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Procedia Earth and Planetary Science 9 (2014) 74 – 82

Procedia
Earth and Planetary Science

The Third Italian Workshop on Landslides

Integrated Physically based system for modeling landslide susceptibility

Giuseppe Formetta[a]*, Valeria Rago[b], Giovanna Capparelli[a], Riccardo Rigon[c], Francesco Muto[b], Pasquale Versace[a]

[a]*University of Calabria, Civil and Environmental Engineering Department - Arcavacata Campus - via P. Bucci - 87036 Arcavacata di Rende (CS), Italy*
[b]*University of Calabria, Department of Biology, Ecology and Earth Sciences - Arcavacata Campus - via P. Bucci - 87036 Arcavacata di Rende (CS), Italy*
[c]*University of Trento, Civil and Environmental Engineering Department – Via Mesiano, 77, 38123 Trento (Tn), Italy*

Abstract

Rainfall induced shallow landslides cause significant damages involving loss of life and properties. Predict susceptible locations for rainfall induced shallow landslides is a complex task that involves many disciplines: hydrology, geotechnical science, geomorphology, statistic. Usually to accomplish this task two main approaches are used: statistics or physically based model. In this paper an integrated system for early warning of rainfall induced shallow landslides is presented. It is based on a hydrological model for solving 3D-Richards equation, a component for safety factor maps computation under infinite slope hypothesis and a GIS for model outputs visualization. The system is tested in Calabria (South Italy) for two river basins in which landslides occurred in the period from 8 to 10 March 2010. Results in terms of time evolution and spatial maps of safety factor at various depths are presented and compared to landslides maps.

Selection and peer-review under responsibility of Dipartimento di Ingegneria Civile, Design, Edilizia e Ambiente, Seconda Università di Napoli.

Keywords: Early warning systems; shallow landslide susceptibility; hydrological modeling

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* Corresponding author. Tel.: +39-0984-496621.
E-mail address: giuseppe.formetta@unical.it

Selection and peer-review under responsibility of Dipartimento di Ingegneria Civile, Design, Edilizia e Ambiente, Seconda Università di Napoli.
doi:10.1016/j.proeps.2014.06.006

1. Introduction

Landslides are one of the most widespread natural hazards in many areas of Calabria (Southern Italy), due to the combination of its peculiar geological, morphological, and climatic characteristics and very often to unsustainable land management[1]. Over the last two winters, in particular, heavy, persistent rainfall put the security of tens of thousands of people into great trouble, involving more than 1,600 events of landslides and floods, creating more than 2,300 crisis points, and affecting about 94% of Calabria's municipalities. Two were the most significant phenomena: i) a thousands of superficial landslides with a maximum of 2 meters depth, and ii) some hundreds deep seated landslides with a maximum depth of displaced mass around 25-35 meters.

Landslides recorded in the last winters were comparable, and sometimes worse, than those occurred in the 50s or early 70s. These events compromised the safety conditions of tens of thousand people, producing unsustainable discomfort. The road system was affected by obvious inconvenience and constant danger.

To protect residential areas and, more generally, infrastructures affected by these phenomena, early warning systems for triggering prediction can be introduced[2, 3].

Currently employed systems are mainly based on rainfall thresholds[4,5] relying on greatly simplified schematizations, which are not always able to follow correctly the physical phenomena underlying the landslides triggering mechanisms.

An improvement of the reliability of these systems depends, therefore, on the ability to implement more complex models[6,7,8], able to correctly simulate for example the infiltration processes under partial saturation conditions and their effects on soil shear strength.

Deterministic models for landslides early warning systems provide a theoretical framework linking hydrology, geomorphology, and geotechnical science with different degree of simplification in order to physically understand landslide location and timing. Infinite slope stability analysis[9] is usually coupled with steady[10,11,12] quasi-steady state[13] and transient[14,7, 15, 16] infiltration conditions in order to compute the safety factor FS

Models can differ for i) differences in the geological contexts and in mechanisms through which rainfall influences slope stability, ii) details adopted for describing the hydrological and geotechnical mechanisms occurring in the slope; iii) the spatial scale range adopted (from regional to single landslide scale); iv) quality and quantity of hydrologic, hydraulic and geotechnical available data.

