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THE VAJONT LANDSLIDE, 9TH OCTOBER 1963: LIMIT EQUILIBRIUM MODEL FOR SLOPE STABILITY ANALYSIS THROUGH THE MINIMUM LITHOSTATIC DEVIATION METHOD

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ABSTRACT

Fifty years ago the giant Vajont landslide slipped in the homonymous lake and caused a disaster. The purpose of this work is to apply classical limit-equilibrium methods as well as a the variant developed by Tinti & Manucci (2006, 2008) and called Minimum Lithostatic Deviation (MLD) method to analyse the stability of the Mt Toc flank from where the slide detached and to study the effect of the various factors influencing stability.

The analysis was conducted on two profiles, one representing the west-side and one representing the east side of the slide, that were taken from the sliding surface as reconstructed by using pre-slide and post-slide topographic maps and by using suitable hypotheses from the literature on the shape of the hidden part of the surface (that is the surface that remained covered even after the slide occurrence).

The analysis shows that the angle of friction is the most relevant parameter influencing the safety factor more than the material cohesion. The analysis shows further that the Vajont slide was close to instability. With data used in this paper, a drop of the basin level from 710 m a.s.l. down to 700 m a.s.l., in conditions of very high piezometric level (790 m a.s.l.) as can be produced by intense rainfall, may have the effect of drawing the safety factor below the critical line of 1 and give rise to instability.

Key words: Vajont landslide, slope stability, limit equilibrium method

INTRODUCTION

The landslide of Vajont, on October 9th 1963, is one of the greatest catastrophes in Italy: the mass that detached from the Mt Toc slope flew into the reservoir at high speed, about 20 m/s (Zaniboni & Tinti, 2013, Zaniboni *et alii*, 2103) and the water it displaced swept away or partially destroyed several villages, including Longarone. The end result was 1917 victims of which 1450 belonging to Longarone, 109 to Codissago and Castellavazzo, 158 to Erto and Casso and 200 employees, technicians and their families who worked for the company operating the dam.

The case of Vajont is still today an important masterpiece for the study of stability, evolution and the effects generated by a landslide, owing to the large amount of data collected during the monitoring of the site since 1936, the year in which the Vajont gulley was chosen for the construction of the dam. And the quantity of data increased even more as the conditions of the slope became critical.

The late 50's and the early 60's were the golden years for Italy in industry and civil engineering and it is in this context that the dramatic event happened. An ambitious project like this would have marked a decisive unprecedented turning in the engineering field for renewable energy sources. But the tragedy was around the corner, and we could say that it had already been written during the first test of the dam. In a letter dated April 20, 1961, Dr Semenza, the project head, says, “Dopo tanti lavori fortunati e tante costruzioni anche imponenti, mi trovo veramente di fronte ad una cosa che per le sue dimensioni mi sembra sfuggire dalle nostre mani" (After many lucky works and impressive constructions, I really face something that for its size seems to me to escape from our hands) (Busetto & Gaiani, 1964).

In this paper our main goal is to apply the model for the analysis of slope stability based on limit equilibrium theory that was developed between 2006 and 2008 by Tinti and Manucci (Tinti & Manucci, 2006 and 2008) and later revised by two of the authors (Paparo & Tinti). This model will be designated as MLD (Minimum Lithostatic Deviation) model throughout the paper. We will also compare some of our results with those obtained by using the classical methods found in the literature and reformulated in a way coherent with the MLD model.

THE GEOLOGY OF THE SLIDE

The Vajont valley is located in the north of the Venetian Prealps and the homonymous torrent incised the gorge along an E-W trending axis, by eroding it along a synclinal (Giudici & Semenza, 1960; Ghirotti, 1992). The particular shape of the valley is mainly due to two erosive phases: the widest part formed in the Würmian glacialism, and the deepest and narrow part during an intermediate or post-glacial phase (Carloni & Mazzanti, 1964b; Carli, 2011).

