Geomatics in support of geotechnics in landslide forecasting, analysis and slope stabilization

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Innovative researches developed by the Authors are described in order to demonstrate the usefulness of GIS (Geographic Information System) in support of geotechnical analysis, with particular reference to risk zoning and mitigation and to the monitoring of slopes. A multivariate statistical procedure for the estimation of landslide susceptibility, an automatic procedure providing maps of the countermeasures to recommend for slope stabilization and reinforcement, and a cognitive/predictive hydrological-geotechnical (IHG) model coupled with a dense, low-cost network of sensors are presented. The contribution of GIS environment to the analysis and prevention of landslide susceptibility, both at wide area and at local scale, as well as to the support in the choice of the suitable countermeasures is highlighted.

***Keywords**: landslide, susceptibility, monitoring, GIS, slope stabilization.*

La geomatica a supporto della geotecnica nella previsione, analisi e sistemazione di versanti instabili. *Al fine di mostrare l'utilità del GIS (Geographic Information System) a supporto delle analisi geotecniche, con particolare riferimento alla zonizzazione e mitigazione del rischio e al monitoraggio dei pendii, vengono descritte le ricerche innovative sviluppate dagli Autori. Si presenta una procedura statistica multivariata per la stima della suscettibilità da frana, una procedura automatica che fornisce mappe degli interventi raccomandati per la stabilizzazione e il consolidamento del pendio, e un modello conoscitivo/predittivo idrologico-geotecnico (IHG) accoppiato con una rete di sensori densa e a basso costo. Sarà evidenziato il contributo dell'ambiente GIS all'analisi e previsione della suscettibilità da frana, sia su area vasta sia a scala locale, nonché al supporto nella scelta degli opportuni interventi di stabilizzazione.*

***Parole chiave**: frane, suscettibilità, monitoraggio, GIS, stabilizzazione di pendii.*

1. Introduction

Italy is the European country with the highest risk of landslide (ISPRA, 2015); landslides are quite common and represent a very important problem, which should be addressed urgently. The characteristics of the Italian territory and the human settlement and anthropization have caused numerous landslides, especially in occasion of heavy rainfalls.

Competent territorial authorities request practical instruments for landslide risk prevention and mitigation.

In this regards, the Authors have provided:

- a procedure for the estimation of landslide susceptibility;
- an automatic procedure providing maps of the interventions to be recommended for slope stabilization and reinforcement;
- the LAMP (LAndslide Monitoring and Predicting) project proposing the use of a dense, low-cost and self-sufficient network of sensors, disseminated on the ground, coupled with a cognitive/predictive hydrological-geotechnical (IHG) model.

These studies are here briefly described in order to highlight the usefulness of GIS in support of geotechnical analysis, with particular reference to zoning, management, monitoring and forecasting.

2. Shallow landslide susceptibility zoning by a GIS-based multivariate statistical analysis

In Italy the preservation of the territory is very difficult and expensive. Recent rainfall events triggered many landslides causing many problems to infrastructures. In this regard, a procedure for the estimate of shallow landslide susceptibility that accounts for factors, such as the climate aggression and the presence of roadways and rails, can be particularly useful in defining "critical areas" and priorities.

The susceptibility analysis is generally based on the assumption that landslides occur in the same geological, geomorphological, hydrogeological, anthropogenic and climatic conditions as in the past, and that are usually controlled by identifiable physical factors. Statistical methods allow to correlate an inventory of past landslides with factors which are supposed to be responsible of slope failure (Cascini, 2008). They are considered suitable when applied to wide and differentiated zones, using GIS to integrate spatial variables; nevertheless statistical approaches sometimes require quite complex calculation procedures (Guzzetti *et al.*, 1999).

