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Stability analysis of the Vallcebre translational slide, Eastern Pyrenees (Spain) by means of a GIS

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Abstract. The stability of the landslide of Vallcebre has been evaluated by means of a GIS. The landslide mechanism is a translational failure which has been analysed as an infinite slope. Soil strength parameters and groundwater conditions are obtained from laboratory tests and monitoring devices. Geometric parameters necessary to compute the factor of safety at each individual cell are generated by interpolation from the boreholes present in the landslide. The results have been checked with the actual behaviour of the landslide and are consistent. The comparison between a conventional slope stability analysis and the GIS-based approach gives similar results, showing the feasibility of the latter.

Key words: landslides, stability analysis, GIS, Eastern Pyrenees

1. Introduction

The use of Geographical Information Systems (GIS) in preparing landslide susceptibility, hazard, and risk maps has extended widely during the last decade. The use of GIS has enhanced the possibilities of systematic mapping of large regions and increased significantly the productivity of mapping procedures.

The purpose of most of the methodologies has been the identification and assessment of the areas most favourable to produce landslides. In that respect, the ground conditions are analysed by considering the presence or absence of factors related to the slope stability. At each land unit, these factors are simply combined (Nilsen *et al*., 1979) or manipulated by means of statistical procedures (Carrara *et al*., 1991; Luzi and Pergalani 1996; Santacana *et al*. 2002). The result may consist of an index or land-category that indicates the degree of proneness of this unit to produce a slope failure. This index has to be understood as a relative stability index rather than a quantifiable magnitude that could be directly incorporated into engineering projects. Recently, several attempts have been made to perform deterministic analysis in a GIS. These attempts used simplified approaches to the slope stability, for instance, the assumption of an infinite slope and simple groundwater conditions (Van Westen and Terlien, 1996; Luzi *et al*. 2000) or simple empirical equations for rotational failures (Sakellariou and Ferentinou, 2001), in order to cover large areas.

The results are expressed as safety factors of the slope. However, as far as we know, these approaches have neither checked the results with other traditional methods of analysis nor validated them with monitoring results.

In this paper we discuss the feasibility of carrying out a slope stability analysis of the Vallcebre landslide (Eastern Pyrenees, Spain) using GIS software (Arc/Info). The results are compared with those of classical limit equilibrium analyses and validated with records of the landslide monitoring network available at the site.

2. The Landslide of Vallcebre

The landslide of Vallcebre is large and active. It is located in the Eastern Pyrenees, 140 km North of Barcelona, Spain. The landslide is situated on the eastern slopes of the torrents of Vallcebre and Llarg. The mobilised material consists of a set of shale, gypsum and claystone layers gliding over a thick limestone bed. The whole landslide involves an area of 0.8 km^2 that shows superficial cracking and distinct ground displacements.

2.1. DESCRIPTION OF THE LANDSLIDE

The Vallcebre landslide is of a translational type. It has a stair-shape profile formed by three main slide units of decreasing thickness towards the landslide toe. Each unit is formed by a gentle slope surface bounded by a secondary scarp of the landslide of a few tens of meters high. At the toe of each scarp, there exists an extension area in the form of a graben. The foot of the landslide reaches the Vallcebre torrent bed and overrides the opposite slope with the ground surface tilted backwards. The average slope of the whole landslide is about 10°. The dimensions of the slide mass are 1,200 meter long and 600 m wide. Figure 1 shows a geomorphologic sketch of the landslide.

The direction of both the transverse scarps and grabens, suggests a movement towards the north-west. A secondary direction of the movement, towards the Torrent Llarg, is also observed in the upper slide units. The most active area is the lower unit, the stability of which will be analysed with the GIS. This unit is bounded, at the south-western side, by the torrents of Vallcebre and Llarg and, at its north-eastern side, by a well developed lateral shear surface.

Between July 1996 and March 1997, fourteen boreholes were drilled in the landslide and equipped with inclinometers, wire extensometers and piezometers. Borehole logs show that the thickness of the lowest unit ranges between 12 and 20 m, while the intermediate unit reaches up to 50 m. The surface of failure of the landslide was deduced from the results of inclinometer readings. It has an average inclination of 10° towards the Vallcebre torrent and it is roughly parallel to the ground surface.

