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<u>Report dell'attività scentifica svolta nell'ambito del Programma Short Term Mobility 2015</u>

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<u>Referente locale:</u> Dr. Leslaw Zabuski

Il seguente report consta di due sezioni, entrambi rappresentano le basi per due articoli scientifici che si intendono inviare entro la fine del 2015.

Il primo, *2D and 3D models of two convergent landslides and the influence of soil layers distribution, a case study in the Carnian alps (Italy),* descrive la modellizzazione di due frani convergenti con modelli 2D e 3D. In questo lavoro si applica inoltre il metodo BoSG (Boolean Stochastic Generation) sviluppato dalla proponente del progetto per quantificare l'errore associato alla variabilità spaziale dei suoli nei corpi di frana. E' la prima volta che tale metodo viene applicato in modelli tridimensionali di frana.

Il secondo, *Capabilities of continuous and discontinuous modelling of rock slopes – a case-study of a landslide in the Carnian Alps (Italy),* confronta i risultati di modelli continui e discontinui per la modellizzazione di frane in roccia su substrati plastici.

Il proponente:

Giulia Bossi

Il referente:

Gianluca Marcato

2D and 3D models of two convergent landslides and the influence of soil layers distribution, a case study in the Carnian alps (Italy)

Authors: G.Bossi, L. Zabuski, A. Scuri, G. Sinigardi, G. Marcato

Abstract

In the Carnian Alps, in the Tagliamento River valley (46°23'49" N, 12°42'51" E), 2 adjacent landslide affect the National Road 52 "Carnica". The phenomena have been studied for more than a decade allowing a detailed geological and geomorphological reconstruction to be delineated. That was done on the ground of a large number of monitoring data collected during more than 10 years of investigations. Moreover, an helicopter-borne Light Detection And Ranging (LiDAR) survey provided a 1 m Digital Terrain Model (DTM) of the area's topography. 120.000

This work focuses on the creation of a numerical model capable of reconstructing the whole dynamic of both landslides and to be consistent with all monitoring data. In this framework results obtained with the 2D code FLAC and 3D code FLAC3D are confronted.

For the 2D analysis 2 sections, one for each landslide, have been modelled. On the other hand the 3D model was designed in order to be congruent with more than 20 inclinometers that were installed during the years. The geometry of the slip surface was reconstructed on the basis of control points like the slip surface readings in each inclinometer and on geomorphological evidence for the contour. With a nearest neighbour interpolation a TIN surface reconstructing the geometry of the slip surface for both landslide was created. Then the DTM of the study area surface and of the TIN of the slip surface where resampled in a 10 x 10 grid in order to allow a reasonable calculation time with FLAC3D. The confront between 2D and 3D results allow to appreciate the capabilities of the two codes. Both simulations are also tested for the influence of soil heterogeneity with the Boolean Stochastic Generation algorithm.

1 Study Area and Monitoring data

In the Carnian Alps, in the Tagliamento River valley (46°23'49" N, 12°42'51" E), 2 adjacent landslide affect the National Road 52 "Carnica". The road connects the Udine and the Belluno provinces, linking the Carnia to the Cadore areas.

The landslides in exams are two convergent phenomena with two distinct crowns that could be classified following the Varnes classification as roto-translational slides. They develop from an altitude of about 800 to 650 meters a.s.l. with a surface extension of about 1 km².

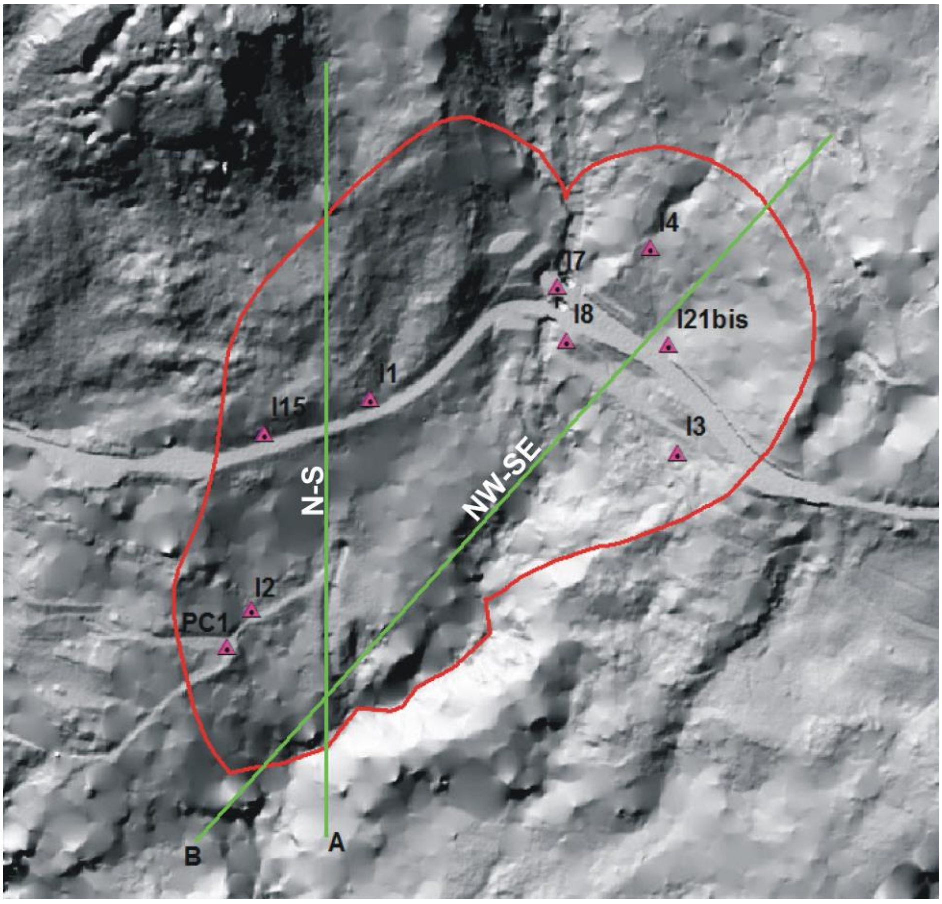

Fig.1 View of the landslide with two cross-sections analysed numerically and the location of the inclinometric tubes installed since 2002. Some inclinometers have been damaged during the years and new boreholes where installed near the broken ones;

An extended monitoring system consisting of 3 piezometers, 20 inclinometers and 5 GNSS benchmarks provided a large amount of data during the years (Fig.1). From this information it is possible to characterize the two movements.

Inclinometer I21 as example shows a defined slip surface located 23 m below the surface for landslide 1 with the upmost part is moving as a rigid body (Fig 2). The velocity of the movement, followed with an in-place inclinometer, is about 5 cms/year with peaks of 20 cms/year with intensive rainfalls. Inclinometer PC1ter shows a similar behaviour (Fig 2): a translational movement along a distinct slip surface at 23 m below the surface. The velocity, recorded also by means of an in-place inclinometer, is still about 5 cm/year with peaks of displacements in sync with I21.

On the other hand, inclinometer I15 shows a different displacement pattern: and the displacement are distributed along the whole layer of soil above the shear surface, which is less distinct (Fig.3).

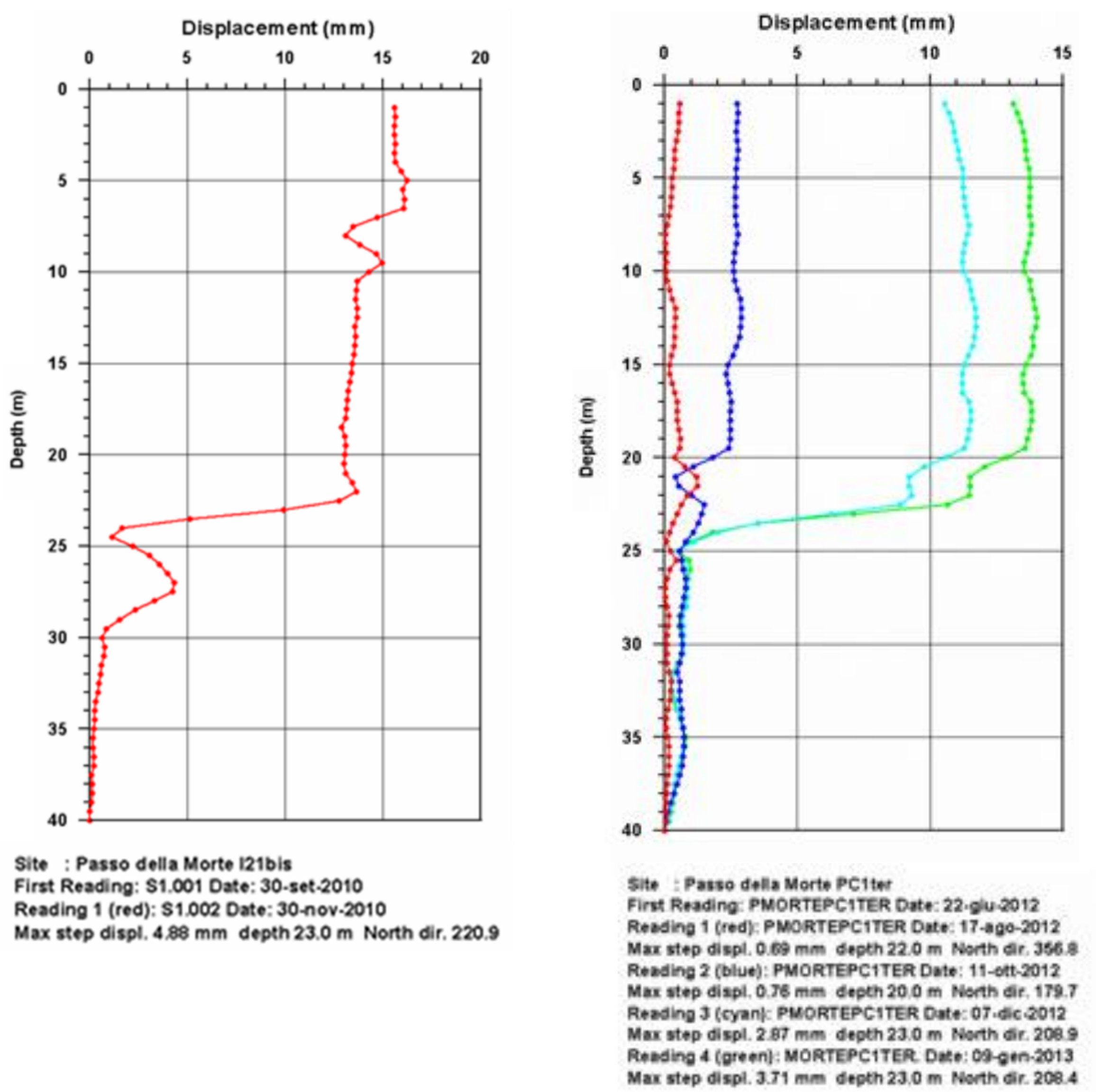

Fig.2 Displacements for inclinometer I21 (on the left) and inclinometer PC1 (on the right)

