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Landslide susceptibility assessment by EPBM (Expert Physically Based Model): strategy of calibration in complex environment

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Abstract

Physically based model may be used to assess landslide susceptibility over large areas. However, majority of case studies are applied for complex phenomena for a one event, a little site or over large areas when landslides have simple geometry and environmental conditions are homogeneous. Thus, assessing landslide prone areas for different type of landslides with several geometries and for large areas needs some specific strategies. This work presents an application of a specific procedure based on a physically based model for one complex area with several landslide types. By different steps, it is demonstrated that it is possible to improve susceptibility map and to take into account different slope failure with different depths. This first attempt encourages us to continue on this path in order to improve the existing susceptibility maps in this area.

Keywords

Landslide, Susceptibility, Physically based model, Calibration, Monte-Carlo, Environmental heterogeneity

Introduction

Landslide hazard assessment (LHA) estimates the landslide probability occurrence on a territory within a reference period for a given intensity (Corominas et al., 2014). It is deduced from information on:

(i) The landslide susceptibility expressed as the potential initiation of phenomena based on the spatial correlation between landslide initiation areas observed in a territory, the predisposing terrain factors (slope, land-use, surficial deposits, etc.), and the occurrence of triggering factors (rainfalls, earthquakes, etc.) for different slope failure surface (Corominas et al., 2014).

(ii) The landslide intensity which integrates the propagation mode depending of the mechanic laws governing runout area (Corominas et al., 2014).

Hence, LHA answers to three questions: where (location), when (timing) and at which intensity and magnitude (size, propagation and velocity) landslides occur.

In order to answer to the two first questions and assess landslide susceptibility, several approaches can be led: (i) inventory-based methods (IBMs), (ii) knowledge-driven methods (KDMs), (iii) data-driven methods (DDMs) and (iv) physically based methods (PBMs; Corominas et al., 2014). PBMs are rely on the modelling of slope failure processes and generally combine hydrogeological model and slope stability model. The methods are applied on complex and deep seated phenomena on little sites (e.g.. for one event) at large scale (< 1: 5 000) or over large areas for landslides with simple geometry (i.e. shallow translational landslides, Salciarini et al., 2008) and for homogeneous environmental conditions (geological, geomorphological, etc., Godt et al., 2008).

Thus, it appears difficult to analyze jointly both shallow and deep seated landslide over large and complex areas because (i) the predisposing and triggering factors are different and (ii) there are large uncertainty and variability on geotechnical parameters. Recently some studies attempted to solve these drawbacks either by combining different spatial approaches (DDMs with KDMs or KDMs with PBMs; Thiery et al., 2007; 2014), or by creating physical based models trying to consider different landslides' geometries and the environmental heterogeneity of study sites (Jia et al., 2012, Mergili et al., 2014a, 2014b). Nevertheless, large simplifications about hydrological conditions or surficial deposits are made (Jia et al., 2012). Hence, the implementation of a landslide susceptibility analysis for a complex and heterogeneous environment over large areas faces two major challenges: (i) taking into account different slope failure (in term of shape and depth); (ii) taking into account the uncertainty of the geotechnical parameters due to inherent spatial and temporal variability and which affect the final computed FoS (i.e. overestimation or under estimation of results; Mergili et al., 2014a; 2014b).

In this work, we present the results of a strategy which aim at taking into account the two challenges mentioned above. The strategy is based on an expert physically based model (EPBM) able to support (i) a complex geomorphology, (ii) several type of surficial formations and geology, (iii) uncertainties of the environment and (iv) geotechnical parameters heterogeneity. A specific calibration was performed by using different slope failure geometries (type, size, depth) in order to test each hypothesis and obtain a robust approach. The model is implemented in a GIS environment.