The slope of the Mt Toc from which the slide detached and the slide body itself were the object of very many geological and geotechnical investigations especially over the years immediately before and after the slide occurrence. The slope was found to be formed by a succession of layers of dolomitic limestone, spaced by thin layers of clays (Genevois & Ghirotti, 2005). But for some years after the disaster, the presence of clay in the rock layers was not commonly accepted and considered questionable (Broili, 1967; Müller, 1968). In our analysis we assume that the slope is composed of Jurassic rocks and that the slide took place in the Fonzaso formation along a slipping surface corresponding to interbeds of clay (Rossi & Semenza, 1965; Semenza, 1965; Genevois & Ghirotti, 2005).

In addition to the specific characteristics of the soil, rain was considered soon a key factor for the stability of the Vajont slopes. During the four years of filling and lowering of the basin level after the dam was built, rainfall was object of careful monitoring. Official monthly and daily precipitation records taken at Erto on the Vajont slope opposite to the one that failed (Hendron & Patton, 1985) are shown in Fig. 1. It can be seen, as expected, an annual cyclicity (monthly panel) with narrow peaks, the highest one occurring in spring 1962. Notice also that a sequence of precipitation peaks was recorded in fall and winter of 1960.

The qualitative interpretation of the effect of prolonged rainfall is that it may leads to failures in stratified soil over an impermeable layer. This is because rain water infiltrations penetrate into the ground until reaching the impermeable layer, over which a water saturated band tends to form with reduced mobilised strength. Consequently the safety factor – see the formal definition in the next section – may drastically decrease (Fredlund & Rahardjo, 1993; Fredlund & Xing ,1994; Kim *et alii*, 2004). In more general terms the increase of the piezometric level is known to correlate quite well with the decrease of the safety factor (Kaneko *et alii*, 2009). It can be stated that creeping processes and ultimately slope failures, and in general the attaining of critical conditions for stability, are more probable to occur after intense and repeated periods of precipitation.

As for the Vajont case, the slope that was to fail in 1963 and whose movements were being monitored by means of a system of benchmarks exhibited a remarkable peak of downslope creep velocity (up to 5 cm/day) after the heavy precipitations in the fall of 1960, as shown in Fig. 2.

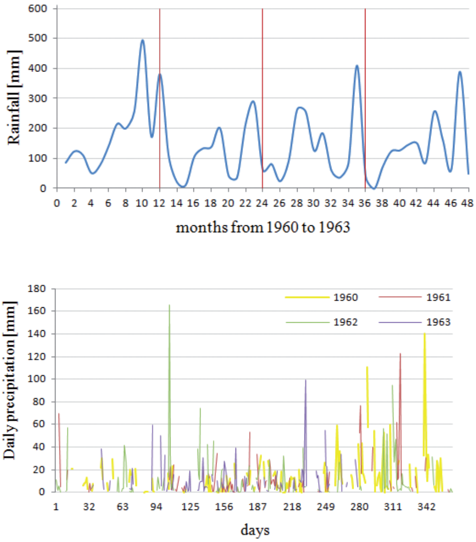

Fig. 1 - Precipitation in mm recorded at Erto from 1960 to 1963 (after Hendron & Patton, 1985). Monthly (upper panel) and daily (lower panel) values

One additional factor playing a role is the level of the Vajont reservoir. Since the dominant material of the valley is limestone, whose permeability is higher than that of clay, if on increasing the basin level a limestone layer is intercepted, then the basin water may infiltrate laterally the underwater slope and form an aquifer confined on the top by impermeable clay layers, and this may cause a decrease of the shear stress along the sliding surface (Faukker & Rutter, 2000; Crawford *et alii*, 2008; Van De Reep, 2009) and favour slope destabilisation.

LIMIT EQUILIBRIUM THEORY

There is a variety of methods proposed for the assessment of the stability of a slope. We focus here on the limit equilibrium approach that is one of the most commonly used in the engineering field. For the sake of brevity and clarity, we will provide only an outline of the method, and present the main formulas we applied in our study.

