GEOQuébec 2015
Challenges from North to South
Des défis du Nord au Sud

A review of geometrical methods for determination of landslide volume and failure surface geometry

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ABSTRACT
This paper presents a first attempt of reviewing the methods developed to define landslide failure surfaces and volumes based on surface information. It reminds the simplest models such as the volume estimation using ellipsoids and the information that can be obtained from surface displacement and morphology. A method to define the volume of rockslide is also presented. Finally the new development related sloping local base level (SLBL), which allows based on a digital elevation model (DEM) to obtain a possible failure surface automatically, are presented. The perspectives are drawn and uncertainty is partially addressed.

RÉSUMÉ
Cet article présente une première tentative de revue des méthodes dédiées à la caractérisation des surfaces de rupture et des volumes des mouvements de versants. Ces méthodes se basent sur des données de surface. On rappelle les modèles les plus simples tels que l'estimation de volumes à l'aide des ellipsoïdes et les informations que l'on peut obtenir à partir de déplacements de surface et de la morphologie. Une méthode pour définir le volume d'éboulement rocheux est également présentée. Enfin, les nouveaux développements liés au sloping local base level (SLBL), qui permet d'obtenir, à partir d'un modèle numérique de terrain, une possible surface de rupture automatiquement, sont présentés. Les perspectives liées à ces méthodes sont abordées et le problème de l'incertitude est partiellement abordé.

1 INTRODUCTION

Even though computers power is increasing, only few methods are available for the volume calculation of landslides, as well as the construction of their failure surfaces or profiles across landslides based on sparse data. However, available data permit now to go to 3D representations.

In this paper we review existing methods that permit to estimate the landslide failure surface in 2D profiles or as full 3D surface. They are based on various information (Hutchinson, 1983). Most methods reviewed here are based on morphometric characterizations, displacement observations, and interpolation techniques, leading to the estimation of surfaces. Some are indirect, using geophysics.

Most of the landslide section or 3D surface are based on expert knowledge, making the synthesis of the available data that are surface morphology, boreholes, geophysics interpretation, etc. But only few methods are based on a systematic approach. The aim of this paper is to present an overview of methods than can help to estimate the depth or/and shape of the failure surface of a landslide. Finally we have the opportunity to present some of our developments of automatic methods such as the splines or sloping local base level (SLBL) that will be soon fully published and available.

2 SIMPLE METHODS

2.1 For landslides

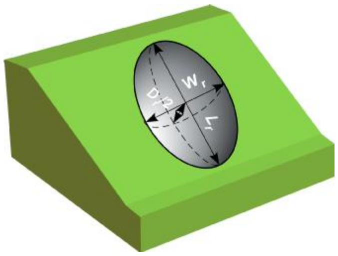


Figure 1. Synthetic way to define volumes of landslides by the failure surface. D_r is the half thickness of the ellipsoid (landslide), and W_r and L_r respectively its width and its length (Modified after Cruden and Varnes, 1996).

The simplest methods used to assess landslide volume is to assume a mean thickness multiplied by the landslide surface area, or to use a semi-ellipsoid (WP/ WLI, 1990; Cruden and Varnes, 1996):

$$V_r = \frac{1}{6}\pi \times D_r \times W_r \times L_r \quad [1]$$

Where the variable are defined in Figure 1. This volume corresponds to the volume defined by the failure surface, with no change of the volume of the material.

Cruden and Varnes (1996) pointed out that the volume V_d of the “displaced mass” or of the “deposit” is related to V_r by the relationship:

$$V_d = \frac{1}{6}\pi D_d \times W_d \times L_d = \frac{4}{3}V_r = \frac{4}{3}V_r = \frac{2}{9}\pi \times D_r \times W_r \times L_r \quad [2]$$

It shows that volume estimation must be clearly defined, depending if we consider the failure surface or the displaced volume, the difference proposed is around 33%.

It must be noted that some authors (Xie et al., 2004; Marchesini et al., 2009) developed an automatic model to get the 3D ellipsoidal shape by fitting an ellipse at surface to determine the W_r and L_r and defining D_r by searching its value based on the minimal safety factor using slice method.