The procedure (applied by some of the Authors of the present paper) consists in a traditional multivariate statistical analysis in GIS,

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being landslide often triggered by a combination of factors intimately connected. This technique is commonly used but details on the influence of various factors on the occurrence and triggering of landslides and a critical review of the choice of the calibration area in terms of extension and characteristic of influencing factors often are missing. A deep analysis of such choices were done and deeply explained in Marzocchi *et al.*, 2015 and Bovolenta *et al.* 2016b. Geographical, geological, climatic and anthropogenic factors were considered, focusing particular attention on climate aggression and proximity to infrastructures, such as roads and railways, since their construction and presence may have a substantial effect on the occurrence of slope instability. In more detail key factors are:

- geo-lithological vector map (1:100.000), for a lithological description of soils;
- elevation, slope and aspect maps obtained by a digital terrain models (DTM), at a resolution of 10 or 20 m (higher resolutions are not necessary for a regional susceptibility zoning);
- the water accumulation map calculated by the DTM, to take into account flow sources, flow direction and soil moisture concentration, strongly correlated to density and spatial extent of landslide;
- land-use cover map and a road map, to take into account for anthropogenic factors which may eventually trigger landslides;
- the rain occurrence and its temporal distribution, described by the modified "Fournier index", also named "climatic aggressivity index", defined by Arnoldus (1977).

The logistic multiple regression was chosen as statistical model for assessing susceptibility to landslide. With this model, the relationship between the occurrence and its dependency on several variables can be expressed as:

$$logit(p) = \ln\left(\frac{p}{1-p}\right) = b_0 + \sum_{j=1}^{n} b_j X_j$$

where X are the variables, b the coefficients and p the landslide occurrence probability obtained by a landslide inventory map. In the present work, b regression coefficients were calculated by the *r.regression.multi* GRASS GIS command (GRASS, 2015; Metz *et al.*, 2014).

Different checks and correlations with the Inventory of Landslide Phenomena in Italy (IFFI project) were performed to refine the model, carefully analyzing the role of stabilizing and triggering factors on the genesis of landslide and evaluating the possible criticality related to the calibration area (Marzocchi *et al.*, 2015; Bovolenta *et al.*, 2016b). The analysis was applied and validated to Liguria (Fig. 1a) and Piedmont regions. The study of some well-documented case histories also proved the idea that roads and railways influence landslide occurrence. Figures 1b and 1c show an example of a very critical area along a road, that is often closed during heavy rainfalls; the statistical model enhances the high susceptibility of the area, while the Basin Plan describes as critical a widespread area.

The procedure provides landslide susceptibility maps, useful also to guide and suggest the selection of appropriate engineering and/or landslide mitigation measures, helping for the proper resource allocation of authorities appointed for territorial planning and preservation.

3. The landslide risk mitigation countermeasures by an automatic procedure in GIS

As a natural continuation of the above mentioned procedure, an automatic GIS procedure was proposed to provide maps of the countermeasures