The geological structure of the landslide, was obtained by mapping superficial exposures, from data provided by geophysical surveys, and by interpreting bore-

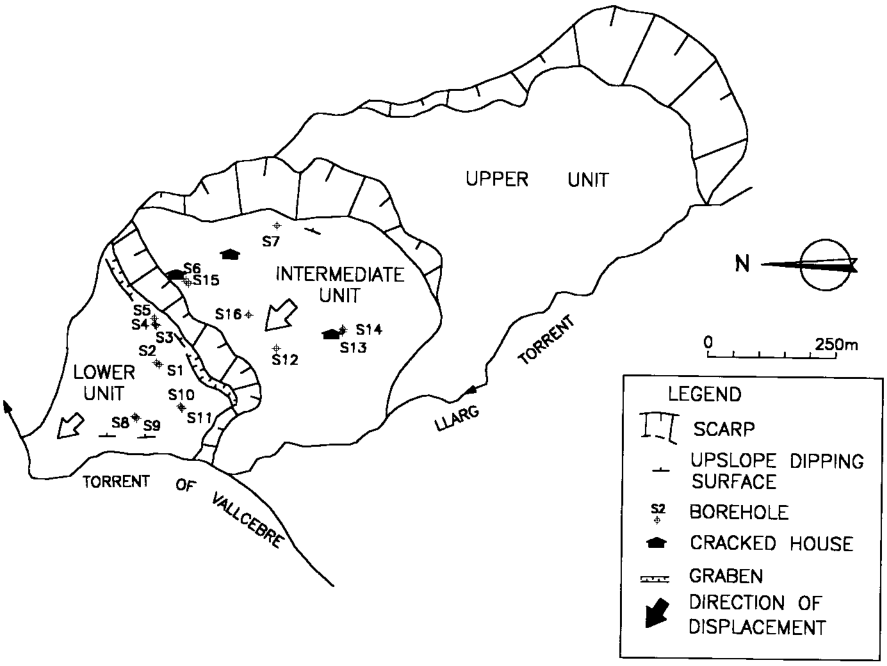

Figure 1. Geomorphological sketch of the Vallcebre landslide. The location of boreholes is also shown.

hole logs. The mobilised material consists of a set of shale, gypsum, and claystone layers gliding over a thick limestone bed. From the bottom to the top it includes: (i) densely fissured shales, 1 to 6 m thick, showing slickensides; (ii) gypsum lenses up to 5 meters thick and some tens of meters long; and (iii) clayey siltstones rich in veins and micronodules of gypsum. In addition to these layers, in the extension zones located at the toe of the scarps colluvium may be found composed of gravel with a silty matrix.

2.2. MONITORING NETWORK OF THE VALLCEBRE LANDSLIDE

The Vallcebre landslide has been monitored since 1987 using conventional surveying and photogrammetry (Gili and Corominas, 1992). Since 1996, systematic measurement of rainfall, groundwater level changes, and landslide displacements is being carried out every 20 minutes and stored in a data logger. Measurements with the inclinometers were made every two or three weeks until they broke, and with differential GPS, at least once in two months. Further details about the site, the fieldwork carried out and the monitoring scheme can be found in Corominas *et al.* (1999).

3. Stability Analysis

The stability analysis has been carried out in the lower landslide unit, which is the most homogeneous and where most of the information is available. Because the surface of rupture is roughly parallel to the ground surface and landslide thickness is small compared to its length, the stability analysis is based on the assumption of an infinite slope (Skempton and DeLory, 1957). The input parameters required in this analysis include the strength properties of the landslide materials, the geometry of both ground and rupture surface, and the position of the groundwater levels or the distribution of the pore water pressures.

The basic equation governing the stability of an infinite slope is expressed by the safety factor (F_s) as in Equation (1)

$$F_s = \frac{c' + (\sigma + u) \cdot \tan \phi'}{\tau} = \frac{c' + (\gamma \cdot d \cdot \cos^2 \beta - u) \cdot \tan \phi'}{\gamma \cdot d \cdot \sin \beta \cdot \cos \beta} \quad (1)$$

where, γ, c', and ϕ' are respectively the unit weight, cohesion and friction angle of the landslide material; d and β are respectively the depth and angle of dip of the surface of rupture; u is the groundwater pressure, τ the shear stress, and σ the normal stress on the failure surface.

The implementation of the procedure in the GIS has some particular aspects. The simplest way to calculate the stability is by neglecting the effect of the neighbouring cells. The equilibrium expression is used to calculate the stability of each individual cell. The consequent performance in all the cells will result in a map of safety factors (Van Westen, 1993).