2.2 For debris-flows

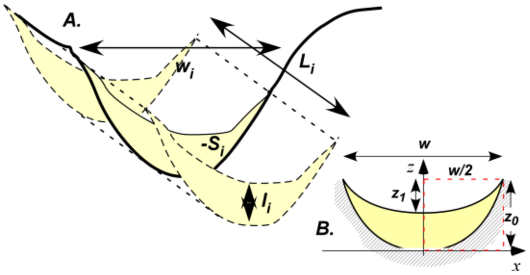


Figure 2. Synthetic way to define volumes of material in a torrent channel. (A) Using observed cross sections and (B) based on parabolic profiles.

In the case of debris-flows, the classical method to estimate the volumes is to perform surveys, multiplying the area of the section S_i of the available sediments by the length of reaches L_i (Figure 2) and to add the initial volume V_{init} in addition to the lateral input V_{lat} (Hungr et al., 2005):

$$V_{total} = V_{init} + \sum_{i=1}^{n} S_i L_i + \sum_{j=1}^{m} V_{lat}^{j} \quad [3]$$

The transversal section can be replaced by polynomial functions to estimate maximum scouring potential, when only few data are available. Using parabola as the bed shape section and for the erodible surface, it can be shown that the section S_i can be replaced by:

$$S_i = \frac{2}{3} w_i \times (z_{i0} - z_{i1}) \times L_i \quad [4]$$

Where z_{i1} is the depth at the centre of the bed from its side and z_{i0} the depth of the expected erosion.

3 LATITUDINAL CROSS-SECTION BASED ON APPARENT DISPLACEMENTS OR VELOCITIES

The observation of the total surface displacements or the velocity vectors field, can lead to the construction of longitudinal profiles of failure surfaces that may be circular or not. The observation of the scarp alone and the total displacement can provide the thickness of the landslide in the case of a translational slide.

3.1 Scarp length and rotation

When the headscarp of a rotational slide is visible and the rotation at the surface is measurable the radius (R) can be estimated (Figure 3). Measuring the high of the scarp Δh and the angle of rotation α, the radius can be deduced by (Jaboyedoff et al., 2009):

$$R = \frac{\Delta h}{2 \cdot \sin\frac{\alpha}{2}} \quad [5]$$

The location of the centre of the circle can be located either by fitting the circle on the scarp or using the scarp and an estimate of the bottom of the initial failure surface.

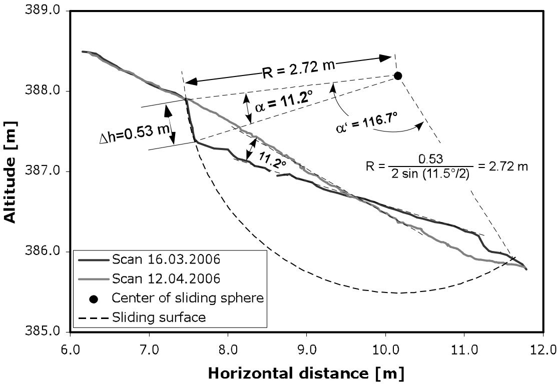


Figure 3: Example of calculation of an observed landslide using terrestrial laser scanners. Note that result fitting a sphere on the head scarp surface is very close to the result of eq. 5 with R = 2.5 m (modified after Jaboyedoff et al., 2009).

3.2 Using balanced cross-section

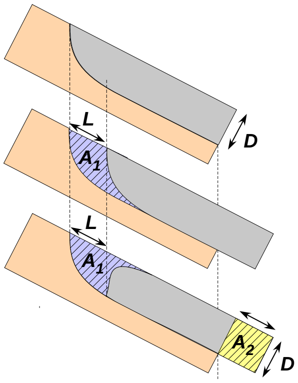


Figure 4: illustration of the principle of the method based on the void scarp to deduce the thickness D (after Hutchinson, 1983).

The thickness (D) of a landslide can be estimated by analyzing topographic profile and the movement along the sliding surface (L) (Hutchinson, 1983). This method is analogous to the balanced cross sections in structural geology. If the movement is translational the void area A1 created in the head scarp area by the motion should exit the system, i.e. surface A_2, where the displacement L is measured. Thus if L is known, the thickness D can be deduced assuming that L × D = A_2 (Figure 4):

$$A_2 = f \times A_1 = D \times L \quad [6]$$

and

$$D = \frac{1}{f}\frac{A_1}{L} \qquad [7]$$

Note that we have added a coefficient expansion f in order to address the volumetric expansion after sliding of the rock mass.

