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LPC® METHODOLOGY AS A TOOL TO CREATE REAL TIME CARTOGRAPHY OF THE GRAVITATIONAL HAZARD

ABSTRACT: HERNANDEZ M., LEBOURG T., RISSER V. & TRIC E., *LPC® methodology as a tool to create real time cartography of the gravitational hazard*. (IT ISSN 0391-9838, 2009).

Landslides represent a serious risk in steep areas like mountainous landscapes. Emergency management planning requires prediction of the damage, associated to the landslide occurrence. This paper presents the recent advances in the LPC (Landslide Predictive Cartography) methodology. For each time laps, this deterministic modelling assesses the slope stability in relation with real or modelled climatic events. The objective of this study is to compare and validate this new methodology to a heuristic approach on the Isola catchment (Maritimes Alps, France). The study area is localised on the Argentera crystalline massif, in a valley showing paraglacial landforms. A field campaign was realised to assess the hydrogeological, physical and mechanical parameters for lithology formations that has been mapped. The LPC methodology has been found to be helpful in the management of landslide zones. One of the simulations examined in this paper, presents a 25 m DEM scale resolution, considering a 20-year return rainfall modelled (48.6 mm cumulated for a one hour rainfall event/occurrence). The results obtained indicate that 18.7% of the studied area might be unstable and that 58.6% of the landslides that have occurred have a Factor of Safety (FS) lower than 1.

KEY WORDS: Hazard Assessment, Slope Stability, Shallow Landslide, Paraglacial Geomorphology, Hydrogeological Dynamic Model, Maritime Alps (France).

RÉSUMÉ: HERNANDEZ M., LEBOURG T., RISSER V. & TRIC E., *La méthode LPC®: outil cartographique de l'évaluation en temps réel de l'aléa gravitaire*. (IT ISSN 0391-9838, 2009).

Dans des régions au relief escarpé, et notamment dans les zones montagneuses, les glissements de terrain représentent un risque important à prendre en considération lors la mise en place des plans de gestion des risques. Ce papier présente les récentes avancées de la méthode LPC (Landslide Predictive Cartography). A chaque pas de temps, ce modèle déterministe évalue la stabilité du versant à l'aide d'événements climatiques mesurés ou modélisés. L'objectif de cette étude est de comparée cette nouvelle méthodologie à une cartographie heuristique de la commune d'Isola (Alpes Maritimes, France). Le site d'étude est localisé sur le massif cristallin de l'Argentera, dans une vallée possèdant une géomorphologie «paraglaciaire». Une étude de terrain fut réalisé afin d'évaluer les paramètres hydrogéologiques, physiques et mécaniques pour chaque formation lithologique cartée. La méthode LPC présente des résultats intéressants pour l'aide à la cartographie de l'aléa glissement de terrain. La simulation examinée dans ce papier est basée sur un MNT (Modèle Numérique de Terrain) d'une résolution de 25 m et une pluie modélisée de retour vingtennale (48.6 mm cumulée pour une durée d'une heure). Les résultats obtenus suggèrent que 18.7% de la zone étudiée pourrait être instable et que 58.6% des zones cartographiées comme potentiellement instable selon l'approche heuristique possèdent selon cette simulation un FS inférieure à 1.

MOT-CLÉS: Aléa gravitaire, Stabilité de Versant, Glissement superficiel, Géomorphologie Paraglaciasne, Modèle Hydrogéologique Dynamique, Alpes Maritimes.

INTRODUCTION

Emergency management planning requires prediction of the damage associated to landslides occurrence. In this paper a new deterministic model, comprising a dynamic hydrogeological model, is presented: the LPC (Landslide Predictive Cartography) methodology. This methodology is based on previous works performed on the the Rucu Pichincha volcano near the town of Quito in Ecuador (Risser, 2000). The aim of this study was to produce a hazard landslide map in order to inform and protect the local population.

In literature three main types of landslide hazard assessment techniques are commonly used: deterministic, statistical and heuristic approaches (Aleotti & Chowdury, 1999, Van Westen, 2004). Deterministic approaches, based on stability models, can be very useful for mapping hazard at large scale, in particular for plane construction purposes (Barredo & *alii*, 2000).

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The studied zone is the Isola catchment area localised in the northern part of the «Maritime Alps» (SE of France). Previous studies were realised north-westard of this zone, near the Barcelonnette catchment area where Mallet (2003) investigated the hydro-mechanical behaviour of the «debris flow» onto the Black Marls. In the Isola area, the lithotypes are acutely different and consequently have a different flow and mechanical behaviour. These materials are mainly made of glaciofluvial deposits and soils, produced by the crystalline basement weathering. The LCP methodology provides information on the failure-triggering thresholds of the zone but not on the flow behaviour.

A previous model (Risser & *alii*, 2007) was used in order to observe the influence of the soil saturation variation in a deterministic model during extreme climatic events (fig. 1). This hazard map uses the Factor of Safety (FS) and the talwegs zones which influence the susceptibility classification. The Factor of Safety (FS) map was produced with a static hydrological model. The soil saturation was estimated using the IDRISI® runoff and measured rainfall data (pluviometer). This model attempts to show the evolution of the shallow landslide (1 to 5m depth) susceptibility during three days. Rainfall on the second day was statistically estimated to be a 50-year return rainfall, which created several important landslides (160.0 mm cumulated for a 24h rainfall event). The first and the third day were estimated to be a 20-year return rainfall.