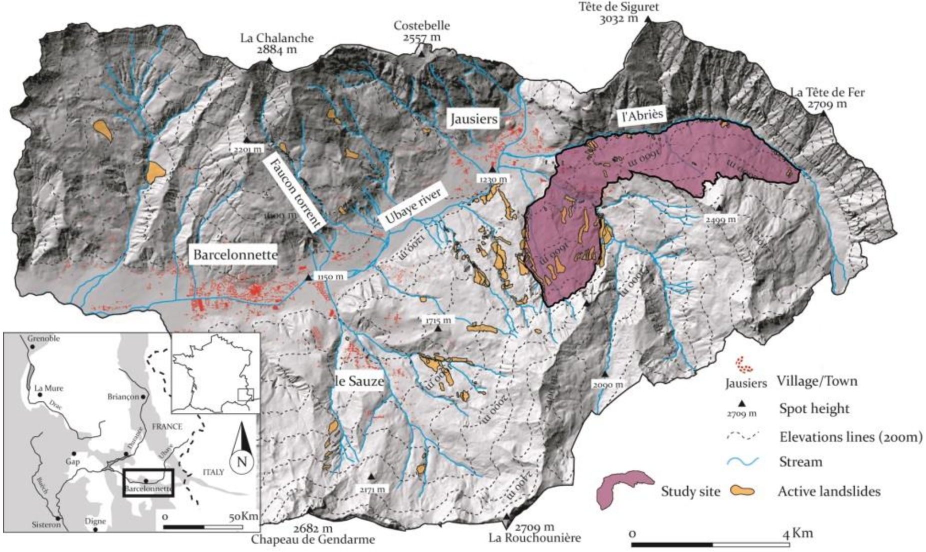

Fig. 1 Location of the Barcelonnette Basin, calibration area and location of active landslides (Thiery et al., 2014).

The paper is organized as follows: in section 2, the EPBM and its concepts are introduced. They are followed by the presentation of the rational and specific strategy applied to calibrate and validate results. The section 3 focuses on the calibration area representative of the total area, and the data used for this research. In the section 4, the results are presented. The section 5 discusses the results and the model performance. Finally we conclude (Section 6) by the future improvements of the model. At each step, statistical tests and expert exchanges allow validating the results.

The model and the specific strategy are applied on a study site located in the French South Alps where numerous different landslide types were observed and analyzed.

Geomorphological settings

The Barcelonnette Basin (Fig. 1)

Located in the middle section of the Ubaye Valley, the Barcelonnette Basin extends from 1100 to 3000 m a.s.l. and is representative of climatic, lithological, geomorphological conditions observed in the South French Alps. The climate is controlled by mountain and Mediterranean influences with (i) high inter-annual rainfall variability (734 ± 400mm over the period 1928-2013) marked by intense and violent summer rainstorms (> 50 mm h-1); (ii) significant daily temperature range (> 20°C) and (iii) between 120 and 130 days of freezing per year. Because the valley is oriented east-west meso-climatic difference on a small scale is current (Maquaire et al., 2003).

Authentic geological window developed in the autochthonous Callovo-Oxfordian black marls, the site, over an area of about 300 km2, is surrounded by the two allochtonous Eocene crystalline sheet thrusts of Parpaillon and Autapie (Maquaire et al., 2003). This particular geomorphological context is the consequence of glaciers' action completing by torrential erosion which have carved out a large basin of 13 000 ha in soft rocks (i.e. black marls; Thiery et al, 2007). Constituted by limestones, sandstones, flyschs and gypsum, the sheet thrusts shape the high crests and the steepest slopes ranging from 2200 and 3100m in elevation. Below them, the upper slopes (from 1800 to 2200m) are covered by scree deposits with a thickness from 2 to 10 m. The lower slopes present irregular topography with (i) in one hand steep slopes (> 35°) carved in black marls outcrops and commonly gullied in badlands and (ii) in other hand more gentle slopes (5-35°) with planar or hummocky topography. Majority of them are composed by moraine deposits (thickness from 2 to 20m) overlaying black-marls and are generally covered by forests and/or natural grasslands. They are affected by large relict landslides, latent and active deep seated landslides (i.e complex and rotational landslides), active shallow landslides (i.e translational and rotational landslides) and/or surficial soil creep. Most of the active landslides are located along streams or on gentle slopes where the moraine deposits or the contact moraine deposits/black marls creates a hydrological discontinuity favorable to failure.

