A physical model to assess landslide susceptibility on large areas: recent developments and next improvements

Roberto Passalacqua\textsuperscript{a,}\textasteriskcentered*, Rossella Bovolenta\textsuperscript{a}, Bianca Federici\textsuperscript{a}, Dario Balestrero\textsuperscript{a}

\textsuperscript{a}DICCA, University of Genova, Via Montallegro 1, 16145 Genova, Italy

Abstract

The Authors have developed and refined, along the past years, a physically-based Integrated Hydrological-Geotechnical model (IHG), which is able to assess the territorial landslide susceptibility per effect of rain histories. The IHG model has been applied on two benchmark sites in Liguria, showing its reliability. Hence, it may become a very useful instrument in order to allow proper risk evaluations and/or land use-planning over wide areas, especially taking into account its forecasting ability if using short/medium term meteorological predictions.

Along the paper the last application of the IHG model, its improvements and the next developments are thoroughly described.

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1. Introduction

Many models have been proposed for rainfall-induced landslide analyses, applying geotechnical models and using the safety factor formulation. 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. 1,2,3]. Often, from the hydrological point of view, only the steady state is considered, while in other cases physically based models of

* Corresponding author. Tel.: +390103532938; E-mail address: roberto.passalacqua@unige.it
hill slope hydrology are adopted to simulate the processes involved [e.g. 1,2,4,5,6,7,8]. Because the computational effort is usually considerable, these models are poorly suited to analyze wide areas. Furthermore, the most common landslide modeling 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 character.

The Authors have developed and improved, along the years [9,10,11,12,13,14], a physically-based Integrated Hydrological-Geotechnical model (IHG) which, using an hydrological balance following the Curve Number method [15,16], is able to assess the territorial landslide susceptibility per effect of rain histories.

Along the paper the last application of the IHG model to the Mendatica site in Western Liguria, the model’s improvements and the next developments are described.

2. The case study of Mendatica

Mendatica is a small town in Liguria (Italy), set in the hinterland of Imperia on the border with Piedmont and France (see Figure 1). The center is located at the foot of Mount Fronté, in the high Arroscia River Valley, about 800m above sea level.

It lies entirely on the accumulation zone of a large relict landslide of about 250 hectares. The whole deposit is made up of several small bodies in the active or quiescent landslide conditions. Reactivations of displacements, mainly due to intense rainfall events, cause the sliding of the entire debris layer downstream and; since there is not only one type of kinematic, the landslide is defined as complex.

2.1. Available data and implemented interventions

In the last century several interventions to stabilize the slope were made. However, only since 2006 geotechnical investigations to support a more proper definition of the site hydro-geological model have been conducted, to aim the design phase of further consolidation measures. 13 boreholes were performed in different areas of the village, in order to obtain precise stratigraphic data and assess the local depth of the bedrock; the depth of the landslide debris, formed by a predominant silty-clay matrix, is variable between 15 and 40 meters.

Some soil samples collected from these soundings have been subjected to geotechnical laboratory analysis, giving a cohesion of less than 10kPa and a friction angle of about 28°. In addition to the vertical boreholes, three down-hole, a seismic refraction and four Lefranc tests were conducted too.

In general, the soil deposit is composed by an extremely heterogeneous material, both from the lithological than the granulometric points of view, being quite often into a loose state. The presence of zones with different permeability is responsible of a very complex underground hydrogeology; in fact, the site investigations have
ascertained levels of groundwater at different depths, with respect to the ground surface, either interconnected or isolated.

In 2007 an instrumental monitoring system was installed in situ: within 13 vertical holes, 9 inclinometers and 4 piezometers were installed, in order to better define the downhill displacements and the water table fluctuations over time. Following an evident reactivation of the landslide mechanism, due to intense rainfall events, most of the instruments have been irreversibly damaged, thus, the installation of a new instrumentation set is now in progress.

In 2015 a rain gauge was placed in situ, for a better assessment of the rainfall regime of this very area because, before, this was obtained by interpolating the data collected at remote stations.

Since 2010 an on-site monitoring system by crack-meters set on man-made artifacts is active: this is very useful in order to correlate the evolutions of the kinematic phenomenon to the vulnerability of the exposed structures.

These surveys and monitoring systems have led to the installation of an electro-pneumatic drainage system in the most sensitive area to collapse, with the aim of limiting the excursions of the groundwater level during intense rainfall events.

2.2. Modeling the site on GIS

To apply the IHG model on the Mendatica site, a Geographic Resources Analysis Support System (GRASS) GIS platform [17] was created, importing the Digital Terrain Model (DTM) at a resolution of 5 m, the Land Use and the Inventory of Landslide maps at a scale of 1:10.000. The Regional Technical Chart (CTR) at a scale of 1:5.000 and the digital orthophotos at a scale of 1:10.000 were used to georeference, with great accuracy, the geognostic survey points.

The digital models of the substrate and the average groundwater level were obtained, by Triangulated Irregular Network (TIN) interpolation, from the scattered survey points and additional points set along the riverbeds, encased in rock; there, the bedrock coincides with the DTM surface and the groundwater level is zero. While the bedrock elevation model resulted quite close to the reality, the average groundwater table elevation model was sometimes inconsistent with the on-site monitoring data, per effect of the hydro-geological complexity of the site. For a better characterization of such surface, a higher density of surveyed points is required. The mentioned digital models are in Figure 2.