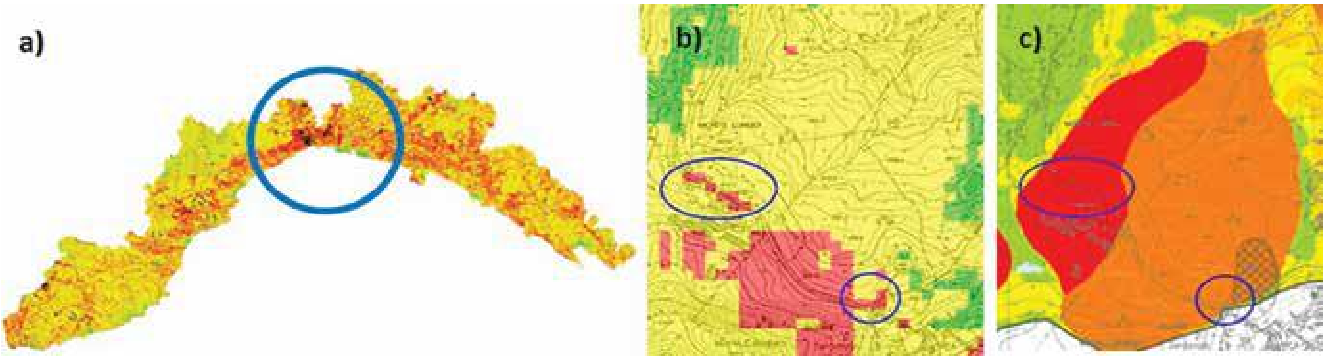

Fig. 1. Example of landslide susceptibility map on regional extension and zoom in the Genova district (a), a zoom on an active landslide area in Montelungo (Val Bisagno, Genova) (b) and the relative Basin Plan (c). Low, medium and high susceptibility values are green, yellow and red respectively. The blu circles indicate two critical areas.

Esempio di mappa di suscettibilità a scala regionale e zoom in Provincia di Genova (a), uno zoom su una frana attiva in Montelungo (Val Bisagno, Genova) (b) e relativo Piano di Bacino (c). I colori verde, giallo e rosso rappresentano valori di suscettibilità bassi, medi e elevati rispettivamente. I cerchi blu indicano due aree critiche.

to be recommended for slope stabilization and reinforcement (Bovolenta *et al.*, 2016a). The tool is able to analyze large territorial extensions in few minutes, given the thematic cartography. Hence, with relatively limited resources, it could be of great help in the increasingly complex management of the territory.

The innovative procedure correlates the factors influencing the occurrence of landslides with different types of countermeasures, obtaining medium or local scale maps suggesting the most appropriate interventions for the mitigation of landslide risk. The six categories of identified countermeasures are: re-profiling, drainage, retaining structures, reinforcement with inclusions, soil bioengineering, rock slope protection. Each of these categories includes a number of countermeasures, which can be subsequently evaluated and chosen in function of the specific characteristics of the site by a proper design. In fact, it is worth underlining that these maps do not replace the designer engineering judgment, or his work. But, they may help the designer in the choice and the territorial protection agencies in planning interventions and allocating funds.

The resulting maps of the countermeasures (Fig. 2) can be easily displayed on a desktop GIS viewer or published on a dedicated webGIS portal. A prototype webGIS, referred to the Genoa District, has been implemented by the free and open source software QuantumGIS Server (see the link: http://www.gishosting.gter.it/qgis/site/qgiswebclient.html?map=/home/gter/progetti/mappa_interventi.qgs). The webmap, if enriched with more information concerning exposure and vulnerability, could provide a Decision Support System (DSS) for a more efficient allocation of resources to technical staff of public administrations, designers, insurance companies, operating in landslide risk management.

4. The rainfall-induced landslide monitoring and forecasting by the LAMP project

The monitoring of slope instability phenomena is usually performed by inclinometers, assessing the horizontal displacements along a vertical profile, and/or by topographic (traditional, GNSS, laser scanner or radar interferometry) monitoring the surface movements. Even if the use of low-cost GNSS sensors for surface displacement monitoring is becoming more and more diffused (Biagi *et al.* 2016; Cina & Piras, 2014; Dabove & Manzino, 2016), the costs of monitoring are quite high (more than 30 k€ for the installation and 10 k€/year for the maintenance). Continuous and slow displacements (a few cm/year) can be gathered with these technologies, and alarms may be activated when defined thresholds are reached.