The test site (calibration area) for this research is located on the north facing hillslope of the basin (Fig. 1). It extends over an area of about 11 km^2 and is representative of the various predisposing factors (lithology, tectonics, climate, and land use) favorable to slope instabilities (Thiery et al., 2014).

Landslides (Fig. 2)

The characteristics and the activity of these instabilities have been studied during the last twenty years by several research teams (Maquaire et al., 2003; Malet et al., 2005; Thiery et al., 2007; Schlögel et al., 2015). On the basis of different information source (Thiery et al., 2007; Schlögel et al., 2015) and a diachronic air photograph interpretation between 1974 and 2004 coupling with field observations, a landslide inventory was compiled at 1:10,000 scale. The boundaries of landslides are digitized in two zones: (i) the landslide triggering zone (LTZ) and (ii) the landslide accumulation zone (LAZ, Fig. 2). The geometrical (perimeter, area, and maximal length and width) and geomorphological characteristics (typology, state of activity, considered magnitude, morphometric characteristics) are stored in a GIS database.

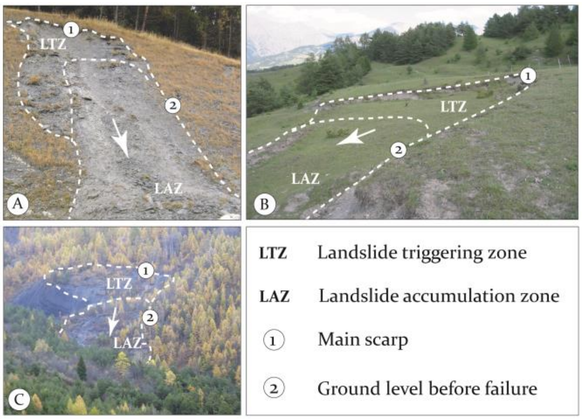

Fig. 2 Example of different landslide type. A. Shallow translational landslide; depth: maximum 3m. Rotational landslide; depth: maximum 6m. C. Complex landside with rotational failure; depth: maximum 10m.

Six types of landslides have been defined according to the typology of Dikau et al. (1996). (i) Shallow translational slides are relatively small and mainly located on steep slopes along streams. They occur on the weathered bedrock or at the contact moraines deposits/bedrock. (ii) Rotational slides are located along streams but more on gentle slopes than the shallow translational slides. They occur principally in moraine deposits sometimes at the contact between surficial deposits and bedrock. (iii) Translational slides are located more on gentle slopes at the contact with the bedrock, and their sizes are very variable. (iv) Complex landslides are a combination of rotational landslide (triggering area) and translational landslide (accumulation area). They occur in majority in thick moraine deposits and sometimes in the weathered marls which cover it. (v) Earthflows occur in weathered black marls, they are the most active landslide in the basin. (vi) Rock-block-slides which occur in black marls principally in the bad-lands areas. For this study only translational shallow and rotational landslides (Fig. 4) are taking into account.

Model, strategy and materials

ALICE® model: concept

ALICE® (Assessment of Landslide Induced by Climatic Events) was developed by the French Geological Survey (BRGM) to support landslide susceptibility mapping for areas ranging from slopes to department (Vandromme et al. 2014, Sedan et al. 2013). Developed in a GIS environment (MAPINFO®), it is a PBM able to support different landslides' geometries, the spatial and inherent heterogeneity of the surficial deposits and geology and their geotechnical parameters, different triggering factors (i.e. water and seismicity) and land use change.