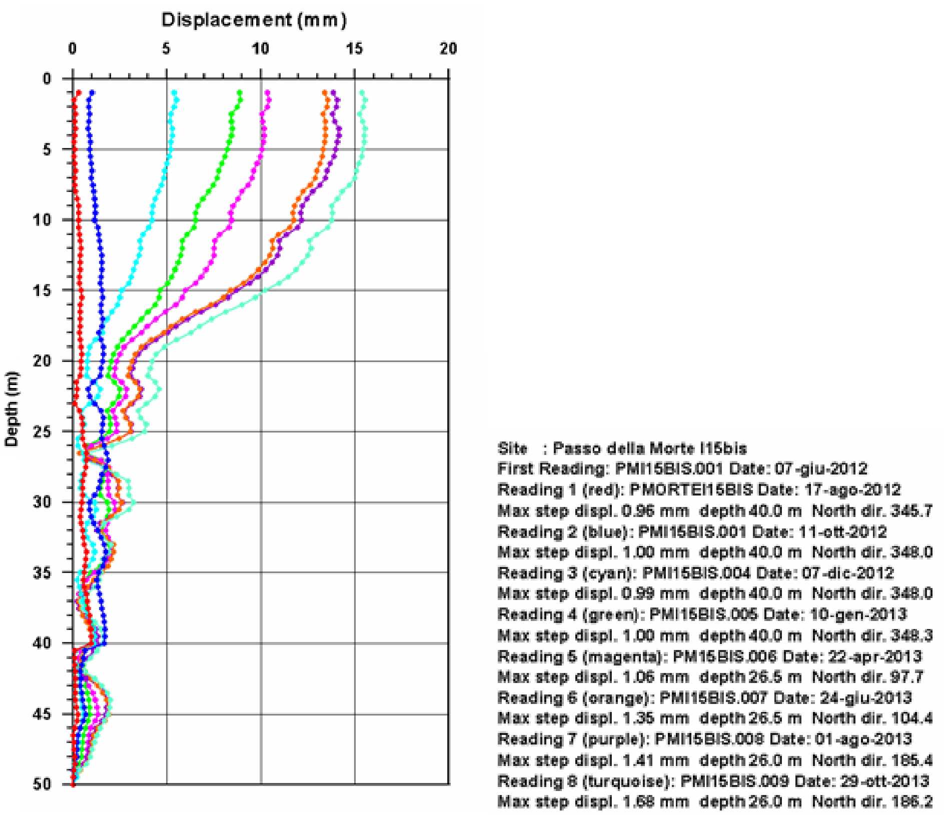

Fig.3 Displacements for inclinometer I15

Similar results have been found in the others inclinometers and that allowed to derive the geomechanical model of the slope. Before this cumulative analysis of all the displacement pattern of the inclinometers and on the basis on sole geomorphological data the two landslide bodies were divided along the stream, called Rio Verde, which passes between the two crowns (continuous lines in Fig 4). Nowadays we can separate the landslide on the basis of the monitoring data and the resulting shape (dashed line in Fig 4) shows a tongue of rigidly moving material, falling in the NW-SE direction, pushed on the western side by another landslide moving from North to South.

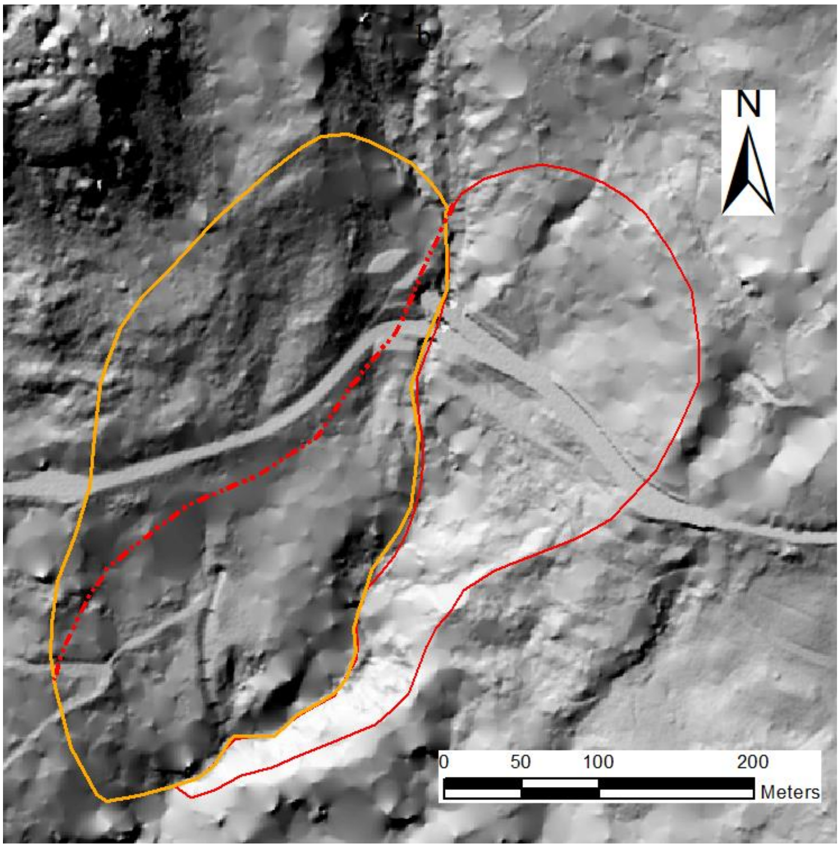

Fig.4 Ladslides contours: before the analysis of the displacements patterns the limits were represented by the solid lines, further research allowed to modify the borders (dashed line) ;

2 Modelling

2.1 2D numerical model

The 2D stability analysis was carried out using computer code FLAC. The investigated cross sections, called N-S and NW-SE are indicated in (Fig.1). Some geotechnical test for the landslide material was available, however for this kind of phenomena it is usually more efficient to select the geotechnical parameters on the basis of a back-analysis procedure in order to match the monitoring data.

2.1.1 Cross section N-S

Inclinometric curve in the upper part of the colluvium reveals that entire zone above the bedrock deforms viscously. Thus, there is no distinct discrete slip surface. On the contrary, in the slope lower part the inclinometric curve shows that the rock mass moves above the narrow slip zone and is internally only slightly deformed. These different mechanisms require different modelling approaches therefore the upper part of the slope was considered as a single layer of soil whereas in the lower part a narrow surface with lesser mechanical proprieties was inserted (Fig.5 and Fig. 6).

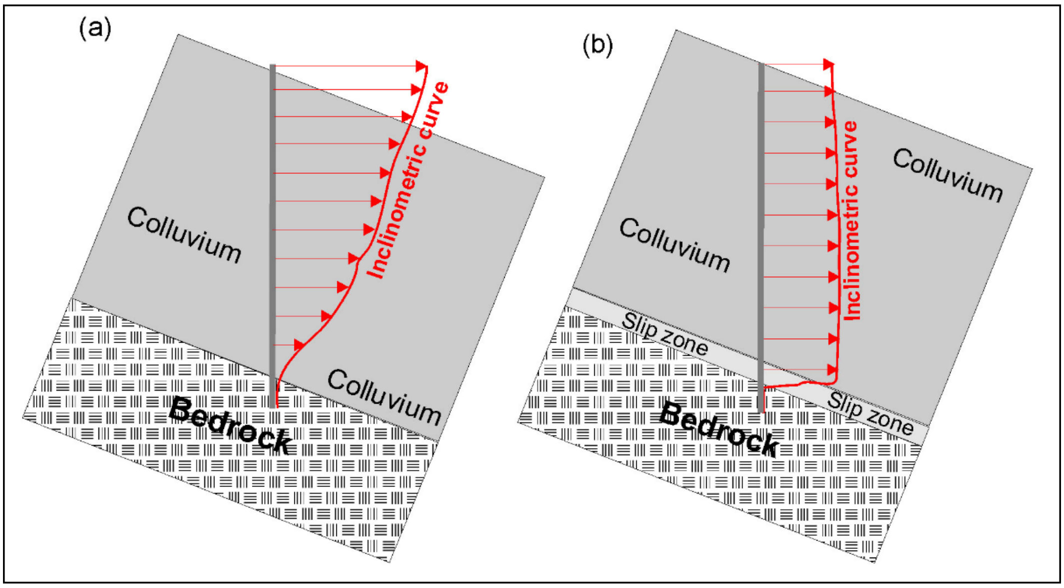

Fig.5. Schematic inclinometric curves; (a) whole zone above the bedrock deforms (creep); (b) rock mass above slip zone moves as a whole, similarly to stiff, non-deformable material

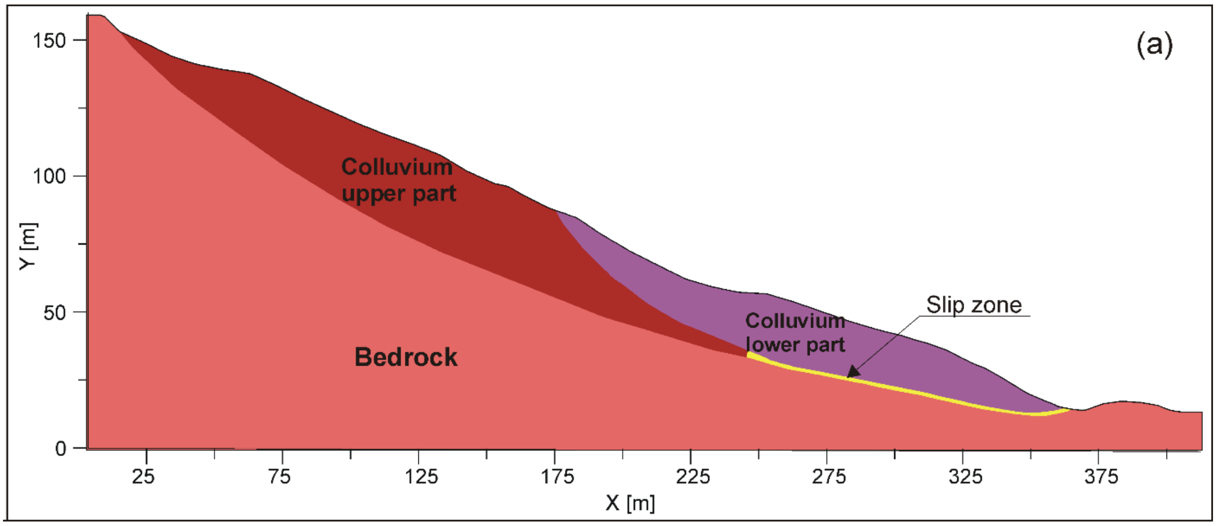

Fig. 6 Division of the model in N-S cross-section into geotechnical layers;