The slope stability calculation depends on the hydrogeological model. The previous static hydrogeological model used only two saturation conditions, and could not provide an evaluation of stability according to the duration of the rainfall event. A new hydrogeological model was developed in order to: improve information on the quality of soil saturation, detail the distribution of the saturated zone and take into account the variation of the saturated zone evolution in time.

The «new» LPC methodology is a deterministic assistance tool for cartographic expertise on landslide risks. This method has similarities with SHALSTAB (Montgomery and Dietrich, 1994) and SINMAP (Stability INdex MAPping) (Pack, 1998) in particular with the infinite slope stability model. Moreover, the LPC method uses the probability of slope failure using the Monte Carlo simulation, as LISA (Level I Stability Analysis) and SINMAP (Hammond & *alii*, 1992) do in a similar way. Deterministic models provide the best quantitative information on landslide hazard. Information that can be used directly in the design of engineering works, or in risk quantification (Van Westen, 2004). Nevertheless, deterministic approaches require the availability of detailed geotechnical and groundwater data, and they may lead to oversimplification if such data is only partially available (Barredo & *alii*, 2000).

This paper presents the recent advances in the LPC methodology. The aim of the study is to compare and validate this new methodology to a heuristic approach (Van Westen & *alii*, 2003) on the Isola catchment. The LPC modelling will provide FS map(s) and the heuristic approach will supply maps of the potential failure zones.

LPC®: A SHALLOW LANDSLIDE SLOPE STABILITY MODEL

Infinite slope stability model

The data input is organized in a grid format depending on the resolution of the Digital Elevation Model (DEM). The LPC methodology uses the limit equilibrium theory to analyse the stability state (Spencer, 1967) for each pixel. The slope stability is based on an infinite slope model including several simplifying assumptions (Selby, 1993) (fig. 2).

The equation (1) of the Factor of Safety (FS) is commonly used in the study of the soil mass equilibrium conditions. This equation is based on the Mohr-Coulomb failure criterion: $\tau_{max}=c'+\sigma'.\tan\phi'$, where τ_{max} is the maximum

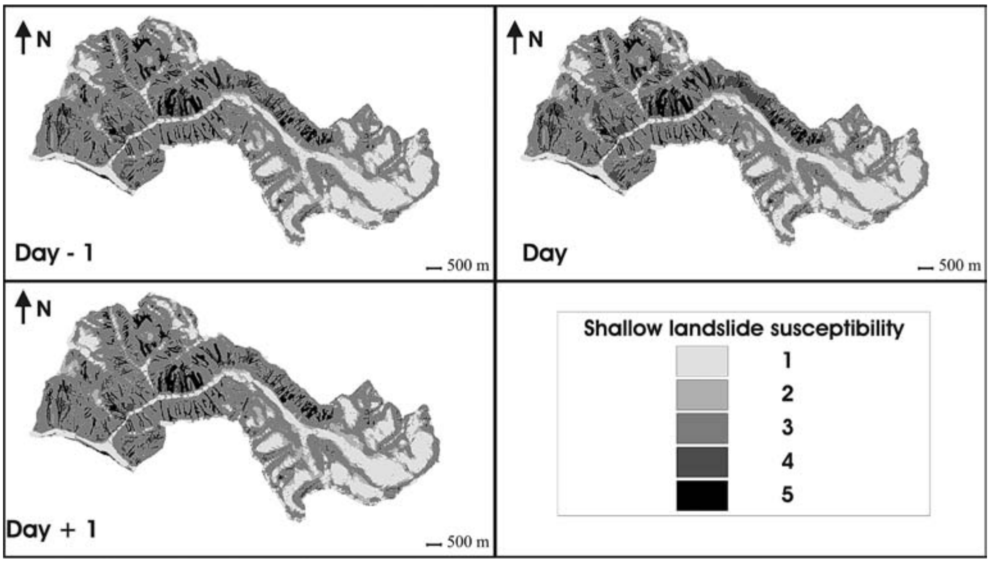

FIG. 1 - Isola catchment area susceptibility map for the shallow landslide (Risser & *alii*, 2007). Shallow landslide susceptibility legend: (1) low (FS>1.8), (2) Low-Moderate (1.8>FS>1.3), (3) Moderate (1.8>FS>1.3 and talweg zone), (4) Moderate-High (FS<1), (5) High (FS<1 and talweg zone).

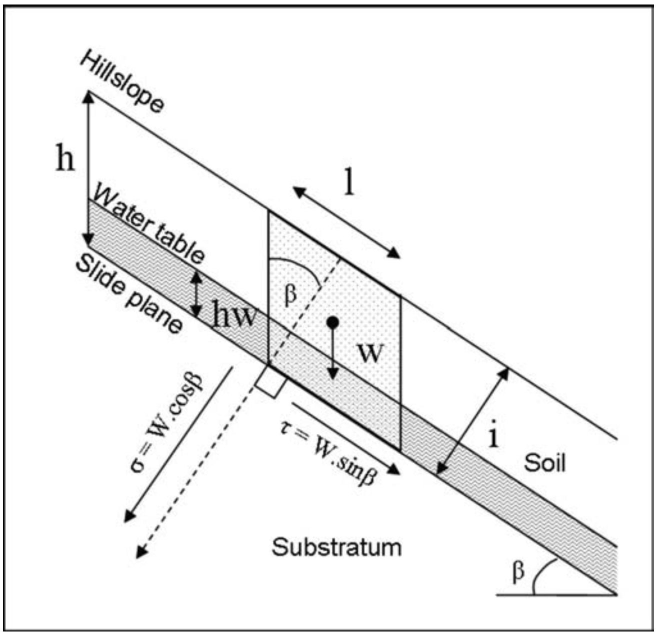

FIG. 2 - Infinite slope stability model, where the resisting force holding the block in place is given by W (mass * the gravitational force) multiplied by the slope angle cosines. The driving force is Wsinβ (inspired by Selby1993).

