the seepage in the slope and limit equilibrium analyses of the slope stability. 2D finite-element analyses (code Seep/W; GeoStudio, 2004) of the effects of the trenches on the piezometric heads were performed for several transversal sections of prototype slopes, location of deep sliding bodies (slopes with GM1-GM3 and M1-M2 classes; FIGS. 12 and 13). FIG. 15a shows the results of the seepage analyses, in terms of pressure head along a deep horizontal plane (45 m depth below the ground level; passing through point A in FIG. 15b), after 5 years since the activation of the drainage trenches. The pressure heads calculated after this time period were found to approach a steady-state condition (Cotecchia, et al, 2011b; 2016c). The highest pore pressures were found to occur below the centre of the system, that was the deepest portion of the spoon-shaped slip surfaces (FIG. 15b). In the figure, the predictions refer to trenches of depth, H, 12 m, spacing, S, variable between 13 and 22 m, and number of trenches, n, ranging between 3 and 7. They exemplify what found also for other trench systems (different values of H, S, n).

In particular, the changes in piezometric head calculated in the several transversal sections were implemented along the slip surface in the LE analyses, to derive the variation in stability factor of the landslide body due to drainage. Referring, for example, to one of the studied slopes (Fontana Monte landslide, maximum depth of 45-50 m, represented by the M1 and GM2B classes), an increase in the stability factor in the range 8.4%-10% was calculated, for example, for drainage systems made of 5 to 7 trenches, with H=16 m, S=12 m (Lollino, et al, 2016).

Therefore, it is recognized that the drainage trench system, on the whole, generates a “group effect”, that allows for a higher depression of the pore water where the slip surface is the deepest. This effect is beneficial to the efficacy of the intervention in the stabilization of deep landslides having a spoon-shaped slip surface, as observed for many landslides in clayey and clayey-rocky slopes. Moreover, it is found that the reduction in piezometric head is controlled not only by the S/H ratio, i.e. the parameter generally considered to control the performance of drainage trench systems (Hutchison, 1977; Desideri and Rampello, 2009), but also by the total width of the trench system, L = n × S. The group effect had not been reported in the literature before Cotecchia, et al, (2011b), probably because the previous studies had always considered the use of drainage trenches solely for the reduction of the piezometric heads at shallow depths.

FIGURE 15. a) Details of the finite-element mesh adopted for the seepage analysis and curves of pressure head calculated for different trench systems at depth z = 45 m from g.l., after 5 years of transient seepage; b) Schematic cross-section of the drainage system and of the slip surface. S–spacing between trenches; H–depth of trenches; z–depth of slip surface; L–total width of the trench system (from Cotecchia, et al, 2018).



These results indicate that the group effect of the drainage trench system makes this mitigation measure capable of risk mitigation not only for shallow landsliding, but also for the deep one (Cotecchia, et al, 2016c). Therefore, the drainage systems are thought to be useful for mitigating the deep, climate-driven, slow-moving landslides, involving the several clayey or clayey-rocky slopes located all around the world.

Furthermore, the use of vegetation as landslide risk mitigation measure has been investigated. If the definition of R, rainfall, ET, evapotranspiration, and RO, run-off, are recalled, the difference R – ET corresponds to the net rainfall (NR); in turn, the difference NR – RO represents the rainfall infiltration (RI) water flux at ground surface. This infiltration generates variations in pore water pressures and, consequently, changes in the effective stresses and available shear strengths, which control the slope stability. Therefore, given the same R and RO, the increase of ET, induced by the presence of a vegetation cover, causes a decrease of RI, thus indirectly influencing the stability of the slope (Cotecchia, et al, 2018; Tagarelli, 2019).

