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Development and Control of Deep Seated Gravitational Slope Deformation: The Case of Colzate-Vertova Landslide, Bergamo, Northern Italy

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Abstract**—**This paper presents the Colzate-Vertova landslide, a Deep Seated Gravitational Slope Deformation (DSGSD) located in the Seriana Valley, Northern Italy. The paper aims at describing the development as well as evaluating the factors that influence the evolution of the landslide. After defining the conceptual model of the landslide, numerical simulations were developed using a finite element numerical model, first with a two-dimensional domain, and later with a three-dimensional one. The results of the 2-D model showed a displacement field typical of a sackung, as a consequence of the erosion along the Seriana Valley. The analysis also showed that the groundwater flow could locally affect the slope stability, bringing about a reduction in the safety factor, but without reaching failure conditions. The sensitivity analysis carried out on the strength parameters pointed out that slope failures could be reached only for relevant reduction of the geotechnical characteristics. Such a result does not fit the real conditions observed on site, where a number of small failures often develop all along the hillslope. The 3-D model gave a more comprehensive analysis of the evolution of the DSGSD, also considering the border effects. The results showed that the convex profile of the slope favors the development of displacements along the lateral valley, with a relevant reduction in the safety factor, justifying the existing landslides.

Keywords**—**Deep seated gravitational slope deformation, Italy, landslide, numerical modeling.

I. INTRODUCTION

DSGSDs are processes induced by gravity, that affect entire hillside, which consequently present characteristic landforms as trenches, double-crested ridges, tension cracks, scarps, and convex toes. These phenomena displace volumes of rock about hundreds of thousands of cubic meters and, even if they are characterized by a very slow moving (mm/year or cm/year), they may damage local infrastructures or trigger smaller failures in the affected area.

This paper presents the case study of the Colzate-Vertova DSGSD, located in the Seriana Valley (Northern Italy, Fig. 1 (a)), in order to describe its development as well as evaluate the factors influencing its evolution. The dynamic of the landslide is studied by a finite element numerical model, running numerical simulations, first with a two-dimensional domain, and later with a three-dimensional one.

More in detail, the paper aims at identifying the possible causes (mainly geomorphological and hydrogeological) that lead to the development of the instabilities involved in the DSGSD, as well as the factors that influence their dynamic and evolution. The most important geomorphological peculiarities of the study area are represented by the widespread existence of landslides along both the slope of the Seriana and Vertova Valleys, which border two sides of the DSGSD.

Therefore, the paper aims at verifying the hypothesis that the convex profile of the slopes can have favored the development of the DSGSD.

II. STATE OF THE ART ON DSGSD

The DSGSDs are processes induced by gravity and characterized by very slow motion, which affect entire hillslopes, displacing volumes of rock about hundreds of thousands of cubic meters [1]. These phenomena are often called "slow or not catastrophic landslides" because of their low displacement rates with values of the order of cm/year or mm/year [2]. Sometimes, the strain state of a sector of the slope may catastrophically evolve, triggering rock avalanches [3].

In general, the rock mass involved in DSGSDs does not present a well-defined shallow rupture zone, otherwise in surface, there are some typical geo-morphological structures that characterize these landslides as trenches, double-crested ridges, tension cracks, scarps, and convex toes [2]. In addition, small slope shifts typical of the phenomenon often trigger secondary failures: within the area affected by DSGSD, there are several smaller landslides or evidences of old collapses.

The DSGSDs are generally classified into:

- Sackung: deformation driven by gravity, which affects mainly metamorphic schistose rocks, with slow and continuous plastic deformations (creep);
- Lateral spread: of rigid blocks of rock above a plastic substrate;
- Block slide: overthrusts involving large masses, generally characterized by a translational motion, along one or more surfaces or shearing zones (more or less defined).

The most important factors that influence the development of a DSGSD are:

- The relief energy: generally in between 500 and 1000 m [4];
- The slope: generally ranging from 18° to 50°;
- The lithological characteristics: which determine the type of DSGSD;

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- The structural setting: the genesis of a DSGSD is often linked to the presence of faults;
- Climatic factors: the debuttressing resulting from melting of glacial masses seems to be the main triggering cause of the most important DSGSDs affecting the Alps.

The study of DSGSDs is difficult because of their considerable complexity, due to both the geological processes involved and their intrinsic spatial variability [5]. The approach generally used to study these landslides is based on numerical modeling of the phenomenon, following the reconstruction of its conceptual model. Actually, the numerical simulations allow to analyze the development of a DSGSD in its various phases [6]: from the very early one (referred to the retreat of glaciers or to the erosion processes of the valleys) to the post collapse, defining the displacement values and the deformation style [7], even considering the effects of the groundwater flow on the landslide evolution [8].

III. The Colzate-Vertova Landslide

A. Geomorphological Setting

The study area is characterized by the presence of two important valley drifts, Seriana and Vertova Valleys, whose erosion occurred during the Quaternary. The Colzate-Vertova lanslide develops where these two valleys intersect each other, extending from the altitude of 1320 m a.s.l. of Cima di Cavlera to 400 m a.s.l. of the Serio River (Fig. 2). Within the study area, there are many trenches and landslide scarps, testifying a widespread instability. Actually, along the slope there are many rock falls, favored by the high fracturing degree of rocks and the high slope. These landslides extend even outside the area previously identified to be a DSGSD [9] and interest the slope of Monte Cavlera facing on the Vertova Valley.

B. Geological and Tectonic Setting

From a geological point of view, the slopes are composed by sedimentary rocks, mainly limestone or claystone. These rocks are highly fractured, because of the presence of different fault systems, among which the most evident is the overthrust that marks the overlap between the oldest dolomitic mass and the more recent formations of Argillite di Riva di Solto and Calcare di Zu (Fig. 1 (b)).

The lithological and structural setting reveals that the weakness layers along which the movement can develop are represented by the fractured zones related to fault systems and the formation of Argillite di Riva di Solto, which is typically a weak rock.