shearing stress and σ' the effective normal stress (Costet & Sanglerat, 1981).

$$FS = \frac{c'}{\rho_s.g.sin\ \beta.cos\ \beta} + \frac{(\rho_s.h - \rho_w.h_w(t)) \times \tan \phi'}{\rho_s.h.\tan\ \beta} \quad (1)$$

Where ϕ' is the effective angle of internal friction (deg), c' is the effective cohesion (kPa) both calculated with triaxial tests, h the vertical soil depth (m) evaluated with electrical resistivity measurements, $h_w(t)$ the vertical dynamic saturated soil depth (m) depending on the hydrogeological model, ρ_s is the dry soil density (kg.m^{-3}) measured with laboratory tests, ρ_w is the density of water (kg.m^{-3}), β is the slope angle (deg), and g is the gravitational acceleration (m.s^{-2}).

A sensitivity study of this equation was realised. The results are similar to those obtained by Borga & *alii* (2002) and Lebourg (2000). The following parameters are quoted in descending order of influence on the safety factor equation: slope angle, effective angle of internal friction, soil thickness and groundwater-soil ratio.

In this study the resolution of the DEM is a grid scale of 25 m and the map projection is the Universal Transverse Mercator 32 (UTM 32 WGS84). The other maps (geological, hydrogeological, landuse) are also organized by grid scale of 25 m with the same projection system. The whole maps are composed by 374 x 665 pixels i.e. 9.35 km x 16.62 km area. Only the Isola catchment area zone is well mapped (geological and landuse cartography), therefore the surface of the effective stability study zone is 49.5 km^2.

Hydrogeological model

The hydrogeological model (evaluation of the parameter $h_w(t)$) is an important part in the Factor of Safety calculation. The groundwater response following a rainfall event can be modelled by hydrologic models such as TOPOG (O'Loughlin, 1986), TOPMODEL (Beven, 1997), and DYNWET (Wilson & Gallant, 2000). The LPC methodology uses its own hydrogeological dynamic model (fig. 3). This model assumes that the shallow subsurface flow has the same behaviour than a perched water table. Taking into account homogenous soil thickness, the shallow subsurface flow downslope follows the topographic gradient. But, to the contrary of other methods, where there is a variation in the soil thickness, the subsurface flow follows the substratum gradient.

The rainfall event can be modelled with the Desbordes (1987) methodology, or else measured by a pluviometer. These two methods provide intensity-duration (I-D) rainfall. The infiltration process derives from the empirical Horton equations. The infiltration capacity reduced in an exponential function from an initial and maximum rate to a final constant rate (Horton, 1933).

After the infiltration step, the one-dimensional vertical flow in the unsaturated zone is based on the simplified equations used in Fuentes & *alii* (1992). Once the accumulation of the water begins at the base of the soil column, the accumulated zone is considered like saturated. The saturated flow is based on the Darcy's equation (Darcy, 1856) (equation 2).

$$q = -Ks \times \frac{dH}{dz} \quad (2)$$

Where q is the flow velocity, Ks is the hydraulic conductivity of the saturated soil (cm d-1), H is the hydraulic head (cm) and z is the vertical coordinate (cm).

The flow direction angle is calculated with the D∞ algorithm (Taborton, 1997). This flow direction angle is determined as the direction of the steepest downward

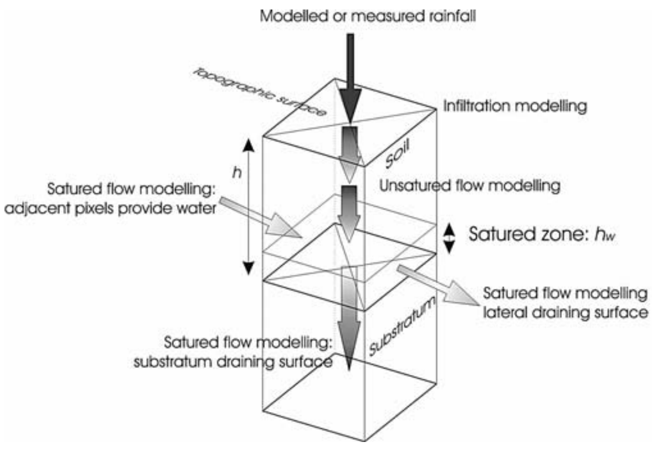

FIG. 3 - LPC Hydrogeological model.

slope on the eight triangular facets formed in a 3 x 3 grid cell window centered on the grid cell of interest.

The hydrogeological model depends on the quality of the landuse mapping for the infiltration rate and on the permeability mapping for the water flow throught the soil.

STUDY AREA AND LANDSLIDES DATA

The Isola catchment is localised in the North of the «Alps Maritimes» (SE, France) bordering the Italy to the South and the Argentera Massif to the south-west (fig. 4).

The context for landslides development is particularly favourable, both in terms of the geomorphic and structural setting of this Alpine region, and of the climatic, hydrologic and seismic factors that are triggering factors (Julian & Anthony, 1996). The incision of valley canyons in the Argentera massif area occurred during phases of glacio-eustatic sea-level fall during the Quatemary (Savoye & Piper, 1993).