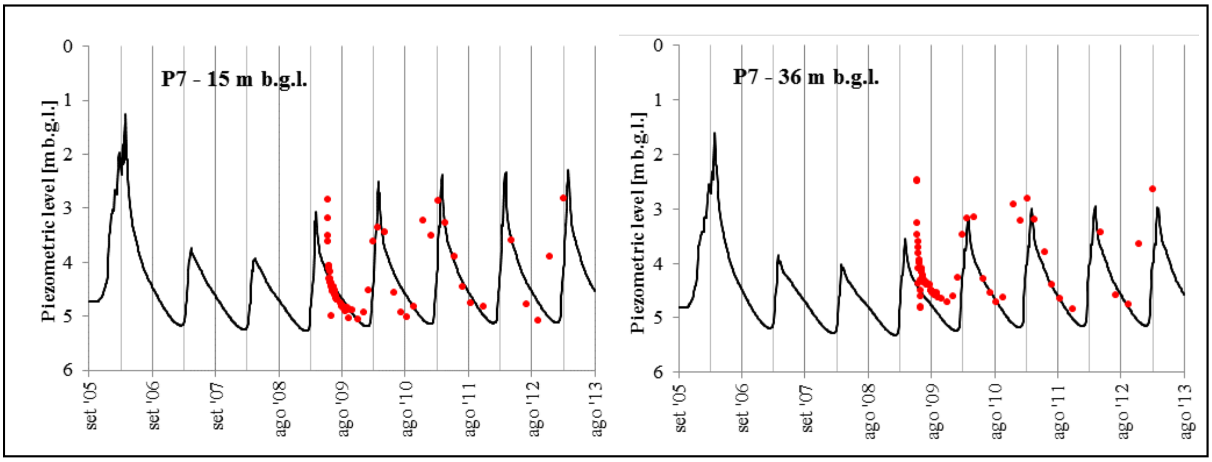
Numerical finite element analyses (code Seep/W-GeoStudio, 2004) were addressed to measure the effects of a crop cover on the hydraulic regime of a prototype slope (GM3A asset and a M2 class in FIGS. 12 and 13; Tagarelli, 2019), which had proved to be representative of several other unstable slopes located throughout the Southern Apennines.

The boundary conditions applied and the mesh features of the FE model are reported extensively in Cotecchia, et al, (2014) and Tagarelli, (2019). Being the soils partially saturated during most of the year, the hydraulic properties of the slope clays, both saturated and unsaturated, once measured in the laboratory, were employed in the simulations (Pedone, 2014; Tagarelli, 2019).

Net rainfall, referring to a representative year according to the average rainfall trend at the prototype slope, was applied cyclically along the rest of the slope ground surface for 8 years (Tagarelli, 2019). Net rainfall was determined as difference between the total daily rainfall and the actual evapotranspiration estimated on a daily basis (Cotecchia, et al, 2018; Tagarelli, 2019) by means of the FAO Penman-Monteith method (Allen, et al, 1998). The dual crop coefficient approach, which provides daily estimations of both the evaporative and transpirative fluxes, was adopted.

The piezometric levels, resulting from the numerical analyses, are compared with the monitoring data in FIG. 16. The numerical predictions are in rather good agreement with the monitoring data, both at shallow and large depths, despite the simplification of the analysis. Indeed, this good agreement can be predicted if the slope model reproduces the current geo-hydro-mechanical setting of the prototype slope and the net rainfall is considered. Moreover, some FE simulations have been carried out in order to evaluate the effects of herbaceous perennial deep-rooted plants at the ground surface, which are able to induce higher transpiration fluxes than the traditional vegetation species, all along the plant life-cycle. Preliminary FE results have shown, so far, the occurrence of a significant lowering of the piezometric heads in the slope as effect of these plants, also at depth, suggesting that these plants may be able to hydraulically contribute to the stabilization of deep sliding bodies (Tagarelli, 2019).

FIGURE 16. Comparison of numerical results (black lines) and in situ measurements at piezometer P7 (red dots).



CONCLUSIONS

A quantitative methodology for landslide hazard assessment and mitigation, based on the geo-hydro-mechanical diagnosis of landsliding, has been presented. The methodology has been framed within the context of the Sendai framework, in accordance with Priority Action 1, as an example of its application to landslide risk.

The application of the MMLM can be performed at any scale, from large to small, also in complex geological contexts. It involves different stages of analysis, first phenomenological, thereafter mathematical/numerical, to both identify and characterize the representative geo-hydro-mechanical settings and landslide mechanisms of the region, together with the factors controlling them.

The validation of the MMLM in the slopes of the eastern sector of the Southern Italian Apennines, where tectonised clays and rocks outcrop, has revealed that, despite the geological complexity of these slopes, the reductionist approach provides a geo-hydro-mechanical knowledge of the landsliding in the region. It is then shown how this knowledge prompts alternative and more sustainable stabilization strategies (i.e. drainage trench systems and vegetation installations) for the landslide risk mitigation, with respect to those traditionally used the most.

