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A preliminary method for the evaluation of the landslides volume at a regional scale

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Abstract Dealing with the evaluation of the risk connected to the formation of landslide dams at regional scale, it is important to estimate the volume of the depleted material that can reach the riverbed. This information, combined with other elements (river dimensions, valley width, landslide velocity, etc.) allows making predictions on the possibility of river blockage. One of the problems of this approach is the lack of data concerning the shape and position of the sliding surface; this does not permit us to estimate the volume of the landslide material. The IFFI (Inventario dei Fenomeni Franosi in Italia, i.e. *Landslide Inventory in Italy*) project furnishes information, at different levels of precision, on nearly totality of the landslides existing in Italy. The first level of the IFFI (compiled for all slides) does not contain information on the depth of the sliding surface but contains data regarding the type and the activity of the slope movement. Along with this information the IFFI project also furnishes vector maps containing the boundary of each landslide and the main sliding direction. This paper describes the implementation of an algorithm aimed to define, with an adequate approximation, the 3D geometry of the sliding surface of rotational slides for which, on the basis of geologic maps available at regional scale, some geotechnical parameters can be known or estimated. The work also required the creation of a computer code useful for the 3D analysis of slope stability (3D safety factor) using the simplified Janbu method. All computer code has been created on a GNU-Linux OS and using shell scripting, based on GRASS GIS and R statistical software.

Keywords GRASS GIS · Landslide volume · 3D slope stability analysis

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1 Introduction

1.1 The evaluation of sliding volume at a regional scale

The evaluation of landslide volume is strictly linked to slope stability analysis. Normally it is necessary to study in detail only a single landslide case, but it can also happen that it is necessary to evaluate the landslide volume at a regional scale. In our case we had to estimate the volume at a regional scale for hundreds of landslides in order to calculate the territorial vulnerability for landslide damming phenomena, that are linked to the volume of depleted material [3]. It was not necessary to have an exact estimation of volume but just an estimate of order of magnitude. This estimation should be done iteratively for more than one hundred slides, so the integration of this slope stability model into a Geographical Information System (GIS) allows us a simpler and more efficient analysis.

1.2 GIS approach to 3D stability analysis models

Trying to determine the sliding surface of a landslide is a hard task because each landslide is usually a complex combination of a lot of small movements. In order to solve this problem many different modeling approaches have been used. The majority of these models performs a two dimensional (2D) modeling of slope stability, using the limit equilibrium method within the domain of geotechnical engineering. The safety factor is commonly assessed using a 2D representation of the slope.

While the results of the 2D analysis are usually conservative, 3D analysis tends to increase the safety factor. The failure surface is assumed to be infinitely wide in 2D modeling, omitting the 3D effects. Some studies conclude that the 3D safety factor is usually greater than the corresponding 2D safety factor calculated for the most critical 2D [4].

Since the 1970s, the development of 3D stability models has attracted growing interest, so the advent of a 3D approach for slope stability analysis has produced a great number of computer programs. The most representative one is CLARA [6], which is commercially available, and can compute both 2D and 3D slope stability analysis. TSLOPE3 [9] is another code that performs 3D slope stability analysis but CLARA satisfies more equilibrium conditions using different methods of 3D analysis.

The Geographical Information System (GIS), with capacities ranging from conventional data storage to complex spatial analysis, is becoming a powerful tool to implement slope stability models. Since the usual slope stability models are able to evaluate the sliding surface but cannot precisely place the sliding surface into a geographic reference system, the GIS approach can improve the analysis and the overall usefulness of the obtained data.

3D analysis provides a better way to model slope stability than 2D analysis and a GIS approach allows the user to assess with precision the extent of the landslide and its position.

One of the first GIS approaches to slope stability analysis was performed by Xie et al. [11, 12] and was finalized to create the landslide susceptibility map of a region.

Recently the same authors improved their algorithm using the Monte Carlo method to generate the centroids of the ellipsoids representing the sliding surfaces [13].