C. Hydrogeological Setting

The geological and tectonic setting also rules the hydrogeological one; actually, the area is mainly characterized by rocky aquifers, with springs mainly located along the tectonic features and the geological contact between formations having different hydraulic behavior. More in detail, in the North-West zone against the overthrust, very important springs are present, representing water flow in the fracture network within the Dolomia Principale formation. In the East zone against the overthrust, hydrogeological structures are less important, since the area is dominated by low permeability rocks (Calcare di Zu) or even by impermeable ones (Argilliti di Riva di Solto). Therefore, two main aquifers can be identified. The deepest one is located within fractures and karst cavities of Dolomia and it constitutes the main regional aquifer feeding the valley floor [10]. The shallow aquifer is separated from the previous one by the impermeable layer of Argillite di Riva di Solto, and it flows within the Calcare di Zu formation, in which water circulation is certainly less important: it arises from local recharge and supplies small springs located along the slopes.

D. The Conceptual Model

Based on the geological, tectonic, and hydrogeological setting previously described, a conceptual model was developed. That means first the geometrical reconstruction of the slope, shown in the cross-section (Fig. 3). The bedrock, consisting of Dolomia Principale, is separated from the weaker formation of Calcare di Zu by the layer of Argillite di Riva di Solto. The deep aquifer seats into Dolomia Principale, while the clay layer acts as an aquitard for a shallow aquifer, within the Calcare di Zu. Because of their high state of fracturing, fault zones also constitute preferential points for water infiltration, also affecting the slope stability with sliding surfaces (Fig. 3) that have a trend similar to the normal faults' one.

The physical model has been completed with the characterization of the geo-materials. At this aim, an elastic-plastic constitutive model was assumed with a Mohr-Coulomb failure criterion. Thanks to the results of previous studies and in situ surveys, it has been possible to assign to each material its mechanical properties, summarized in Table I. This deformative style is the result of the slope destress arising from the valley erosion. Therefore, the normal faults, as well as the sliding surfaces, can be considered not only a cause of instability but also as a result of the stress-strain filed. This is the reason why in the following analysis both these hypotheses were considered, in order to point out the effects of the valley excavation on the stress-strain filed and therefore on the slope dynamic.

TABLE I
VALUES OF THE PARAMETERS CHARACTERIZING THE DIFFERENT GEO-MATERIALS (DO=DOLOMIA PRINCIPALE, ZU=CALCARE DI ZU, ZUF=CALCARE DI ZU FRATTURATO, AG=ARGILLITE DI RIVA DI SOLTO, F=FAULTS)

	Do	Zu	Zuf	Ag	F
Φ [°]	4	30	25	20	10
c' [kN/m^2]	105844	1572	1256	328	0.5
E [kN/m^2]	$5.6 * 10^7$	10^6	$5.6*10^6$	$3.1*10^6$	10^5
ν [/]	0.35	0.3	0.25	0.25	0.3
γ_{sat} [kN/m^3]	27	25	25	18	25
K [m/s]	10^{-3}	10^{-6}	10^{-4}	10^{-9}	10^{-2}