It follows that the application of the MMLM, starting from the deterministic understanding of the processes (FIG. 2; Priority Action 1 of the Sendai Framework), addresses and impacts several technical and socio-economic aspects and enhances the resilience of the contexts affected by landsliding (Priority Action 3, e.g. long-term mitigation measures, land use, urban planning, building codes, health and safety standards).

At the same time, the advancement provided by a more rigorous assessment of landslide hazard is supposed to increase the transfer of knowledge from the scientific community to the institutions, industry and civil society (UNISDR, 2015), according to the Priority Action 2 of the Sendai Framework.

REFERENCES

Allen, R. G., L. S. Pereira, D. Raes and M. Smith 1998. Crop evapo-transpiration (guidelines for computing crop water requirements. FAO Irrigation and Drainage. Paper 56.

Basu D., A. Misra and A.J. Puppala 2015. Sustainability and geotechnical engineering: perspectives and review. Canadian Geotechnical Journal, Vol. 52: 96-113.

Biot, M.A. 1941. General Theory of Three-Dimensional Consolidation. Journal of Applied Physics, 12: 155-164.

Cafaro, F., F. Cotecchia, F. Santaloia, C. Vitone, P. Lollino and G. Mitaritonna 2017. Landslide hazard assessment and judgment of reliability: a geomechanical approach. Bulletin of Engineering Geology and the Environment, Vol. 76, Issue 2: 397–412.

Cascini, L. 2015. Geotechnics for urban planning and land use management. Italian Geotechnical Journal, Vol. 49, Issue 4: 7–62.

Chandler, R. J. 1974. Lias clay: the long-term stability of cutting slopes. Géotechnique, Vol. 24, Issue 1: 21–38.

Chandler, R. J., and A. W. Skempton 1974. The design of permanent cutting slopes in stiff fissured clays. Géotechnique, Vol. 24, Issue 4: 457–466.

Corominas J., C. van Westen, P. Frattini, L. Cascini, J.P. Malet, S. Fotopoulou, F. Catani, M. Van Den Eeckhaut, O. Mavrouli, F. Agliardi, K. Pitilakis, M.G. Winter, M. Pastor, S. Ferlisi, V. Tofani, J. Hervás and J.T. Smith 2014. Recommendations for the quantitative analysis of landslide risk. Bulletin of Engineering Geology and the Environment, Vol. 73, Issue 2: 209–263.

Cotecchia, F., C. Vitone, F. Cafaro and F. Santaloia 2007. The mechanical behaviour of intensely fissured high plasticity clays from Daunia. In: 2nd Inter Workshop on "Characterisation and Engineering Properties on Natural Soils", Singapore. Taylor & Francis, London, Vol. 3-4: 1975–2003.

Cotecchia, F., G. Mitaritonna, G. Elia, F. Santaloia and P. Lollino 2009. Meccanismi di frane in pendi in argille dell'Italia Meridionale ed effetti delle precipitazioni meteoriche. In: 1st Int Workshop on Landslides ''Rainfall induced landslide and nowcasting models for early warning system'', Naples, Italy: 31–43

Cotecchia, F., F. Santaloia, P. Lollino, C. Vitone and G. Mitaritonna 2010. Deterministic landslide hazard assessment at regional scale. Geoflorida 2010 "Advances in Analysis, Modelling and Design", West Palm Beach, Florida, Geotechnical Special Publication, Issue 199: 3130–3139.

Cotecchia, F., F. Santaloia and P. Lollino 2011a. Slow landsliding as effect of hydro-mechanical coupled processes: examples of resulting damages and mitigation strategies. In: 2th Italian Workshop on Landslide, Naples, Italy: 71–79.

Cotecchia, F., G. Mitaritonna, P. Lollino and G. Elia 2011b. Interventi di stabilizzazione nei pendii dell'Appennino Dauno: analisi dello stato esistente e proposta di criteri innovativi. XXIV Convegno Nazionale di Geotecnica "Innovazione tecnologica nell'Ingegneria geotecnica", Napoli: 695-702.

Cotecchia, F., F. Santaloia, P. Lollino, G. Mitaritonna and C. Vitone 2012. Applicazione delle linee guida JTC-1 secondo un approccio multi-scalare. In: Criteri di zonazione della suscettibilità e della pericolosità da frane innescate da eventi estremi (piogge e sisma). Cascini L (ed), Composervice srl, Padova: 46–51.