The geometry of the studied area is entered as a dataset in raster format: topography, geometry of geological and/or surficial deposits layers represented by a DTM (i.e. basal surface of the layer). Geomechanical characteristics: cohesion (c'), friction angle (φ') and volumetric weight (γ'), are associated to each geologic and surficial deposits layers. These parameters can be implemented by a constant value or by probabilistic distributions in order to take into account environmental variability and uncertainties. The probability distributions can be defined by the expert and the help of literature if no survey or geotechnical test can be made.

Additionally, the tool allows defining the geometry of failure areas (i.e length, depth, and type -). The triggering factors taking into account are (i) the ground water level (GWL), or (ii) seismic acceleration. GWL can be implemented empirically in the formations considered as favorable to instabilities by increasing the saturation level form 0 (dry conditions) to 1 (saturated conditions) or with the help of a hydrogeological model taking into account the effective rainfall.

Based on a Limit Equilibrium Method (LEM), the slope stability calculation is used to solve the forces applied on sliding bodies along a potential slip surface for an area. To calculate the FoS, the Morgenstern and Price method (1967) was chosen because (i) it satisfies the equilibrium conditions and involves the least numerical difficulty; (ii) any slip surface geometry can be calculated; (iii) it takes into account interslice forces across the sliding mass. The iteration process is based on the Zhu (2005) concept which reduced the number of iteration about the interslice function. The hypothetical failure surface is divided into n vertical slice. Each slice I is subject to the normal shear interslices forces, to the shear resistance:

$$R_i = [W_i \cos\alpha_i - u_i b_i \sec\alpha_i]\tan\phi_i' \cdot + c_i' b_i \sec\alpha_i \qquad [1]$$

and the moving forces:

$$T_i = W_i \sin\alpha_i \qquad [2]$$

With W_i: weight; α_i: base inclination; u_i: average water pressure; b_i: width of the slice; ϕ'_i: effective friction angle; c'_i: cohesion along the base; and R_i: sum of the shear resistances, except the normal shear interslice forces; T_i: component tending to cause instability.

The fraction of the contrasting forces acting on the failure is expressed by the factor of safety (FoS). The slope stability assessment is performed on regularly spaced 2D profiles automatically produced on the whole area and based on maximum gradient lines from the topographic raster.

Once all parameters (geotechnical, landslide, GWL) implemented in the model, it performs a random selection of each geotechnical value (if they are defined by probabilistic distributions) by Monte Carlo simulation. Thus, several sliding surface are computed along each profile for each cell. The final result is either a FoS (if no distributions were defined) or a probability of failure (the lowest probability calculated by cell is retained) for each cell.

Strategy of calibration and validation (Fig. 3)

During the last decade ALICE® was used by the BRGM in French mountain areas (Baills et al., 2012; Vandromme et al., 2014; Bernardie et al., 2017) and West French Indies (Sedan et al., 2013, Thiery et al., 2015). Nevertheless, for each case study, large discrepancies about the calibration strategy were observed. As a result, the BRGM has engaged an action to develop a calibration method based on different steps. The method should be applicable for different environment but also for other PBMs similar to ALICE®.

The strategy is made: (i) to obtain representative failure slope type taking into account shallow and deep-seated landslides, (ii) to reduce the uncertainty linked to the environment, (iii) to obtain reliable results representative of field observations. To achieve these objectives, it is split in three main steps (Fig. 3):