The limit equilibrium method is widely used since it represents a simple and practical approximation to describe the equilibrium of a mass having the potential to detach and slide along a slope. Usually and also here it is applied to two-dimensional profiles and the mass is divided into blocks or slices by vertical cuts (Bishop, 1955). It is based on the definition of the parameter F, which takes the name of safety factor, given by the ratio

$$F = \frac{S_{\max}(x)}{S(x)}$$

where $S_{max}(x)$ is the mobilized shear strength at any point along the slip surface and *S(x)* is the shear stress at the corresponding point. This parameter can assume different values, depending on the condition of the slope: when it is equal to 1 the blocks are subject to the maximum shear stress sustainable along their base. Therefore when the ratio falls below 1 the blocks are no longer in balance and the whole system becomes unstable and is ready to move. On the contrary, if the value is greater than 1, the system is stable.

The mobilized shear stress can be expressed by means of the failure criterion introduced by Mohr-Coulomb in the following way

$$S_{max}(x)=c(x)+[P(x)-u(x)]\tan\varphi(x)$$

where *c(x)* is the cohesion, *P(x)* is the normal stress along the slip surface, *u(x)* is the pore pressure and *φ(x)* is the angle of shearing resistance (Fellenius, 1936; Terzaghi, 1943, Bishop, 1955).

Let's consider a 2D generic slice of the body with vertical side walls placed at *x-dx/2* and *x+dx/2* where *dx* is the horizontal slice width, and let's denote the slip surface and the top surface of the body by the functions $z_1(x)$ and $z_2(x)$ respectively. If the base and the top surfaces have local inclination angles *α* and *β*, then the following equilibrium conditions should hold (see Tinti & Manucci, 2006, for details):

$$\frac{dE}{dx} + P\tan\alpha - S - D\tan\beta = 0$$

$$\frac{dX}{dx} + P + S\tan\alpha - D - \rho g(z_2 - z_1) = 0$$

$$\frac{dA}{dx} - X - D\tan\beta(z_2 - z_1) = 0$$

The first two equations come from imposing the equilibrium of the horizontal and vertical components of the forces acting on the slice, while the third one comes from the momentum balance. In the above equations *P* and *S* denote the respective normal and shear components of the stress taken at the base of the slice, *E* and *X* are internal normal and vertical forces applied on the vertical slice walls, *A* is related to the momentum associated with internal forces, *D* is a load function applied on the slice top, ρ is the soil density and g the gravity acceleration. In the problem, the functions *X(x)*, *E(x)* and *A(x)* have to satisfy the conditions at boundaries of the slide, i.e. in the positions x_i and x_f where the slide starts and ends:

$$E(x_i) = E(x_f) = X(x_i) = X(x_f) = A(x_i) = A(x_f) = 0$$

The functions *P(x), S(x), X(x), E(x)* and *A(x)* are unknown and since their number is greater than the number of equations which describe the problem, there cannot exist a unique solution (Tinti & Manucci, 2006, 2008).

In the following we briefly outline the MLD meth-

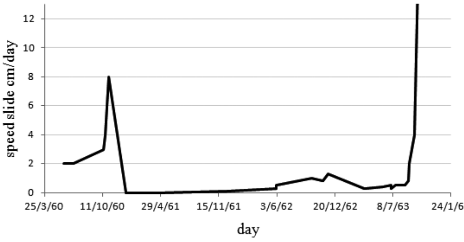

Fig. 2 Rate of creeping recorded on the slope that was involved by the Vajont slide from 1960 to 1963 (after Hendron & Patton, 1985)

od by Tinti & Manucci (2006) that introduces a minimization principle to find a solution to the problem.