Geological setting and data used for calibration

Located in the southern part of the Western Alps, the Argentera massif belongs to the paleo-European basement of the external domain (Faure-Muret, 1955; Vernet, 1964; Malaroda & *alii*, 1970). It results from a polyphased deformation history, from Hercynian to Alpine orogenies (Bogdanoff, 1986; Corsini, 2004). The Argentera massif is constituted of two different petrographic units: the occidental and oriental units (Malaroda, 1999). These units are in contact along a mylonitic shear zone: the Valetta Molières shear zone.

The Isola catchment is localised on the south-western bound of the Argentera massif at the conjunction between these two units as shown in figure 5.

In order to obtain the mechanical parameters used in the Factor of Safety calculations, databases were collected and laboratory tests were performed. Previous study on the weathering of the gneissic rock has been realised in the Anelle and Rabuons formation (Hernandez & *alii*, 2008).

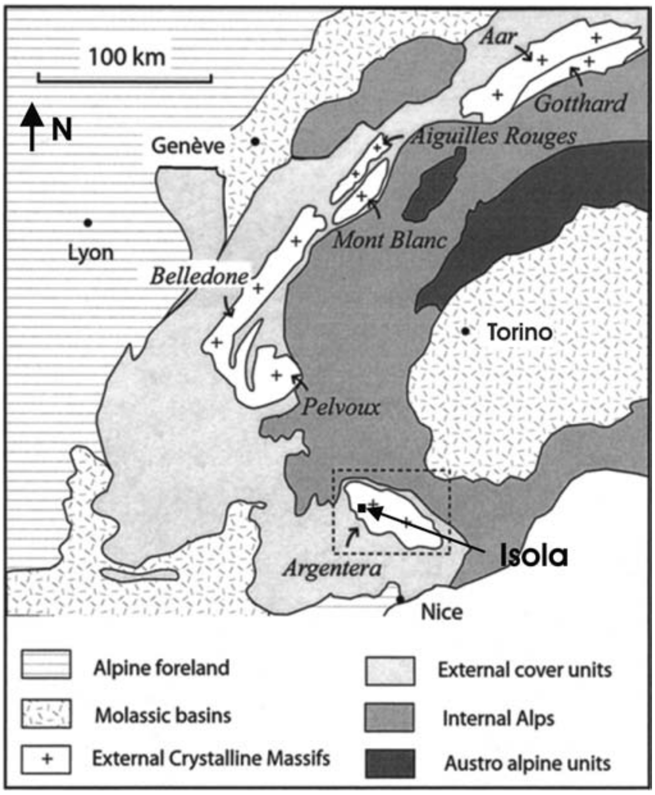

FIG. 4 - Location of the Argentera External Crystalline Massif in the Western Alps.

In the case of rock geological formation like gneiss, the triaxial tests were performed on the fresh weathered material localised at the contact between the soil and the healthy rock which corresponded to 90% of the material affected by landslide. In the case of recent deposits, the triaxial tests were performed on the matrix formation with particle-size inferior to 2 cm.

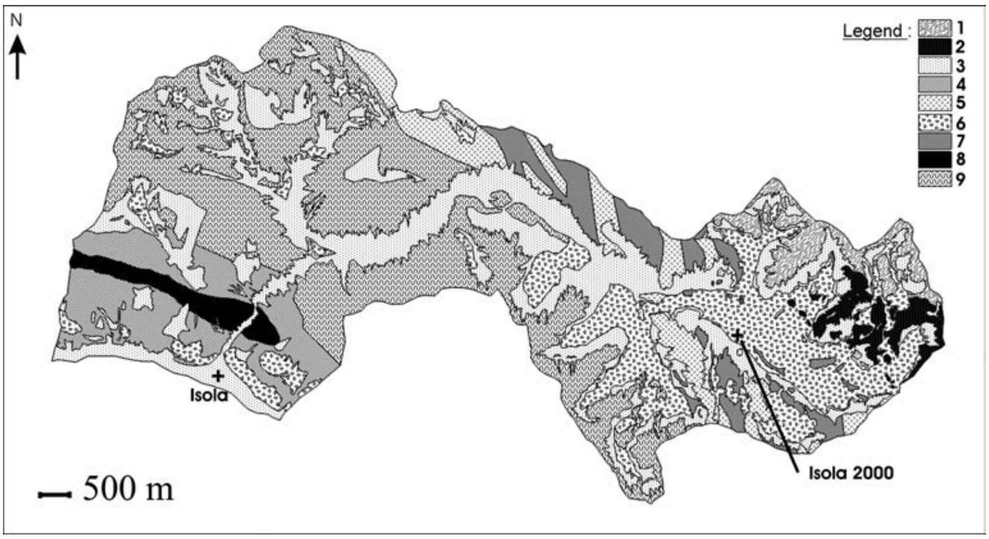

FIG. 5 - Geological map of the Isola catchment area. *Occidental Unit*: (1) Gneiss and migmatites (Anelle formation), (2) Diorite quartzite, (3) Gneiss and migmatite (Rabuons formation); *Oriental Unit*: (4) Embrechite, (5) Gneiss (Malivern Chastillon formation), (6) Anatexite, (7) Granite; *Recent formation*: (8) Glaciofluvial deposit, (9) Alluviums. UTM32 projection.