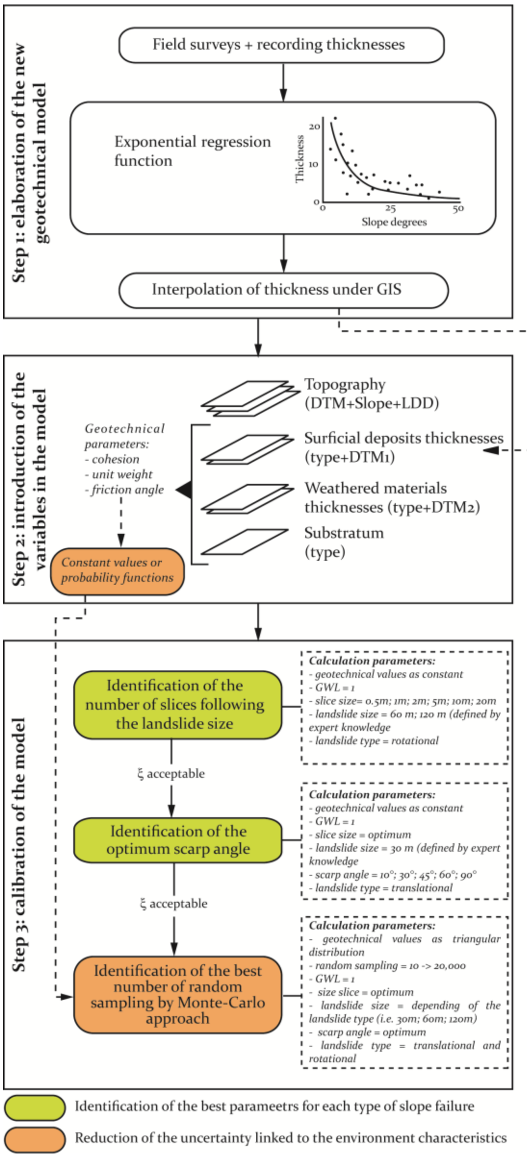

Fig. 3 Strategy used to calibrate ALICE®.

(i) The first step consists in designing a new geotechnical model for the surficial formations (i.e. moraines deposits, colluviums, weathered marls, etc…) and their depths.

(ii) The second step aims to introduce each variable in the model and the associated value.

(iii) The third step identifies the different parameters to introduce in the model (i.e. optimal number and size of slices, geotechnical parameters, probability distributions and minimum number of random sampling by Monte-Carlo simulation). It is split in 3 sub-steps. At each sub-step the best parameters retained previously are introduced in the followed sub-step (Fig. 2). The landslide size is defined according to previous work by Thiery et al. (2007, 2014).

The validation of each step is performed by calculation of (i) the relative error which compares landslide inventory depletion areas and the highest probabilities calculated and (ii) the calculation of success rate (SR) plotting the cumulative percentage of observed landslides against the percentage of areas classified as positive (with high probability of failure, Chung and Fabbri, 2003). The area under curve (AUC) is used to assess the success accuracy; more the AUC is near 1, more the degree of fit of the model is considered as good.

Materials

The variables used in this work can be grouped in five classes: lithological map (LM), surficial formations map (SFM), topography (DTM), surficial formation thickness (DTM 1), weathered lithology thickness (DTM 2). The SFM is obtained by the segmentation of the landscape in homogeneous geomorphological macroareas closely associating facies and shape (Thiery et al., 2007).

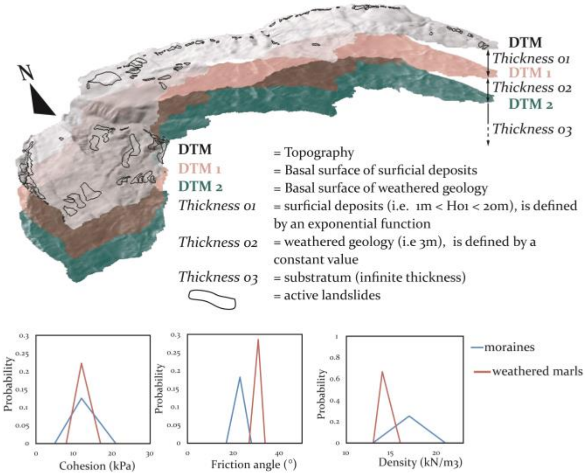

Fig.4 Conceptual scheme of the layer concept by DTMs and examples of triangular distribution for moraine deposits and weathered marls.

The DTM is obtained by the kriging of a network of triplets issued from the digitization of elevation lines from 1:25,000 scale topographic maps enlarged by the French Geographical Institute at 1: 10,000 scale.