In this study, a 3D deterministic slope stability analysis is combined with a GIS based grid system to create a procedure useful to determine the volume of the slope movements reported on a landslide inventory map. It was developed to work with a large number of landslides (>1000) but, at the moment, it has been tested only over a small subset of them (we present the results from 5 landslides). Moreover a stand-alone procedure was created to perform a classical 3D stability analysis of a slope. Both procedures have been implemented using two free/open source softwares, GRASS GIS [5], [8] and R [10] running on a GNU-Linux OS (Debian Testing). The interoperability among three elements is guaranteed by the GNU-Linux Bash Shell.

The code is available under the terms of the GNU-GPL license at the website: http://www.unipg.it/~ivanm/scripts/.

2 The procedure to estimate landslide volume at regional scale

The procedure has been developed according to the available italian landslides inventory map and in particular the recently published data of the IFFI Project (Inventario dei Fenomeni Franosi in Italia). The IFFI contains a vector area map, a database of attributes of all the known italian landslides, and also a vector line map representing the main directions of the landslides (see Fig. 1). The lines always start at the top of the landslide. The structure of the algorithm is shown in Fig. 2, where the code is represented by means of three nested rectangles representing the three phases, or cycles, of the algorithm. In the figure, the developed Bash shell scripts are also indicated. In general the main script (represented by the outer rectangle) is a simple cycle through all the area features in the landslide inventory map.

In particular, at the moment, the procedure can be only applied to a sampling of landslides performed by means of a geographical intersection with a geologically homogeneous area (limestones, sandstones and marls, geological formations, etc.). This allows working with the same average values of geotechnical parameters (volume weight, friction angle, cohesion) that can be used by the procedure as input data. Moreover the algorithm considers a single layer and assumes completely saturated conditions.