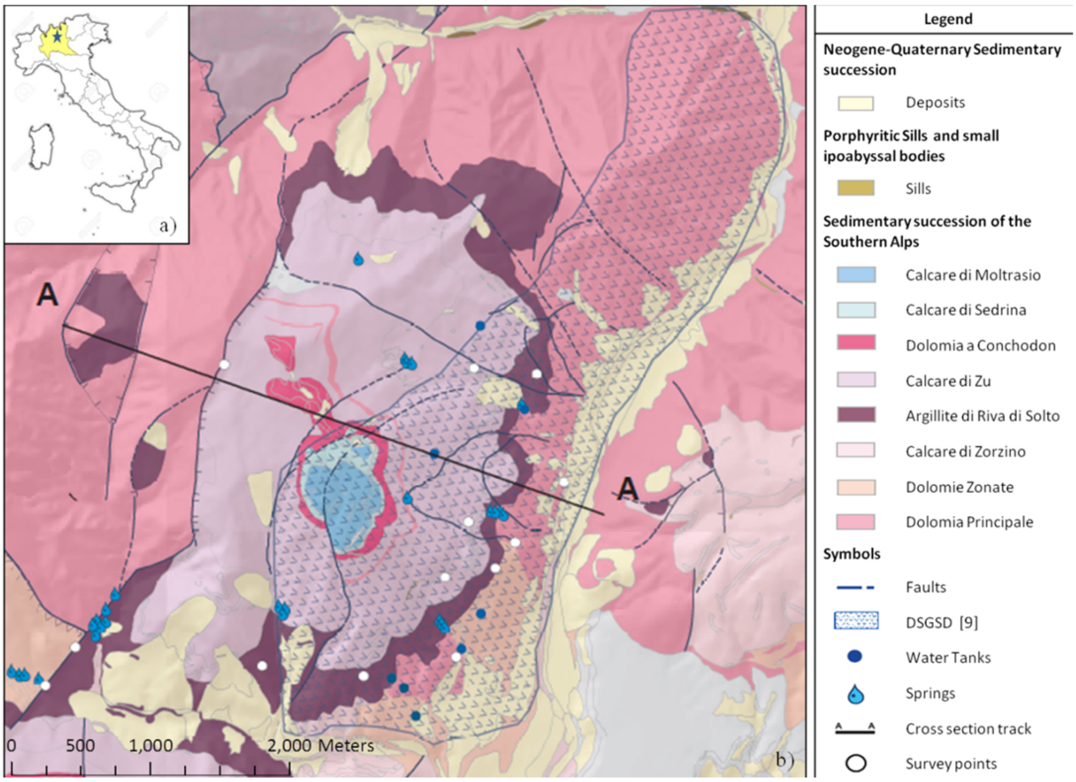

Fig. 1 (a) Geographical framework and (b) Geological map of the study area

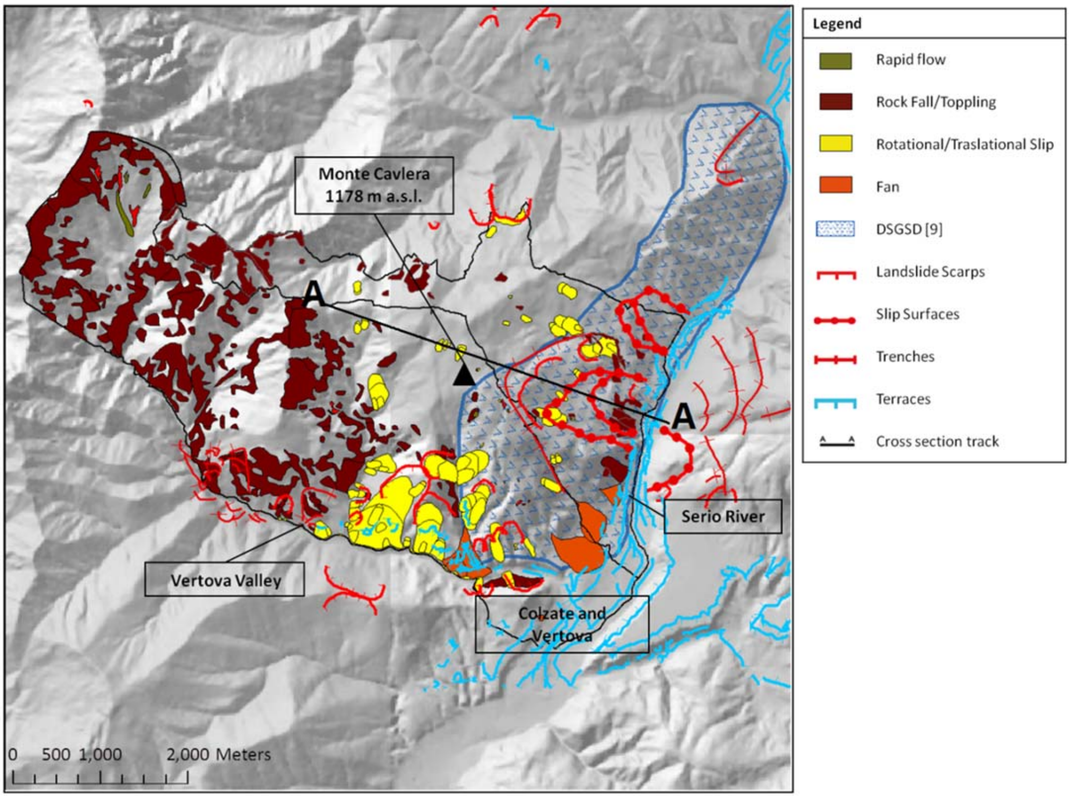

Fig. 2 Geomorphological map

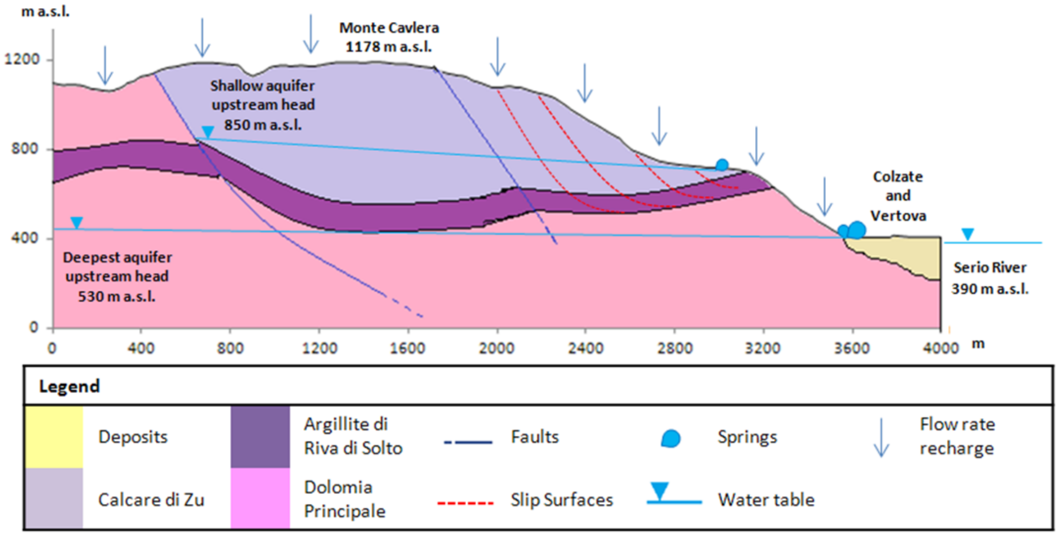

Fig. 3 Cross-section describing the conceptual model of the landslide

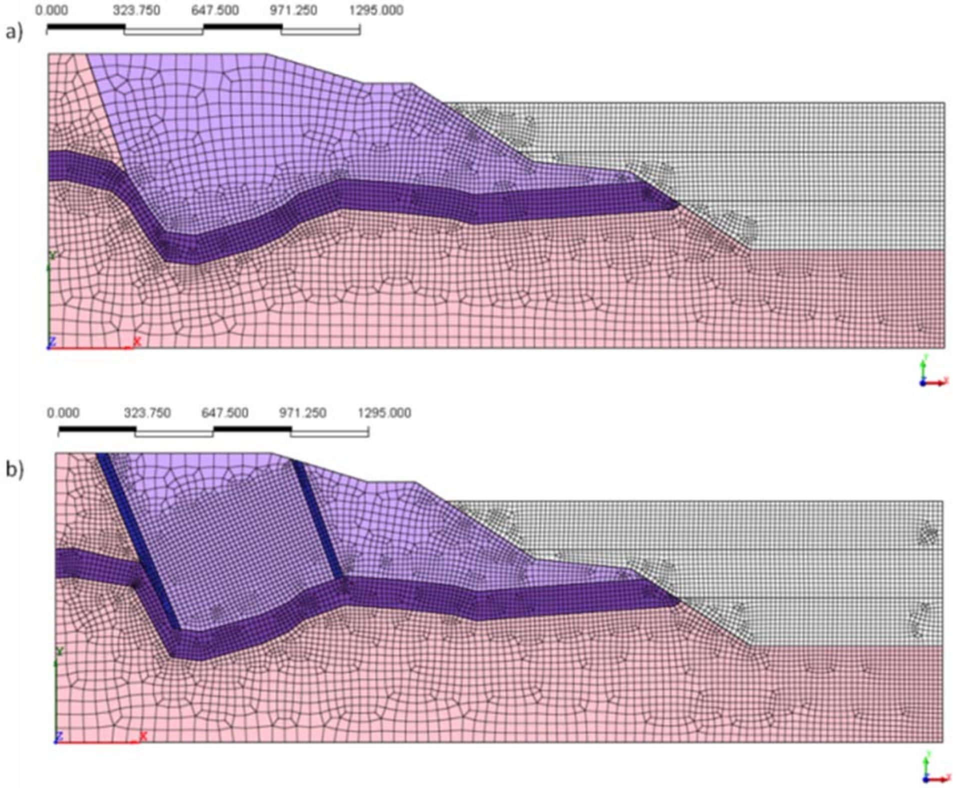

Fig. 4 2D geometric domains a) Without faults b) With faults. The white material is the one subjected to erosion

IV. 3D Numerical Modeling

A. Model Implementation

Based on the conceptual model previously described, a numerical model was implemented for the dynamic assessment of the landslide. Numerical analyses are performed both considering and not considering the presence of the normal faults before the slope destress. These different geometries lead to evaluate the effect of the faults presence on the results of the numerical simulations.

The domain was subsequently discretized with a squared mesh, whose elements size ranges in between 20 and 50 m (Figs. 4 (a) and (b)).

The analyses were carried out in two stages: first the erosion process of the Seriana Valley was simulated, then the actual conditions were considered with the present days groundwater flow, in order to evaluate its effect on slope stability.