MINIMUM LITHOSTATIC DEVIATION METHOD

The method of the Minimum Lithostatic Deviation (MLD) was developed from 2006 to 2008 by Tinti and Manucci (Tinti & Manucci, 2006; 2008). Since an infinite number of solutions exist to the problem of equilibrium in the formulation of the limit equilibrium theory, it was noted that one can always find a solution where F is smaller than 1 or larger than 1, and therefore find that the slope is at the same time unstable and stable. This inherent ambiguity was corrected by introducing a minimization criterion and by considering F not as an unknown like it is assumed in the classical methods (Fellenius, 1936; Bishop, 1955; Janbu, 1957, 1973; Aryal *et ali*, 2006; Spencer, 1967), but as a free parameter. The best solution was assumed to be the one minimising the lithostatic deviation, that was defined as:

$$\delta = W^{-1}\left[\frac{1}{(x_f - x_i)}\int_{x_i}^{x_f}[E(x)^2 + X(x)^2]\,dx\right]^{\frac{1}{2}}$$

This is the ratio of the average magnitude of the inter-block forces and the total weight W of the sliding mass. A range of values of F is given as input, [F_{min}; F_{max}], where F_{min} is smaller than 1 and F_{max} is larger, and for each of them the problem is solved. The value of F providing the solution with the smallest value of δ is taken as the safety factor of the slope.

In Figures 3 to 5 the solutions we found for the profile 2 of the Vajont slide (see next section) by means the MLD method and some of the most common classical methods. In the application of the MLD method, the solution was searched by imposing that $X(x)$ is a sine series truncated to the third order (see Tinti & Manucci, 2006, for details). The curves shown in the Figs. 3, 4 and 5 are the unknown functions $E(x)$, $X(x)$ and $A(x)$ and should vanish at the beginning and at the end of the trial slide as imposed by the boundary conditions. It can be seen that the plotted curves do not differ too much from one another, but only the curves calculated through the Spencer's method and through the MLD method fulfil the conditions in all the graphs.

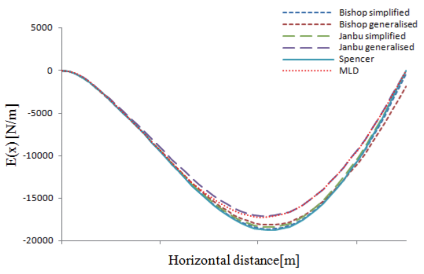

Fig. 3 - *Curves of the horizontal inter-slice force E(x) for different methods. At the boundaries the function E should vanish. Notice that none of the Bishop methods (simplified and generalised) provide a solution that goes to zero at the right boundary. Curves refer to the profile 2 of the Vajont slide in case of dry soil and water basin at the level of 700 m a.s.l*

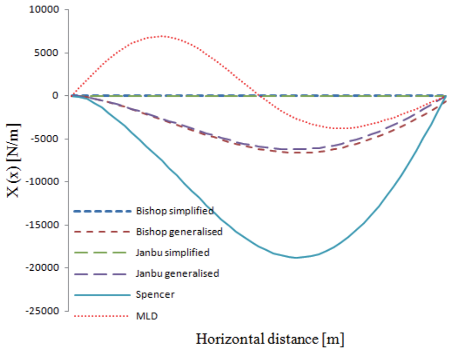

Fig. 4 - *Curves of the vertical inter-slice force X(x) for different methods. Notice that, like in Fig.3, the generalised Bishop method provides a solution that does not vanish at the right boundary. Notice further that X is assumed to be identically equal to zero by the simplified Bishop method. The horizontal x axis is the same as in Fig.3. See caption of Fig. 3 for further details*