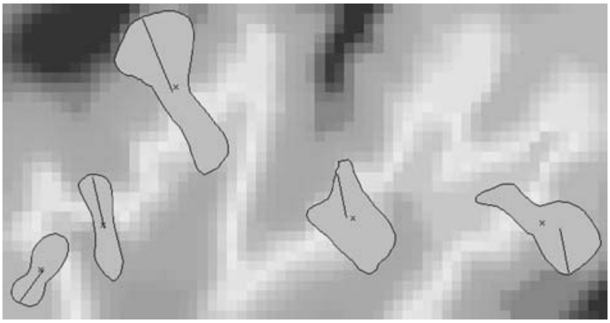


Fig. 1 Subset of the IFFI dataset

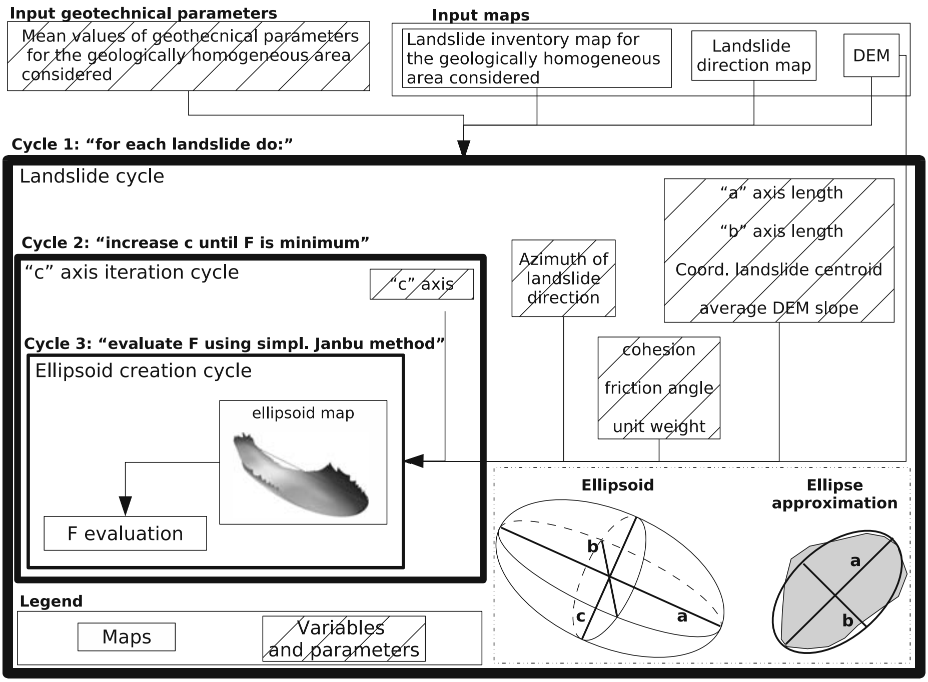


Fig. 2 Procedure structure

For each landslide area the script calculates the elevations and the direction of the movement. The azimuth.c code (http://www.igc.usp.br/pessoais/guano/downloads/azimuth2.c) is used to calculate the azimuth from the linear features representing landslide directions. Moreover, an approximation of the planar shape of each slide to an ellipse is performed. This allows the definition of the semi-axes "a" and "b", as shown in Fig. 2. It has to be pointed out that the length associated with the "a" axis is the 3D length (estimated by means of DEM data) and not its projection on the plane. The intermediate rectangle represents the second phase of the procedure. Here a first value for the "c" semi-axis is hypothesized (assuming the landslide shape as a portion of an ellipsoid) and passed on to the third and last phase of the procedure. More precisely, the value of the "c" semi-axis, initially set to a fixed value of 0.5 m, is progressively doubled before to be passed to the third phase. In the last phase the ellipsoid for the "a","b","c" values is calculated and oriented, in the GIS reference system, in such a way that the **"a"** semi-axis is parallel to the landslide direction, passes through the centroid of the landslide area and is inclined at an angle equal to the mean slope angle of the DEM. In Fig. 3 an example of the lower half of a similar ellipsoid is shown (the grid represents the DEM and the closed line the mapped slide area). During the third phase of the procedure slope stability analysis is also performed. The Janbu [7] simplified method is used to estimate the safety factor (F) for well defined "a","b","c" semi-axes. The procedure ends when the "c" length determining the minimum F is found; the corresponding hemiellipsoid is then considered as the sliding surface and used to calculate the volume of the sliding mass.

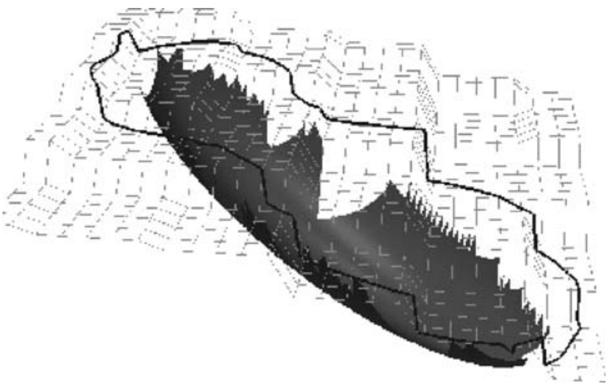


Fig. 3 Example of the ellipsoidic sliding surface

In the following paragraphs some details regarding the implementation of the procedure are given.

3 Ellipsoid creation and orientation

As already explained, the procedure assumes that the shape of the sliding surface can be described by an hemiellipsoid. It is simple, inside the R workspace, to write the standard equation describing an ellipsoid (local reference system).

$$\frac{x_1^2}{a^2} + \frac{y_1^2}{b^2} + \frac{z_1^2}{c^2} = 1 \tag{1}$$

The problem arises when we must describe the ellipsoid in a different reference system (global reference system), like the italian Gauss–Boaga Roma40 we were working with using GRASS GIS (Fig. 4). This task has been addressed, among others, by Xie et al. [12] with an equation that allows the expression of the three coordinates of a point in a reference system (x_1, y_1, z_1) by means of the coordinates of the same point in another system (x,y,z):

$$\begin{bmatrix} x_1 \\ y_1 \\ z_1 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} x \begin{bmatrix} x - x_0 \\ y - y_0 \\ z - z_0 \end{bmatrix} \tag{2}$$

where

x_0, y_0, z_0 are the known coordinates of the centroid of the landslide area,
a_{11}, a_{12}, ..., a_{nm} are constants. The constants can be easily calculated and depend on the direction and inclination of the "a" axis.

Since the x,y coordinates where the ellipsoid must be calculated (i.e. the cells bounded by the landslide perimeter) are known, it is possible to create an R dataframe containing the pairs of these x,y values. This means that, for each cell and from the equation of Xie et al. [12], one can express x_1, y_1, and z_1 as a function of z only.