The DTM 1 was represented initially by the subtraction of the surficial formations thickness class (SFT) with DTM (Thiery et al., 2007). In so far as (i) SFT oversimplified the different thicknesses of each surficial deposit and (ii) it is a key parameter which control instabilities (Jia et al., 2012), a new SFT map is derived from direct thickness observations of outcrops along streams and slopes (min = 0.5 m; max = 20 m). Each observation was located by DGPS. The different formations are closely in relation with slope degrees value (e.g. moraine deposits are located on gentle slopes, colluviums are observed on steep slopes, Thiery, 2007). Thus an exponential regression function obtained by plotting thicknesses and slope was performed for each surficial type in order to obtain a spatial prediction and continuous values.

The DTM 2 is obtained by subtraction of a constant value to DTM1 (i.e. 3m; value generally observed on the field area – Thiery et al. 2007). Under it, the substratum is considered as continuous and infinite. Fig. 4 shows an overview of the layer concept used in ALICE®.

Results

Step 1

The exponential regression function is created to predict the spatial distribution of the surficial deposits thickness (i.e. moraine deposit, moraine colluviums, colluviums, torrential formations). Sample points introduced to calculate the regression function were used to evaluate the accuracy of DTM1. Three indices (Mean absolute error MAE, Root Mean Square Error RMSE, Mean Absolute Percentage Error MAPE) are calculated from observed value and predicted value.

Table 1 Statistical accuracy indices for the new DTM1. MAE = Mean Absolute Error. RMSE = Root Mean Square Error. MAPE = Mean Absolute Percentage Error. R^2 = Determination Coefficient.

MAE	RMSE	MAPE	R^2
1.63	2.18	16.1%	0.67

Statistical results are presented in the Tab. 3. The calculated values for MAE and RMSE respectively are low to moderate but they are acceptable from a statistical perspective. It should be noted that, the determination coefficient (R^2) of predicted surface for surficial deposits is 0,67, which means that 67% of the variation in predicted thickness can be explained by the exponential function. As mention Jia et al. (2012), it is impossible to explain 100% of the variation of surficial deposits thicknesses with few variables because other factors influence the spatial distribution such as deglaciation, vegetation, etc.. Finally, the value of R^2 is in the range of admitted value for different surficial deposits properties (i.e. 0.39-0.82; Florinsky et al., 2002). Once the new DTM 1 calculated, it is introduced in the model with DTM, DTM2 to represent the different surficial and geological layers.

Step 2

The step 2 consists in using the different geotechnical value for each surficial deposits and geology of the study area. The values were derived from the literature and different studies.

Step 3

Fig. 4, Tab. 2 and Tab 3. display the different parameters used to calibrate the model. The influence of GWL is not performed, its value is constant and equal to 1 (saturated material).

Table 2 Parameters used in ALICE® for each type of landslide. R = Rotational landslide. ST = Shallow Translational landslide.

Landslide type	Size of the LTZ (m)	Depth of the failure (m)	Size of slices tested (m)
R	30	0-3	0.5; 1; 2; 5; 10
	60	3-6	0.5; 1; 2; 5; 10
	120	6-10	0.5; 1; 2; 5; 10
ST	30	0-3	0.5; 1; 2; 5; 10

The first sub-step aims to identify the number and the size of slices following the landslide type and size. Indeed, this parameter is often neglected and the different models use a default value. Nevertheless as mentions Pilot (1966), not take into account this influence can biased the final results. Large discrepancies between simulations with slices of 1 m and slices of 10 m were noticed, especially on the accuracy test. The different simulations for the two landslide types show a step of the model performance for slice with a size equal to 1m. This value is retained for other simulations.

The second sub-step should identify the best scarp angle for shallow translational landslide because following this angle, the internal forces for each slice are not the same and the instable volume will be modified. Hence, series of simulations were carried out with scarp angles of 10°, 30°, 45°, 60° and 90°. Following the angle value, models overestimate or underestimate results, especially for low scarp angles (> 10°) and very high scarp angles (>45°). Best results were obtained with an angle of 45°; this value is retained for the sub-step 3.