In the case of Vallcebre, we proceeded with the following steps: (1) introduction of the necessary parameters into the GIS, (2) generation of both rupture and piezometric surfaces by means of interpolation; (3) creation of variables required to calculate the factor of safety; (4) calculation of the factor of safety, and (5) validation of the results

3.1. INTRODUCTION OF DATA

The Digital Elevation Model (DEM) used in the Vallcebre landslide had cell sizes of 15x15m supplied by the Catalonian Cartographic Institute. Most of the operations were made using the module GRID of Arc/Info. The DEM has been used as a reference surface from which the other surfaces were generated

The location of the boreholes have been georeferenced in the field by means of GPS and digitised so as to be introduced into the GIS. Core logs of the boreholes were used to define the materials involved in the landslide.

Inclinometric readings provided the location of the rupture surface of the landslide which was incorporated as a thematic layer . Four years of continuous piezometric readings were available in Vallcebre. These readings allowed the definition of a maximum groundwater level during which the landslide is able

Table I. Unit weight (γ), cohesion (c') and residual friction angle (ϕ'_r) of the materials of the Vallcebre landslide

Material	γ (kN/m^3)	c' (kPa)	ϕ'_r (°)
Clayey siltstones	21.2	38	14.7
Fissured shales	21.3	44	11.8
Fissured shales (shear surface)	21.3	0	7.8

to progress at a rate of 1 cm/day, and a minimum one with which the landslide stops (only one of the boreholes equipped with wire extensometer shows tiny displacements).

Finally, laboratory tests provided a range of values for the geotechnical parameters of the fissured shales, the materials directly affected by the surface of rupture, and for the clayey siltstones. Because the surface of rupture is well developed, only the residual strength of the materials has been considered (Table I).

3.2. GENERATION OF SURFACES

Solving the stability equation at each landslide cell requires the definition of the rupture surface and of the position of the groundwater level. These two parameters are of continuous nature through the landslide. The validity of the stability analysis relies on the proper determination of the landslide geometry, groundwater levels and soil strength parameters.

The first attempt to define the surface of rupture was made by interpolation from the available inclinometers in the landslide (Figure 1). Even though this landslide may be considered as a heavily instrumented one, it soon became evident that the number of available points, where the surface of rupture is known, was inadequate. This fact produced, in some cells, a meaningless interpolation. For instance, some cells produced an interpolated failure surface above the ground surface. Furthermore, the shape of the surface was different from that expected from the knowledge of the landslide context. Therefore it has been necessary to include additional information from field observations and from geological, geomorphological and hydrogeological interpretation of the landslide.

Three parts of the landslide unit have been identified as requiring further information to be included in the GIS: (a) the landslide toe; (b) the northern boundary; and (c) the furrow located at the landslide foot.

At the *landslide toe* (Figure 2), the surface of failure outcrops next to the Vallcebre torrent. The landslide toe forms a scarp, which is the result of lateral river erosion. There, the depth of the failure surface has been drastically reduced from 15 m at borehole S-8 to about 5-7 m, the height of the landslide toe scarp. Due to the resolution of the DEM (15 $\times$ 15 m), it has not been possible to split the toe

Figure 2. Front scarp of the Vallcebre landslide toe (left), which overrides the torrent bed. The ground surface at the toe is tilted backwards while a furrow is developed (right) indicating the location of the former bed. Water seepage is observable on the lower half of the scarp (dark colour).

scarp into different cells. This implies that the thickness of the landslide all along the toe could not be determined from the scarp height and it had to be included manually. The *northern boundary* is a vertical lateral shear surface. It corresponds to the outcrop of the surface of rupture at this boundary. By default, the Arc-Info interpolator would have made this surface to outcrop with a constant dip from the closest known depth, giving a gentle plane. Instead, from geological and geomorphological interpretation, the lateral shear surface is expected to form an almost vertical boundary. This information has also been introduced manually, by giving a landslide thickness to all the cells next to the northern boundary. Finally, a *furrow at the landslide foot* has been deduced from topographical and geomorphic features of the landslide surface (Figure 2). The topographic surface of the landslide foot is tilted backwards. As it has already been said, it is interpreted as the landslide burying the former valley bottom and overriding the opposite slope. The buried valley is identified by the furrow at the landslide surface, which is often filled with water and covered with phreatophyte vegetation. Therefore, the presence of the buried valley has also been considered. All these described features have been taken into account in the GIS by including several 'virtual' boreholes. These holes introduce the information that has been observed in the field. Figure 3 shows the results of the interpolated rupture surface of the landslide using exclusively the existing boreholes (top) and adding several 'virtual' boreholes (bottom).