In order to simulate the hydrogeological setting of the area, boundary conditions are imposed, such as:

- Constant head (equal to 850 m a.s.l. for the shallow aquifer, and 530 m a.s.l. for the deeper one) upstream the two aquifers, based on the springs' altitude.
- Constant head (equal to 390 m a.s.l.) downstream, corresponding to the Serio River.
- Flow rate recharge (equal to $3.8*10^{-9}$ m/s) along the slope surface.

B. Modelling Results

The results of the two-dimensional analyses revealed that the stress release of the slope arises from the gradual erosion of the Serio River furrow (Fig. 5). The presence of fracture zones associated with faults involves destressed bands along the faults themselves: as anticipated, they are normal faults, resulting then from a destress process.

Consequently to change in stresses distribution, displacement field develops along the slope, involving a block, which tends to crush and swell downstream (Fig. 6).

Afterwards, considering the actual conditions, the analyses showed that the groundwater flow (Fig. 7) influences the displacement field (Fig. 8).

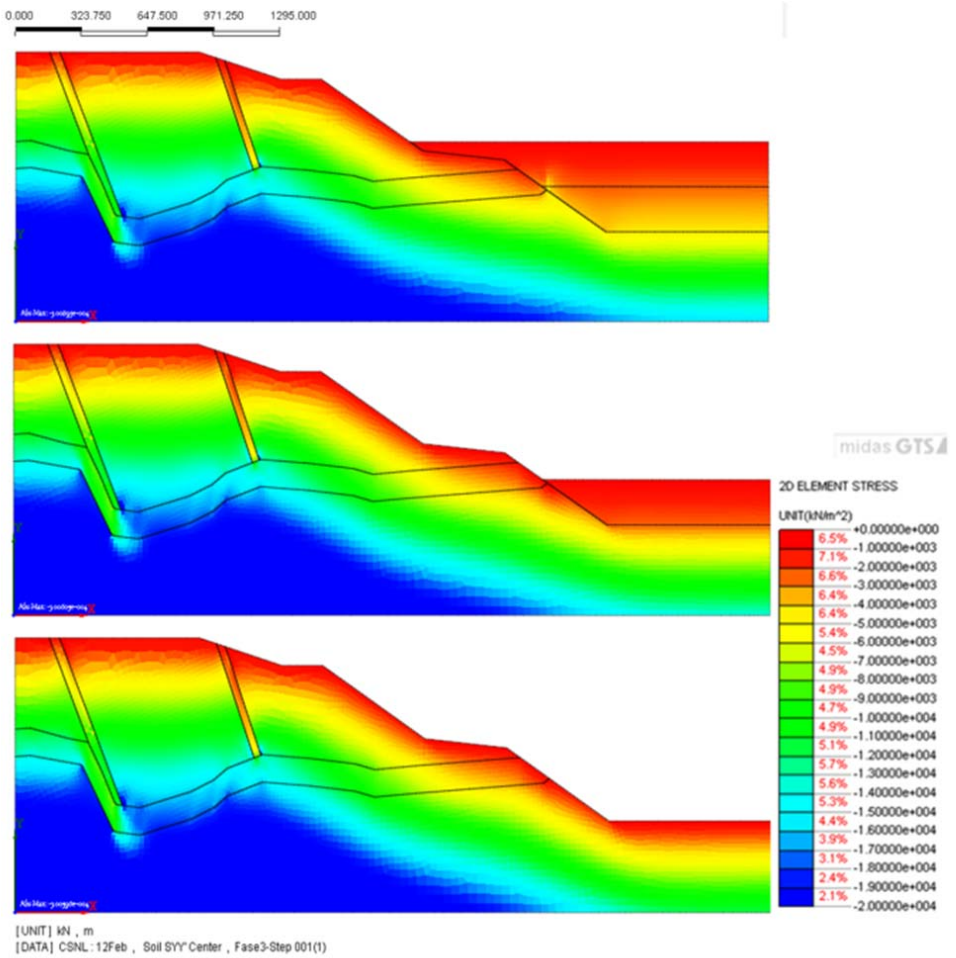

Fig. 5 Vertical stress distribution during erosion process.