There is no doubt that in order to ensure a correct and proper application, the models must be properly calibrated, possibly on experimental observations (monitoring systems, site investigation and laboratory testing of physical models), and finally implemented in early warning systems.

In this context, the article proposes and integrated system for landslide early warning made of three parts: a hydrological model for solving 3D-Richards equation, a component for safety factor maps computation and a GIS for model outputs visualization. The system is applied for two sites in Calabria along the Salerno-Reggio-Calabria highway. In the study area some landslides were identified and, after having retrieved the necessary data for the analysis, the model was applied by checking its predictive capabilities.

2. Methodology

The integrated system for landslide susceptibility evaluation is based on three main components: a hydrological model for soil suction and soil water content estimate, a component for the computation of the factor of safety (FoS) based on infinite slope hypothesis and the uDig (http://udig.refractions.net) Geographic Information System (GIS) for visualization of the outputs, Figure 1.

GEOtop model[8,17,18] is a three-dimensional (3-D), physically based, spatially distributed model that performs water and energy budgets. It models subsurface saturated and unsaturated flows, surface runoff, channel flows, and turbulent fluxes across the soil-atmosphere interface (e.g., latent and sensible heat fluxes, soil temperature, etc.).

Model inputs are: maps (digital elevation model of the basin, slope, aspect, soil type, landcover), meteorological files containing precipitation, air temperature, and other meteorological data (such as relative humidity, shortwave radiation, wind velocity) if available, and finally other parameters (residual and saturated water content, Van Genuchten soil water retention curve parameters, numerical parameters for convergence criteria). Main model outputs are: soil moisture, soil suction, water table depth maps at different soil depths (for each layer of the soil model).

The component for FoS computation is based on the infinite slope hypothesis[19,20,21]. The model works in a distributed mode: it takes raster maps of slope, soil suction, soil moisture, friction angle, soil and root cohesion and it provides the FoS for each pixel of the basin and for each layer in which the soil is discretized according[22]:

$$FoS = \frac{\tan\phi'}{\tan\alpha} + \frac{2\cdot c'}{\gamma\cdot H\cdot \sin(2\alpha)} - \frac{\sigma_s\cdot(\tan\alpha + \cot\alpha)}{\gamma\cdot H}\cdot\tan\phi' \tag{1}$$

where φ' [degrees] is the friction angle, c' [kPa] is the soil cohesion, γ [kN/m^3] is the specific weight of the soil, H [m] is the soil depth, α [degrees] is the slope angle, and σ_s [kPa] is suction stress characteristic curve of the soil defined in eq. (2):

$$\sigma_s = \begin{cases} -(u_a - u_w) & if \quad (u_a - u_w) \le 0 \\ -\dfrac{(\theta - \theta_r)}{(\theta_s - \theta_r)}(u_a - u_w) & if \quad (u_a - u_w) > 0 \end{cases} \tag{2}$$

where ϑ [-] is the soil water content, u_a [kPa] and u_w [kPa] are the pore air and the pore water pressure respectively, and ϑ_r [-] and ϑ_s [-] are the residual and saturated water content respectively.

GEOtop provides the multilayer computation of soil moisture and pore water pressure and the FoS component computes multilayer maps of factor of safety. Finally model results can be visualized in the GIS open source uDig.

The components integration is performed according the modeling framework Object modeling system[23] (Oms). It is a java-based framework that allows to program by components[24]; three main features identify each component: Input (@In), Parameters (@Par), and Output (@Out). Oms offers the possibility to link each other model components building a modeling solution[25] by using the fields @In and @Out. Moreover Oms provides parameters optimization algorithms to tune model parameters (@Par) in order to fit experimental data[26, 25].