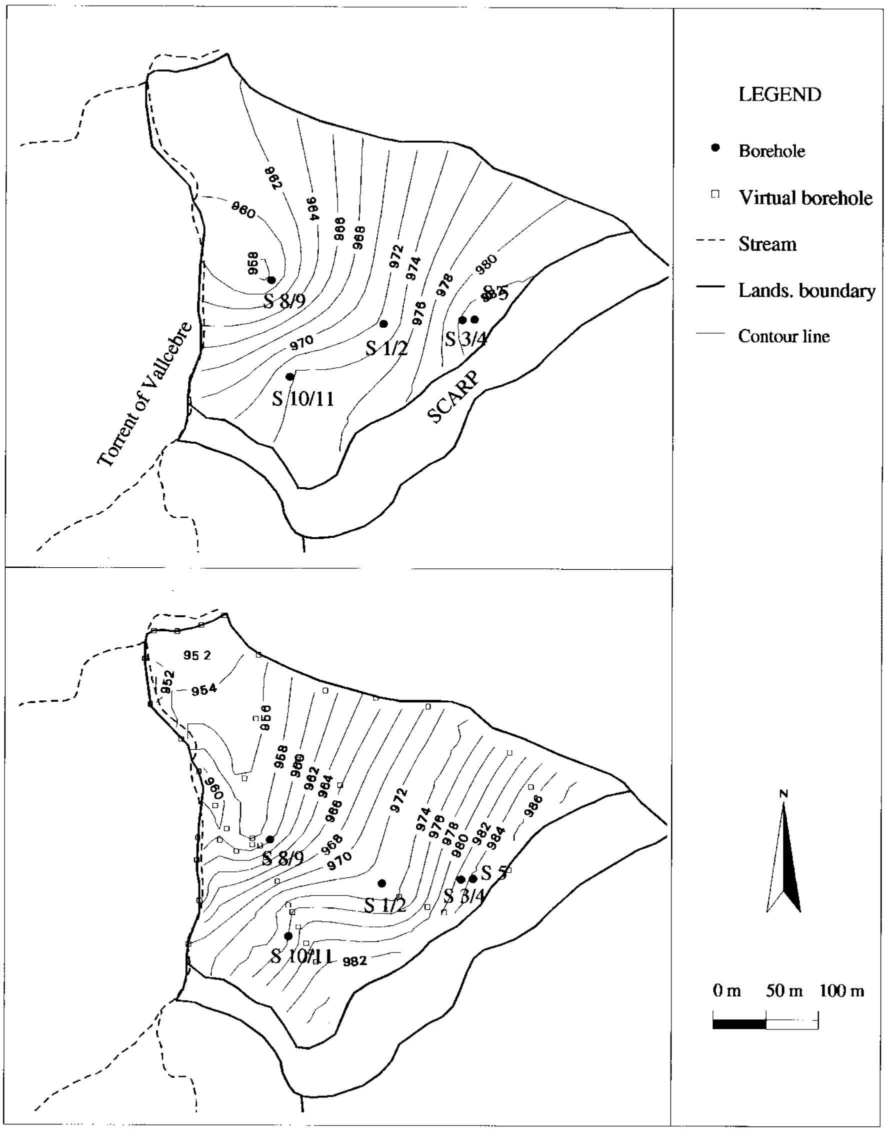

Figure 3. Surface of rupture of the lower unit of the Vallcebre landslide generated by interpolation from available inclinometers (top). The same surface generated after the inclusion of virtual boreholes (bottom).

The interpolation of the groundwater table position was simpler. First trials gave a consistent but unrealistic surface when compared to the piezometric readings. However, the shape of this surface is strongly affected by the geometry of the seepage zone located at the landslide foot scarp. The seepage takes place on about two thirds of the scarp height (Figure 2), that is, up to 4 to 5 m above the