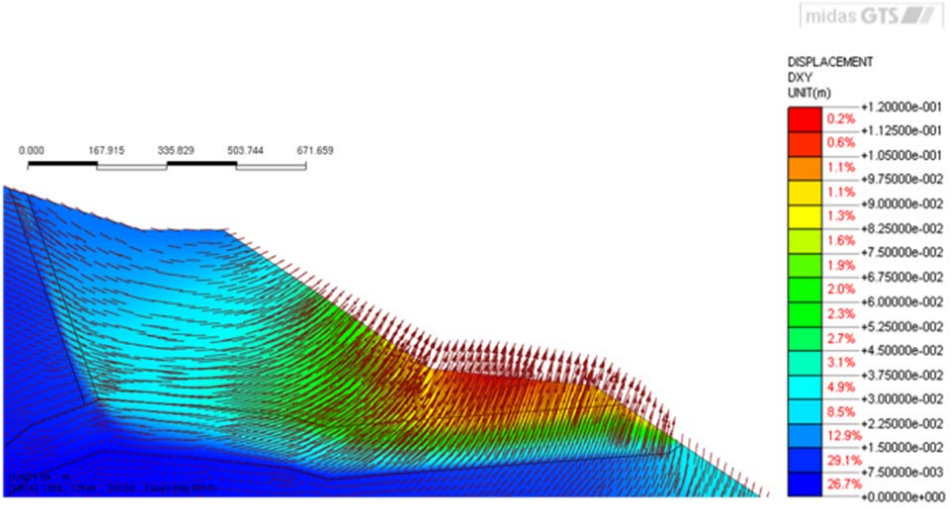

Fig. 6 Displacement field and related vectors triggered by erosion process

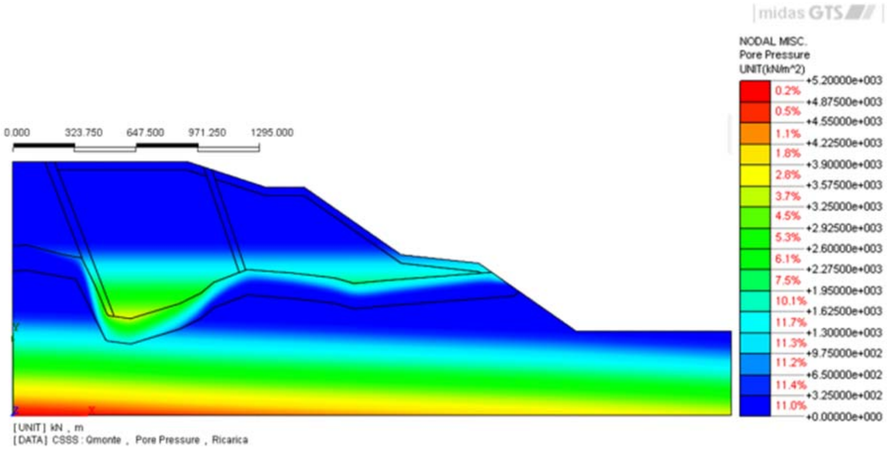

Fig. 7 Water pressure distribution into the slope

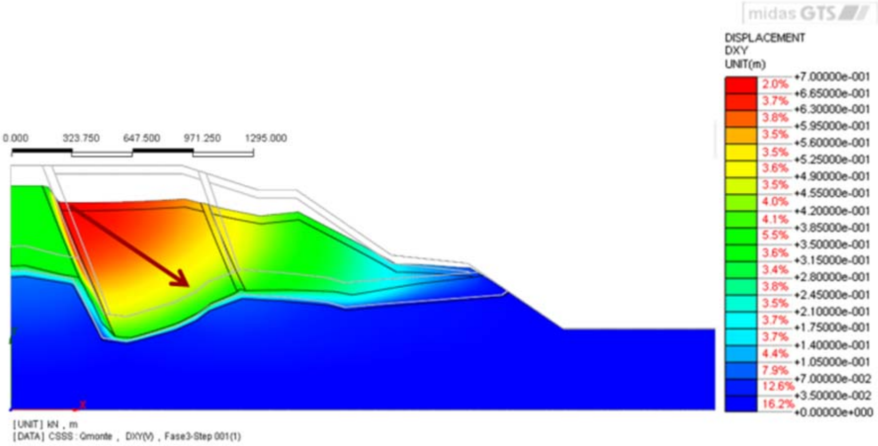

Fig. 8 Displacement field at present day, due to groundwater circulation in the slope

Faults are weakness horizons that favor movement; in fact, shear stress trend confirms that the tectonic features and the surrounding areas are the zones with the greatest concentration of stresses (Fig. 9 (a)); therefore they represent potential sliding surfaces. The direction of the shear stresses confirms the presence a crushing motion. Slopes are so affected by an extensional displacement, with a deformation style typical of a sackung. The Argilliti, which typically performs plastic deformations, represents the weakness level that leads to the development of failure surfaces within the overlying Calcare di Zu, which consequently is divided into blocks moving and crushing on the clay layer.

Consequently, faults can be seen as the result of the stress release due to the erosion process. In fact, during erosion, fault zones sustain a destress; after the formation of the valley furrow, the same areas represent the weakness surfaces that facilitate the motion of the volumes of rock, so they are shear stressed (Fig. 9 (b)). However, the failure is not triggered, as the analyses suggest a high value of the safety factor (higher than 1.8). This value is associated with a discontinuous failure surface (Fig. 10): it is reasonable to think that this surface is not well defined because associated with the slow deformation of DSGSD and not with a collapse failure.