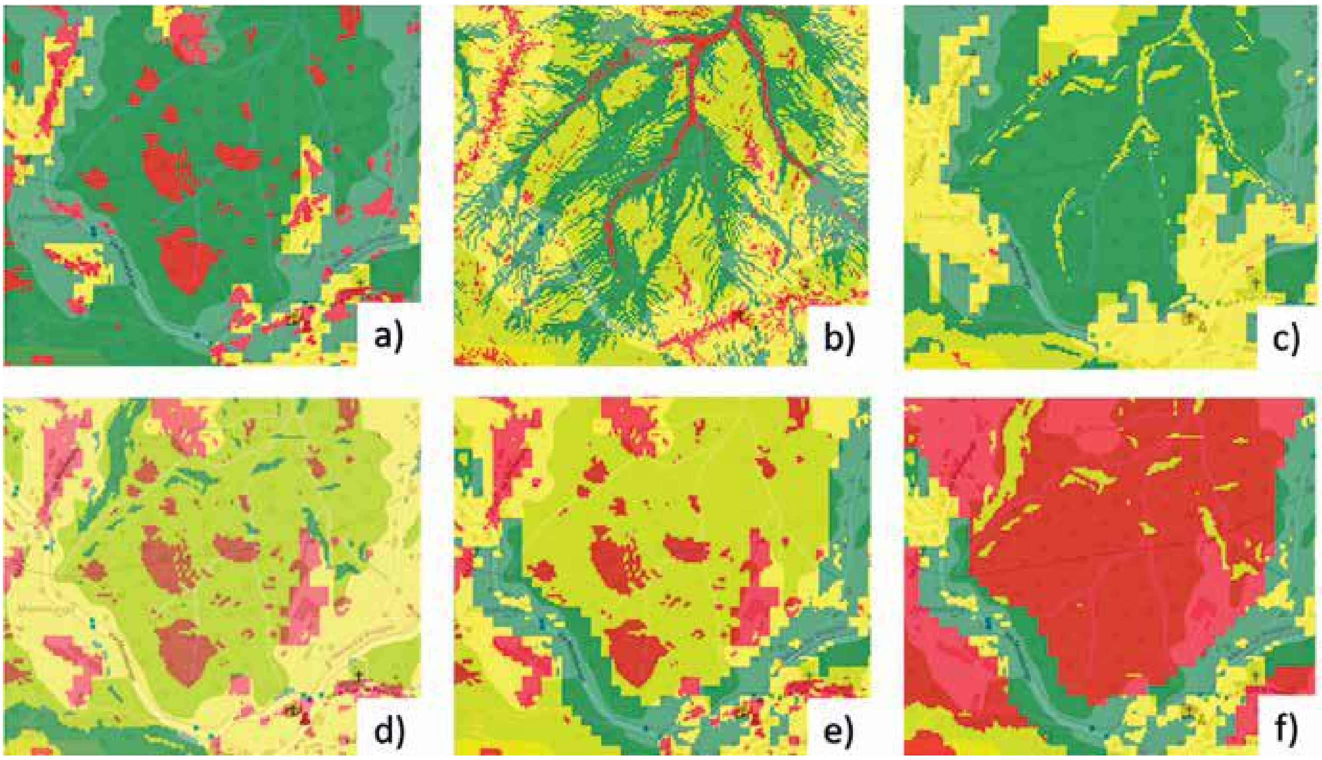

Fig. 2. Example of countermeasure maps for the site of Figure 1b-1c: a) reinforcement; b) drainage; c) soil bioengineering; d) reprofiling; e) protection; f) retaining structures.[green, yellow, red] colors indicates [yes, maybe, no] recommended countermeasures.
Esempio di mappe di intervento per il sito di Figura 1b-1c: a) rinforzo; b) drenaggio; c) ingegneria naturalistica; d) riprofilatura; e) protezione; f) strutture di sostegno. I colori [verde, giallo, rosso] indicano gli interventi consigliati [sì, forse, no].

A significant number of landslides affecting Italian territories is triggered by rainfalls. In literature many geotechnical models have been proposed for rainfall-induced landslide analyses. The soil is usually assumed isotropic and homogeneous or, at least, the horizontal heterogeneity is accounted for by allowing input values to vary from cell to cell (e.g. Baum *et al.*, 2010; Iverson, 2000; Montrasio and Valentino, 2008). From the hydrological point of view, the steady state is often considered, in other cases physically based models of hill slope hydrology are adopted (e.g. Baum *et al.* 2002; Lu and Godt, 2008; Montgomery and Dietrich, 1994). Because the computational effort is usually considerable, these models are poorly suited to analyze wide areas. Furthermore, the most common landslide modelling approach, consisting in two-dimensional limit equilibrium stability analyses, is inadequate to a full basin scale, or when the kinematic phenomena have a pronounced three-dimensional nature. Usually the models are not coupled with instrumental monitoring.