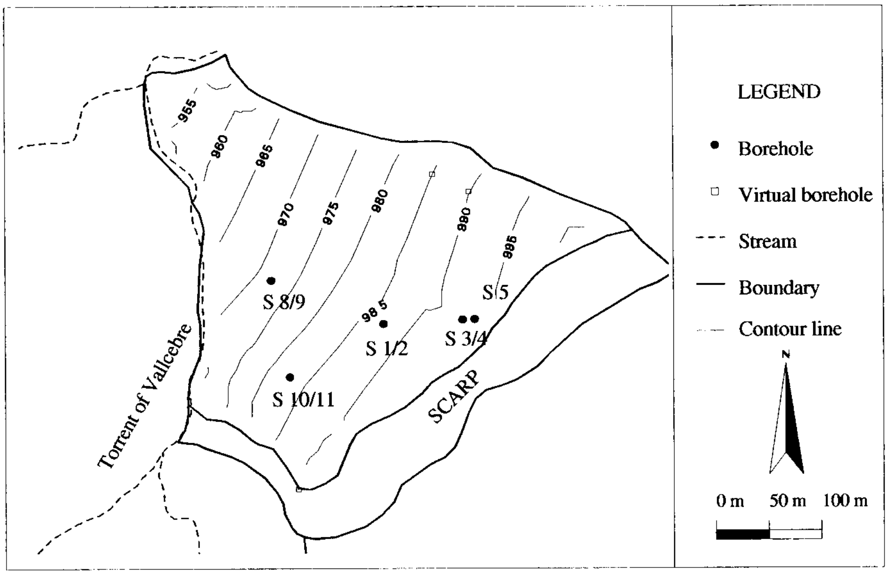

Figure 4. Groundwater level of the lower unit of the Vallcebre landslide generated by interpolation from available piezometers and with the inclusion of a seepage front at the landslide foot. The surface corresponds to the highest groundwater level recorded in the piezometers (January, 1997).

Vallcebre torrent. Groundwater also appears in the furrow where phreatophytes (mostly reeds) grow.

Among the different groundwater surfaces generated, two of them have been chosen for the analysis. They correspond to the extreme positions recorded in the available piezometers. The highest level is that of January 1997 (Figure 4) during which the landslide experienced one of the most active periods ever recorded, with displacements up to a cm/day. The lowest level occurred in November 1998. At that time, most of the boreholes equipped with the extensometers showed no displacement.

3.3. CREATION OF PARAMETERS REQUIRED FOR THE STABILITY ANALYSIS

The equation of the infinite slope stability analysis has been solved at each individual cell. In order to do so all the required parameters were determined. The depth of the surface of rupture was calculated by subtracting it from the ground surface (DEM). Similarly, the groundwater pressure was calculated using the position of the piezometric surface in relation to the surface of rupture. Finally, the dipping angle (β) of the rupture surface was derived from the interpolated surface using the Arc/Info command. These parameters have been added to the available soil strength parameters provided by laboratory tests.

Table II. Safety factors calculated along different longitudinal profiles of the Vallcebre landslide (see location in Figure 5). Three friction angle values, and the highest and lowest groundwater level positions ever recorded, have been considered

	Profile I	Profile II	Profile III	Profile IV	Global
Friction angle 8°					
High gwl	0.84	0.69	0.87	0.95	0.91
Low gwl	1.26	0.89	1.07	1.06	1.09
Friction angle 10°					
High gwl	1.05	0.86	1.10	1.19	1.14
Low gwl	1.58	1.11	1.34	1.32	1.37
Friction angle 12°					
High gwl	1.27	1.04	1.32	1.43	1.38
Low gwl	1.90	1.34	1.61	1.60	1.65

3.4. RESULTS OF THE STABILITY ANALYSIS

Once all the boundary conditions were defined, the stability analysis was performed by considering a range of soil strength properties and several positions of the groundwater table. The results are shown in Table II.

The outcome of the analysis may also be represented as a safety factor map. Figure 5 shows the map, with the cells having safety factors above and below unity, which is difficult to interpret. We must take into account that, even though several zones with different levels of stability may be identified, we are dealing with a landslide behaving as a single rigid block. Therefore, zones having safety factor values well below unity should not necessarily experience either the greatest instability or the largest displacements within the landslide. There are two main reasons for this: (a) the safety factor, in this case, is computed as the ratio between resisting and driving forces at each cell. Different pairs of forces may give the same ratio, or safety factor, but with an unbalanced force of different magnitude. Instability and displacements are primarily caused by the magnitude of the excess of the driving force rather than by the ratio between the latter and the resisting force. (b) On the other hand, if we consider a longitudinal profile, the resulting driving force in a given cell may be counterbalanced by a resultant resisting force in a neighbouring cell. Therefore, it is the overall ratio between driving and resisting forces in the profile and in the whole landslide which indicates whether the landslide is stable or unstable. Neither the 3-D effects nor the interslices forces have been considered in this analysis.