Cotecchia F., G. Pedone, O. Bottiglieri, F. Santaloia and C. Vitone 2014. Slope-atmosphere interaction in a tectonized clayey slope: a case study. Italian Geotechnical Journal, Vol. 48, Issue 1: 34–6.

Cotecchia, F., C. Vitone, F. Santaloia, G. Pedone and O. Bottiglieri 2015. Slope instability processes in intensely fissured clays: case histories in the Southern Apennines. Landslides, Vol. 12, Issue 5: 877–893.

Cotecchia, F., F. Santaloia, P. Lollino, C. Vitone, G. Pedone and O. Bottiglieri 2016a. From a phenomenological to a geomechanical approach to landslide hazard analysis. European Journal of Environmental and Civil Engineering, Vol. 20, Issue 9: 1004–1031.

Cotecchia, F., F. Santaloia, P. Lollino, C. Vitone, G. Pedone, F. Cafaro and O. Bottiglieri 2016b. A geomechanical approach to landslide hazard assessment: the Multiscalar Method for Landslide Mitigation. Procedia Engineering, Vol. 158: 452–457.

Cotecchia, F., P. Lollino and R. Petti 2016c. Efficacy of drainage trenches to stabilise deep slow landslides in clay slopes. Géotechnique Letters, Vol. 6, Issue 1: 1-6.

Cotecchia F., C. Vitone, R. Petti, I. Soriano, F. Santaloia and P. Lollino P. 2016d. Slow landslides in Urbanised clayey slopes: an emblematic case from the south of Italy. Landslide damage assessment at the intermediate to small scale. Proceeding International Symposium on Landslides and Engineered Slopes. Experience, Theory and Practice, Vol. 2: Pag. 691-698.

Cotecchia, F., F. Santaloia and V. Tagarelli 2018. Geo-hydro-mechanics for quantitative landslide hazard assessment (QHA). XVI Danube "European Conference on Geotechnical Engineering, Skopje, R. Macedonia. Ernst & Sohn Verlag für Architektur und technische Wissenschaften GmbH & Co. KG, Berlin ce/papers 2 (2018), Nos. 2 & 3. DOI https://doi.org/10.1002/cepa.662.

CRED Crunch 2016. Disaster Data: A Balanced Perspective. Issue No. 41, February. Available at http://reliefweb.int/sites/reliefweb. int/files/resources/CredCrunch, 41.pdf. Accessed 19 Oct 2016.

Cruden, D.M. and D.J. Varnes, 1996. Landslide Types and Processes. In: "Landslide-Investigation and Mitigation", A. K. Turner and R. L. Schuster Editions, Transportation Research Board, Special Report n. 247, National Research Council, USA: 36-75.

Desideri, A. and S. Rampello 2009. Stabilizzazione dei pendii mediante sistemi di drenaggio. "Mitigazione del rischio mediante interventi di consolidamento e rinforzo dei terreni", Conferenze di Geotecnica di Torino, XXII ciclo: 1–48.

Elia G., F. Cotecchia, G. Pedone, J. Vaunat, P. J. Vardon, C. Pereira, S. Springman, M. R. Rouainia, J.V. Esch, E. Koda, J. Josifovski, A. Nocilla, A. Askarinejad, R. Stirling, P. Helm, P. Lollino, P. Osinski 2017. Numerical modelling of slope-vegetation-atmosphere interaction: an overview. Quarterly Journal of Engineering Geology and Hydrogeology, Vol. 50, Issue 3: 249-270.

Fell R., J. Corominas, C. Bonnard, L. Cascini, E. Leroi and W.S. Savage 2008a. Guidelines for landslide susceptibility, hazard and risk zoning for land use planning. Engineering Geology, Vol. 102, Issue 3-4: 85–98.

Fell R., J. Corominas, C. Bonnard, L. Cascini, E. Leroi and W.S. Savage 2008b. Guidelines for landslide susceptibility, hazard and risk zoning for land-use planning, Commentary. Engineering Geology, Vol. 102, Issue 3-4: 99–111

Fredlund, D.G. and H. Rahardjo 1993. Soil Mechanics for Unsaturated Soils. John Wiley & Sons, New York.