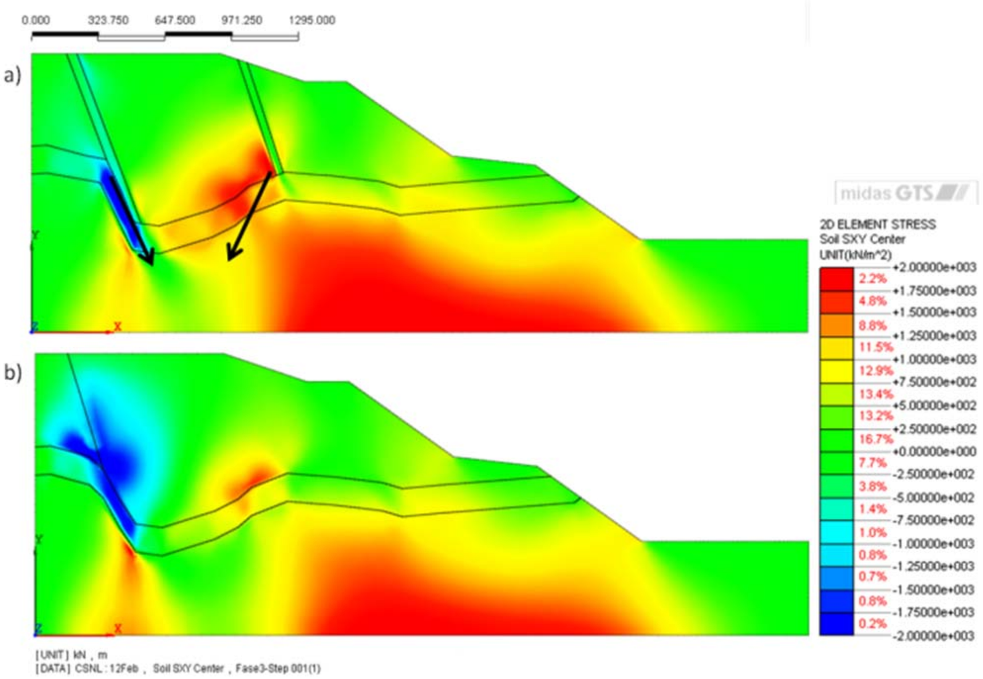

Fig. 9 Shear stress distribution (a) considering and (b) not considering the presence of fracture zones along faults

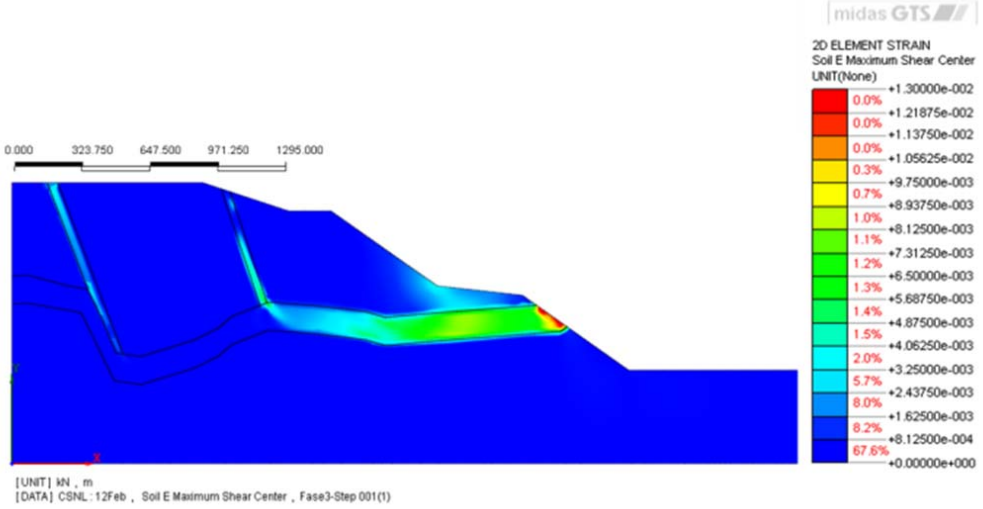

Fig. 10 Failure surface associated with DSGSD deformation

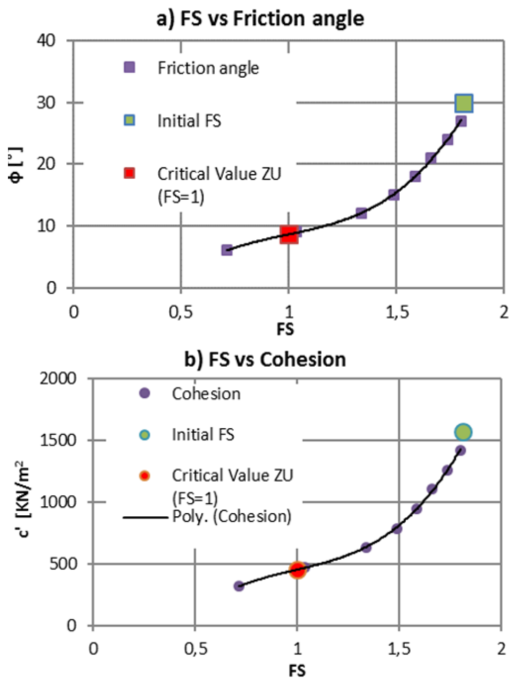

Fig. 11 FS vs friction angle (a) and cohesion (b)

On the other hand, the geomorphologic map revealed the presence of many shallow landslides, affecting the Calcare di Zu formation. These instabilities probably arise from a significant reduction in the mechanical characteristics of the rocks, event due to climatic agents or tectonic activity. In order to assess the surface stability, a sensitivity analysis on Calcare di Zu's strength parameters was carried out. The results are summarized in Fig. 11 and they show a well-defined failure surface, tangent the clay layer, according to which the system would reach the collapse (Fig. 12).

V.3D NUMERICAL MODELING

A. Model Implementation

Three-dimensional model was then implemented, in order to assess the side effects on the numerical modeling of a DSGSD. In fact, along the slope of Monte Cavlera facing on the Vertova Valley there are many secondary landslides, which could be caused by the presence of the DSGSD, and that can, on their turn, affect the global stability.