More sophisticated methods have been applied to more complex landslide, permitting to draw a succession of cross-sections in case of a multi-failure surfaces, based on surface displacement and the rotation of the targets (Chase et al., 2001).

3.2.1 Example using balanced cross-section

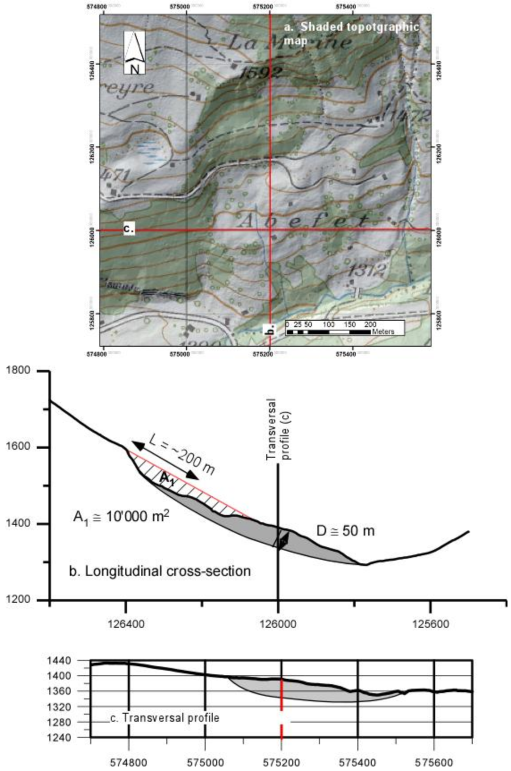


Figure 5: a. shaded topographic map (data from swisstopo) and location of the cross-section b and c. b. interpretative longitudinal section of the landslide based on the thickness D deduced from the displacement L and the surface A1. c. base on a. and b. interpretation of the transversal profile.

As an example we show how to use this method on the dormant “Abeffet” landslide located in Switzerland. The topographic profiles permit to deduce a surface A1 = 10^4 m^2 (Figure 5). The displacement of D = 200 m is in that case estimated in the scar where we consider that the thickness of the landslide material is significant.

3.3 Surface velocities or displacements

In the presence of a rotational landslide the failure surface is considered as circular. When displacement measurements are available in 3D (2D respectively), Carter and Bentley (1985) propose to use the special properties of these vectors to reconstruct the surface in 2D making the assumptions as follow:

- A unique sliding surface
- The landslide behaves locally as a block
- The surface movement direction is perpendicular to the radius of the circle defining the failure surface.

The construction method is as follow (Figure 6):

1. Draw a line from the scar or foot parallel to the closer surface movement.
2. Draw lines (= radius) perpendicular to all motion vectors
3. Draw bisectors between two successive radius
4. The bisectors are limiting the segments of the failure surface
5. Draw step by step the segments connecting the segments created in (1) from the first bisector to the next one perpendicular to the next radius.
6. Perform if possible the same procedure but starting from the opposite (scar or foot).

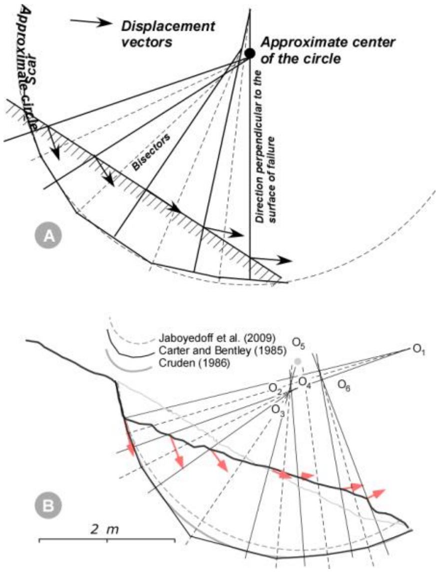


Figure 6: A. Illustration of the method of Carter and Bentley (1985). B. with the displacements deduced roughly from the laser scanner data from Figure 3, the three methods are compared.

Cruden (1986) argued that it is better to draw the failure surface by drawing arc of circle from the head scarp using each radius defined by the successive radius (Figure 6b). Comparing both methods the results are very similar with the scarp length and rotation method from Figure 3.