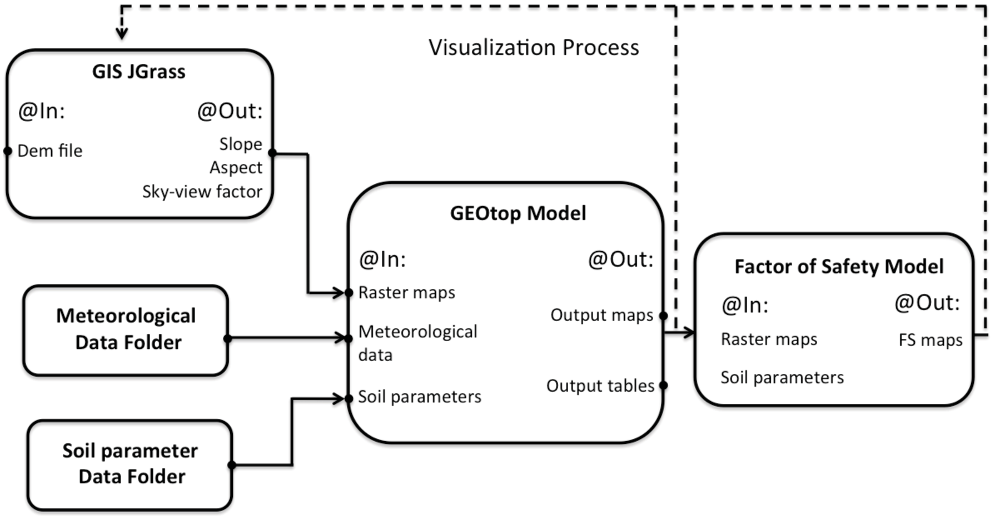


Fig. 1. Integrated System for landslide susceptibility maps.

3. Test Site

The study was carried out in the left side of the Albicello creek catchment, located in the southern portion of the Crati basin (western sector of northern Calabria) (Figure 2). The Albicello Torrent flows from the SO to the NE and extends from 39°12'41" N, 16°22'22" E to 39°15'32" N, 16°15'36"E. In the study area the topographic elevation has an average value of around 300 m a.s.l., with a maximum value of 550 m a.s.l. Slope gradients, computed from DEM, range from 0 to 37 degrees, while their average is about 26 degrees.

The climate is sub-humid, with average annual precipitation of 1200 mm, distributed over 105 rainy days, and average temperature of 16 °C. Rainfall peaks occur in the period October–March, during which mass wasting and severe water erosion processes are triggered[27,28,29].

The Crati Basin is a Pleistocene-Holocene extensional basin filled by clastic marine and fluvial deposits[30,31,32]. The stratigraphic succession of the Crati Basin can be simply divided into two sedimentary units as suggested by[33]. The first unit is a Lower Pliocene succession unconformably overlying the bedrock and cropping out extensively along the western side of the basin. It consists of conglomerates and sandstones passing upward into silty clays[33] second unit unconformably lies either on the first unit or directly onto the bedrock. It consists of a Plio-Pleistocene succession of clayey deposits grading upward into sandstones and conglomerates referred to Emilian and Sicilian, respectively[33], as also suggested by data provided by[34]. In the study area outcrops the second unit; under a topsoil of about 1,5 m there are sandy - gravelly and sandy deposits, generally well-stratified, with widespread intercalations from conglomeratic to conglomeratic-sandy and with local intercalations of silt and sandstones. Mass movements were analyzed by integrating aerial photography interpretation acquired in 2006, 1:5000 scale topographic maps analysis, and extensive field survey.

In particular, slides and complex slide-flows, already present in 2006, and shallow mass movements occurred on 08-10 March 2010 has been recognized as reactivation of pre-existing dormant landslides.

All the data were digitized and stored in GIS database, which was the basic input needed to generate the landslide susceptibility assessment[1].