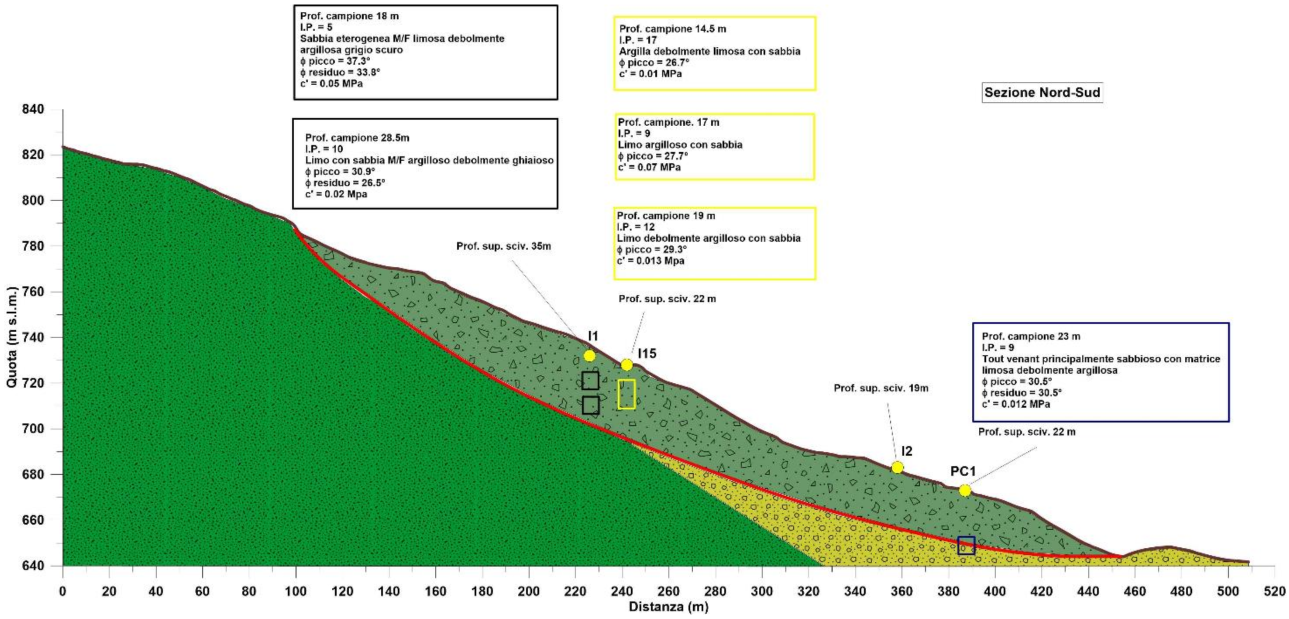

Fig.7 Cross-section N-S with the results of laboratory tests and previous geomechanical model

The first trial of numerical simulation was realised with the geotechnical parameters of the rock layers, taken from the laboratory tests (Fig. 7). However, the model with these parameters was stable, whereas the real slope is moving. That means that the parameters of the model (obtained in the laboratory) do not represent well the soil behaviour in the field. To find the state of limit equilibrium with the safety factor = 1.0, in order to reproduce the state of the landslide which is moving but not collapsing, the parameters were step by step decreased. The set of parameters found with this procedure is listed in Table 1.

Table 1: geotechnical parameters for cross section N-S

Layer	Cohesion c [kPa]	Angle of friction Φ [degree]
Upper part of slope	14.0	22.5
Slip zone in the lower part	5.0	15.0
Lower part of slope above slip zone	11	27
Bedrock	Elastic	model

In figure 8 displacement vectors and field of horizontal displacement are shown respectively. The state is very close to limit equilibrium state and although displacement are relatively small yet, even small decrease of the plasticity parameters cause extensive failure.

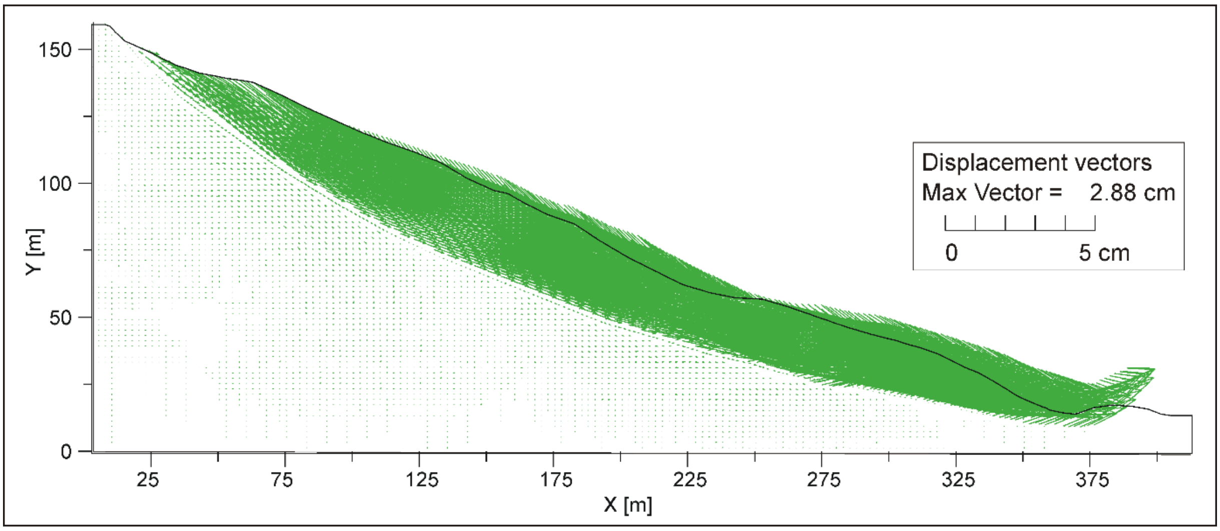

Fig.8. Displacement vectors of the slope in N-S cross-section without support;

The appropriateness of the model assumptions, concerning the division of the slope into upper and lower part with thin slip zone can be confirmed by comparison of the real displacement curves in both parts drawn schematically in Fig.9 is seen.

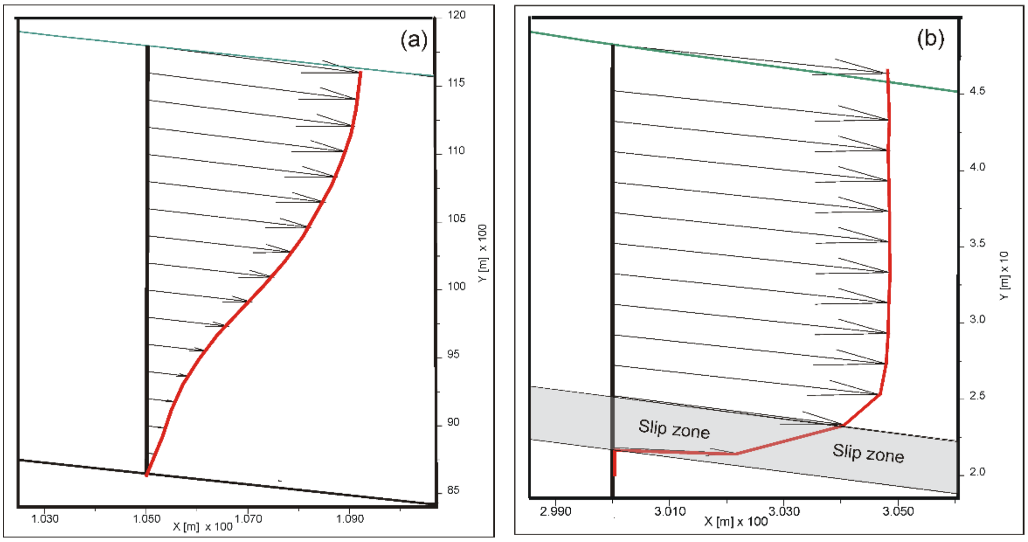

Fig. 9 Shapes of calculated displacement curves of; (a) upper part of the slope, X ≈ 100 m; (b) lower part of the slope, X ≈ 300 m

2.1.2 Cross section NW-SE

The analysis of NW-SE cross-section followed the same procedure as for cross section N-S. The geomechanical model of cross-section NW-SE was divided in three zones, namely bedrock, colluvium and narrow slip zone between them (Fig. 10). The geotechnical parameters are consistent with those determined for N-S cross-section. The displacement pattern recreates well the in-situ measures (Fig. 11).

