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A geomechanical approach to landslide hazard assessment: the Multiscalar Method for Landslide Mitigation

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Abstract

The landslide hazard assessment, when based on the deterministic diagnosis of the processes, can be pursued only through the interpretation and the geo-hydro-mechanical modelling of the slope equilibrium. In practice, though, landslide hazard assessment is still seldom dealt with slope modelling, in particular when it addresses vast areas, where either heuristic or statistical methods do not entail any geo-hydro-mechanical knowledge of slope features and stability. The Multiscalar Method for Landslide Mitigation (MMLM) is an original methodological approach for intermediate to regional landslide hazard assessment. It is based on the geo-hydro-mechanical knowledge achieved from the application of a stage-wise diagnostic methodology of the landslide mechanism at the slope scale. The paper discusses the main steps of the MMLM aiming at diagnoses of landslide hazard based on hydro-mechanics, for small scale hazard mapping (at the large area).

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1. Introduction

The landslide risk assessment is the necessary premise for the sustainable development of mountainous areas,

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where sustainable is any initiative for development "that meets the needs of the present without compromising the ability of the future to meet its own need" [1]. To this aim, a scientifically advanced approach to landslide risk management is required, in order to improve the quality of life and reduce the risk trade-off among different decisional strategies [2,3,4]. This implies that the knowledge about landsliding achieved through the most advanced scientific studies should be transferred to the institutions, industry and civil society, with the aim of developing a deep consciousness of the risk associated to landsliding and of the possibility of identifying adequate mitigation options only through the use these study. The numerous deaths and losses, which are still recorded, despite the improved regional landslide risk mapping [5,6,7], testify that this transfer of knowledge is still limited. 2.620 landslide events were recorded worldwide during 2004 - 2010, causing a total of 32.322 fatalities [8] and, just only in Europe, the material losses amounted to over 1700 Million USD during the 20th century [9]. With reference to the Italian peninsula, the landslide risk is also very high [10,11]: 2.713 landslide events occurred from 1900 to 2008, causing 5.196 deaths, and from 1944 to 2010 the damage due to landslides and floods amounted to over 61 Billions of Euro [12]. It follows that landslide risk characterization should be improved at any scale. This improvement requires a more diffuse application of the procedure nowadays available to achieve the diagnosis of the landslide mechanisms, with the recognition of the landslide causes based on quantitative slope modelling [13,14,15,16,17]. In practice, such a deterministic assessment is commonly considered not feasible at the regional scale, i.e. at the small scale [6], where instead hazard assessment is usually carried out by means of either heuristic or statistical methods [18,19,20]. In the following, an original methodology for intermediate to regional scale quantitative landslide hazard assessment, called the Multiscalar Method for Landslide Mitigation, MMLM [13,14,15,21,22], is briefly presented.

2. The Multiscalar Method for Landslide Mitigation

The MMLM consists of two phases: the first entails the characterization of landsliding in the whole study region (Fig. 1(a)), background of the hazard assessment within any given territorial cell of the region, which is the subject of the second phase (Fig. 1(b)). This paper focuses on the first phase, in order to show how results of quantitative studies at the site scale (i.e. large scale; studies eventually available, or carried out on purpose) bring about the knowledge about the landsliding across the vast area and, as such, support the landslide hazard assessment at the regional scale [13,23,24]. At the base of the MMLM there are two main assumptions (Fig. 1), which have to be fulfilled in order to carry out the assessment of the landslide hazard at the small scale using the knowledge about the hydro-mechanical conditions of single slopes. Hypothesis 1 asserts that, despite the variability of the geological landscape, in any region of given single paleo-geographic origin, a limited number of representative and most recurrent geo-hydro-mechanical set-ups and failure mechanisms can be distinguished for the region. Such hypothesis can be considered plausible, since the variability in the hydro-mechanical properties of soils and rocks, that control the failure mechanisms, is known to be much lower than that of the soil geological features and the characterization of a landscape based on the soil mechanical features may be simpler than its geological characterization. Despite different geological origin and histories, geo-materials can exhibit similar behaviour at the slope scale and, as such, be considered similar with respect to the slope mechanics. They may be considered part of the same class of material in schematic geo-hydro-mechanical set-ups; these set-ups are called GMi in the MMLM. The recurrence of similar geo-hydro-mechanical set-ups in a region implies a limited number of representative set-ups, GMi, for the region, and a corresponding limited number of landslide mechanisms representative for the region, which are referred to as Mi (hypothesis 2). The first phase of the MMLM (Fig. 1(a)) is intended to sort out which are the GMi and the Mi of the region, through a reductionist approach [25]. To this aim, work is extensively devoted to the creation of a regional database of both the internal (e.g., geological, mechanical and hydraulic properties) and external (e.g., climatic, anthropic, seismic actions) slope factors [26]. The generation of such database requires extensive surveying of the slopes across the region [14], with the acquisition of both small scale study data and site scale data at diverse locations in the region. The database could be implemented in a regional GIS [27]. The study of this database should allow the sorting out of the GMi classes of the region that could be reported in a Regional Landslide Manual (RLM). This represents the handbook gathering the geo-hydro-mechanical knowledge about the slopes of the region, of reference for all the operators involved either in the slope management, or in the construction of operas interacting with the slopes.