4 TRANSVERSAL CROSS-SECTION BASED MORPHOLOGY AND SPLINES

In order to perform failure surface profile automatically splines may be used as in 3D geological modeling (de Kemp, 1999). It is possible to get reliable estimate based on simple spline in one-dimension using geomorphic features (Jaboyedoff and Derron, 2013, 2014). Splines are commonly used in 3D geological models (de Kemp 1999). For example, a topographic section (x-z) where the surface of failure starts at point x_1 and the end at x_2, are identified and the derivative known in that points, a third order polynomial (1D-spline) can be drawn be using (Bartels et al., 1987):

$$z(u) = A + Bu + Cu^2 + Du^3 \text{ with } u = \frac{x - x_1}{x_2 - x_1} \qquad [8]$$

The well-known La Frasse landslide is used to illustrate this method (Noverraz and Bonnard, 1988). The results are compared to the geologist interpretation (DUTI, 1986) which was based on boreholes. It shows a very good agreement (Figure 7).

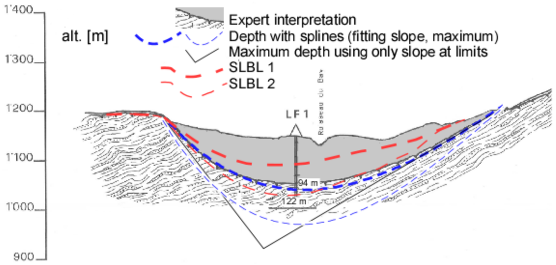


Figure 7: Comparison of the splines method and SLBL one with the geologist interpretation (modified after DUTI, 1986 and Jaboyedoff et al., 2014).

5 3D SURFACES

The modelling of 3D failure surfaces and volumes can be performed using a digital elevation model (DEM) and morphometric features providing the limits of the unstable volume of rocks or soils. This can use various interpolation techniques such as 3D splines, surface fitting, iterative procedure, etc.

5.1 For structured rocks

In the case of rock inabilities, the major discontinuities defining the instability limits observed at surface are used to extrapolate them in the rock mass in order to define their volumes. This is performed by mapping the extent of the instability and the morphology of its surroundings either by fitting manually a plane on the outcropping surface using the point cloud or extrapolating discontinuity traces using structural analysis of the area based either on airborne or terrestrial laser scanner (ALS or TLS) or photogrammetric point clouds using the software such as PolyWorks® (Innovmetric©). The later coming either from field survey or topographic point cloud data. Figure 8 shows the procedure: (1) Creation of the contour of the rock instability using the basal and rear-bounding surfaces delimiting the instability; (2) extrapolation of the discontinuity; (3) computation of the volume and thickness map usually based on DEM difference within a GIS environment.

It must be underlined that such an approach gives often the maximum volume that can be involved in a rock failure because most of the time the failure surface is more complex and “follows” path using more discontinuities than those considered, but most probably contained within the volume defined previously.

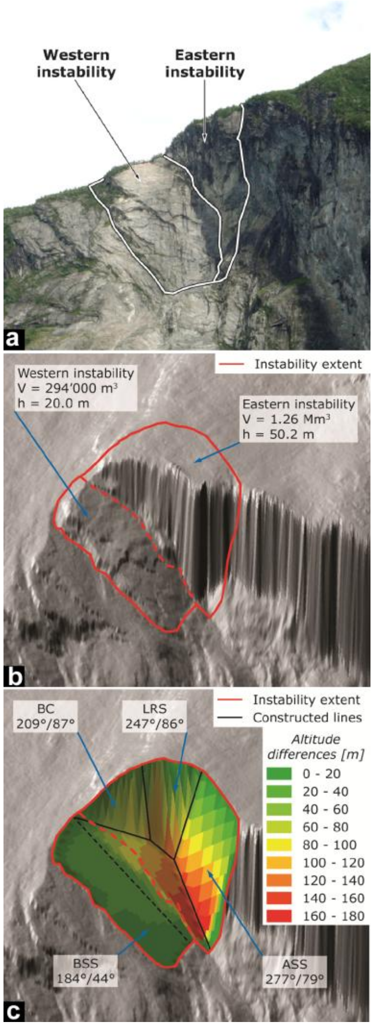


Figure 8: A. Pictures of the Langhammaren instabilities (Norway) and detailed volume analysis of the eastern instability. 3D views of the instability: B. shaded relief representation of the High Resolution-DEM with the instabilities' extents and volumes; C. computed altitude differences between the constructed failure surface and the topography (from Oppikofer, 2009).