Substituting such three new equations into the ellipsoid standard equation, a second order equation in z may be obtained. The smallest values from this equation

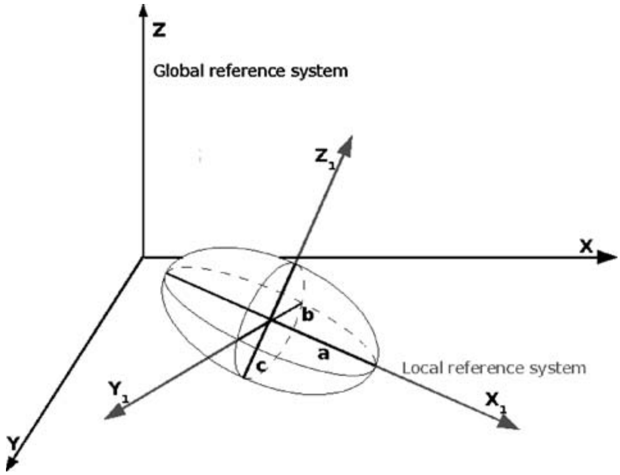


Fig. 4 Global and local reference system

represent, for each x,y pair, the elevation (z) of the lower part of the ellipsoid oriented along the slope affected by the slide movement and characterized by well defined “a”,”b”,”c” semi-axes. Hence it represents the elevation of the sliding surface.

4 Evaluation of the safety factor (F)

The simplified Janbu method was applied on the basis of the discrimination of the landslide in *n* prismatic elements. The projected area of the base of each prism is defined by the resolution adopted by the user in GRASS GIS. The real area of the

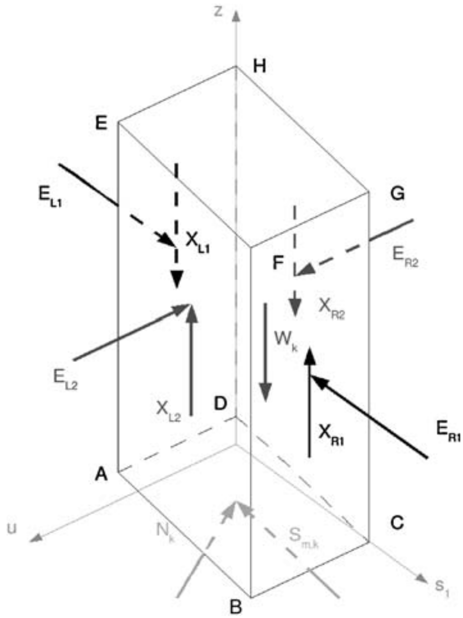


Fig. 5 Prismatic element of the landslide

base of each prism depends on the inclination of the ellipsoidal sliding surface. The aspect (dip direction) and inclination (α) of each cell constituting the sliding surface are simply derived by the terrain analysis instruments of GRASS GIS (*r.slope.aspect* module). In Fig. 5 a single prism is represented. Since the simplified Janbu method assumes that the internal forces among the prisms are purely normal, we assume that the tangential forces on the vertical sides of the prisms are null, i.e. $X_{L1} = X_{L2} = X_{R1} = X_{R2} = 0$.

At the base of each prism we have normal (N_k) and tangential ($S_{m,k}$) forces related to the gravitational forces (W_k). On the vertical sides of the prisms the normal forces (E_{L1}, E_{L2}, E_{R1}, E_{R2}) act respectively counterbalancing each other. Only along the "a" semi-axis the dip-direction of the cells (s_1) corresponds to the landslide direction (s). In all other cases there is an angle (λ) between the two directions (see Fig. 6). This means that to evaluate the contribution of each prism to the instability of the landslide volume we have to calculate the component along "s" direction of the sliding force acting at the base of each prism by $N\sin(\alpha)\cos(\lambda)$. The same is true for the tangential forces. Obviously, when λ is greater than 90° the prism acts to stabilize the landslide.