The 3D domain (Fig. 13) was reconstructed by using a digital terrain model of the area, assuming an area whose boundaries are defined by hillslopes' ridges in the north and west sides, and by the Serio River and Vertova Valley in the east and south sides.

Material geometry has been simplified, especially for the Argillite layer, which is represented by an 80-m thick layer, slightly dipping against the slope facing on the Seriana Valley. Furthermore, for computational reasons, faults are not considered, based on the results obtained in the 2D model.

The domain has been discretized using a tetrahedral mesh, whose elements size ranges in between 80 and 100 m. After this, boundary conditions previously seen are imposed, so the model is ready to run.

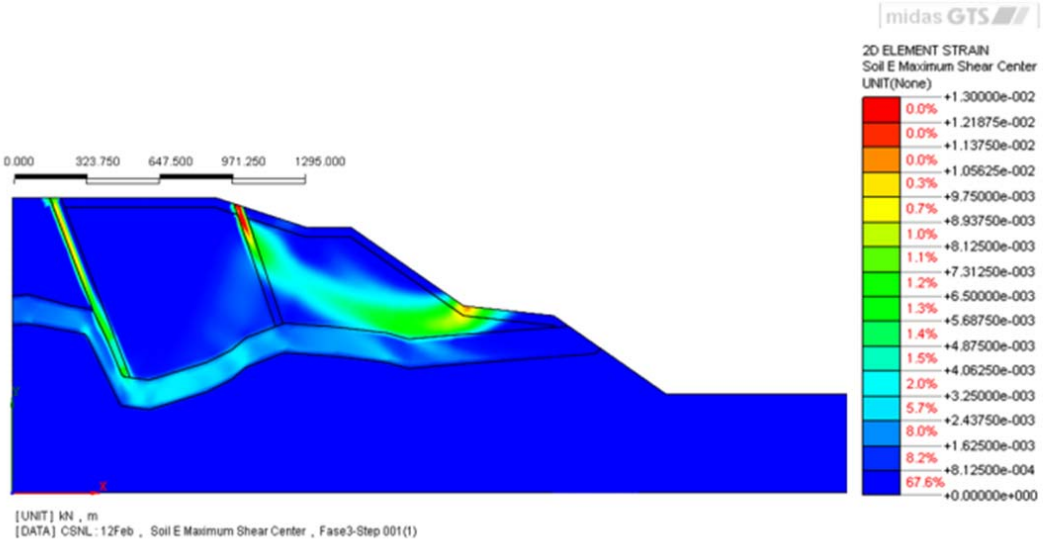

Fig. 12 Failure surface associated to a shallow failure of the slope, within the Calcare di Zu

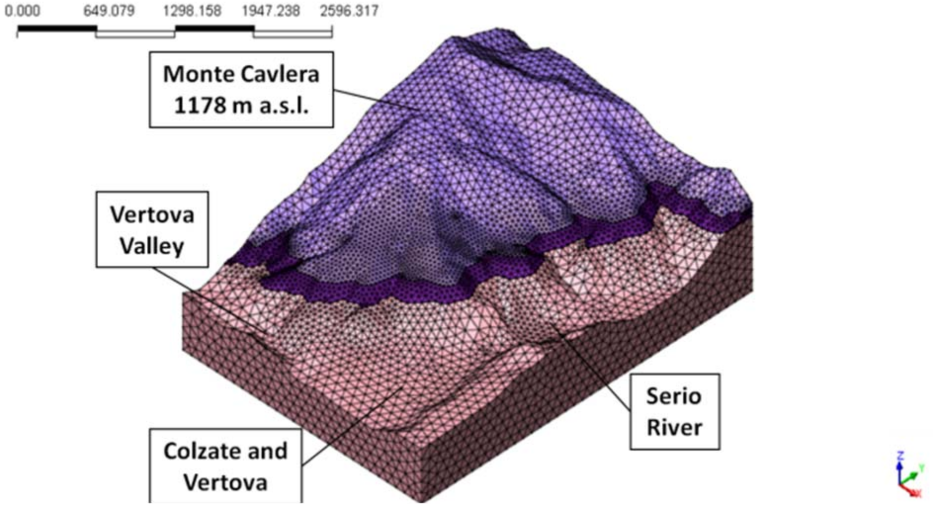

Fig. 13 3D domain and its mesh

B. 3D Numerical Results

Three-dimensional analysis confirmed the hydrogeological structure, with two aquifers (Fig. 14), but in this case groundwater tends to move mainly towards the Vertova Valley, which is therefore richer in water than the Serio Valley, as it is also pointed out by the concentration of springs in that area.

Because of the intense groundwater flow towards the Vertova Valley, a displacement component arises along slope facing this valley (Fig. 15), testifying the presence of side effects.

The shear deformation distribution (Fig. 16) confirms this evidence: the results show that the convex profile of the slope favors the development of lateral movements, along the slope facing on the Vertova Valley. Such movements laterally unlock the Monte Cavlera slope, so it can collapse more easily towards the Serio River, with a decrease in the stability conditions. In fact, the safety factor reduces to 1.01.