Gens, A. 2010. Soil environment interactions in geotechnical engineering . Géotechnique, Vol. 60, Issue 1: 3-74.

Geo-Studio 2004. Seep/w and Slope/w codes. User's manual. Calgary, Canada: Geo-Studio.

Günther A., M. Van Den Eeckhaut, J. Malet, P. Reichenbach and J. Hervás 2014. Climate-physiographically differentiated Pan-European landslide susceptibility assessment using spatial multi-criteria evaluation and transnational landslide information. Geomorphology, Vol. 224: 69-85.

Haque U, P. Blum P, P.F. da Silva, P. Andersen, J. Pilz, S.R. Chalov, J. Malet, M.J. Auflič, N. Andres, E. Poyiadji, P.C. Lamas, W. Zhang, I. Peshevski, H.G. Pétursson, T. Kurt, N. Dobrev, J.C. García-Davalillo, M. Halkia, S.Ferri, G. Gaprindashvili, J. Engström and D. Keellings 2016. Fatal landslides in Europe. Landslides, Vol. 13, Issue 6: 1545-1554.

Hungr O., S. Leroueil and L. Picarelli 2014. The Varnes classification of landslide types, an update. Landslides, Vol. 11, Issue 2:167–194.

Hutchinson, J.N. 1988. Morphological and geotechnical parameters of landslides in relation to geology and hydrogeology. In: Proceedings 5th International Conference on Landslides, Bonnard Ch (ed), Lausanne, Vol. 1: 3–35.

Klose M., B. Damm and B. Terhorst 2016. Landslide impacts in Germany: a historical and socio-economic perspective. Landslides, Vol. 13: 183-199.

Leroueil, S. 2001. Natural slopes and cuts: movement and failure mechanisms. Géotechnique, Vol. 51, Issue 3: 197-243.

Lollino P, G. Elia, F. Cotecchia and G. Mitaritonna 2010. Analysis of landslide reactivation mechanisms in Daunia clay slopes by means of limit equilibrium and FEM methods. Geoflorida 2010 Advances in Analysis, Modelling and Design, West Palm Beach. Geotechnical Special Publication, ASCE, Florida: 3130–3139.

Lollino, P., G. Mitaritonna, C. Vitone, F. Cotecchia and F. Santaloia 2012a. Applicazione dei metodi avanzati al fronte appenninico apulo-lucano: analisi di II livello della metodologia multiscalare. In: Criteri di zonazione della suscettibilità e della pericolosità da frane innescate da eventi estremi (piogge e sisma), Cascini L (ed), Composervice srl, Padova: 219–230.

Lollino, P., F. Cotecchia, G. Mitaritonna, C. Vitone and F. Santaloia 2012b. Applicazione dei metodi avanzati del fronte appenninico apulo-lucano secondo l'approccio multiscalare: analisi di III livello. In: Criteri di zonazione della suscettibilità e della pericolosità da frane innescate da eventi estremi (piogge e sisma), Cascini L (ed), Composervice srl, Padova: 357–371

Lollino, P., F. Cotecchia, G. Elia, G. Mitaritonna and F. Santaloia 2016. Interpretation of landslide mechanisms based on numerical modelling: two case-histories. European Journal of Environmental and Civil Engineering, Vol. 20, Issue 9: 1032–1053.

Mancini, F., C. Ceppi and G. Ritrovato 2008. Analisi del rischio da frana in ambiente GIS: Il caso del Sub-Appennino Dauno (Puglia). In: 12th Natational Conference of ASITA, L'Aquila, Italy: 1393–1398.

Norwegian Geotechnical Institute 2010. Safeland Project. Deliverable D2.1, 2010. Overview of landslide hazard and risk assessment practices; edit by Corominas J. and Mavrouli O; available at: http://www.safeland-fp7.eu.

Palmisano, F. and Elia, A. 2014a. Behaviour of masonry buildings subjected to landslide-induced settlements. International Journal of Structural Engineering, Vol. 5: Issue 2: 93-114.

Palmisano, F. and Elia, A. 2014b. Assessment of masonry buildings subjected to landslide by using the Load Path Method. International Journal of Civil Engineering, Vol. 12, Issue 14: 312-330.

Palmisano, F. 2016. Rapid diagnosis of crack patterns of masonry buildings subjected to landslide-induced settlements by using the Load Path Method. International Journal of Architectural Heritage: Conservation, Analysis, and Restoration, Vol. 10, Issue 4: 438-456.