The safety factor is evaluated by means of the equation of global equilibrium to the horizontal translation:

$$\mathrm{F}=\frac{\sum_{k=1}^{n}\left[c_k A_h + (N_k - u_k A_k)\tan\varphi_k\right]\cos\alpha_k\cos\lambda_k}{\sum_{k=1}^{n} N_k\sin\alpha_k\cos\lambda_k} \tag{3}$$

where

A_k and α_k are respectively the area and the inclination of the k^{th} prism base,
c_k is the cohesion,
u_k is the hydraulic head;

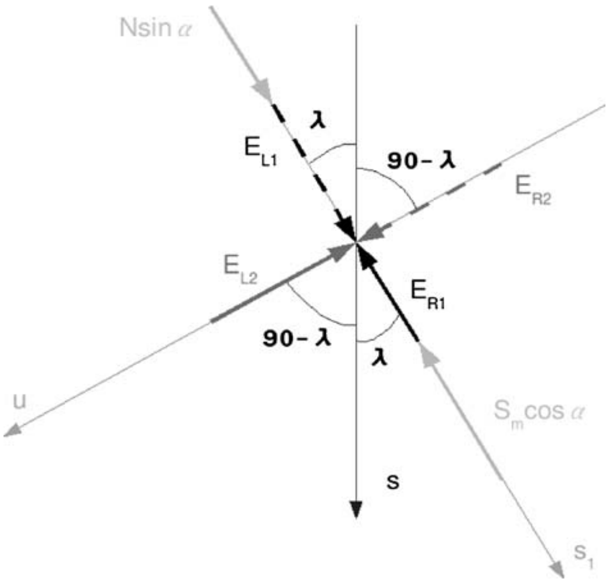


Fig. 6 The angle between the landslide direction and cells direction

and by means of the equation of the local equilibrium of each prism to the vertical translation:

$$N_k = \frac{1}{m_\alpha}\left[W_k - \frac{1}{F}\left(c_k A_k - u_k A_k \tan\varphi_k\right)\sin\alpha_k\right] \tag{4}$$

where

N_k is the normal force acting on the base of the k^{th} prism,
W_k is the weight of the prism, ϕ_k is the friction angle,
$m_{\alpha,k}$ depends on α_k, ϕ_k and F:

$$m_{\alpha,\mathrm{k}} = \cos\alpha_k\left(1 + \frac{1}{F}\tan\alpha_k\tan\varphi_k\right) \tag{5}$$

Substituting the normal forces into the equation of global equilibrium to horizontal translation, a non linear equation that determines the safety factor in implicit form is obtained. The solution of this equation is obtained using an iterative algorithm implemented into R. The iterative process stops when the difference between the assumed F and the calculated one is less than 0.001.

Since the simplified Janbu method tends to underestimate the safety factor as the depth of the sliding surface increases, the obtained value of F is corrected by means of a coefficient f_0 which depends on a coefficient k that is equal to 0.5 (cohesive materials) or 0.31 (non cohesive materials):

$$f_0 = 1 + k\left[\frac{c}{2\mathrm{a}} - 1.4\left(\frac{c}{2\mathrm{a}}\right)^2\right] \tag{6}$$

The simplified Janbu procedure can sometimes be numerically instable due to the value assumed by the $m_{\alpha,k}$ coefficient. In particular some problems arise when $m_{\alpha,k}$ is really small, null or negative, because this determines infinite or negative values of the normal forces N_k. This can happen when α_k is negative and contemporary $tan\phi/F$ is large or when α_k is large but $tan\phi/F$ is small.

A solution to this problem is to limit the inclination (α_k) of the sliding surface into the range defined by the theory of the active and passive state of Rankine [1].

4.1 Defining the "c" semi-axis length

We can define "critical c": the value of "c" semi-axis for which the calculated F is minimum. As we said before, we decided to hypothesize values progressively doubled for the length of the "c" semi-axis. For each hypothesized value, the F safety factor is calculated. When the last obtained F value (corresponding to the c_n semi-axes length) is larger than the previous one ($F_{(cn-1)}$, the algorithm returns to add 1 meter to the c_{n-1} value. If the $F_{(cn-1+1)}$ is larger than $F_{(cn-1)}$ then the algorithm stops and assumes the c_{n-1} length as the "critical c"; on the opposite, if the $F_{(cn-1+1)}$ is smaller than $F_{(cn-1)}$, the calculation continues adding 2, 4, 8,..meters to the c_{n-1} length.