5.2 Sloping Local Base Level (SLBL)

The Sloping Local Base Level (SLBL) is a method which provides a 3D surface from DEM based on the assumption that a failure surface can be extrapolated from the limits of the unstable mass assuming some geometrical properties about its shape such as border, slope, curvature etc. The advantages of the SLBL method are that it can be easily parameterized and fairly automated.

The principle is rather simple. First the perimeter of the instability must be defined. Then by an iterative process it digs out “numerically” a grid DEM ($z(t)_{ij}$) the volume within the defined limits as follow (Jaboyedoff et al., 2004, 2009):

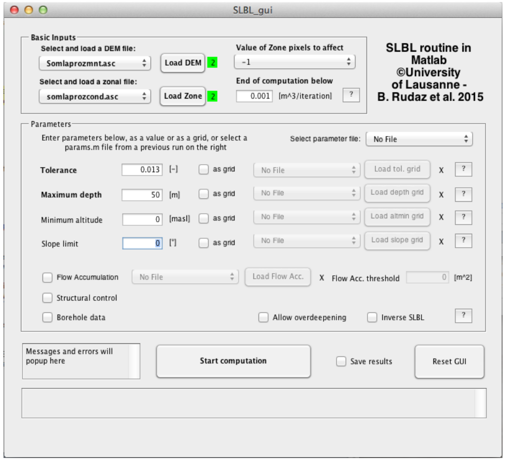
1. For each grid nods and at each iteration t, it estimates an “averaged” of all the altitudes ($f(z_n(t-1)$); where z_n means a set of neighbors) of the

previous iteration $z(t-1)_{ij}$ of the points plus a positive constant C (tolerance), i.e.:

$$z_{temp}(t)_{ij}= (f(z_n(t-1)) + C) \qquad [9]$$

This is performed either by a simple average of a given number of neighbors or by fitting a surface.

2. It creates a new grid considering that if $z_{temp}(t)_{ij} < z(t-1)_{ij}$ then $z(t)_{ij} = z_{temp}(t)_{ij}$, otherwise the value is unchanged. An additional condition can be added that $z(t)_{ij}$ value is not below a limit defined by another DEM.
3. The iteration is repeated until all the differences over the grid are $(z_{temp}(t-1)_{ij} - z(t)_{ij})$ smaller than a given threshold. It can also be based on the total volume change between two successive surface iterations.



Select and load a DEM file: Somlaprozmnt.asc 2

Select and load a zonal file: somlaprozcond.asc 2

Value of Zone pixels to affect: -1

End of computation below: 0.001 [m^3/iteration]

SLBL routine in Matlab ©University of Lausanne - B. Rudaz et al. 2015

Enter parameters below, as a value or as a grid, or select a params.m file from a previous run on the right

Select parameter file: No File

Tolerance 0.013 [-] ☐ as grid No File X

Maximum depth 50 [m] ☐ as grid No File X

Minimum altitude 0 [masl] ☐ as grid No File X

Slope limit 0 [°] ☐ as grid No File X

☐ Flow Accumulation No File X Flow Acc. threshold 0 [m^2]

☐ Structural control

☐ Borehole data

☐ Allow overdeepening

☐ Inverse SLBL

Messages and errors will popup here

☐ Save results

Figue 9: interface of the Matlab© version of SLBL routines, with all the possible parameters.

Note that C depends on the grid mesh size value. In addition, as normally C is constant all over a landslide, it can be related to the ratio e of its maximal vertical thickness z_{max} and it width L, thus is can be shown that:

$$C = \frac{4e}{L}\Delta x^2 \qquad [10]$$

This permits for instance to keep the ratio e constant for any landslide. In addition, a slope limit below the digging stops may be used. Note that it is also possible to fill holes by changing the sign of C and reversing the condition in point 2.

5.2.1 Example of SLBL using Matlab© GUI routine

To be more concrete for this method we present here the requirement to perform such analysis. The SLBL routine, requires a DEM raster file, and a raster describing the landslide contour. In this case the iteration stops when the volume estimation does not change anymore (see Figure 9). The following parameters are used: C, a maximum depth, a minimum altitude and a slope limit. All those parameters can be defined for the whole area or be loaded as raster file when one is not uniform on the whole area of interest. Additional constraints can be added through a flow accumulation file (to identify local slope relief above streams), structural control (in case of a rock instability), or borehole data when available. Finally an "Inverse SLBL" option allows to reconstruct the volume of a landslide scar by filling the topography.