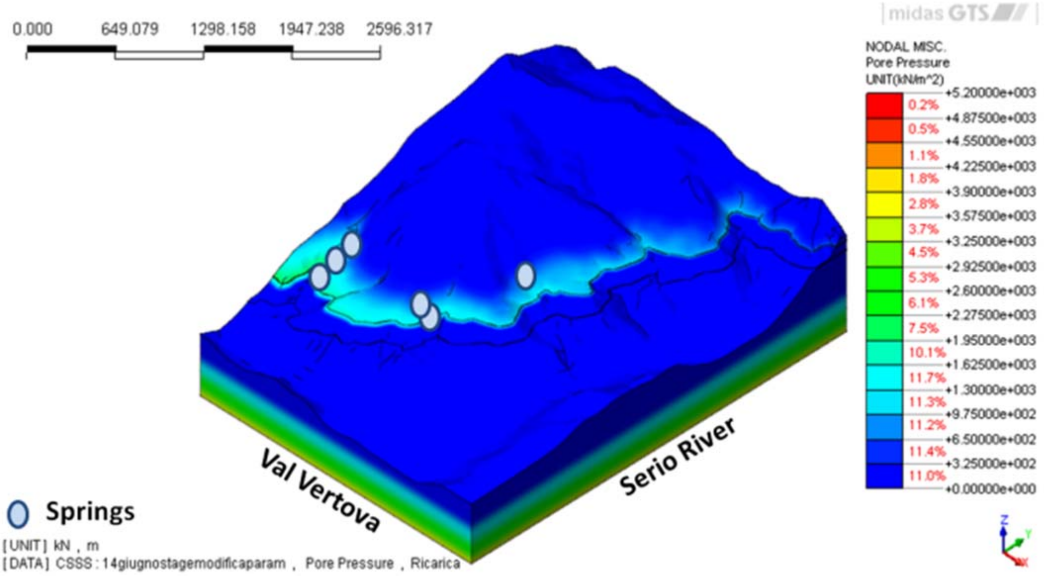

Fig. 14 3D water pressure distribution

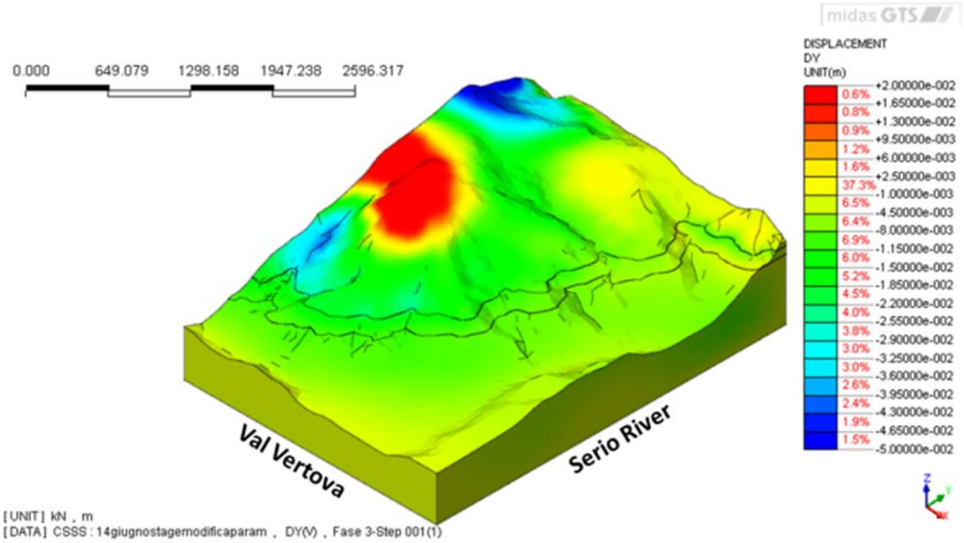

Fig. 15 Displacement along slope facing on the Vertova Valley

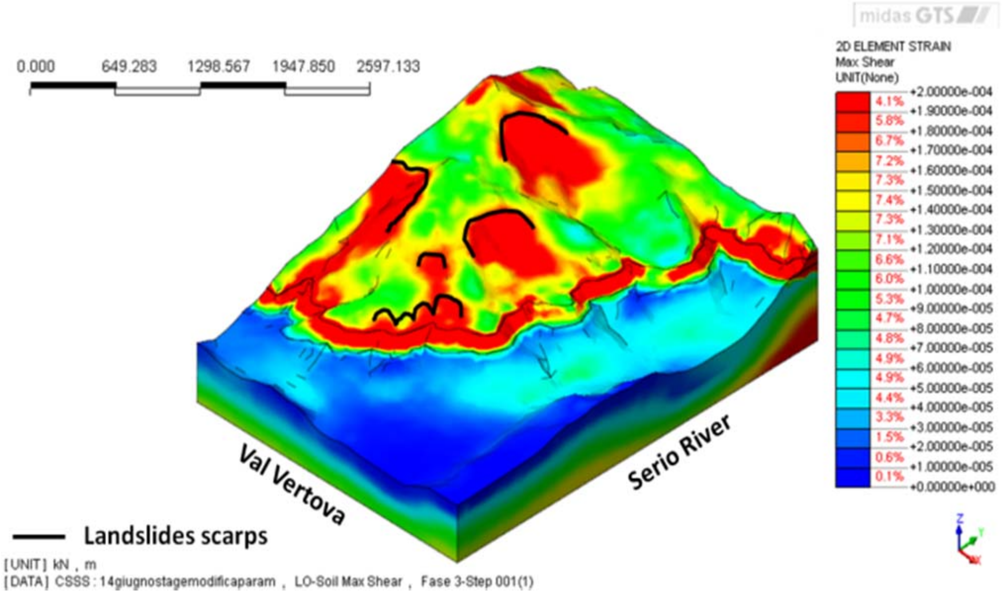

Fig. 16 3D shear strain distribution

VI. CONCLUSIONS

This study investigated some important issues involved in the dynamics and evolution of DSGSDs.

In particular, the development of the Colzate-Vertova DSGSD is ruled by the geomorphological slopes evolution, which experienced stress release processes, arising from the erosion of the Seriana Valley. Moreover, the following points have been highlighted:

- fracture zones along normal faults can be further weakened during the evolution of the phenomenon and faults can be seen as the result of the destress process that triggered the DSGSD;
- the presence of deformable clay units, lying sub-horizontal at the base of the rigid and fractured masses of dolomite and limestone favors the development of a deformation style typical of a sackung;
- a convex profile of slope favors the development of lateral displacements and, therefore, the presence of side effects.

The latter conclusion leads to state that, although the 3D model developed for this case study does not allow to get into specifics, the DSGSD should be studied and analyzed by 3D model, in order to have a more comprehensive view of the phenomenon.

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