The third sub-step consists in reducing the uncertainty linked to the geotechnical characteristics of an environment. This step has to define the minimum number of random sampling to obtain stable results. Indeed, a small number of random sampling with the same probability distribution can give different results (Thiery et al., 2015). To overcome this point, several series of simulation on geotechnical parameters with a range from 10 to 20,000 random sampling by Monte-Carlo simulation were engaged. 21 maps were produced for each landslide type. The different accuracy tests (Tab. 3) show a first step around 1,000 random sampling and a second step around 10,000 random sampling. In general, from 10,000 random sampling the discrepancies between results are below 1%, except for the shallow translational landslides for which largest differences are observed especially on areas where slope angles change abruptly. Thereby, 10,000 random sampling are considered as a minimum to obtain robust probabilities for rotational landslides (shallow and deep). For translational landslides 20,000 random sampling seems the minimum.

Table 3 Accuracy tests for some simulations and some parameters. R = rotational landslide with depth between 3 and 6m. ST = Shallow translational landslide. ξ = relative error. Sr = success rate. - = no calculations.

Sub-step & parameters		R		ST	
		ξ	Sr	ξ	Sr
01- Slice (m)	0.5	0.18	0.85	0.21	0.82
	1	0.18	0.84	0.22	0.82
	2	0.20	0.84	0.23	0.81
	5	0.21	0.75	0.25	0.75
	10	0.05	0.52	0.07	0.62
02-Scarp angle (°)	10	-	-	0.98	0.00
	30	-	-	0.09	0.82
	45	-	-	0.09	0.81
	90	-	-	0.03	0.51
03-Monte-Carlo simulation (n)	100	0.32	0.75	0.22	0.68
	1.000	0.21	0.82	0.19	0.75
	10.000	0.16	0.84	0.17	0.81
	20.000	0.15	0.84	0.16	0.82

Discussion

We presented an Expert Physically Based Model based on Morgenstern and Price (1967) equations solved with Zhu et al. (2005) algorithm. The model is able to take into account several parameters and uncertainty of environment. Furthermore, it is able to model different slope failure type, which is a key point in the landslide susceptibility and hazard assessment topic. The model was used for different mountain areas recently but with oversimplifications of variables and hypotheses.

Thus, some parameters, to obtain a calibration strategy for complex mountainous environments, were iteratively modified for different slope failure type (i.e. translational, rotational) with different depth (i.e. shallow and deep) and size. The different parameters tested were: the number of slices, the scarp angle for translational landslide, and the number of random sampling by Monte-Carlo simulation for geotechnical characteristics.

As expected, it is possible to improve the results obtain by Baills et al. (2012). Indeed, their results for the same GWL, showed a high probability of landslides mostly in badlands carved in weathered black marls and moderate probabilities were located in the moraine deposits. This was due to:

(i) An oversimplification of the geotechnical model used. The introduction of a new geotechnical model greatly improved results;

(ii) The use of only one type of phenomenon with average characteristics. Obviously, this study proves that a particular attention have to be paid to the different landslides' parameters to include in the model. By a sensitivity analysis, it is possible to obtain an error quantification and to reduce them;

(iii) The minimum number of random sampling was not tested. Nevertheless, this sensitivity analysis is indispensable to obtain reliable results. The Monte-Carlo theory is based on the law of large numbers and because a wide range of geotechnical value is used, it is essential to proceed to a large number of random sampling to minimize uncertainties.

Concerning the calibration strategy some parameters were not tested yet, as:

(i) The size of the calculation cells. This work was recently hired by Thiery et al. (2015) on small sites but need to be improved;

(ii) The influence of the type of distribution. For this work triangular distributions were used, which means that at the apex of the distribution there is more likelihood that these values were chosen. Compare different distributions when significant uncertainty exists appears as essential in order to not influence the results;

(iii) The real influence of triggering factors such as GWL or seismicity. For this research, simulations were performed with a maximum GWL (= 1) in this sense the surficial materials are considered fully saturated. This consideration does not correspond to reality. A sensitivity analysis on the influence of GWL has to engaged, as the influence of seismicity on landslides, especially for the Barcelonnette area highly subjects to earthquakes.