The test selected as most suitable for evaluating the mechanical parameters is the triaxial compression test (Costet & Sanglerat, 1981). For each sample, 4 tests were performed, with consolidation and drainage (CD tests), at 100 kPa, 200 kPa, 300 kPa and 400 kPa for a 25% maximum deformation and for 3 mm/mn compression velocity. Several tests were performed for each lithology.

TABLE 1 - Mechanical parameters used in the LPC modelling calibration

Lithology	Effective frictional angle (°)	Effective cohesion (kPa)	Dry soil density ($kg.m^{-3}$)	Number of samples
(1) Gneiss (Anelle)	30.0 ± 1.2	3 ± 1	2.0 ± 0.3	10
(2) Diorite quartzite	–	–	–	–
(3) Gneiss (Rabuons)	34.4 ± 0.5	5 ± 2	1.9 ± 0.2	11
(4) Embrechite	33.2 ± 0.5	7 ± 2	2.0 ± 0.5	3
(5) Gneiss (Malivern Chastillon)	35.0 ± 0.7	5 ± 1	2.3 ± 0.4	7
(6) Anatexite	31.3 ± 0.9	12 ± 2	2.6 ± 0.4	5
(7) Granite	35.5 ± 1.1	9 ± 1	2.1 ± 0.3	3
(8) Glaciofluvial deposit	40.2 ± 0.7	3 ± 1	2.8 ± 0.2	4
(9) Alluviums	25.3 ± 0.6	10 ± 3	2.3 ± 0.1	5

Geomorphological setting

In the Argentera Massif the landscape is the result of glacial, periglacial, hillslope and fluvial processes (Musumeci & *alii*, 2003). The Isola valley shows paraglacial landforms with a U-shape at the upper part and a V-shape at the lower one. In this environment the earth-surface processes, sediments, landforms, landsystems and landscapes are the consequence of glaciation and deglaciation periods (Ballantyne, 2002; Fabre & *alii*, 2003).

In the lower part of the catchment area, below a rock bar (at the point: 348530, 4896860 in the UTM32 projection) an active paraglacial reworking of the drift-mantled slopes is present. Moreover, below this rock bar, the intense erosion activity of the Guerche River modifies the classical U-shaped glacial valley into a deep incised V-shaped valley. This modification accentuates the drift-mantled slopes movements.

In the upper part of the catchment area, the slopes along the main valley are in a stable-state. The vegetation is well developed on relict debris fans. The erosion activity is less developed than in the lower part, furthermore most of the upslope is compound by several adjacent valleys.

Hydrogeological setting and calibration

In large natural systems such as a watershed, and particularly in mountainous context, the spatial variability of rain and snow fall, soil hydraulic and substratum conductivity are highly heterogeneous (Nielsen & *alii,* 1973; Vauclin & *alii*, 1994). Nevertheless the stability slope model needs the knowledge of the vertical saturated soil depth.

In previous study, Haverkamp & *alii* (1998) established a relationship which predicted textural hydraulic parameters from the textural data. This textural data is calibrated from the traditional grain size distribution analysis (Haverkamp & Parlange, 1986; Haverkamp & *alii*, 2002). In this study, grain size distribution analysis tests were performed for each soil sample used for the triaxial test. The results were compared to the 660 soils of the GRIZZLY soil database (Haverkamp & *alii,* 1998).

The soil saturation on the Isola catchment for a 20-year return rainfall event is shown in figure 6.

Considering the slope stability and in order to have the most critical situation; we chose the hydrogeological map with the maximum soil saturation coming from a 20 year-return rainfall modelling (48.6 mm cumulated).

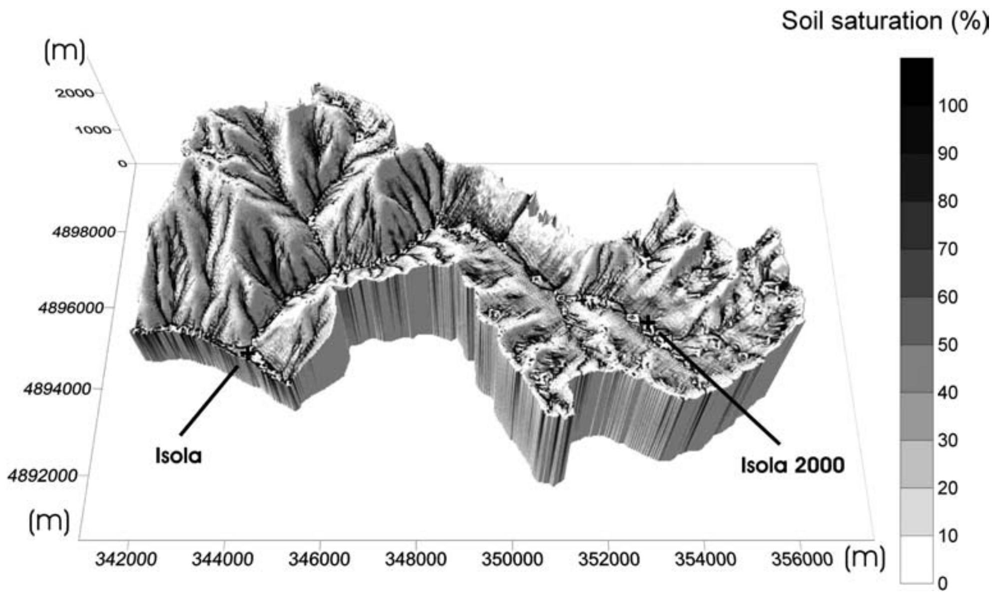

FIG. 6 - Soil saturation on the Isola catchment, (Maritim Alps, France) for a 20-year return rainfall event, approximately 60 min after the beginning of the rainfall. UTM32 projection.