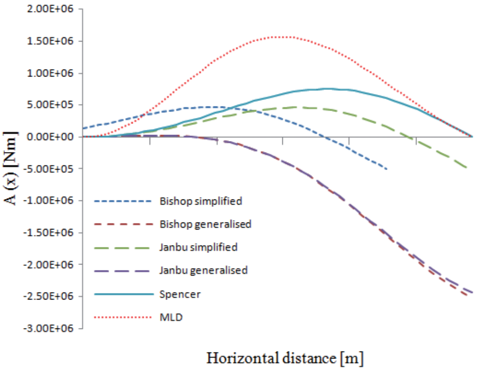

Fig. 5 - *Curves of the momentum A(x) for different methods. Only for the Spencer and MLD method A vanishes at both boundaries. The horizontal x axis is the same as in Fig. 3.Other details in caption of Fig.3*

ANALYSIS OF STABILITY

To analyse the stability of a slope one needs a trial basal curve representing the boundary where the rupture is going to take place. In principle, the rupture surface in 3D analyses, or the rupture curve in 2D, is unknown. In this case a number of potential curves are examined and one takes the one giving the smallest value of the safety factor, under the assumption that it is the most prone to break. This kind of approach is appropriate to examine stability before failures, which is the most common application. In this paper we study a slope, namely Mt Toc flank, where a failure already occurred, and that therefore showed to be unstable. The purpose therefore is to find the main factors leading to the instability over a surface that is already known.

We take advantage of the reconstruction of the sliding surface of the Vajont slide that was made by the authors to investigate the dynamics of the slide (see Zaniboni & Tinti, 2013 and Zaniboni *et alii,* 2013). The surface was obtained by exploiting the available topographies of the pre-slide (in front of the slide) and of the post-slide (in the detachment niche) slopes and by connecting them in the intermediate section on the basis of the conjecture that the west side and the east side of the surface have distinctly different shapes: namely chair-like downslope cross-sections on the west and parabolic on the east (see Selli & Trevisan, 1964 & Hendron & Patton, 1985). The conjecture is based on the main observation that breaking occurred in correspondence of an exposed clay layer on the west while affected limestone on the east and it was proven to imply that the slide experienced very different basal friction in the two sides (Zaniboni *et alii*, 2013).

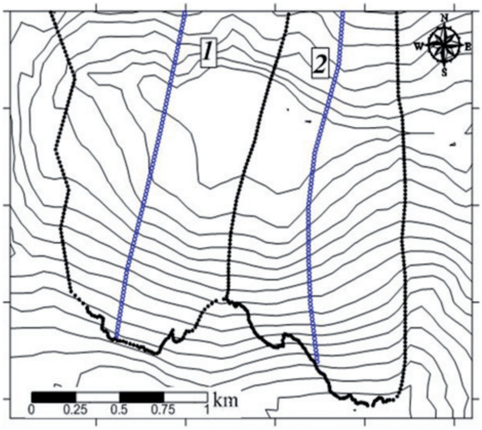

Fig. 6 - Topography of the sliding surface (after Zaniboni et alii, 2013) and boundary of the area swept by the slide during its motion. The slide is subdivided in two parts. For each part we selected one profile

The reconstructed topography over which the mass slid down is depicted in Fig. 6, where also the boundary of the area that was swept by the moving slide is given. In this paper we have selected two profiles as trial curves for the stability analysis, also plotted in the Fig. 7: profile 1 on the west and profile 2 on the east side.

Cross-sections of both profiles are portrayed in Fig. 7, where also the top of the slide (pre-failure topography) together with the level of water basin and of a possible piezometric line are shown. The trial surfaces are approximated by circumference arcs, also plotted in Fig. 7, we used to apply classical limit equilibrium methods

Tables 1 and 2 report the geotechnical parameters we used to study the stability of the respective profiles 1 and 2, that are taken from the literature (Hendron & Patton, 1985). As the first step of the analysis we have considered profile 2 and have used the assumptions that there is no water in the basin