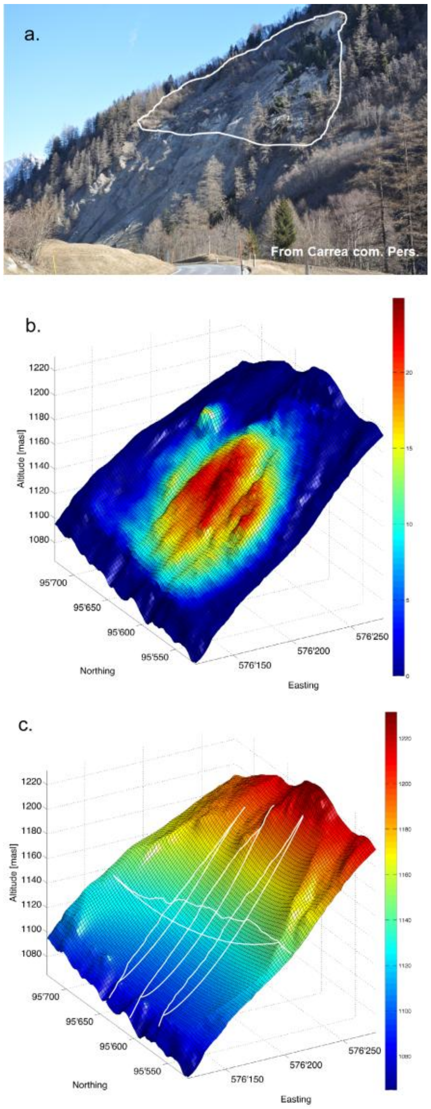


Figure 10. Example of SLBL method applied to a 2 m DEM. A. picture of the Som-La-Proz site. b. present topography and depth of the SLBL in color c. failure surface as defined by the SLBL (from swisstopo).

As an example we produce a result for the Som La Proz landslide (Switzerland). Based on a pre-failure 2 m grid DEM (from swisstopo) using C = 0.013 m, and with a volume threshold of 0.001 m^3 to stop iterations (Figure 10). The results gives a volume of 188'800 m^3. The 3 views permit to visualize the thickness and profile of the landslide. The advantage is to give a fast results for volume and failure surface. In a few seconds the parameters can be modified, and the surface computed to reach a reliable results for the user.

5.2.2 Examples of application based on GIS files for inventories

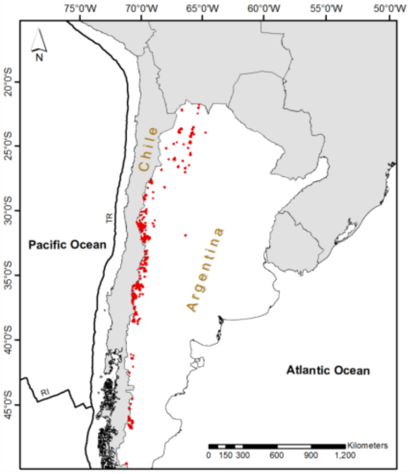


Figure 11: Rockslides distribution in Argentina (red dots) where a reconstruction of the pre-existing topography on headscarp was carried out.

Another possibility is to automatically compute landslide volumes at regional scale. For that purpose we have built another implementation of the SLBL method, using C++ and the GDAL library. This application can either reconstruct potential surfaces of failure on slopes instabilities, or reconstruct pre-existing topographies (headscarps but also past topographies on depositional areas of landslides). The input data required by the application is a shapefile with the polygons of areas where volume will be computed, containing the tolerance “C” and the slope limit parameters for each polygon, and a DEM covering all the area of the inventory. The volumes computed can be automatically stored in the shapefile, and volume statistics can be saved in it. C can be scaled according to the landslide area A and cell size using the assumption that L ≈ √A. This makes the resulting curvature independent of the DEM details, by putting e constant:

$$C = \frac{4e}{\sqrt{A}} \Delta x^2 \qquad [10]$$

This version has both GUI and command line interfaces, the latter being quite useful for batch processing. Furthermore, all parameters used are saved to a file to ensure reproducibility of the results.

We computed volumes for an inventory of 237 middle to large scale rockslides in the Argentinean Andes, most of them are observed north of 40°S (Penna et al., 2011). The computation was done based on inverse SLBL as the reconstructions was done on scars (Figure 11 and 12). Based on inverse SLBL the volume distribution the scars of the Argentinian rock avalanches range from $1*10^6$ m^3 to km^3 (Figure 12).