LPC determinist model results: FS calculation

Based on an infinite slope model, LPC only maps the potential translational failure zones throughout a Factor of Safety map (fig. 7). The LPC methodology doesn't take into account the complex rheology and the propagation of the debris flows.

According to the calculated FS map, 18.7% of the studied area should be unstable for a 20-year return rainfall (black areas on the fig. 7). Along the adjacent valleys localised in the upper part of the catchment, some zones are estimated to be unstable. A careful evaluation is required for the results interpretation in this zone, considering the difficulty to distinguished bedrock outcropping. Indeed, there are several cliffs in this zone which can invalidate the FS calculation. On figure 7 there is a gap in the FS values in the south-western part of the Isola catchment. This gap comes from the geological nature of the zone. Indeed, the diorite quartzite (fig. 5) is a very resistant rock and forms large cliffs. As a consequence the equivalent outcropping area was excluded from the FS calculations.

Landslides localisation: heuristic approach

The heuristic approach can be subdivided into a direct and an indirect method. In direct mapping the geomorphologist, relying on his experience and knowledge of the field conditions directly determines the degree of susceptibility (Barredo & *alii*, 2000, Van Westen & *alii*, 2003). The indirect approach uses data integration techniques, including qualitative parameter combination (Shaw & Johnson, 1995, Van Westen & *alii*, 2000, 2003).

Based on field investigations and aerial photography analysis, a direct heuristic approach was used to map the potential failure zones (fig 8). The heuristic hazard mapping is

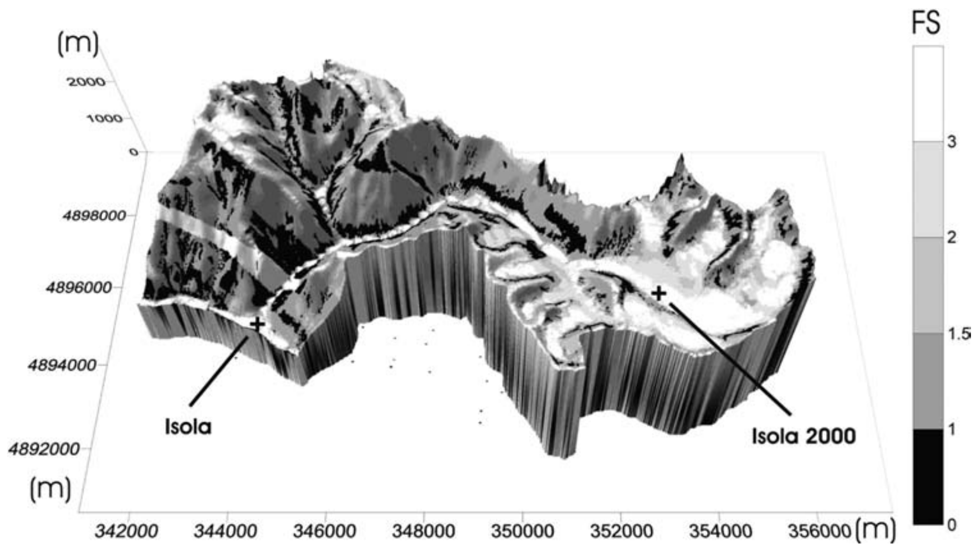

FIG. 7 - Factor of Safety map of the Isola catchment area. UTM32 projection.

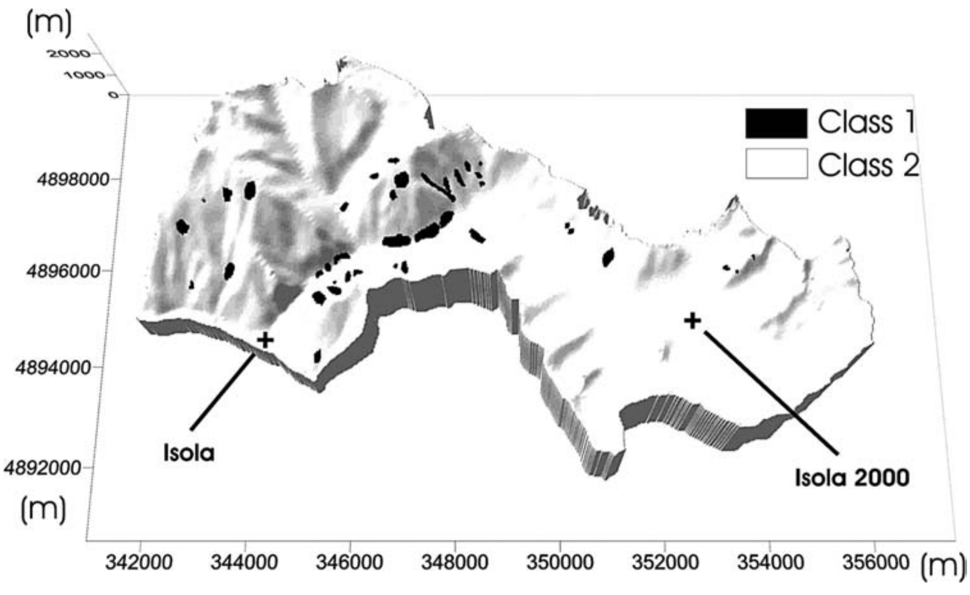

FIG. 8 - Heuristic hazard zonation map: Class 1: potential landslides failure zones; Class 2: stable zones. UTM32 projection.

made of two classes: stable and unstable zones. On the whole catchment area, 25 active landslide zones were mapped.