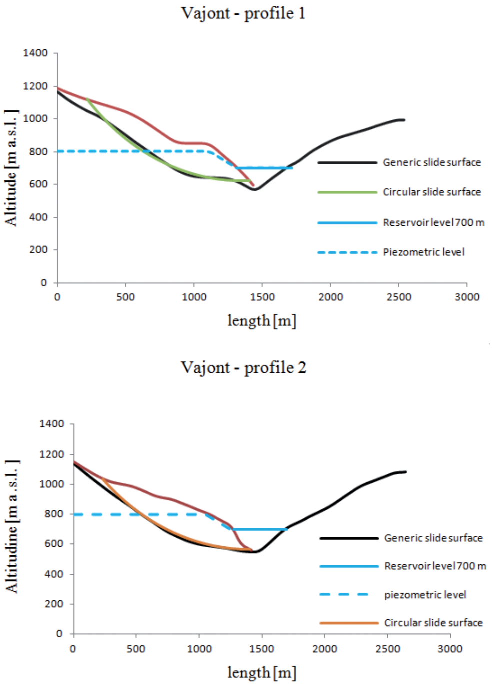

Fig. 7 - Cross-sections of the profiles 1 and 2 selected for the stability analysis. The best fitting circumference arcs are the trial curves we used for the classical stability methods. The basin level and a possible piezometric level are also shown

and that the soil is perfectly dry. The computed values of the safety factors are given in Fig. 8. Classical methods were conceived for arc-like trial curves only and hence the profile base has been approximated by a circumference arc. On the other hand, we mention that an extension of those methods was developed by two of the authors (Paparo & Tinti) to allow the application to generic trial curves.

By looking at Fig. 8 it is clear that all the methods predict that the slope is stable with F ranging however between 1.10 and 1.4, with the generalized Janbu's method giving the smallest value and the generalized Bishop's method the largest one. Further, it is also evident that approximating the bottom surface by a circumference arc leads to a systematic increase of the estimates for *F*. Differences between the computed values are small, but not negligible. For the rest of the analysis we will use only the MLD method and drop the unnecessary approximation of the arc-like bottom.

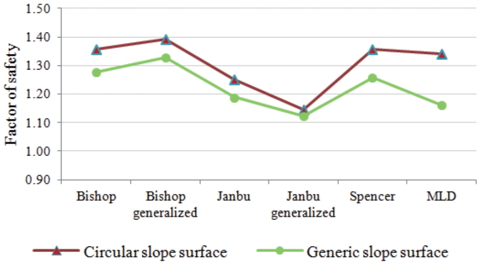

Fig. 8 - Values of the factor of safety computed for profile 2 with unsaturated soil by means of all the methods mentioned in the paper

Specific weight of the Vajont limestone 26 KN/m^3
Friction angle of the fissured limestone - clay contact 22°
Friction angle in saturation conditions 8°
Coefficient of cohesion 20 kPa
Coefficient of cohesion in saturated conditions 10 kPa

Tab. 1 - Geothecnical parameters for profile 1 (Hendron & Patton, 1985)

Specific weight of the Vajont limestone 26 KN/m3
Friction angle of fissured limestone 22°
Friction angle in saturated conditions 17°
Coefficient of cohesion for a rock fracture matrix 20 kPa
Coefficient of cohesion in saturated conditions 10 kPa

Tab. 2 - Geothecnical parameters for profile 2 (Hendron & Patton, 1985)

Case 1	Unsaturated soil , hydrostatic load: increasing the basin level to 710 m
Case 2	Like case 1 + piezometric level aligned with basin level
Case 3	Like case 2 + lower cohesion below the basin level
Case 4	Like case 2 + lower friction angle below the basin level
Case 5	Like case 2+ lower cohesion and friction angle below the basin level
Case 6	Like case 5 + increasing the piezometric level placed up to 790m, with constant basin level at 710 m

Tab. 3 - Cases analyzed in the slope stability study

The stability of profiles 1 and 2 was studied with the goal of examining the influence of the various factors intervening in the process. The main idea is that the slope is affected by lateral infiltration of the water from the basin and by infiltration from the top of rain water. Both processes determine the increase of the piezometric level with consequent increase of the interstitial pore pressure. We make the further hypothesis that varying the water level in the basin affects also the properties of the rock, passing from unsaturated to saturated soil conditions (see Tabs 1 and 2) (Lee & De Freitas , 1989; Kim *et alii*, 2004). Our analysis is static, that is time-independent and neglects the time needed to transform dry soil into saturated soil. Further we assume that the soil is saturated below the level of the water in the basin and unsaturated above, which means that increasing the basin level increases the portion of the bottom surface characterised by saturated soil properties.