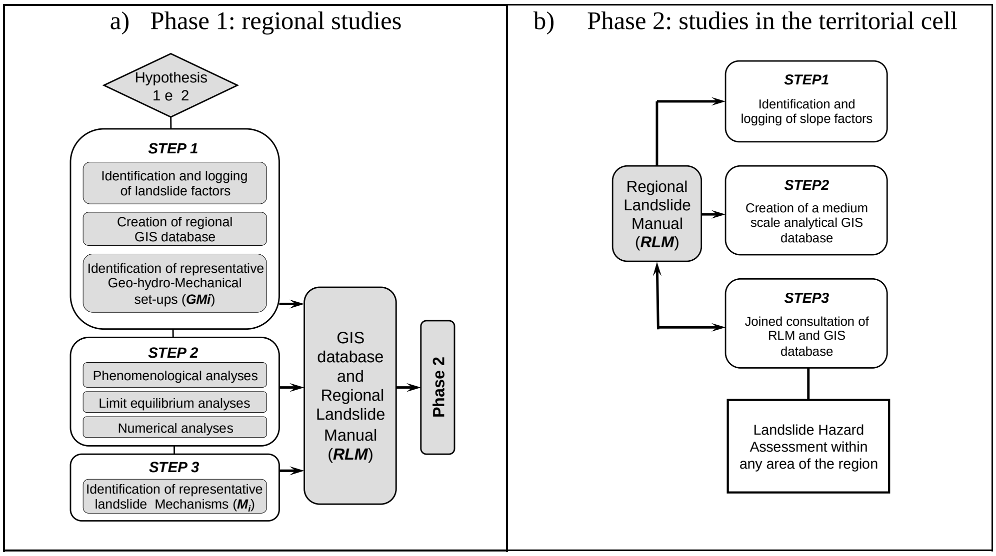

Fig. 1. Flow chart of the Multiscalar Method for Landslide Mitigation [13,14,15,21].

Step 2 (Fig. 1(a)) of MMLM entails the recognition of the connections between slope factors and instability processes, hence it is addressed to the diagnosis of the representative landslide mechanisms of the region. These are to be interpreted through site studies at several sites of the region, that will be just phenomenological (I level) for all the slopes selected for the analyses, or otherwise more advanced (limit equilibrium, II level, or numerical, III level [14]), for the slopes location of the most recurrent instabilities. These studies will be the base for the identification of the Mi classes within the region (Step 3 in Fig. 1(a)), to be outlined in the RLM. Therefore, the regional landslide database is created through a synergy of small scale studies and site-scale studies, with the belief that the latter ones reveal the mechanisms and causes of the landsliding active also at other locations, surveyed with the small scale studies. This is because the availability of the knowledge reported in the RLM makes it possible, for any operator, to address the risk mitigation to the landslide causes, or otherwise, to account for the expected landslide movements. The second phase of the MMLM deals with the hazard assessment within any territorial cell of interest of an operator (e.g., either urban areas or specific slopes) and with the interpretation of the slope conditions and of the eventual instability causes, based on the results of the first phase (Fig. 1(b)). It entails the generation of a local scale database, storing the data about the factors of the slope under study, as outlined in an on purpose methodology reported in the RLM, to be defined according to the knowledge acquired about the landslide phenomena of the region.