By far the dominant agent of erosion and sediment transport acting on steep sediment-mantled slopes in recently deglaciated mountain valleys is debris flow (sediment-gravity flow) (Ballantyne, 2002).

In order to compare the Factor of Safety map obtained with the LPC methodology and the landslide maps, the landslide areas are drawn keeping only the potential failure zone and deleting the accumulation zones.

The potential landslides surface corresponds to 1558 pixels i.e. 0.97 km^2 or 1.95% of the total studied area.

Comparison between heuristic approach and LPC methodology

The comparison between the landslide map (heuristic approach) and the Factor of Safety map (determinist methodology) is an interesting test for the model. The results are shown in figures 9 and 10, respectively the Factor of Safety distribution in the studied area and the Factor of Safety distribution in the landslide zones. These two distributions give some information about the modelling efficiency in order to correctly «predict» the unstable zones.

In this simulation, the Factor of Safety distribution on the Isola catchment (fig. 9) shows that 18.7% of the studied zone is considered as unstable.

In the zones characterised by the landslide susceptibility (fig. 7), the Factor of Safety repartition can be evaluated (fig. 10): 58.6% of the pixels have a FS lower than 1.0; 37.8% are contained between 1 and 1.8; and 2.7% have a FS higher than 1.8.

The two previous figures (fig. 9 and 10) can be synthesised in a proportional representation of the FS and the

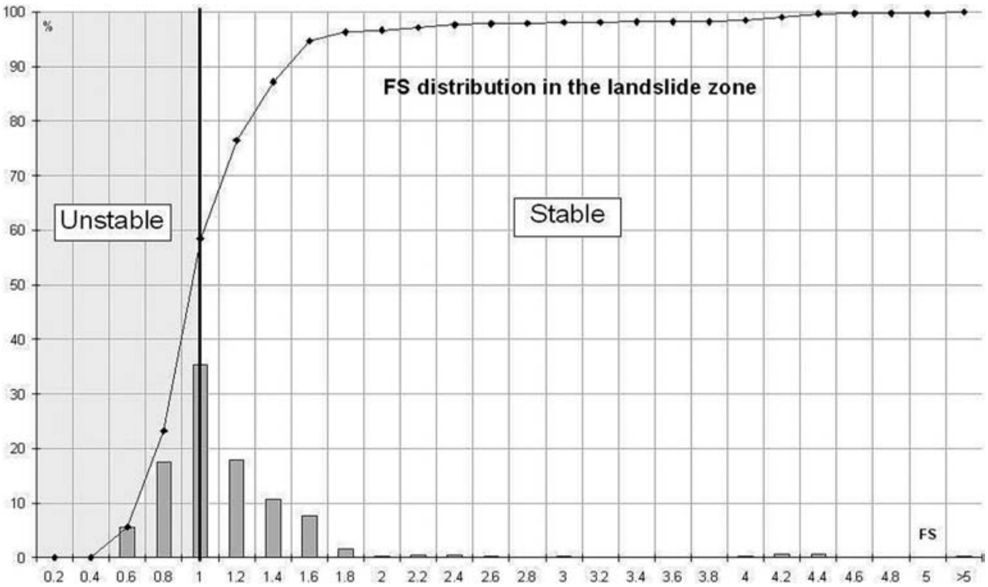

FIG. 9 - Factor of Safety distribution in the studied area. The black line graph represents the cumulated percentage and the bar chart represents the percentage for each class. The number indicated under the x axes is the upper value of a class. Example: 1.0 corresponds to the class [0.8; 1.0].

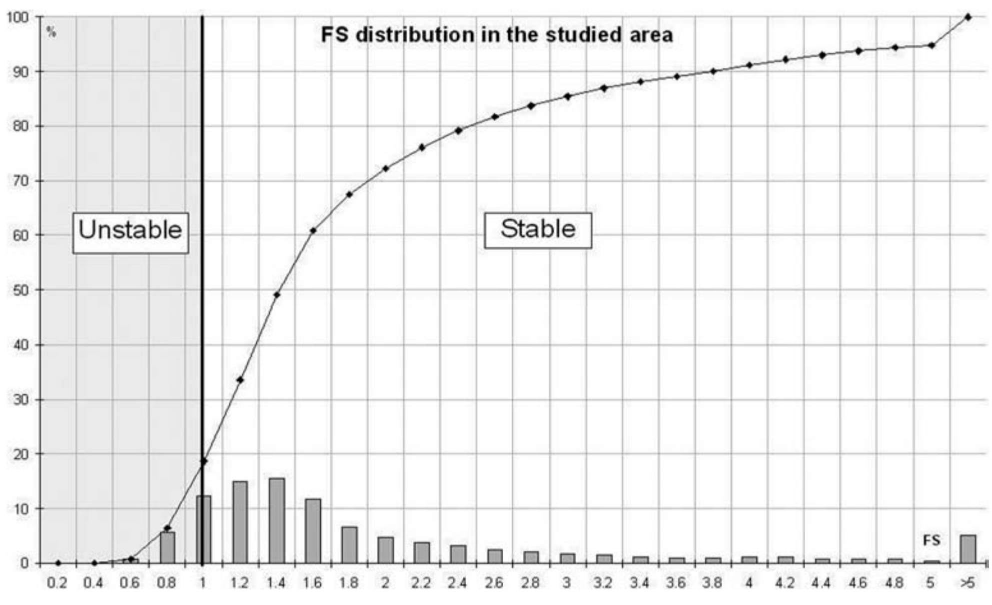

FIG. 10 - Factor of Safety distribution in the landslide zones. The line graph represents the cumulated percentage and the bar chart represents the percentage for each class. The number indicated under the x axes is the upper value of a class. Example: 1.0 corresponds to the class [0.8; 1.0].