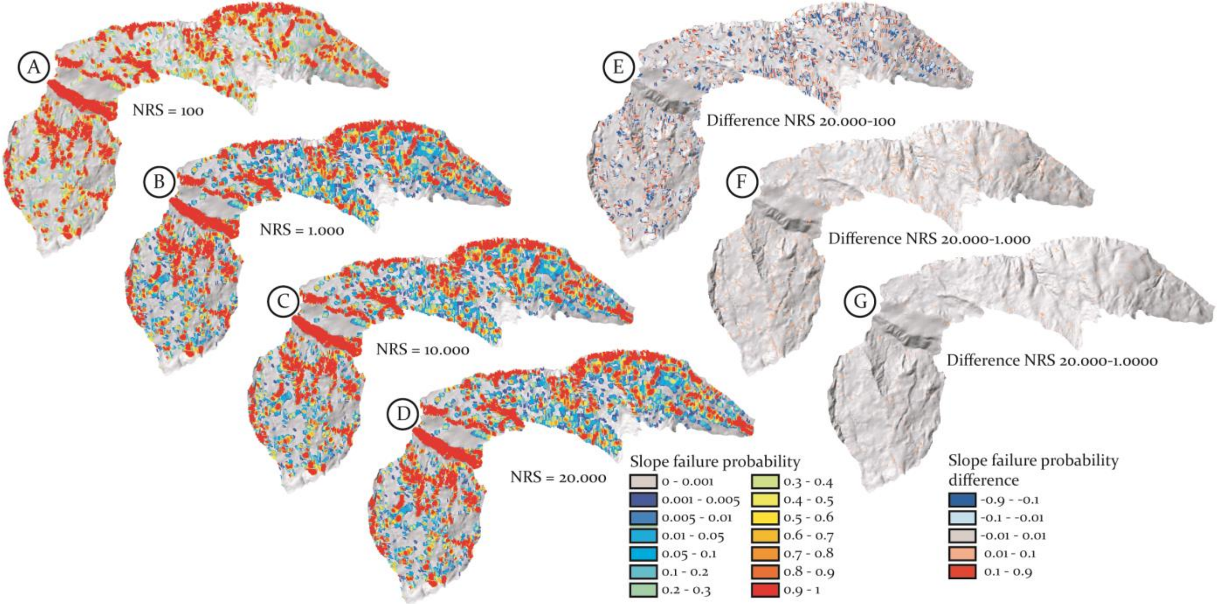

Fig. 5. Examples of different results with different number of random sampling by Monte-Carlo simulations for rotational landslides with a maximum depth of 6 m. A. Number of random Sampling (NRS) = 100. B. Number of Random Sampling (NRS) = 1.000. C. Number of Random Sampling (NRS) = 10.000. D. Number of Random Sampling (NRS) = 20.000. E. Differences between D and A. F Difference between D and B. G. Differences between D and C.

Conclusion and perspectives

A spatialized physically based model implemented in a GIS environment was tested in the Barcelonnette area. Several parameters were tested in order to take into account the heterogeneity and the complexity of this site. The sensitivity analysis on the calibration area is still in course and some parameters have to be tested to reinforce the reliability of the results. These first results encourage us to continue on this path in order to improve the existing susceptibility maps in this area and once all parameters calibrated, the model will be applied on the whole area (i.e. 400 km^2).

Finally, considerable efforts are needed (i) to improve the model, especially to assess uncertainties of computed probabilities; (ii) to integrate future changes as precipitation (following some climatic scenarii) and landuse like the studies in Cauterets located in Pyrenean mountains (Bernardie et al. 2017); (iii) to take into account runout area in order to assess landslide hazard for several landslide types.

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