3. Validation of the MMLM in the outer sector of the Italian Southern Apennines

The proposed methodology has been implemented across a large number of mountainous urban centers in the Daunia and Lucanian Apennines (Southern Italy; Fig. 2), and to some extra-urban areas, where important infrastructures lie [13,14,15,22,23,24]. As recurrently observed in the urban centers of the Daunia Apennines, the historical center benefits from being founded on the most stable outcropping whereas, the most recent urbanization is often damaged because it has compelled the founding of buildings not only on high plasticity clay outcroppings but also on soils either part of the landslide bodies shown in the map, or in interaction with the landslide bodies [28,29].

The Apennine sector of reference is made up of sedimentary successions, belonging to a stack of Meso-Cenozoic tectonic units covered by Neogene-Quaternary thrust-sheet-top deposits. Despite the huge geological complexity of this area, the extensive application of the first phase studies has brought about a regional database of the slope factors. From this, it has been deduced that the geo-mechanical set-ups of the region can be grouped into four main classes, GM1-GM4 (Fig. 3(a)), each of which includes set-ups whose overall mechanics is similar and makes failure propagation processes similar. In general either rocky, or conglomerate-sandy or fine soil units form these set-ups (Figs 3(a) and 4).

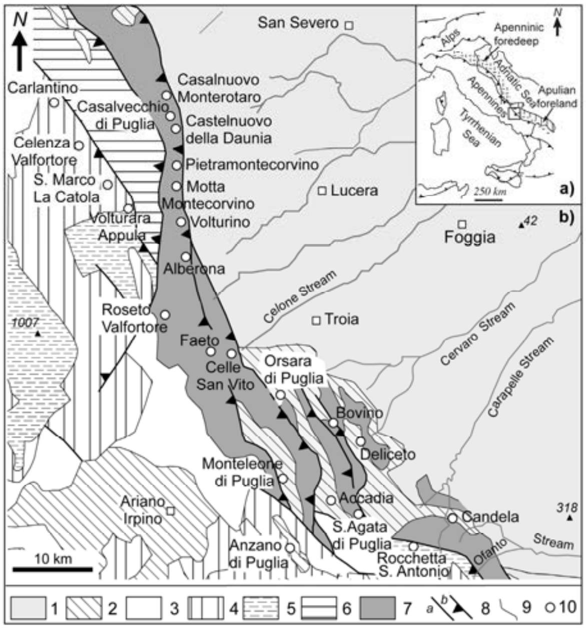

Figure 2. a) Schematic structural map of Italy, the study area is in the rectangular frame. (b) Simplified geological map of the Apennine sector where the studied area is located ([30], modified). Key: (1) continental and marine deposits (Lower Pleistocene-Holocene) and subordinate volcanite and volcanoclastic deposits (Middle Pleistocene-Holocene); (2) undifferentiated Pliocene deposits; (3) uppermost Messinian/lowermost Pliocene Torrente Calaggio Caotic Complex; (4) uppermost Tortonian-Messinian terrigeneous deposits unconformably overlying the Apenninic units (San Bartolomeo Flysch and Toppo Capuana Marls); Apenninic Units: (5) Sannio Unit (Lower Cretaceous-Serravallian; locally also including Fortore Unit deposits); (6) Tufillo-Serra Palazzo Unit (Paleogene-Messinian; locally also including Fortore Unit deposits); (7) Daunia Unit (Paleogene- Messinian); (8) tectonic contact (a-fault, b-thrust) (9) stratigraphic contact; (10) areas of detailed studies.