Landslide cumulated surfaces according to the total surface (fig. 11).

Each class of the figure 11 is detailed in the table 2.

TABLE 2 - Surfaces distribution of each class determined in the figure 11. The conditions stable and unstable are the LPC methodology conditions. The conditions landslide and no landslide are the heuristic approach conditions

Class	Conditions	Proportionality
1	Stable; No Landslide	90.50% of the Total surface
2	Unstable; No Landslide	17.59% of the Total surface
		94.06% of the FS < 1 cumulated surfaces
3	Stable; Landslide	0.80% of the Total surface
		0.98% of the FS > 1 cumulated surfaces
		41.40% of the Landslide cumulated surfaces
4	Unstable; Landslide	1.11% of the Total surface
		5.94% of the FS < 1 cumulated surfaces
		58.60% of the Landslide cumulated surfaces
1 + 3	Stable zones	81.30% of the Total surface
2 + 4	Unstable zones	18.70% of the Total surface
1 + 2	No Landslide zones	98.05% of the Total surface
3 + 4	Landslide zones	1.95% of the Total surface

Description of the principal classes in figure 11 and table 2:

1. This class represents the stable surface (FS > 1) with no landslide mapped. The LPC methodology and the heuristic approach forecast overlap. This represents the first accordance point between the two approaches.

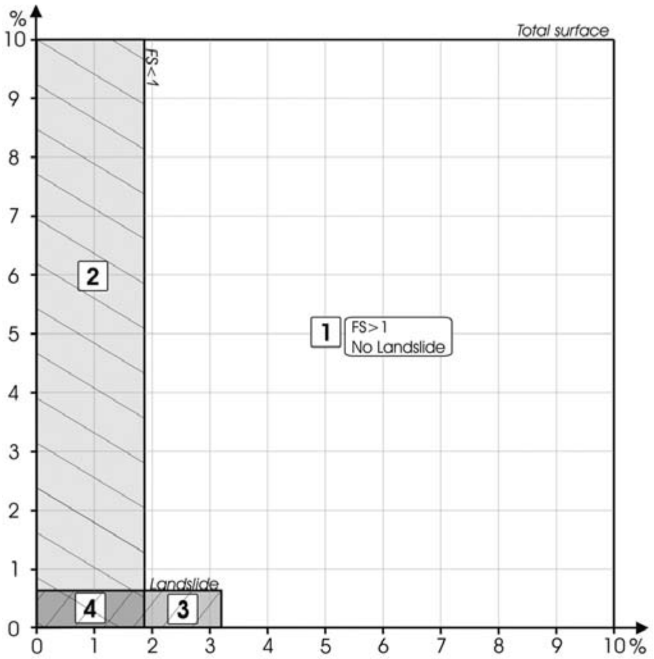

FIG. 11 - Proportional representation of the FS and the Landslide cumulated surfaces according to the total surface. Each case represents 1% of the total surface.

2. This is the first discordance point of the model: the LPC methodology considers these zones like unstable (FS<1), whereas no landslide susceptibility is mapped. These zones can therefore be interpreted in different ways:
   – There could be a calibration problem of the LPC model.
   – There could also be an unexpected condition variation (geomorphological, mechanical, hydrogeological and anthropological).
   – This may be a wrong analysis of the heuristic approach.
   – Finally, these zones could become future unstable areas.
3. This is the second discordance point of the model. This class represents the stable zones (FS >1), whereas landslide susceptibility is mapped. These zones can also be interpreted in different ways:
   – There could be one of the first three interpretations of the class 2.
   – If the landslides are in a stabilisation motion, these areas may become future stable zones.
4. This class represents the second accordance point between the two approaches: when unstable zones and landslide susceptibility fit.

The comparison between these two approaches could be resumed to these four classes with the two accordance and the two discordances points. An expert's analysis is an important step to take into accounts the two discordance points.

CONCLUSION

This paper presents the recent advances in the LPC methodology. The aim of the study is to compare and validate this new methodology with direct heuristic approach on the Isola catchment (Maritimes «Alps», France). The LPC methodology is a deterministic model and requires several calibrations: mechanical and hydrogeological parameters are necessary to compute the simulation. Whereas direct heuristic approach is based on the expert experience and knowledge of the field conditions in order to directly determine the degree of susceptibility.

The results obtained in this study show that, for a 25 m DEM resolution, the LPC methodology is a suitable application on the Isola area. Indeed, the results obtained indicate that 58.6% of the occurred landslides have a Factor of Safety less than 1, i.e. these zones were «predicted» like unstable by the LPC methodology.

This result is moderated with the class 2 and 3: respectively the unstable zones (LPC approach) with no landslide susceptibility (heuristic approach) and the stable zones with landslide susceptibility. Class 2 represents 19.7% of the total surface and class 3 represents 42.4% of the cumulated landslide surface. Complementary studies are necessary to treat the two discordance points (Class 2 and 3) and refine the future hazard maps.

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