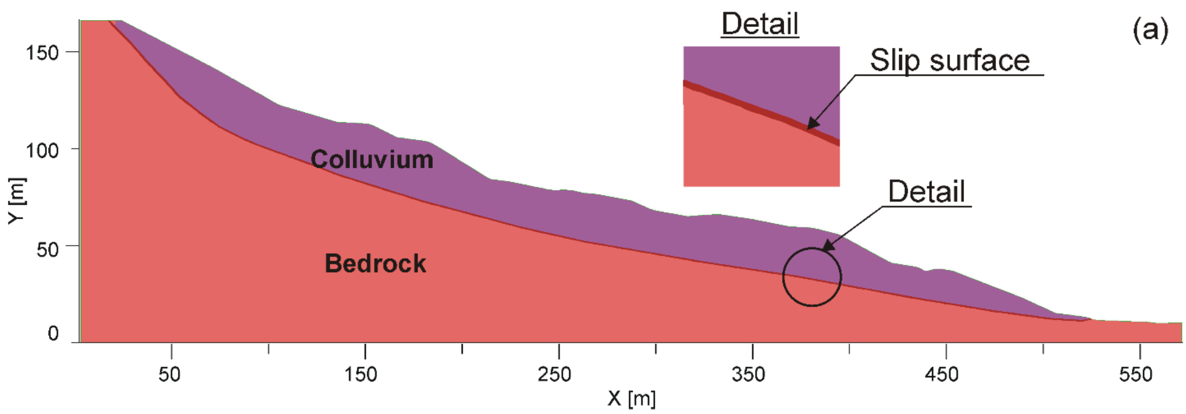

Fig.10 Division of the model in N-S cross-section into geotechnical layers;

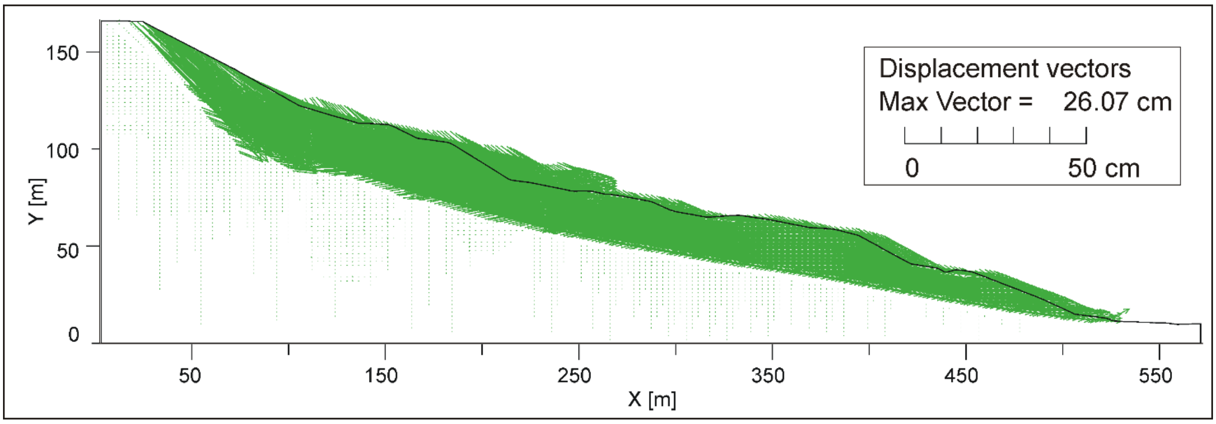

Fig.11 Displacement vectors of the slope in N-S cross-section without support;

2.2 *3D numerical model*

2.2.1 Reconstruction of the 3D slip surface

The geometry of the slip surface was reconstructed using ArcMap software. As control points where used the location of the slip surface recorded in the inclinometers and the contour of the landslides. Then with a nearest neighbour interpolation a TIN surface was created. The geometry of the 3D slip surface is indicated in Fig. 12.

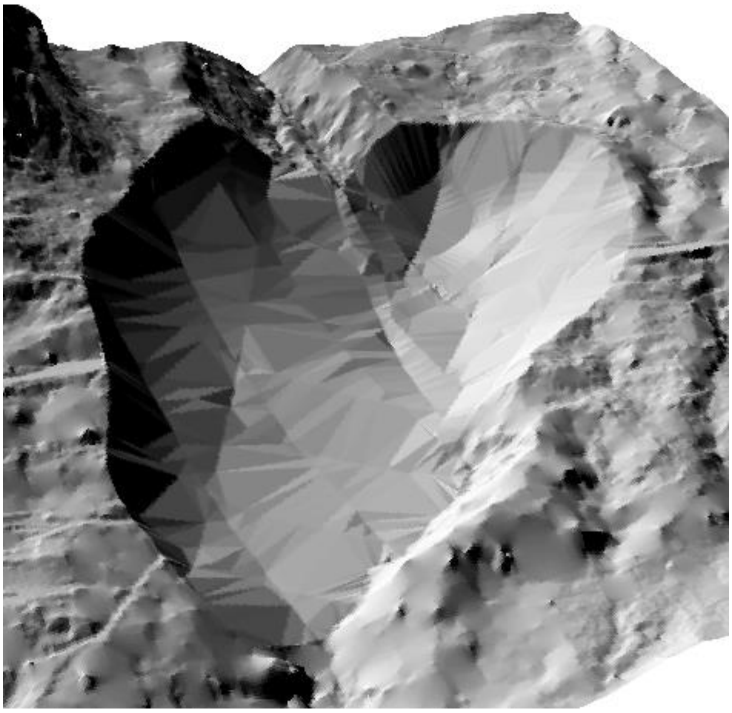

Fig.12 – Slip surface reconstructed for both landslides

Then the DTM of the study area surface and of the TIN of the slip surface where resampled in a 10 x 10 grid in order to allow a reasonable calculation time with FLAC3D.

2.2.2 3D modelling

The dynamic of the two landslides was recreated with the commercial software FLAC3D. As starting data base the surface and the slip surface geometry where used. Moreover to the two phenomena different soil propreties where to be assigned and for the eastern landslide (section NW-SE) also the distinct slip surface (Fig. 13 and Fig. 14). This was done with a specifically coded algorithm in Matlab that allowed to create such complex geometry in FLAC 3D. The mesh of the model is composed by 20014 hexahedral elements.

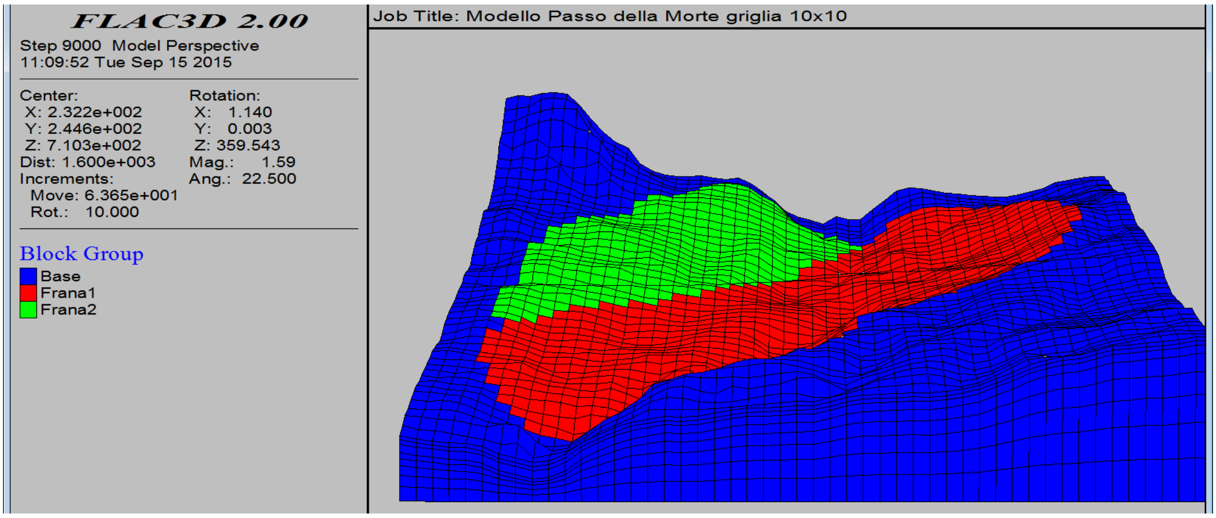

Fig.13 – Reconstruction of the slope surface with material models assigned to each cell in FLAC 3D

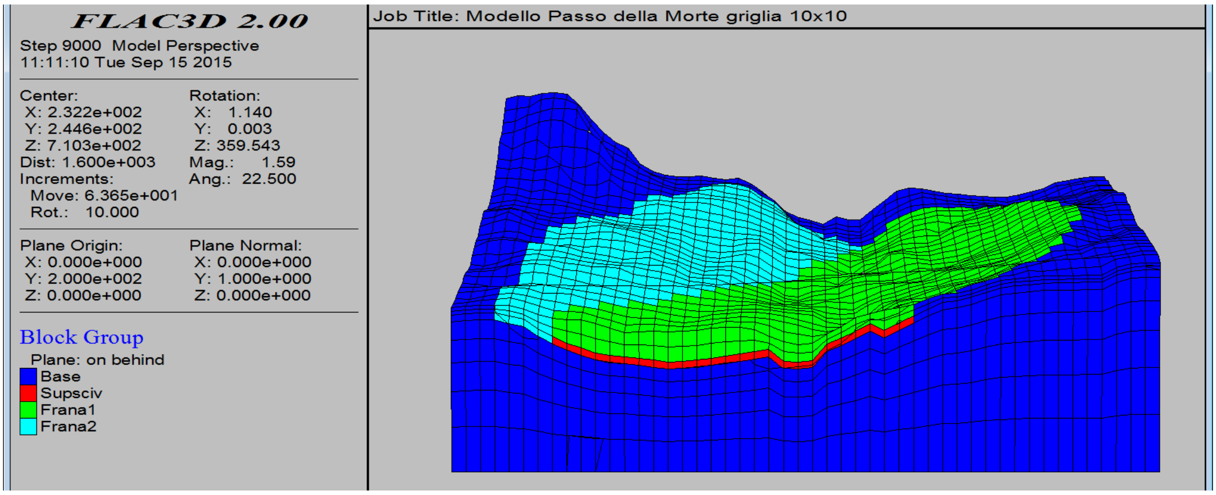

Fig.14 – Section of the slope with material models assigned to each cell in FLAC 3D – it is possible to appreciate the location of the slip surface below the eastern landslide (Frana1 in the figure)

The properties of the soils involved in the process for the first trial model were the ones obtained with the back analysis procedure for the 2D. The displacement patter do recreate the whole slope dynamic (Fig. 15). The calculation time requested to reach convergence is about 20 minutes in a 3.10 GHz processor with 4 GB of RAM.