The different units are distinguished considering the lithotype geotechnical properties, which mainly control the mechanical behaviour of the geo-mechanical unit. Therefore, different geological formations can belong to the same geo-mechanical unit. The rocky unit (Fig. 3(a)) includes stiff, high-strength materials (limestones, sandstones or marls with very few thin clayey strata Figs 4(a-c)). For instance, the rocky unit could belong to the calcareous member of the Faeto Flysch Formation (Figs 4(a-b)), or to the sandstone member of Pliocene formations (Fig. 4(c)). Weakly cemented pebbles with sands or pebbly sands identify the conglomerate-sandy units (Fig. 3a and Figs 4(d-e)), usually belonging to the Pliocene-Quaternary successions. The fine soil unit (Fig. 3(a)) consists of clays, silty clays (Figs 4(f-g)) or clayey successions with very few rock strata (Fig. 4(h)). At places, the clays are fissured, laminated or sheared, as those belonging to the highly fissured Red Flysch Formation. Through the first phase of the MMLM (Fig. 1(a)), four main landslide mechanisms, M1-M4 (Fig. 3(b)), have been identified. As resulting from the phenomenological analyses performed across the region (Fig. 1(a)), most of the landslides involve slopes already location of failure in the past and often reactivated as slow to very slow mass movements. Most of them are found to be triggered by the seasonal variations of the pore pressures, relating to the 180-day cumulated rainfall [13,15]. Besides, the first-time landslide activation seems to have been recurrently the effect of the slope deforestation, generally occurred between the XVIII and the XIX century. The weakness of the clays hosting landsliding, which are often of high plasticity and fissured, represents one of the major internal predisposing causes of landsliding in the whole region [15]. At the same time, the piezometric heads, relatively high down to large depths, are also recognized as predisposing factor of failure, from small to large depths [13,15].

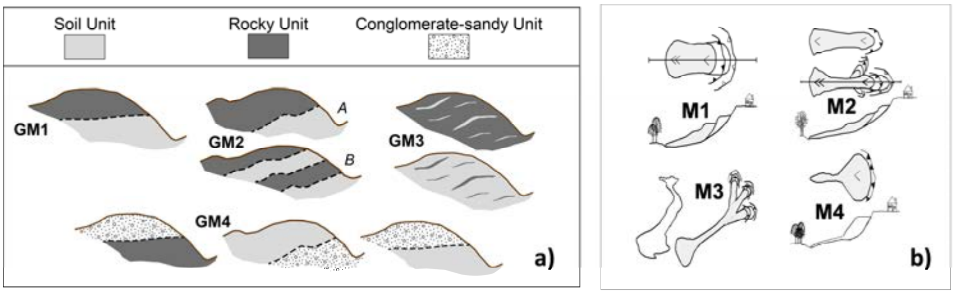

Fig. 3. (a) Geo-hydro-mechanical setting; (b) landslide mechanisms recurrent in territory of reference [31, modified].

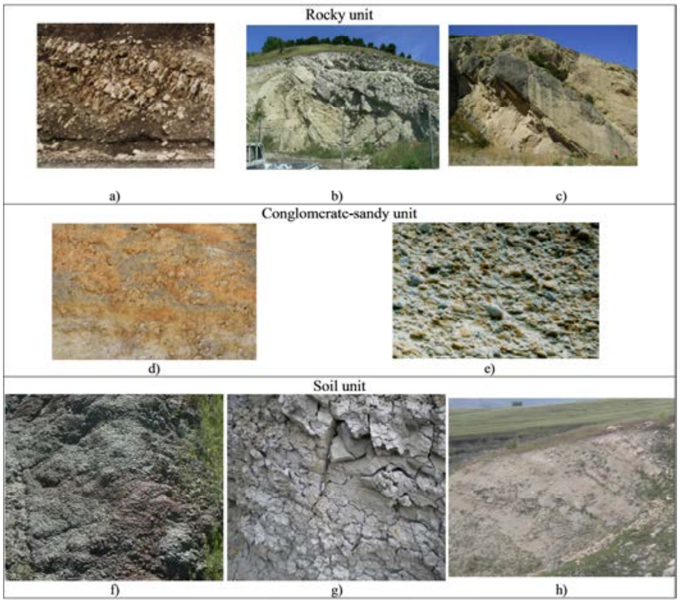

Fig.4. Daunia–Lucanian Apennine: examples of rocky units, i.e., (a-b) Faeto limestone unit; (c) Pliocene sandstone unit; (d) conglomerate-sandy units; (e) Pliocene-Pleistocene Synthem units and fine soil units, i.e. (f) Red Flysch clayey unit; (g) Pliocene clay unit; (f) Faeto clayey unit.

4. Conclusions

The proposed methodology for regional landslide hazard assessment and mitigation, MMLM, is based on a reductionist approach and on a deep geo-hydro-mechanical knowledge of the soil masses across the region of interest. It represents a new strategy to perform regional studies of landsliding using the site scale procedures of diagnosis of slope failure. It brings about knowledge of the possible landslide mechanisms in the region, to be addressed in any decision making procedure for landslide risk mitigation.

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