Palmisano, F., Vitone, C., and Cotecchia, F. 2018. Assessment of landslide damage to buildings at the urban scale. ASCE Journal of Performance of Constructed Facilities, 32(4)

Patacca, E. and P. Scandone 2007. Geological interpretation of the CROP- 04 seismic line. Bollettino della Societa Geologica Italiana (Supplemento), Vol. 7: 297-315.

Pedone, G. 2014. Interpretation of slow and deep landslides triggered by slope-atmosphere interaction in slopes formed of fissured clayey turbidites; PhD thesis, Technical University Bari, Italy.

Petley, D. 2012. Global patterns of loss of life from landslides. Geology, Vol. 40, Issue 10: 927–930.

Potts, D. M., N. Kovacevic and P.R. Vaughan 1997. Delayed collapse of cut slopes in stiff clay. Géotechnique, Vol. 47, Issue 5: 953-982.

PS_119 Project 2006-2010. Multidisciplinary Strategic Project - Assessment of landslide risk in the planning of small towns in chain areas: the case of the Daunia. Funded by Apulia Region (CIPE n.17/03 e 20/04).

Reichenbach, P., Rossi, M., Malamud, B.D., Mihir, M. and Guzzetti F. 2018, A review of statistically-based landslide susceptibility models. Earth-Science Reviews, Vol. 180: 60-91.

Santaloia, F., F. Cotecchia and C. Vitone 2012a. Applicazione dei metodi avanzati al fronte appenninico apulo-lucano: analisi di I livello. In: Criteri di zonazione della suscettibilità e della pericolosità da frane innescate da eventi estremi (piogge e sisma), Cascini L (ed), Composervice srl, Padova: 130–140.

Santaloia, F., F. Cotecchia and C. Vitone 2012b. Le aree test dell’approccio multiscalare. In: Criteri di zonazione della suscettibilità e della pericolosità da frane innescate da eventi estremi (piogge e sisma), Cascini L (ed), Composervice srl, Padova: 88–95.

Silvestri F., C. Vitone, A. d'Onofrio, F. Cotecchia, R. Puglia and F. Santucci de Magistris 2007.The influence of meso-structure on the mechanical behaviour of a marly clay from low to high strains. Soil Stress-Strain Behaviour: Measurement, Modelling, Analysis, Springer, the Netherlands: 333-350.

Sorbino, G. and F. Cotecchia 2012. Gli effetti delle piogge sull'innesco e sull' attivazione delle frane. In: Criteri di zonazione della suscettibilità e della pericolosità da frane innescate da eventi estremi (piogge e sisma). Cascini L (ed), Composervice srl, Padova: 249–255.

Tagarelli, V. 2019. Analysis of the slope-vegetation-atmosphere interaction for the design of the mitigation measures of landslide risk in clayey slopes. PhD Thesis, Polytechnic University of Bari.

Terzaghi, K. 1950. Mechanism of landslides. In Paige, S. (ed.), Application of Geology to Engineering Practice. Berkey Volume, Geological Society of America, 83-123.

UNISDR 2015. Sendai Framework for Disaster Risk Reduction 2015–2030. In: UN world conference on disaster risk reduction, 2015 March 14–18, Sendai, Japan. Geneva: United Nations Office for Disaster Risk Reduction. Available at http://www.unisdr.org/files/ 43291_sendaiframe workfordrren.pdf. Accessed 19 Oct 2016.

UNISDR 2016. Report of the open-ended intergovernmental expert working group on indicators and terminology relating to disaster risk reduction: 1-41.

Vitone, C. and F. Cotecchia 2011. The influence of intense fissuring on the mechanical behaviour of clays. Geotechnique, Vol. 61, Issue 12: 1003–1018.

Vitone, C., F. Cotecchia, A. Federico and G. Viggiani 2018. On the geomechanical characterisation of complexities in clays. Experimental studies. Italian Geotechnical Journal, Vol. 52, Issue 2: 7-29.

ACKNOWLEDGEMENTS

The research was carried out with the support from: the Apulia Region (PS_119), the Apulian Aqueduct S.p.a. (2008–2011), the Italian Ministry for Research and University (PRIN 2011-2003, 2007, 2015).