An example of this procedure is shown in Fig. 7 where the F values are plotted against the "c" values. The "critical c" is equal to 79 meters and is found in

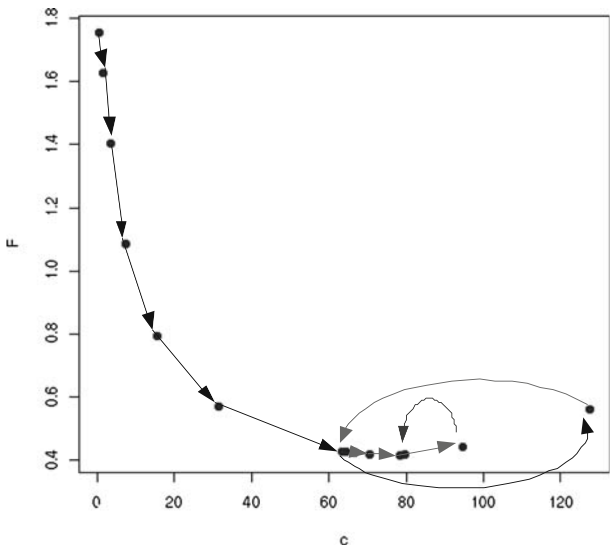


Fig. 7 Safety factor vs *c* semi-axis

correspondence of a F value of 0.42. The “critical c” corresponds to the minimum of the function “F vs c”. It could happen sometimes that the function “F vs c” does not reach a minimum into the range from a minimum of “c”=0 to a maximum of “c”=”b” . In this case, the minimum F is obviously assigned for “c”=”b”.

5 Application

The procedure was applied to five landslides located in the Umbria region (Central Italy). All landslides are located on the same geological homogeneous formation (“Marnoso-Arenacea Formation”, a marly-arenaceous fractured lithological complex). The geotechnical parameters used came from a previous study [2] concerning a landslide located on the same geological formation and close to the 5 landslides analyzed. The results of the stability analysis performed using the procedure just described are summarized in Table 1. The table shows that, for each landslide, a safety factor less than one was found, as expected. To better understand this point, we should consider that every landslide is classified as an active or quiescent landslide and the soil moisture hypothesis (terrain completely saturated) is strictly conservative. In Fig. 8 an example of a calculated sliding surface is shown.

Table 1 Results of the stability analysis

Landslide id	X center	Y center	a (m)	b (m)	c (m)	F	Volume (m^3)
1	2316944	4813433	137.9	78.3	46.5	0.76	1012445
2	2317430	4813421	147.3	53.0	78.5	0.41	1129841
3	2316146	4813302	93.3	30.0	34.5	0.59	213714
4	2316306	4813415	138.7	26.1	33.5	0.44	390441
5	2316493	4813764	217.4	41.4	70.5	0.52	1387780

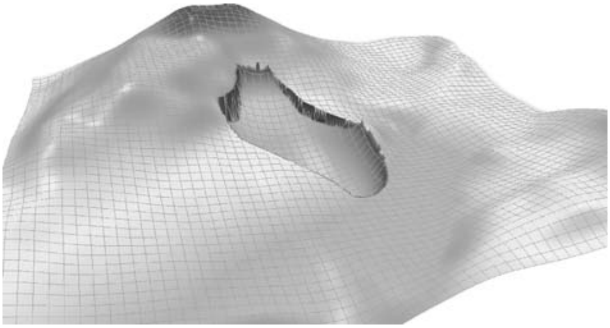


Fig. 8 Example of calculated sliding surface

6 The stand-alone script for 3D slope stability analysis

A new stand alone script was written to perform a 3D slope stability analysis. Starting from the scripts described before, we tried to create a model to analyze slope stability. The new bash script asks the user for a vector line map defining the direction along which we need to perform the slope stability analysis. Such direction should be egual to the more tilted slope direction because here is where we usually expect to find landslide phenomena. The vector line map represents the domain where the model has to perform the slope stability analysis. We call this line "domain line" (Fig. 9). The script splits this line into an equal number of segments as defined by the user. The user also has to provide an anisotropy ratio between the major semi-axis (a) and the semi-axis (b). The model iteratively centers the corresponding ellipsoid at the connection of two consecutive segments and on the basis of the anisotropy ratio, it assigns a starting value for "a" and "b" semi-axes (Fig. 10).