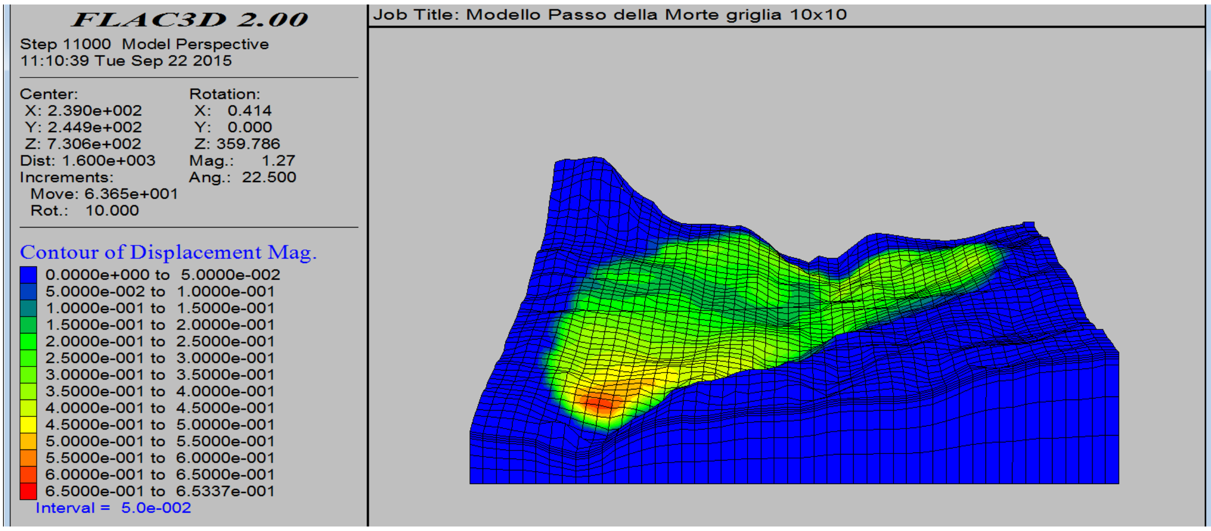

Fig.15 –Displacement on the surface for the 3D model

2.2.3 Boolean Stochastic Generation (BoSG) modelling

The distinction in the soil model of 4 types of material (for the two landslides, the slip surface and the bedrock) is an assumption based on the stratigrapic data and the geomechanical model. However, this distribution is inferred and may be subject to errors. In order to assess the possible errors associated with a local perturbation of the soil properties a Boolean Stochastic Generation (Bossi, 2015) run was performed. As the less homogeneus stratigraphy was the one of the eastern landslide in that body some lenses with the soil properties of the slip surface were inserted.

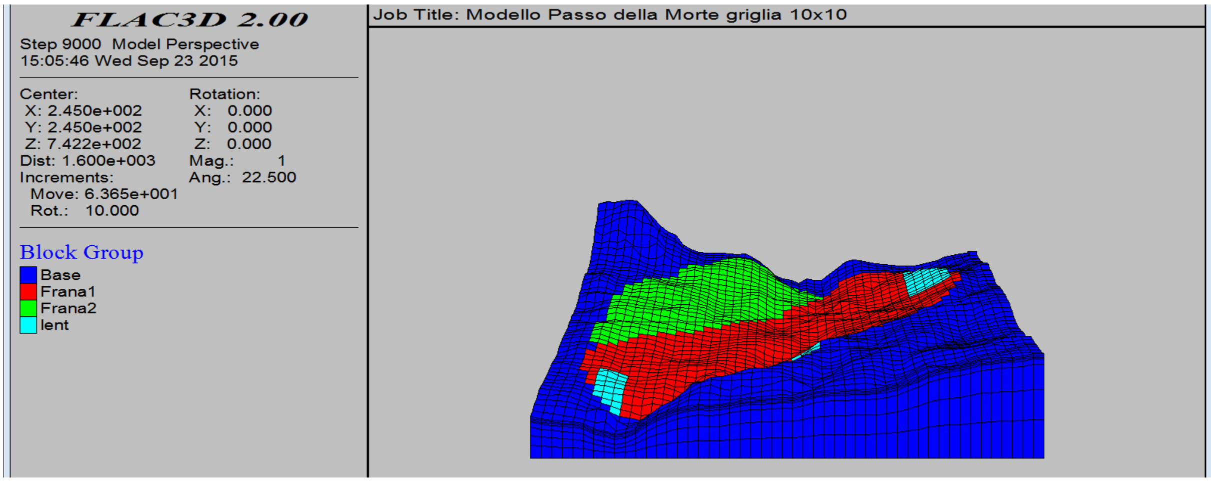

Fig.16 –Generation of lenses with the BoSG method

Result show that even though the properties differences are marked between the matrix and the lens most of the solutions are clustered around the non-perturbed values (Fig.16, Fig.17 and Fig.18). That means that the model has little uncertainty linked to the soil distribution in the eastern landslide.