3. Improvements of the IHG model

The IHG model applied to the first benchmark site referred in [13] was improved, to better model the evapotranspiration and the fictitious effective porosity.

![Fig. 2. Digital model of the bedrock on the left image (the red dots show boreholes or emerging rock locations) and of the average groundwater table (on the right image where the black dots show piezometers or wet riverbeds locations).](image-url)
3.1. Evapotranspiration

The evapotranspiration (ET) is a phenomenon that combines the evaporation of liquids from the soil and water mirrors and the transpiration from plants/vegetation, so as to define the total amount of water that is transferred from the catchment area to the atmosphere. The assessment of this parameter with direct methods is very expensive, for which the adoption of indirect methods that allow the calculation of evapotranspiration potential (ETP or ET0) calculated at standard conditions are preferred. Inside the IHG model the approximate method by Hargreaves & Samani [18], with proven reliability as from different studies, was implemented. It allows evaluating the ETP as a function of air temperature only (maximum, medium and minimum).

The effective evapotranspiration is finally the ETP multiplied by the crop coefficient of single plant. This coefficient fluctuates around the unit, depends on the type of crops, the speed of winds and the relative humidity.

Since the objective of the IHG model is the estimation of an evapotranspiration value representative of the entire area of interest, variable day to day depending on the temperature, the crop coefficient was assumed equal to unit, equaling the actual evapotranspiration with that potential.

3.2. Fictitious effective porosity

Among the various parameters at the base of the hydrological model defined in [9], the effective porosity is necessary to calculate the thickness of the saturated layer, depending on the amount of rain infiltrated into the ground. However, the use of the standard effective porosity highlights the simplifying assumptions of the original theory, such as the hydrological independence between adjacent land portions and the imprecise definition of the site hydrogeology, compromising the outcome of the procedure.

In the present study the "fictitious effective porosity" was therefore introduced, so that to keep implicitly into account, for each pixel, the lateral intakes due to the groundwater flow. The values of the fictitious effective porosity vary in function of the intensity of the rain, of the thickness of the saturable layer between the ground level and the average groundwater level. More relevant thicknesses of saturable layer have minor values of fictitious effective porosity, as they are most sensitive to the lateral contribution due to the underground flow’s runoff.

The calibration of this parameter takes place starting from the oscillations measured with piezometers, then obtaining empirical correlations to determine, in a GIS environment, the values of the fictitious porosity which depends on the thickness of the layer between the ground level and the average level of the water table.

4. Validation and critical analysis of the results obtained for the Mendatica site

The improved IHG model was applied to Mendatica site in relation to an intense and to a moderate rain, with good results as regards the modeling of groundwater oscillation. Figure 3 shows a detail of the map relative to the percentage of saturated layer as a result of heavy rainfall; critical values are evident in the zone where the electro-pneumatic drains have recently been installed.

The stability analysis allows defining safety factors in different groundwater level conditions. In favor of safety, the ground was supposed as non-cohesive with a shear resistance angle equal to 28°. In figure 4 the initial safety factor related to the mean groundwater level is shown; several critical situations in different areas of interest are evident. The north-east area near one of the rivers delimiting the relict landslide are considered critical, having slope angles greater than the friction one; in effect these areas are not unstable, because the bedrock quite often emerges, with very little or no thickness of loose soil. The IHG method also does not consider the positive contribution to the stability provided by retaining structures, which are showed in the zoom at right in Figure 4.

Finally, under the simplified assumption of independence of the single geotechnical cells, for which the adjacent land portions are not considered as interacting from the mechanical point of view, the instability of the downstream portions does not influence its contiguous upstream portions, leaving their safety factors unchanged. This requires a particular attention in assessing the local results of the analysis of stability, in fact, the model is still under development, so, the true limit border between a “safe” area and a “non-safe” one (see this anomaly in the following Figure 5) has still to be properly screened.

A deeper analysis of the results will be presented at the congress.
Fig. 3. Percentage of saturated layer in the zone subject to drainage interventions.

Fig. 4. The computed Factor of Safety and, on the right zoom in black, the layout of the unaccounted for retaining structures.

Fig. 5. Local errors, due to the simplified assumptions of the current method.
5. The LAMP approach

The next development of the IHG model is a new approach, named LAMP (LAndslide Monitoring and Predicting), with which the Authors propose the use of a dense, low-cost and self-sufficient network of sensors to be disseminated on site, whose measures shall be sent by a Wireless Sensor Network to the IHG model [14]. The sensor network could monitor the local hydro geological conditions. The IHG model, fed by the sensor data, could analyze, in real time, the propensity to collapse of different portions of the territory, by establishing a cause-and-effect relationship between rainfall and occurrence of the landslide. The LAMP’s final products will be maps of landslide susceptibility in occasion of the real rainfall and maps forecasting the susceptibility evolution, in occurrence of the expected short term rain. The knowledge of the dynamics that trigger the phenomenon can pinpoint areas with high susceptibility and can activate alarms before the phenomenon manifests itself, offering real-time indication of susceptibility to instability, and being able to forecast critical events potentially triggered by expected short term rain.

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