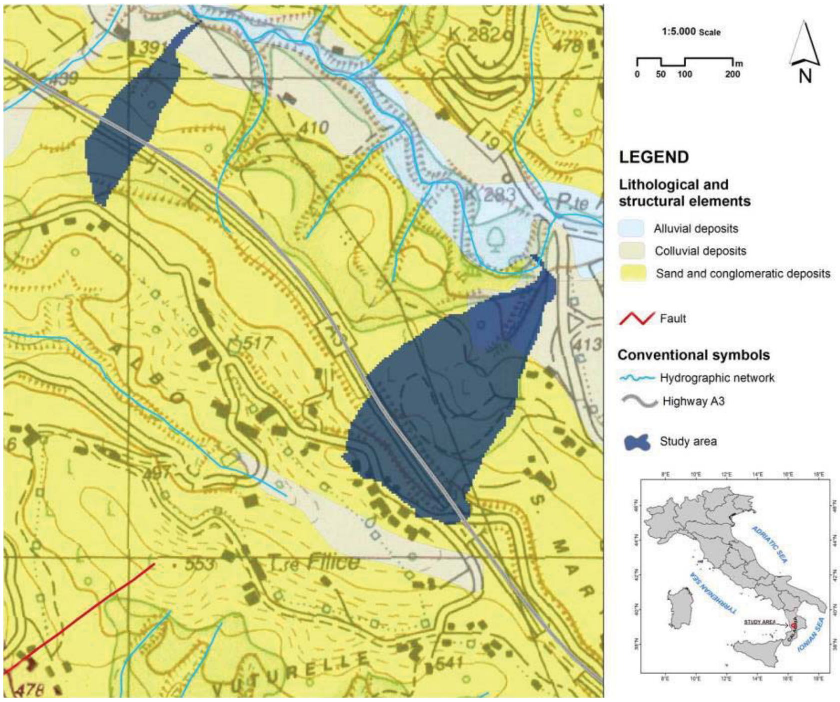


Fig. 2. Study Area, basins in which the model is tested and lithological and structural elements.

4. Applications

The integrated system is applied in Calabria, Italy, along the highway Salerno-Reggio Calabria in the Cosenza municipality. The application is developed as part of the PON Project: “Integrated Systems for Hydrogeological Risk Monitoring, Early Warning and Mitigation Along the Main Lifelines”. The objective of the application was to verify if the system was able to simulate the landslide event occurred on 10/03/2010 over two basins B1 and B2, Figure (3, a).

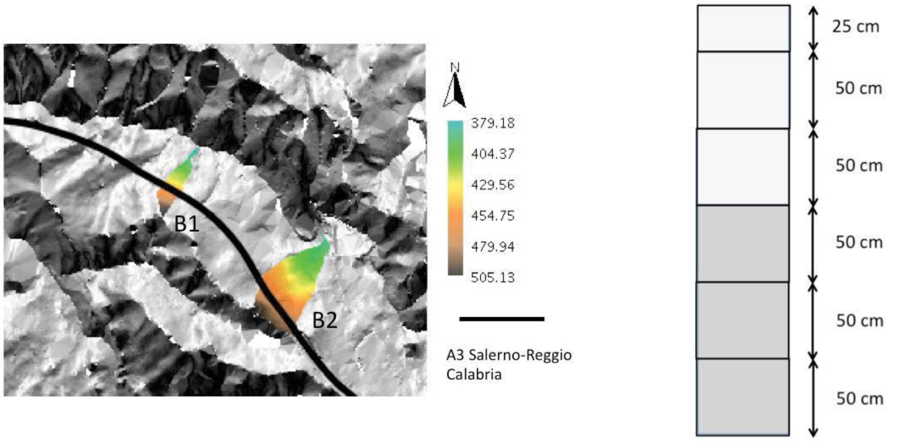
Model input maps were: digital elevation model, slope, aspect and sky view factor. Soil type and land cover were assumed constant over all the basins.

Table 1. Soil parameters used in the GEOtop model. Dz is the soil layer thickness; kh and kv are the horizontal and vertical soil hydraulic conductivities respectively; α and n are the Van Genuchten’s soil water retention curve parameters.

Dz [mm]	Kh [mm/s]	Kv [mm/s]	θr [-]	θs [-]	α [1/mm]	n [-]	c’[kPa]	φ' [°]
250	0.01	0.01	0.05	0.7	0.004	1.65	10	28
500	0.01	0.01	0.05	0.7	0.004	1.65	10	28
500	0.01	0.01	0.05	0.7	0.004	1.65	10	28
500	0.005	0.005	0.05	0.65	0.006	1.45	15	30
500	0.005	0.005	0.05	0.65	0.006	1.45	15	30
500	0.005	0.005	0.05	0.65	0.006	1.45	15	30

The soil is discretized in 6 layers with variable depth according to the stratigraphy presented in Figure (3,b). Two soil layers are used (light and dark grey) and soil parameters are presented in table (1) for each layer. Free drainage boundary conditions were assumed in the model simulations. This was justified by the groundwater absence during in situ measurements. Rainfall and air temperature were available at hourly time step from the closest meteorological station (Rogliano, Cosenza). The simulation period was from 01/07/2009 to 11/03/2010 with hourly timestep.