In order to obtain landscape conditions before the occurrence of landslides, two reconstructions are required: 1) reconstruct the depositional surface before the collapse (“excavation of relief”), and of the headscarp. In this last case by using inverse SLBL reconstruction (“filling of relief”). The example below show the reconstructions done for the Potrero de Leyes rock avalanche in the Pampeanas Ranges of Argentina (Figure 13), which detached from Paleozoic metamorphic rocks outcropping in the Pampeanas Range (González Díaz et al., 1997). The scar volume corresponds to 0.23 km^3 of granites involved in the collapse leading to a deposit of 0.31 km^3 providing an expansion coefficient of approximately 35%.

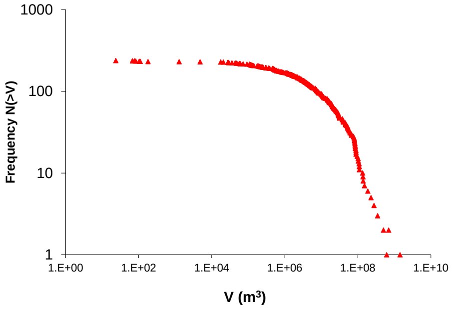


Figure 12: Inverse cumulative distribution of the volumes obtained by reconstruction of the headscarp (filling of relief) for the Argentinean inventory, in log-log scale.

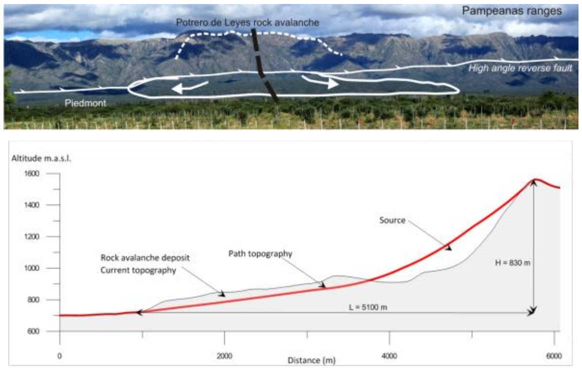


Figure 13: Panoramic view of the Potrero de Leyes rock avalanche and cross section showing current topography and reconstructed topography carried out with SLBL.

6 UNCERTAINITY ASSESSEMENT

The uncertainty of the failure surface estimation is not an easy task. It completely depends on the available data and the method used. Nevertheless some attempts can be made to provide an estimate of the range of possible values.

It is clear that one way to get an idea of the validity of interpretation is to use several different approaches to get results, the agreement between them giving an idea of the quality of the interpretations.

In the next lines we present two different aspects of the uncertainty assessment which are valid theoretically but which can be completely wrong if the input data are erroneous.

In the case of rockslides, the failure surfaces are mostly usually complex. Thus, the first challenge is to reconstruct a full failure surface. If the discontinuity frequency distributions of the spacing lengths and orientation are known it is possible to simulate the volumes that are potentially unstable (Figure 14). Grenon and Hadjigeorgiou (2008) used such an approach to perform a statistic of potential wedge slope failures. Another solution has been proposed in longitudinal section which tests the probability that a continuous failure surface exists and daylight for a rockslide (Oppikofer et al., 2011). It turns out that it give a probability of having a continuous failure surface.

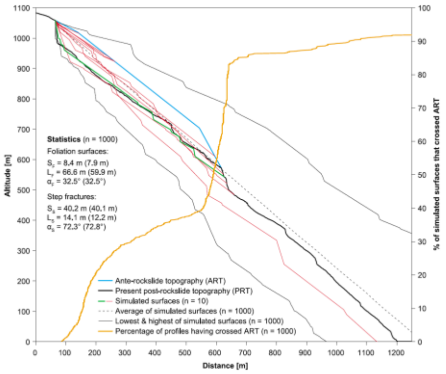


Figure 14: Simulated stepped surfaces of the Åknes rockslide based on the distribution of spacings, orientations of two discontinuity sets. In bold black the topography. The cumulative histogram (orange line) of surfaces delighting indicates that approximately 50% of all surfaces daylight above the reconstruction by other method based among others on boreholes (From Oppikofer et al., 2011).