Keeping this in mind, a different map has been prepared in Figure 6. This map shows the resultant force acting at each landslide cell, for the highest recorded water level. Positive values correspond to an excess of driving forces while negative values indicate an excess of resisting forces. The locations of four longitudinal

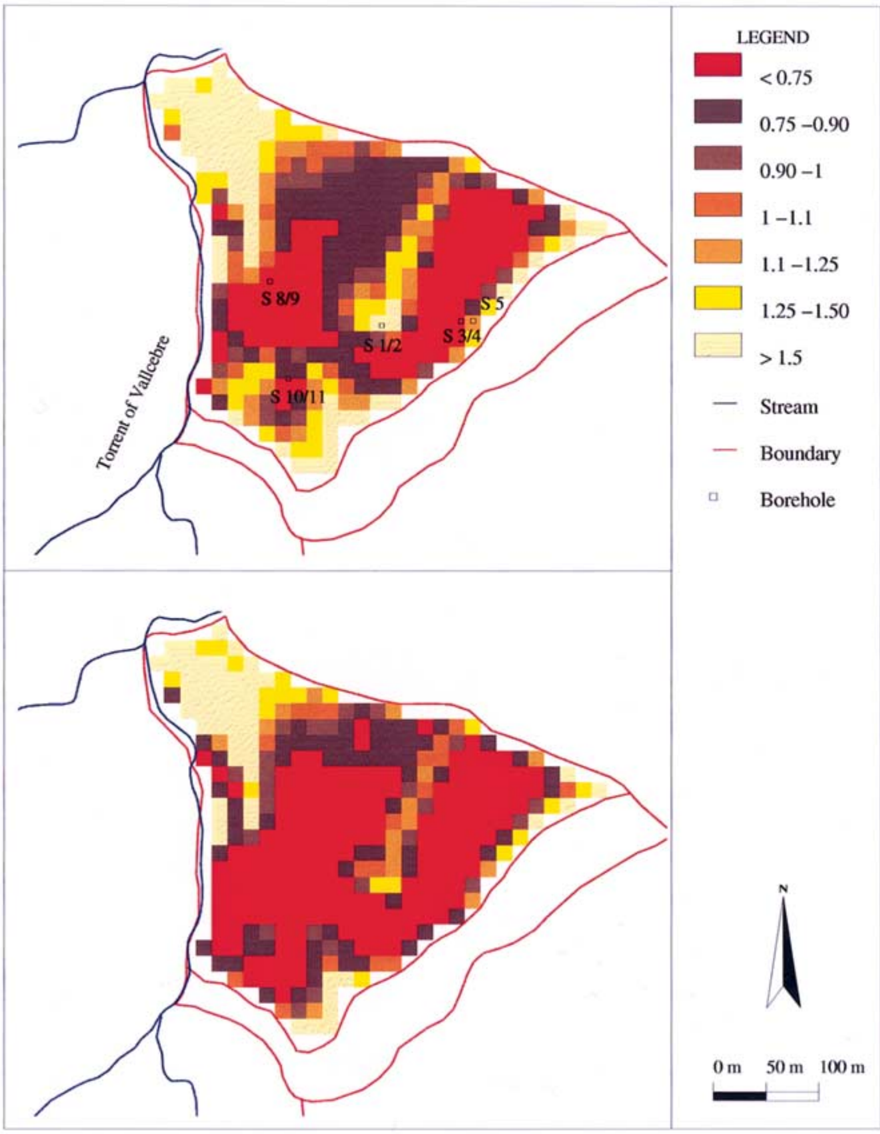

Figure 5. Map of factors of safety at each cell of the Vallcebre landslide. The analysis has been performed considering a friction angle of 8° and both low groundwater (top) and high groundwater levels (bottom).

cross-sections are also indicated, in which the overall driving and resisting forces, and safety factors have been calculated (Table II). The results are consistent and reproduce the observed landslide behaviour. For the highest groundwater level, all longitudinal cross-sections indicate instability while for the lowest recorded groundwater level, the landslide is mostly stable. Only cross-section II gives some degree of instability, which is in agreement with readings of the wire extensometer