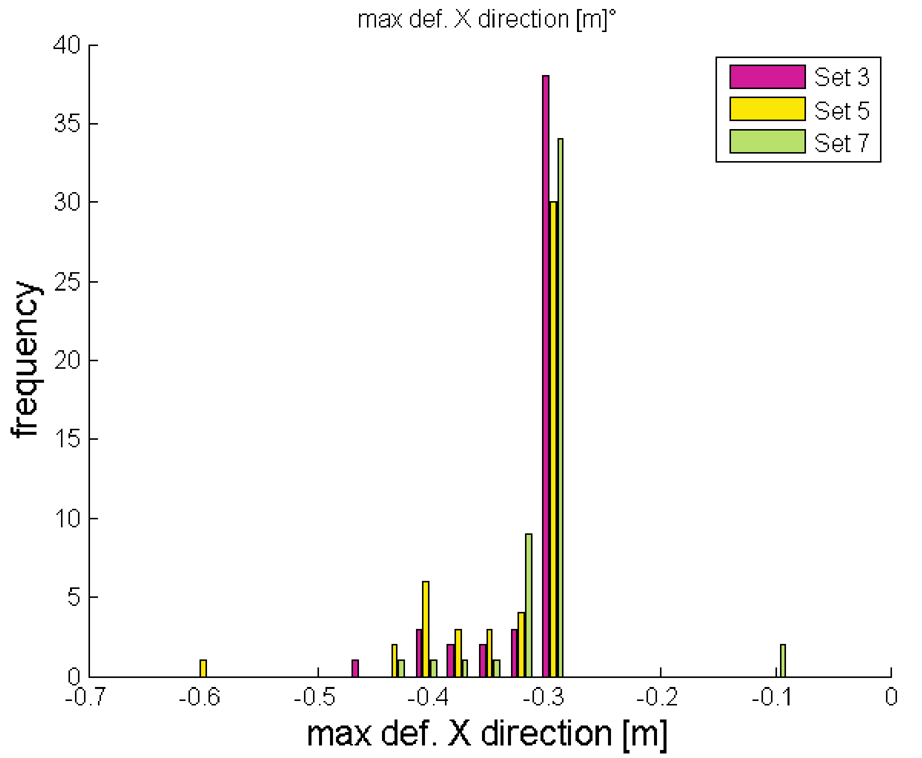

Fig.16 –Variation of maximum displacements in the X direction

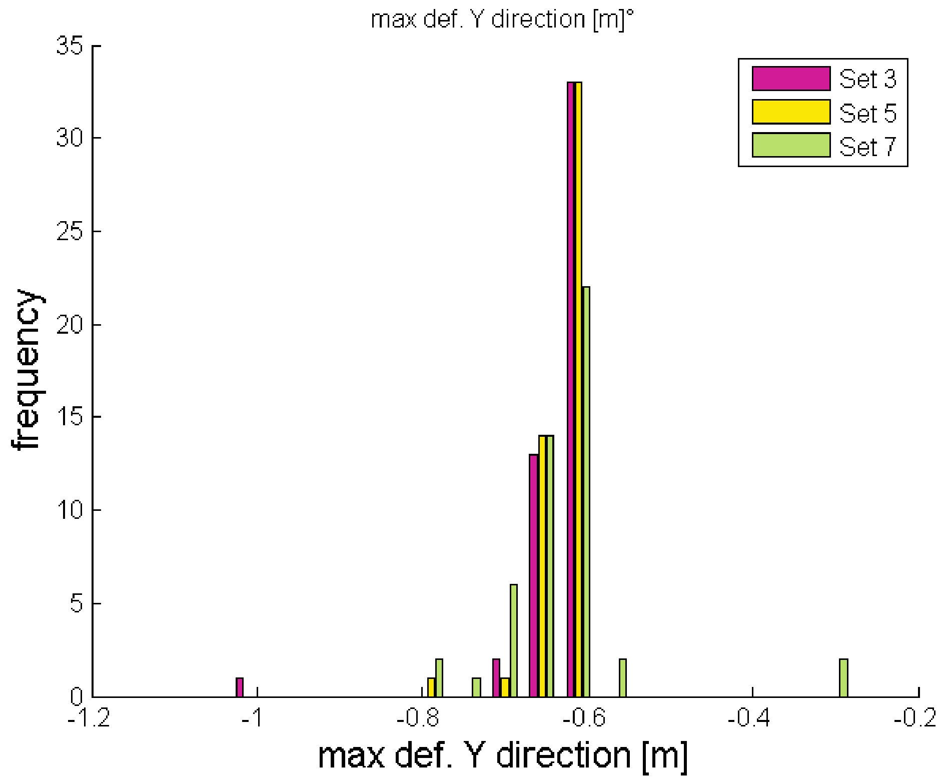

Fig.17 –Variation of maximum displacements in the Y direction

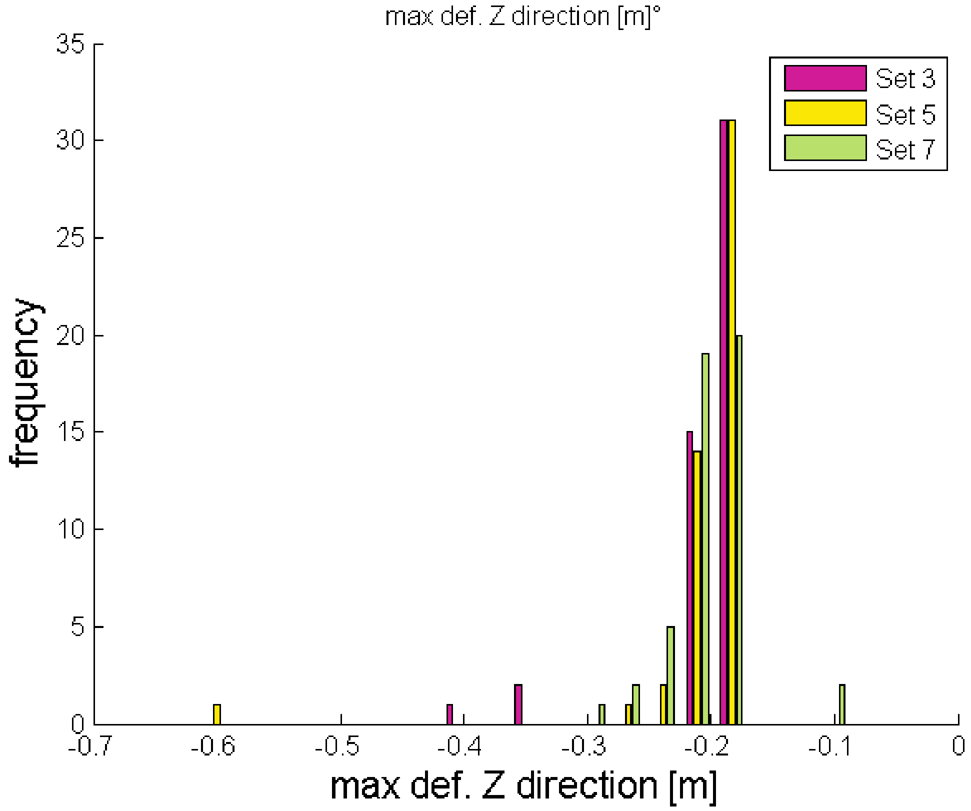

Fig.18 –Variation of maximum displacements in the Y direction

3 References

Bossi G., Borgatti L., Gottardi G., Marcato G.. 2015. The Boolean Stochastic Generation method - BoSG: A tool for the analysis of the error associated with the simplification of the stratigraphy in geotechnical models. Eng. Geo. In Press. DOI:10.1016/j.enggeo.2015.08.003

Capabilities of continuous and discontinuous modelling of rock slopes – a case-study of a landslide in the Carnian Alps (Italy)

G.Bossi, L. Zabuski, G. Marcato

Abstract

The paper presents a comprehensive study that has been carried out in several years of a landslide located in Passo della Morte (eastern Italian Alps). A detailed geological investigation permitted to identify and locate the different soil layers. Along with long term monitoring data it allowed to understand the dynamic of the process and therefore to implement sound numerical models. A comparison between a continuous and a discontinuous model for the landslide is also presented. Both numerical solutions permit to describe different cinematics for the landslide and permit to delineate a comprehensive risk scenario. The comparison of above two approaches (discontinuous and continuous) shown their capabilities, advantages and disadvantages.

1 Introduction

Numerical techniques have been proven to be a powerful tool to assess the dynamic of rock slopes (Stead et al., 2006). However rock is Discontinuous, Anisotropic, Inhomogeneous and Not-Elastic (DIANE) (Hudson and Harrison, 2000) mostly due to the presence of fractures, joints, faults (Mandl, 2005). Therefore in order to provide a sound numerical model a meticulous structural characterization of the site is needed (Stead and Wolter, 2015). Besides, as the dynamic of the phenomenon could be complex, monitoring data are extremely useful to comprehend all the elements involved in the process (Willenberg et al., 2002).

Nevertheless the modeller needs to simplify the medium (Starfield and Cundall, 1988) in order to reach an approximate numerical solution (Jing, 2003). Two approaches are mainly used: continuous and discontinuous modelling (Barla, 2012; Eberhardt, 2006; Scheldt, 2003). If the rock mass is treated as a whole medium with few discontinuities the modelling method is called continuous and the computational algorithm relies on Finite Element or Finite Difference methods (Bell, 2013). On the other hand in discontinuous modelling the rock mass is divided in small blocks with determined function that control their the interaction (Cundall and Hart, 2014).

However most situations would benefit from the use of a hybrid approach (Hatzor et al., 2002; Stead et al., 2006) as in the case of a rigid but fractured rock mass superimposed over a plastic layer. Continuous method cannot detect rockfalls and topplings as detaching is not permitted, vice versa discontinuous methods overlook stresses inside the single block.

The objective of this paper is to compare the results of the numerical simulation of the slope deformation and stability, by applying continuous and discontinuous model. The comparison is particularly interesting because it relies on a detailed geological survey and long term monitoring data.

2 Study Area

The study area is located in the Carnian Alps, north-eastern Italy, on the right flank of Tagliamento river valley. The area is subjest to different slope instability phenomena and has been studied for more than a decade.

The landslide subject of this study intercepts the route of the former national road S.S. 52 including 130 m of a half tunnel installed to protect the road from rock-falls and snow avalanches. The construction nowadays shows fissures and cracks due to the movements of the landslide. For these reason, understanding the dynamic of the phenomenon is particularly relevant. The landslide covers an area of 0.54 km^2 with an estimated volume of about 1 million m^3.

2.1 Geology

The slope on the left bank of the Tagliamento is characterized predominantly by carbonatic, siliciclastic and evaporitic lithotypes of Triassic age, ranging between the Ladinian and Carnian Superior. In particulary the Units that emerge primarily in the study area are Schlern dolomite (Upper Ladinian) and dark laminated limestones of the Lower Carnian that a low-angle thrust led to arrange over silty varicoloured clays and gypsum of the Carnian Superior.

The structural setting is characterized by thrusts trending east-west, south-verging results of deformation dating in the Neogene age. The structural framework is rather

complex due to the presence of numerous tectonic disturbances, some of regional importance, other minors, both influenced by the previous structures developed in the extensional Triassic phase. The most important thrusts are the Line of Sauris and the Alto Tagliamento Line that indicate compressional stresses in the north-south direction. The southernmost branch of the Sauris thrust is the feature that affects the northern slope. It is a very low-angle thrust bearing soils ranging from the Scythian and the Lower Carnian, ie the formation of Werfen to dark stratified limestone, to thrust on those of the Carnian Superior (silty clays and varicoloured gypsum).
therefore rigid carbonatic units overlay younger more plastic formations.
In particular the landslide here in exam in the upper part is composed of limestone dismantled in regular blocks by the gradual weakening of the underlying layers that causes very slow creep movements. The principal disjunctive system is oriented N 168 ° / 68 °; the arrangement of the planes of discontinuity within the dolomitic rock creates geometries susceptible to instability , which can evolve both as falls and as topplings.

3 Monitoring data

The landslide in exam is monitored by

- A GNSS (Global Navigation Satellite System) benchmark is located over a concrete retention wall positioned along the former national road SS 52
- An in-place inclinometer that records in continuum the deformations along the slip surface since 2011. The slip surface was previously identified by means of a standard inclinometer, monitored for one year, and it is located 25 m below the surface
- A piezometer that records in continuous
- A crackmeter positioned along a large fracture on the dolomitic rock that could detect possible topplings of the rock mass.

The GNSS benchmark has been monitored for 11 years, and it shows a mean velocity of 1 cm/year. Data analysis of the in-place inclinometer confirms the linear dynamics of the phenomenon (*Fig. 1*) with deformation of about 1 tenth of a degree per year. The displacements are therefore minimal but the trend confirms that the measured deformation is effectively connected to an active landslide and not an instrumental error. In particular a trend so markedly linear is clearly indicative of a viscous deformation (or creep), and therefore intrinsically linked to the substrate material constantly overloaded by the weight of overlying rock and little influenced by other external factors.

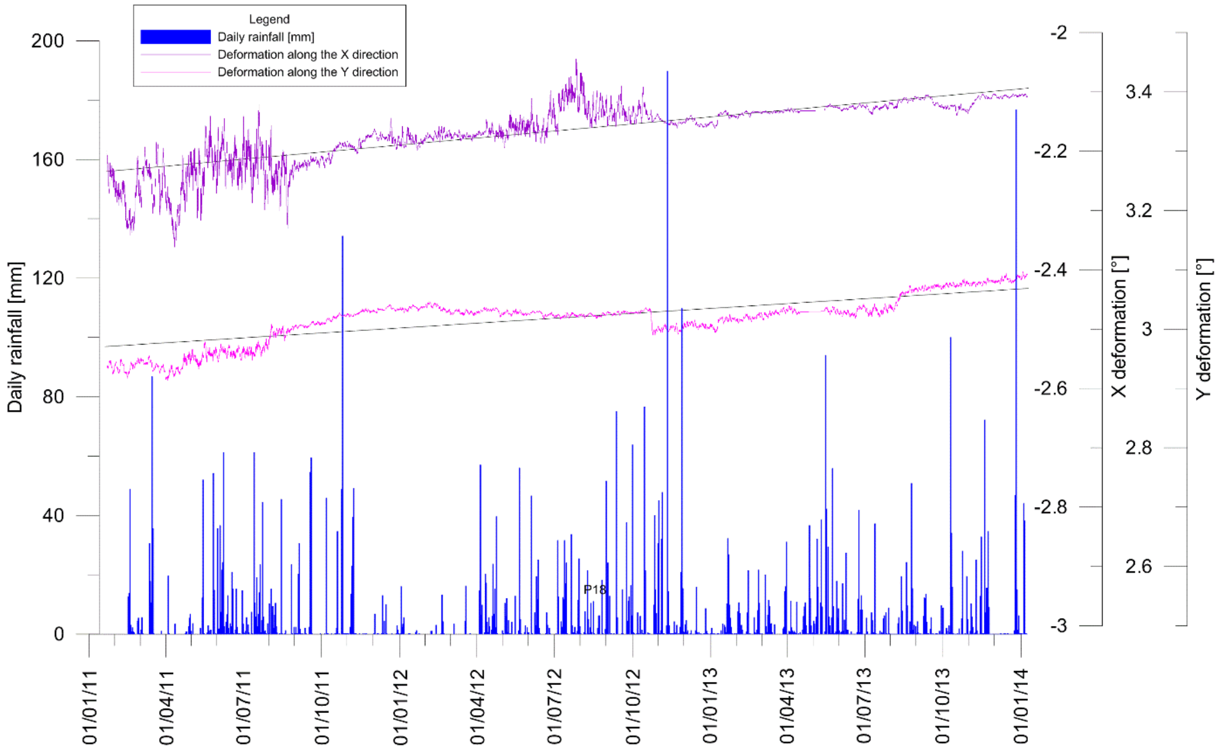

Fig. 1: deformations recorded in the in-place inclinometer, the displacements follow a linear trend that is not influenced by heavy precipitations

4 Modelling

4.1 Principles of rock mass modelling methods

Discontinuous medium can be modelled with the presence of any discontinuities when the Distinct Element Method (DEM) is applied. The principles of the method were elaborated in 1971 by P. Cundall (Cundall, 1971). The basic features of DEM are as follows:

- The medium is modelled as a set of blocks, with contacts between one another on boundaries and corners
- Discontinuities are considered as “interactions” of the boundaries between the blocks
- Blocks can be non-deformable (modulus of elasticity equal to infinity) or deformable. In the first case movement (displacement, rotation) is possible only

along or across the discontinuities, whereas internal deformations of the blocks are possible in the second case. The option with non-deformable blocks is particularly useful in cases of very hard rock, intersected with individual joints of joint sets. When the rock deformability is comparable with that along the discontinuities, the option with deformable block is more appropriate.