We have examined the cases listed in Tab. 3 and the results are shown in Figs. 9 and 11 for profile 2 and in Figs. 10 and 12 for profile 1.

The general trends of the curves are similar for both profiles but differ significantly from case to case. In case 1 we use the properties of a dry soil (see Tables 1 and 2) and we consider the load of hydrostatic nature exerted by the water in the reservoir on the slope,

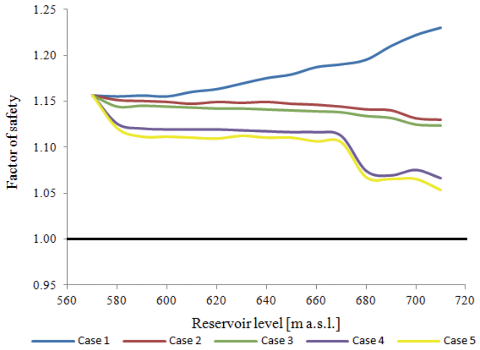

Fig. 9 - Trend of F with varying reservoir level for cases from 1 to 5 of Tab. 3 for profile 2

tending to stabilize it. It is seen that the safety factor increases, along with the level of the water in the basin. The maximum water level considered in the analysis is 710 m asl. Though the highest allowed level according to engineering specification for the Vajont dam was 722 m asl, the level of 710 m asl was the highest reached during the reservoir filling tests carried out by the dam engineers.

It is found that on increasing the water level by about 140 m the safety factors increases by less than 0.1 in both profiles. In addition to the stabilizing water load, case 2 includes laterally infiltrated water and assumes that the piezometric level is the same

as the basin level. According to the Mohr-Coulomb criterion, an increment of the pore pressure following the raise of the piezometric level entails a reduction of the mobilized shear stress and weakening of the slope. From Figs. 9 and 10 it seems that the resulting safety factor remains almost constant, varying only by less than 0.03. This means that the destabilization effect of pore pressure increase counteracts and slightly exceeds the hydrostatic stabilization of the basin.

Cases 3 and 4 consider the effect of the change of the properties of the rocks in the transition from dry to saturated values of the cohesion and of the friction angle. As already enunciated above, it is assumed that at the interface between the slide and the underlying rock, that is on the bottom surface of the slide, one finds the saturated lower cohesion and lower friction angle values below the basin level, while above that level the dry values are found. It follows that increasing the water in the basin implies an extension of the area of the bottom surface where the mobilized shear strength is lower, and hence a lower safety factor is expected. It is worth noting that in these cases the piezometric level is also changed exactly as in case 2. The effects of cohesion and friction angle changes are studied separately. It is seen that lowering cohesion (case 3) is much less effective than lowering the friction angle (case 4). And this is also confirmed where both effects are considered together (case 5), since the safety factor curve of case 5 is yet lower but only slightly than the curve of case 4.

Case 5 is the one providing the lowest values of the safety factor and the smallest value of F is expectedly corresponding with the highest basin level considered in the analysis. If we compare findings for profiles 1 and 2, we see that both profiles remain stable for any level of the water and that profile 2 is closer to instability conditions than profile 1. Further we observe that curves of in Fig. 10 are more regular than the ones of Fig. 9. Especially when the changes of friction angle are taken into account (cases 4 and 5) curves show a quick decrease (around level 660-690) for profile 2, where they decrease steadily for profile 1, which is probably to be linked with the different geometries of the two profiles.