To monitor and predict rainfall-induced landslides, the LAMP (LAndslide Monitoring and Predicting) project proposes the use of a dense, low-cost, self-sufficient Wireless Network of Sensors (WSN), disseminated on the ground (Fig. 3b), coupled with a cognitive/predictive hydrological-geotechnical (IHG) model implemented by some of the Authors of the present paper. The sensors observe superficial soil water content, rainfall and air temperature, so to monitor the local hydrogeological conditions of the ground. The IHG model, fed by the sensors, evaluates in real time the propensity to collapse of different portions of the territory, establishing a cause-and-effect relationship between rainfall and landslide occurrence. Low-cost GNSS sensors could be added to validate the model results.

The proposed IHG model (Federici *et al.*, 2014; Passalacqua *et al.*, 2016) performs a water balance based on the modified Curve Number method, CN (SCS 1972-1975), for each cell of the study area. Hence it calculates the evolution of the groundwater level due to the occurred rainfall. Then it checks the eventual overcoming of the limit equilibrium conditions of the soil by a rather simplified Global Limit Equilibrium method (Skempton and Delory 1957). The IHG model requires geo-lithological characterization of the territory (through geophysical and geotechnical surveys to supplement the cartographic base) and the average surface of the water table. The flow chart in Figure 3a synthetizes the IHG model.

The total soil mass of interest is modelled in a GIS platform, taking into account the detailed morphology, the different features of soil strata, the water table etc. The analyzes are performed on single elements, but the unit cells may have different properties and conditions (from the geometrical, geotechnical and hydraulic standpoint), hence the shape of the entire three-dimensional collapse surface may be rather irregular. Finally, the results of the whole procedure are rendered in raster format, suitable even for not GIS expert users thanks to the immediacy of the semaphoric color scale (Figure 3b).The comparison of the results by the IHG model with the ones obtained by three-dimensional finite element methods (generally not diffused because of their costs, computational time and difficulty) has shown an excellent accordance (Carminati, 2017).