For each timestep and for each soil layer GEOtop provides soil moisture and soil suction maps. The outputs of GEOtop model were used as input for FoS component. Moreover it uses other geotechnical parameters specified in table 1 and defined for each layer of soil. The outputs of FoS component were safety FoS maps for each timestep, uploaded in the GIS uDig and ready for user visualization.



(a) (b)

Fig. 3. (a) study area, basins in which the model is tested. (b) soil stratigraphy used in model simulation.

Results for basin B1 and B2 are presented in Figures 4,5 and 6,7, respectively. Time series of FoS were computed for one point inside the landslide area both in B1 and in B2 (Figures 4 and 5, respectively). Moreover maps of safety factor were computed at 3 depths (50, 90 and 130 cm) for B1 and B2 (Figures 5 and 6, respectively) and for three selected timesteps: 21-07-2009, 28-01-2010, and 09-03-2010 at 10.00.

Results in Figures 3 and 4 show the evolution in time of the safety factor at three depths (50, 90, and 130 cm) and in two control points in B1 and B2 respectively. FoS is higher than 2.0 both for 90 and for 130 cm during the whole simulation period and for both the sites B1 and B2. Instability is observed for the 50 cm around the date of landslide movement (8-10 March 2010). FoS starts to decrease from around 10 February in both the test sites, B1 and B2. The analysis of Figures 5 and 6 shows the capability of the model to detect landslided area. In correspondence of the day 09 March pixels with FS lower than 1 are inside the mapped landslides. This is much more evident in the test case B2 where both landslides are detected. In the test case B1 even if the model provides a higher number of false positive respect to the B2 application, it is able to detect instability up the highway's side.

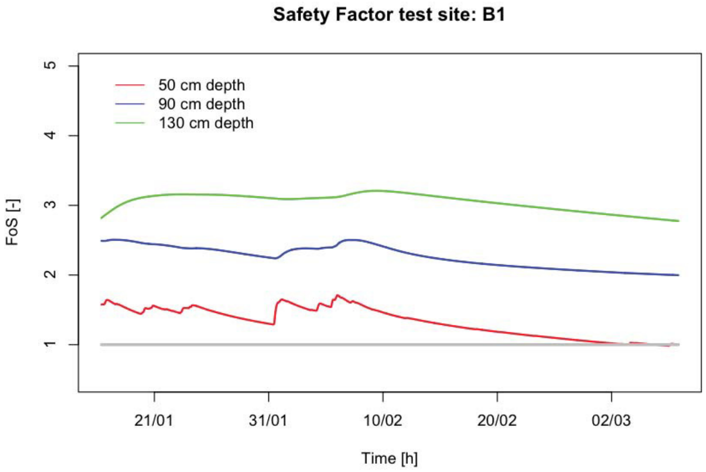


Fig. 4. FoS time series for site B1 from January to March 2010.

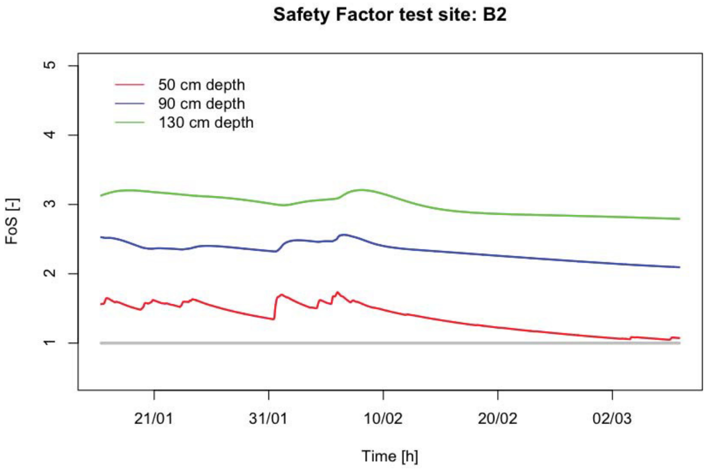


Fig. 5. FoS time series for site B2 from January to March 2010.