Then the script starts to increase the semi-axis "c" in order to find the minimum safety factor, as already explained in the Section 4.1. Once the "critical c" is found, the script doubles the "a" value and starts again to increase the "c" value. The safety factor calculated with the new "a" value is then compared to the previous one. If the new F is smaller than the previous F, the script continues to double the

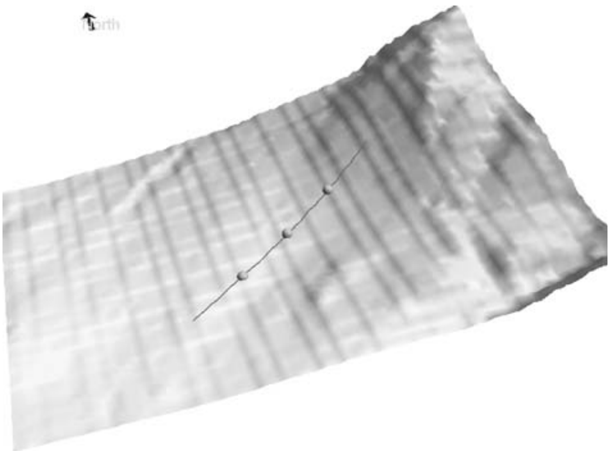
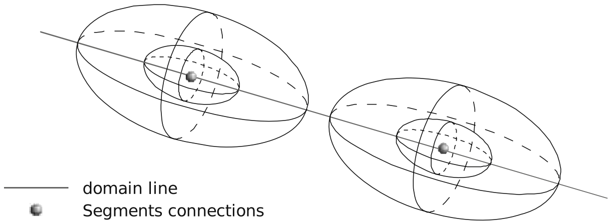


Fig. 9 Example of a "domain line", along which we need to perform the slope stability analysis

Fig. 10 Schema of the increasing ellipsoid dimensions, at the junction of consecutive segments, along the "domain line"



"a" value; conversely it stops, writes "c" and F values on a text file and passes on to the next connection between segments. The output of the module is a text file containing, for each centroid position, the coordinates, the minimum safety factor and the corresponding landslide volume.

7 Conclusions

The study of the risk connected to the formation of landslide dams cannot neglect the sliding volume parameter. The GIS approach to 3D analysis of slope stability allows modelling the sliding surfaces at a regional scale and to evaluate the sliding volume for each landslide; moreover it improves the management of the input data and of the results obtained. Performing this kind of analysis is a hard task and, due to the scale of the analysis, it must be accomplished with some approximations concerning geotechnical parameters and terrain saturation. The availability of a detailed landslide inventory map, of a DEM and of a numerical geological map of the target area, gave us the chance to build a computer procedure which allowed the approximate estimation of the mass of a large number of slope movements. The first results obtained on a subset of landslides have shown that the calculated safety factors and the corresponding sliding volumes are realistic. The planned application of the algorithm to well known and monitored landslides will allow further verifications of its effectiveness. This goal could be also achieved by applying the stand alone procedure developed for a 3D stability analysis along a slope. Although the work is still in progress and the developed code needs to be improved to optimize the velocity of execution and to consider stratified materials with different conditions of water saturation, the approach seems to be promising and the interoperability between Grass Gis and R allows researchers with a limited programming experience to test, update and improve the code. The GNU-GPL License guarantees the freedom to execute, study, copy and alter the code if later code is released under the same license.

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Pierluigi De Rosa received a degree cum laude in Environmental engineering from University of Perugia in 2004, in November 2005 he got a Master's degree in Environmental Geotechnologies from University of Siena. He is pursuing a PhD in Earth Science and Geotechnologies from University of Perugia (graduation expected in February 2009). His background includes knowledge and implementation of open source geographic information system, geostatistical analysis, landscape environmental modeling.