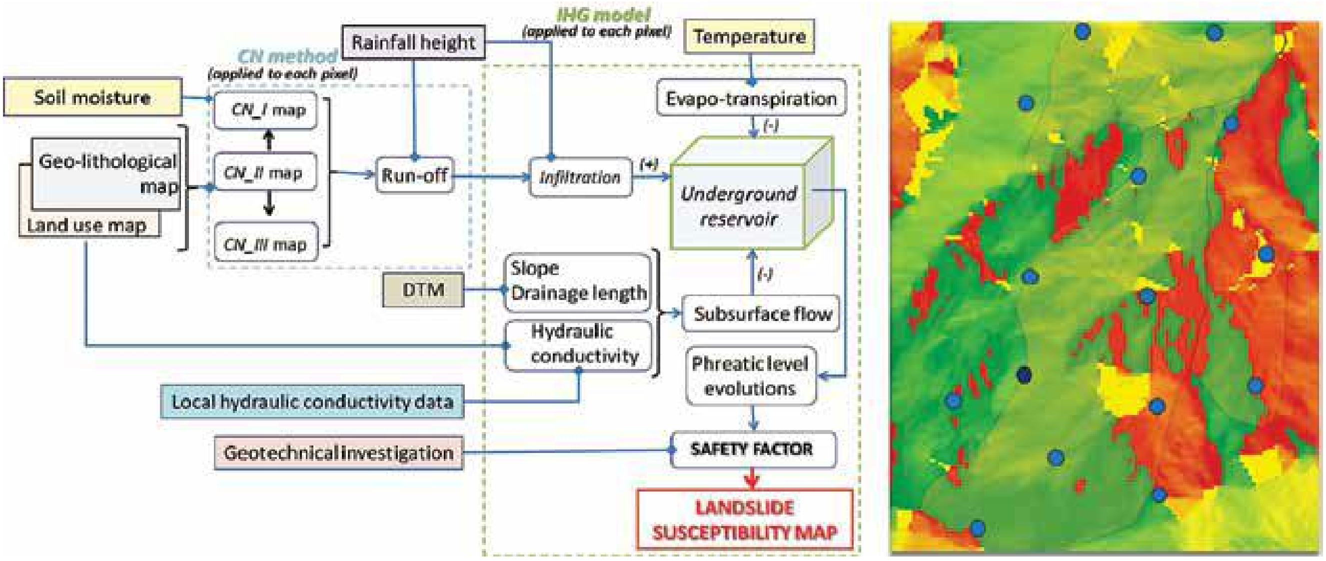

Fig. 3. a) Flow chart schematizing the implemented procedure; b) example of susceptibility map (green, yellow and red colors correspond to low, medium and high landslide susceptibility), of a sensors' network (blu dots) and the sensor's gateway (black dot).
a) Diagramma di flusso che schematizza la procedura implementata; b) esempio di mappa di suscettibilità (i colori verdi, gialli e rossi corrispondono a bassa, media e alta propensione al dissesto) e di rete di sensori (pallini blu) con il nodo accentratore (pallino nero).

When the IHG model is fed by a superficial sensors network (Fig. 3b), the final products are a map of landslide susceptibility in the occurrence of the real time rainfall and a map forecasting the susceptibility evolution in occurrence of the expected short-term rain (Bovolenta *et al.*, 2016c). The resulting maps may be released through a user-friendly web application for the non-expert GIS users.

It is believed that the adoption of low-cost and autonomous sensors, integrated with a model able to establish a cause-and-effect relationship between rain and landslide, can provide a useful support to the land-planning, design, management and maintenance of the slopes.

The knowledge of the dynamics activating these phenomena allows:

- to highlight areas with a significant susceptibility to instability;
- to produce alarms before the phenomenon is unleashed, having at disposal a real-time indication of the susceptibility to collapse;
- to provide indication of critical situations, potentially triggered by precipitation issued by weather forecasting models;
- to suggest countermeasures aimed at mitigating the phenomenon (e.g. drainages), thus assigning a priority scale.

5. *Conclusions*

Since the safety, or rather drastic and widespread risk mitigation on our territory would imply significant works that are not feasible in the short term, appropriate plans of forecasting and protection have to be prepared.

Effective forecasting and alarm systems allow one to limit the loss of life, as well as the economic ones. To prevent, of course, it requires an adequate understanding of the phenomena taking place in the territory, allowing to highlight the local critical issues, then pro-acting in due proportion to their expected seriousness.

The analysis of the territory features and of the triggering factors may contribute to identify in advance the types of interventions which could be proposed, supporting (but not replacing) the designer; moreover, it could be also a support in land management and land use planning for a more effective allocation of resources.

The studies described in this paper have been developed in a GIS environment (and the relative scripts are available on https://github.com/diccaunigegeomatica/geotecnica.git). The free and open source software GRASS GIS has been used both for its high speed processing capacity, and for the possibility to realize automatic procedures ad hoc for the specific problem. The free and open source QuantumGIS Server has been adopted to publish resulting maps on the web in an easy way. Besides the ethical and scientific implications of free software, regulations regarding software reuse (eg. Digital Administration Code) make these applications more suitable for use by public administrations.

Moreover, GIS software makes easy to manage the various georeferenced information on large areas and to obtain products that are immediately usable and that can be quickly updated if the need arises.

At the territorial scale, GISs are extremely effective in spatial planning and, if appropriately integrated by specific geotechnical assessments, can provide guidance on the general typology of landslide mitigation countermeasures. At the local scale, the GISs are an effective support in addressing the classical local analysis and monitoring of slope stability; furthermore, with the indispensable support of the geotechnical component, they can be a useful tool for addressing the design of sliding safety countermeasures.

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