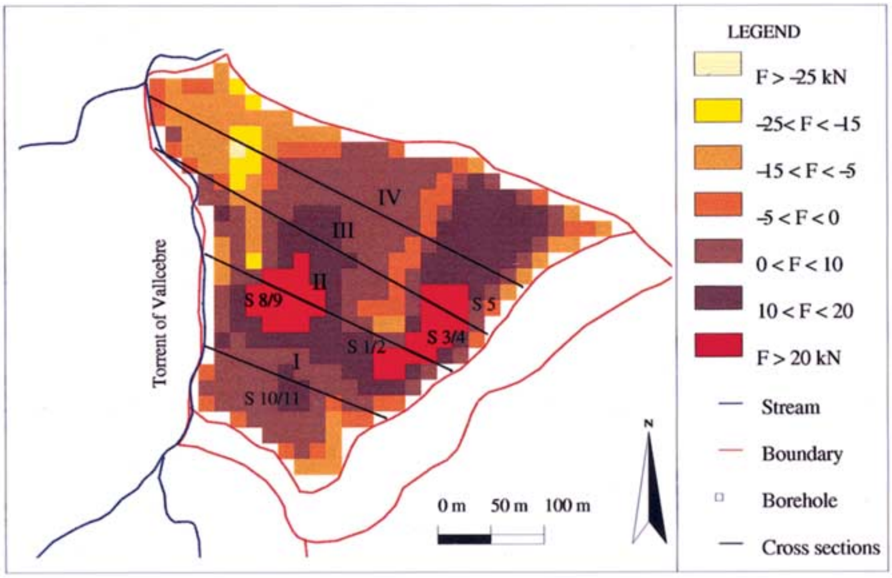

Figure 6. Map of resultant sliding force (in kN) at each cell of the Vallcebre landslide for the highest recorded water levels.

located at borehole S-2. From these results we may conclude that the GIS- based stability analysis reproduces adequately the observed behaviour of the Vallcebre landslide.

3.5. COMPARISON WITH CONVENTIONAL SLOPE STABILITY ANALYSIS

Even though the results are consistent, we have compared the results of the stability analysis performed within the GIS, with traditional methods of stability analysis. To this purpose, we have carried out a limit equilibrium analysis using the program PC-STABL-5M, developed by the University of Purdue.

In order to use a well-defined geometry of the landslide, we have chosen a longitudinal cross-section, basically coinciding with cross-section II of the GIS analysis. This cross-section has been drawn using data yielded by boreholes S-8, S-1 and the projection of boreholes S-3 and S-5, along with the support of the field observations (furrow located at the toe and height of toe scarp). As the boundaries of the surface of rupture are well defined by the presence of a graben at the rear of the landslide unit, from the outcrop at the landslide toe and from readings of the inclinometers, a fixed geometry of the surface of rupture has been established.

The soil strength parameters and groundwater levels introduced as input parameters were the same as used in the GIS analysis. The results are presented in Table III and show excellent agreement between both procedures.

Table III. Safety factors for cross-section number II obtained with GIS-based and STABL limit equilibrium analyses

	GIS profile II Factor of safety	STABL profile II Factor of safety
Friction angle 8°		
High groundwater level	0.69	0.75
Low groundwater level	0.89	0.89
Friction angle 10°		
High groundwater level	0.86	0.92
Low groundwater level	1.11	1.10

4. Concluding Remarks

(1) A GIS-based deterministic analysis of translational landslides is feasible. A test performed at the Vallcebre landslide using two different positions of the groundwater levels has given coherent results.

(2) Limit equilibrium analyses with a GIS require precise definition of the landslide boundaries as in classical slope stability methods. However, the GIS allows a better visualisation of all geometric features used in the analysis which helps the comparison and checking with geologic and geomorphologic models.

(3) Interpolation methods are very sensitive to the spatial distribution of data points. Rupture and groundwater level surfaces may change significantly depending on the location of these points. In Vallcebre, besides the information provided by the boreholes, it was necessary to incorporate additional information into the GIS from field observations and from both geological and hydrogeological interpretations. This constraint, however, is the same as that found in other conventional procedures used for slope stability analysis.

(4) Safety factors calculated at each cell cannot be interpreted individually as they may give senseless conclusions. Each cell is only a part of the landslide and the resultant force at the failure surface may be counterbalanced by that of neighbouring cells. The degree of stability of the landslide has to be considered globally. It is thus advisable that, in regional susceptibility and hazard analysis, the stability of distinct large landslides is estimated as a whole instead of considering the cells as behaving independently from each other.

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