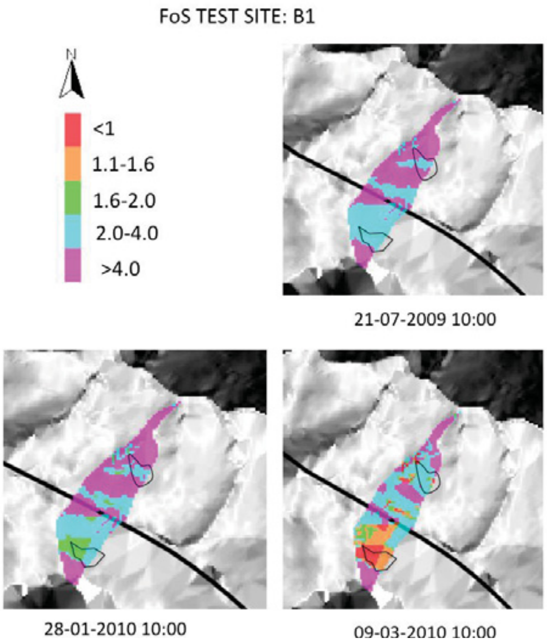


Fig. 6. FoS maps for site B1 at 50cm depth for three time steps: 21-07-2009, 28-01-2010, and 09-03-2010 at 10.00. The black polygons are the mapped landslides occurred during the 8-10 March 2010 event.

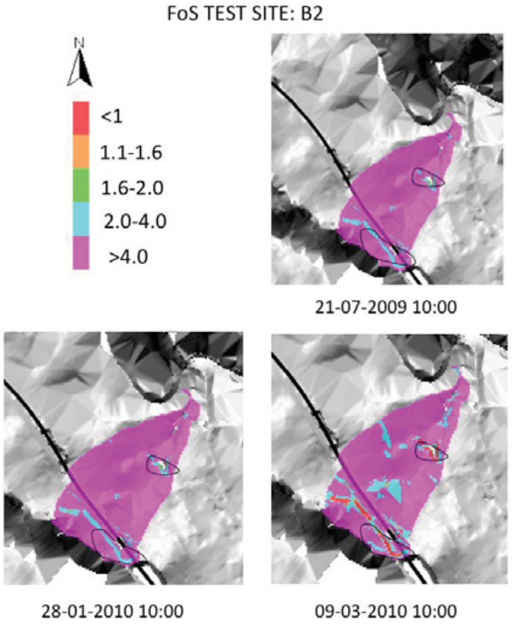


Fig. 7. FoS maps for site B2 at 50cm depth and for three time steps: 21-07-2009, 28-01-2010, and 09-03-2010 at 10.00. The black polygons are the mapped landslides occurred during the 8-10 March 2010 event.

5. Conclusions

An integration system for rainfall induced shallow landslides modeling is presented. The system has three main components: the hydrological model for the resolution of 3D-Richard equations in stratified soils, a component for the computation of the safety factor and a GIS system for the input maps computation and for output maps visualization.

The system is tested in a case study in Calabria along the highway Salerno-Reggio Calabria in the Cosenza municipality. The system is applied in order to reproduce the shallow landslides happened on 8-10 March 2010. The model results in term of safety factor time evolution and safety factor maps were presented and discussed.

The observed depths of the sliding surface during the events of 8-10 March were around 30-100 cm. Even if the model was able to detect the more shallow landslides in both the applications, safety factor spatial simulations of the present false positive and false negative pixels. This could be due to the uncertainty about soil parameters distribution, definition of the boundary condition, and meteorological input data. The modularity of the system allows further analysis of these problems. Uncertainty on soil parameters can be investigated by calibrating them in order to fit available soil moisture and soil suction measurements. Boundary condition effects can be studied by modifying their schematization in the model code.

Developments of the system are planned. Integration with OMS automatic calibration algorithms will be useful in order to optimize soil parameters and reproduce field measurements such as soil moisture and soil suction. This procedure could improve model performance also in term of safety factor computation. Finally future works on uncertainty of geotechnical soil parameters as friction angle and soil cohesion will be carried out.

Acknowledgements

This research was funded by the Italian Instruction, University and Research Ministry (MIUR), PON Project No. 01_01503 “Integrated Systems for Hydrogeological Risk Monitoring, Early Warning and Mitigation Along the Main Lifelines”, CUP B31H11000370005.

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