Many features of the medium can be taken into account, e.g.:

- Different elastic properties, both for the rock mass and discontinuities
- Complex systems of discontinuities of different orientation and spacing
- Non-linear and inelastic (plastic, viscous) behaviour of the medium components.

The algorithm of UDEC (Universal Distinct Element Code) (Itasca Consulting Group, 2004) program is based on above described method.

On the other hand the commercial software FLAC (Fast Lagrangian Analysis of Continua) (Itasca Consulting Group, 2008) is based on finite difference method (FDM). FDM is a method to solve differential equations, in this case the laws of continuum mechanics. In some cases rock mass can be treated as continuous, as soil, especially when the density of discontinuities is high. A mesh of variable geometry is the main feature of this kind of model, to each element different properties could be assigned.

- Different elastic properties in different zones and sub-spaces of the model
- Non-linear and inelastic (plastic, viscous) behaviours
- Static or dynamic loadings
- Water flow through the medium.

Differences in the reaction to shear and tension stresses in the two models are described in *Fig. 2*.

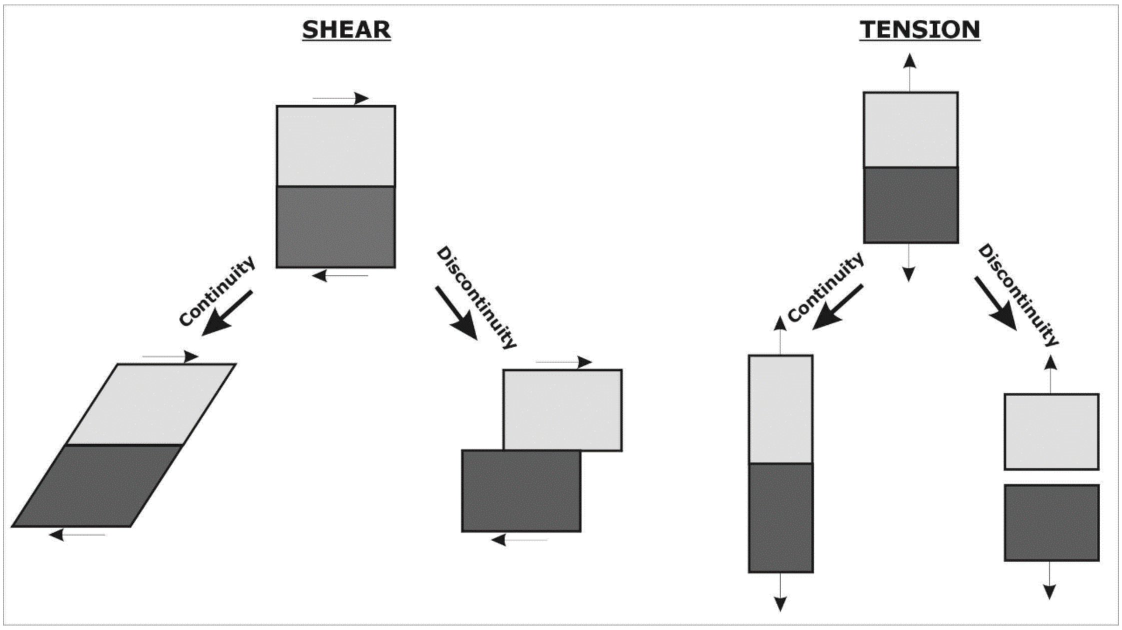

Fig. 2 Discontinuous and continuous behaviour of the medium subjected to shear and tension loading

4.2 Modelling of the slope

Two 2D numerical codes were applied in the simulation of the landslide movement, namely FLAC (Itasca, 2002) and UDEC (Itasca, 2004).

Fig. 3 presents the geomechanical setting of discontinuous model. The layers are splitted into deformable blocks of intact rock by two sets of joints on the base of the data collected during the geological survey. In continuous model are layers identically arranged, but they are not splitted. However, it is assumed in this case that so-called "ubiquitous joints" exist in this model, inclined at an angle of 30° to the horizontal. It has to be pointed out that the joints are not geometrical objects, but only represent the direction, assumed on the base of rock mass structure. This model, known as "ubiquitous" has a possibility to fail in this direction, as well as in two others – determined by Coulomb-Mohr criterion.

The geomechanical parameters of the models are set in tables Y1 and Y2. Parameters of joints inclined at 30° in both the models are the same. It is necessary to mention that the values in the tables were determined taking into account two assumptions:

- large deformation (failure) of the models is possible,
- failure mode in both cases is approximately similar.

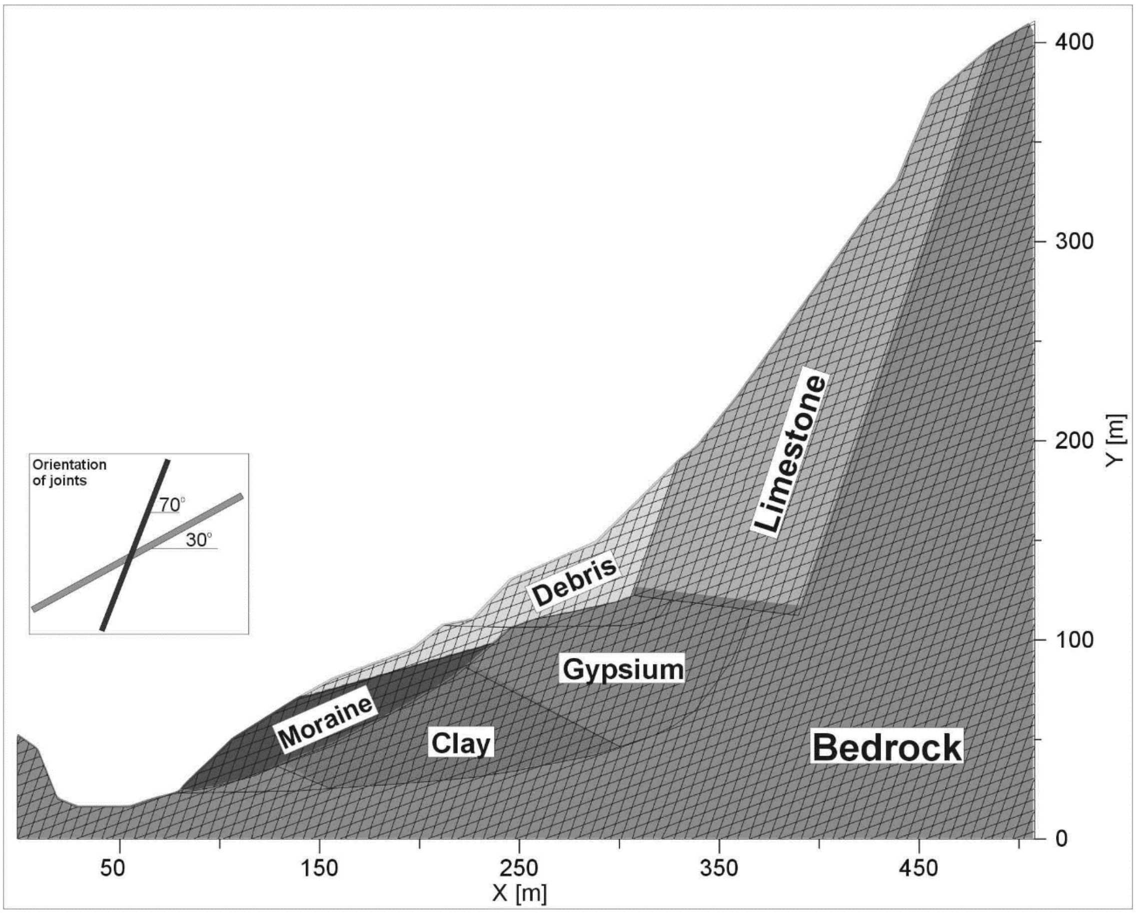

Fig. 3 Discontinuous model of the slope

Table Y1. Geomechanical parameters of rock layers

Rock type	PARA-METER						
	Density [t/m3]	Bulk modulus [kPa]	Shear modulus [kPa]	Cohesion [kPa]	Tension strength [kPa]	Friction angle [o]	Dilation angle [o]
Bedrock (dolomite)	2.5	1.17E7	5.38E7				
Limestone	2.3	6.25E6	2.88E6	1000	0	42	21
Debris	1.9	8.35E5	3.85E5	0	0	40	20

Gypsum	2.0	2.50E6	1.15E6	100	50	35	17.5
Clay shale	2.1	2.67E6	1.23E6	250	125	18	0
Moraine	1.8	2.78E6	9.26E5	50	0	38	19

Table Y1. Geomechanical parameters of discontinuities

<table>
<tr><th>Model</th><th>Orientation</th><th>Cohesion [kPa]</th><th>Tension strength [kPa]</th><th>Friction angle [°]</th><th>Dilation angle [°]</th><th>Shear stiffness [kN/m]</th><th>Normal stiffness [kN/m]</th></tr>
<tr><td rowspan="2">Discontinuous</td><td>30</td><td rowspan="3">0</td><td rowspan="3">0</td><td rowspan="3">20</td><td rowspan="3">0</td><td>1E4</td><td>1E5</td></tr>
<tr><td>70</td><td>1E6</td><td>1E6</td></tr>
<tr><td>Continuous (ubiquitous)</td><td>30</td><td colspan="2"></td></tr>
</table>

4.3 Results of the simulations

Results are presented in form of displacement fields. Such presentation allows to compare in easy way the simulated general behaviour of the slope in both cases, with UDEC and FLAC. Fields of horizontal and vertical displacement for the discontinuous and continuous model are shown in figs. Fig. 4 and Fig. 5, respectively.