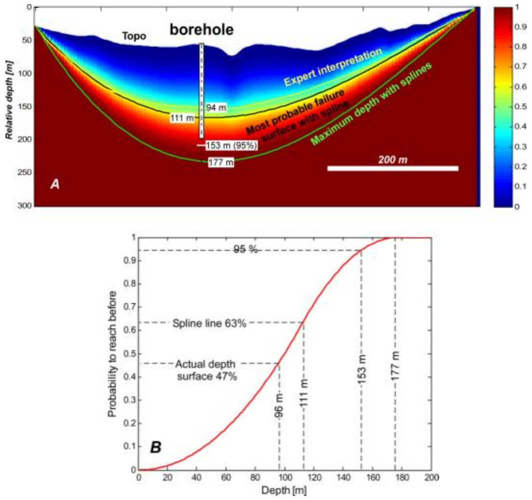


Figure 15. (A) Cross-section displaying the probability to find vertically the failure surface above a given depth. (B) Probability distribution function for likelihood of reaching the failure surface at the location of the borehole above a given depth (From Jaboyedoff and Derron, 2014).

On way to estimate the uncertainty is to have an a priori knowledge about the surface of failure closest to the surface, one about the deepest and the most probable surface. These surfaces or profiles can be based on expert knowledge methods such as splines, SLBL, etc. or mixed between all of them. The first one for instance can be simply the topographic surface.

Now assuming that all three surfaces are known, then a triangular function distribution (Kotz and van Drop,. 2004) can be assumed for the probability to find the failure surface at a certain depth by assuming that the lower limit is the upper surface, upper limit the deeper surface and the most probable depth the maximum of the triangular distribution. Using such an approach applied to the cross-section of Figure 15, the probability to reach a certain level is based on the surface, a spline as described above and a spline designed with a slope at the limit of landslide 10° steeper that the most probable. This shows that there was a 47% chance that the failure surface reached by a borehole was found above this limit (Jaboyedoff and Derron, 2014).

7 DISCUSSION

As shown here there exists several tools to get information about the geometrical characteristics of failure surface, i.e., volumes, thickness, sections, etc. But they are only rarely used.

In the process of landslide study there is a need of knowledge about the volume, the failure surface geometry etc. to start to perform appropriate investigations. In addition, when implementing a borehole or to prepare a geophysics campaign, the depth to investigate must at least be estimated. As a consequence, to have available tools that are applicable to different situation seems to be important.

In addition, in most of the case landslide investigations have no sufficient means to investigate in detail the landslides. That is why it is important to be able to provide information, in order to evaluate failure surface geometry, which may permit to calculate factors of safety.

The automatic volume estimation of landslide has not been studied extensively, despite an interest for hazard assessment or erosion rates estimates by using volume distribution (Hovius et al., 1997; Hantz et al., 2003). Usually quite simple rules are used such as ellipsoidal volumes (Xie et al., 2004; Marchesini et al., 2009; Nikolaeva et al., 2014), or using simply relationship between surface area and thinness (Hovius et al., 1997):

$$V = 0.05 \times A^{1.5} \qquad [10]$$

The distribution of volumes of landslide potential or realised permits to weight the hazard as proposed by (Hantz et al., 2003). But the method to estimate volume has to be systematised. Such approach needs still to be developed.

Uncertainty at present can be set in several ways depending if it applies to only one landslide or to an inventory. In the first case it seems that the best is to compare different methods and if all of them gives a coherent scheme the uncertainty is most probably low, but this depends on the appreciation of the experts. In case of automatic method which can be applied for instance to an inventory, the best is probably to use a procedures that permit to give a minimum, maximum depth for the failure surface and if possible the best solution.

It is also important to remember that the first criterion for a landslide it is that it must be geometrically feasible, before the stability analysis as for kinematic test for rocks. This underlines the important of geometric landslide characterization.

8 CONCLUSION AND PEPECTIVES

This paper gives an overview of the different tools that are existing to estimate failure surface geometry based on geomorphic features. The aim is also to make an overview of ongoing work that are or will be detailed in different papers. A more complete paper about all the geometrical method will be performed. In addition, when the paper will be published the two presented software for SLBL will be freely available.

It underlines also that there is a need to develop a tool containing most of the simple geometric tools in order to be able to extract some information about the geometry of the failure surface. It must be underlined that all these methods can provide important information on landslide geometry and volume when detailed field investigations are lacking, especially using Hi-resolution DEM.

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