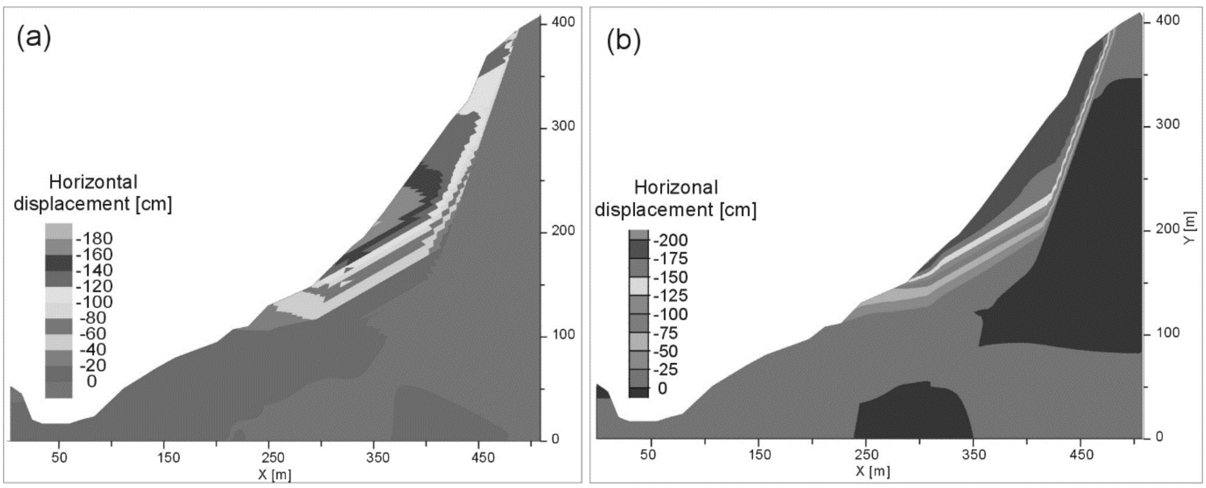

Fig. 4 Field of horizontal displacement; (a) discontinuous model, (b) continuous model

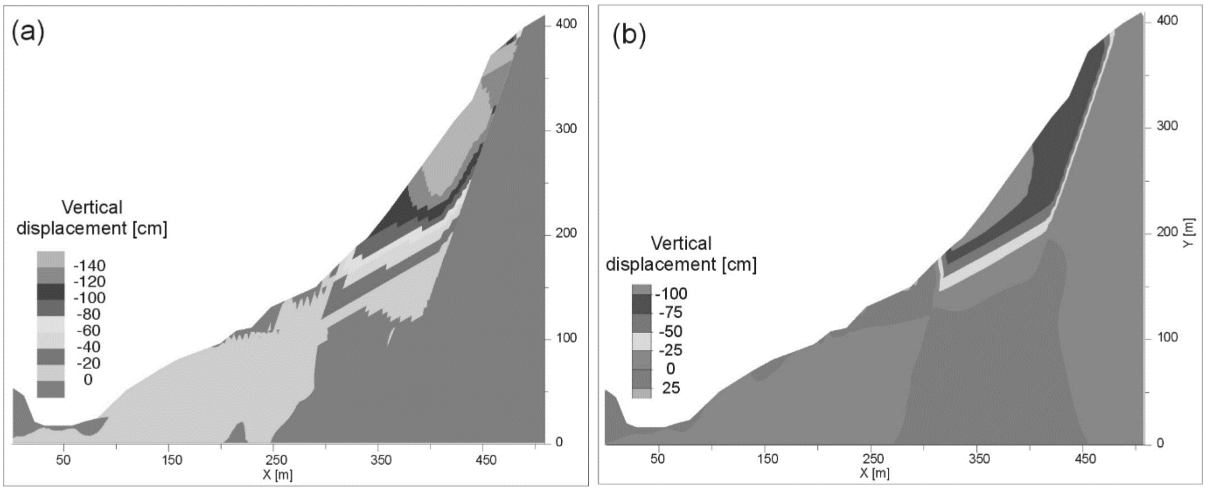

Fig. 5 Field of vertical displacement; (a) discontinuous model, (b) continuous model

The displacement fields demonstrate both some similarities and differences. First, the region which deforms and moves in horizontal and vertical directions, embraces mainly the limestone column. However, horizontal displacement in CM case prevails over vertical more significantly than in DM, so the ratio of maximum horizontal to vertical displacement in the first case, expressed as U/V is approximately equal to 2.0, whereas it is equal to 1.3 in the second one. The vertical movement in DM is relatively large due to the shear displacements along the joints inclined at 70° (see Fig. 5), modelled in explicit way.

It is also worth noticing that the largest horizontal displacement in DM case is mainly concentrated in the lower part of limestone, whereas in CM it is more or less equally distributed along the length of its near-surface zone.

Vertical components show a different pattern – the largest values in CM are visible in the most upper part of the limestone, whereas in DM maximum values appear in the middle-lower part. This difference is more distinctly presented in Fig. 6, where displacement vectors are compared. Also very significant displacements occur in the lower part of CM meaning that the slip surface outcrops there. This phenomenon is not so distinctly observed in DM. In both cases relatively large vectors of displacement in the most upper part indicate toppling process. The true mechanism of the toppling cannot be reconstructed in the CM, whereas it is possible in DM solution (Fig. 7). If the blocks arrangement in the figure is analysed, very clear picture of the failure processes reveals. First of all it can be seen that all blocks of the limestone most upper part tend to fall down. Moreover, the blocks in the lower part slide along the joints, thus the slip failure occurs concurrently. Both above processes are accompanied by settlement of the whole limestone column. It can be also expected that individual blocks may lose contact with the slope mass and fall down, increasing the volume of debris deposits below the limestone.

It is true that also an analysis of the displacement field in CM allows to remark these processes, but they are not so clearly indicated.

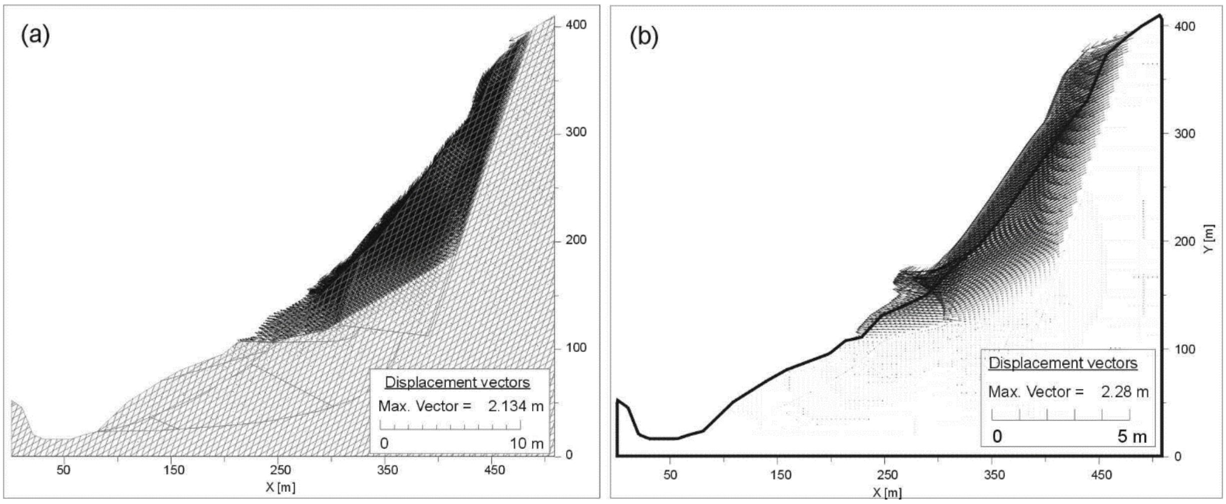

Fig. 6 Field of displacement vectors; (a) discontinuous model, (b) continuous model

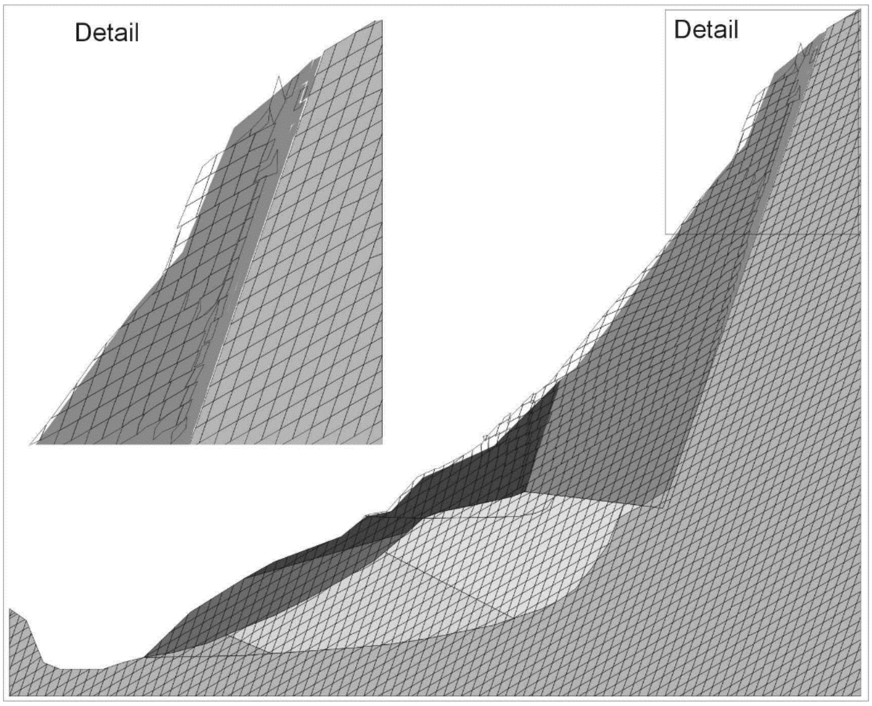

Fig. 7 Final arrangement of the blocks in discontinuous model

5 Final remarks and conclusions

The results show the capabilities of discontinuous and continuous modelling of the rock media. Application of discontinuous model makes possible to highlight the possible toppling mechanisms. Continuous approach allows first of all to simulate in a proper way the sliding behaviour of the layers, although it also hints to toppling.

On the base of the results it is possible to conclude that for these types of phenomena discontinuous approach provides more information about possible deformation processes and failure mechanisms. However, this is possible if a reliable geomechanical reconstruction of the slope is available. The largest uncertainties are linked to the determination of the material properties and joints shear and normal stiffness as they strongly influence the calculation results.

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