Case 6 considers a condition where the water basin is kept constant at the level of 710 m asl, and the piezometric line is increased from 710 m to 790 m (Hendron & Patton, 1985). This increase can be viewed as the consequence of heavy rains and rain water infiltration in the slide from the top surface. So what is studied here is the effect on stability of an increased pore pressure, all the rest remaining unchanged. The results are shown in the plots of Figs. 11 and 12 respectively for profiles 2 and 1. For both profiles one can observe that the safety factor further

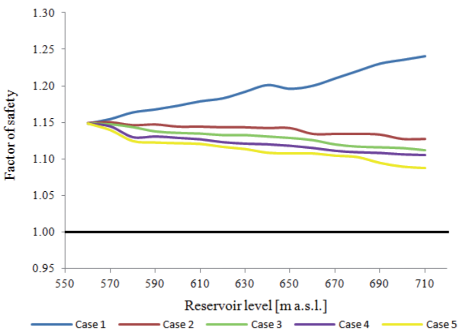

Fig. 10 - Trend of F for profile 1 for different cases from 1 to 5 (see Tab. 3)

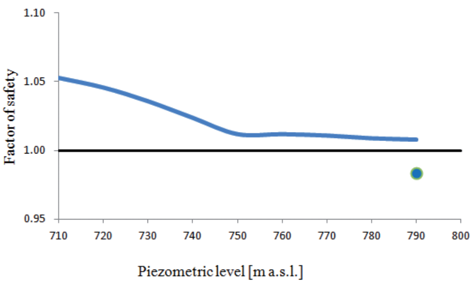

Fig. 11 - Trend of F for case 6, profile 2. While keeping the reservoir level constant at 710 m, we raise the piezometric level from 710 to 790 m (Hendron & Patton, 1985). Lowering the level basin from 710 m to 700 m, instability conditions are attained (blue dot)

decreases and reaches values quite close to the critical condition of failure.

As a final consideration we have considered a sudden decrease of the water level from 710 m to 700 m, without any further change of the other conditions. As seen in the analysis of case 1, decreasing the level destabilizes the slope. And indeed what is obtained is that for both profiles the safety factors drops below 1 (blue dot points in the graphs) and both profiles reach conditions for failure. This last step, though sounding artificial, respects indeed what happened in the Vajont valley on October 9th 1963. The slide occurred after the level of the basin was lowered down to 700 m and after a period of heavy rainfall.

DISCUSSION AND CONCLUDING REMARKS

The main purpose of this paper was to study the stability condition of the flank of Mt Toc that was involved in the Vajont slide and the consequent disaster. In this paper we have applied the limit equilibrium theory in a variant, denoted minimum lithostatic deviation (MLD) method that was developed by Tinti & Manucci (2006 and 2008).

In the first part of the paper a short outline of the basic limit equilibrium theory and of the MLD method was given. It was also noted that the classical limit equilibrium methods in their original formulation require a slide bottom with an arc shape and that a generalisation was developed by two of the authors (Paparo and Tinti) to account for generic bottom surfaces. The most common classical methods and the MLD method were applied to an exemplary case and were shown to provide similar results though with differences that cannot be neglected. Indeed the case examined as an example was the profile 2 of the Vajont slide, and the values of *F* we found are in the range 1.1-1.4 with a spread that is much higher than changes produced by physical factors (pore pressure, cohesion, friction angle).

The analysis of the slope was performed by using the MLD method and was applied to two profiles that were obtained by cross-cutting the sliding surface of the Vajont slide as reconstructed by Zaniboni *et alii* (2013): one profile on the west- and one profile on the east-side where geometries and conditions are different following conjectures by Hendron & Patton (1985).

We have examined the separate and the combined effect of increasing the pore pressure, of decreasing the inner cohesion and of decreasing the angle of friction of the material forming the slide. As expected, the pure hydrostatic load was found to increase stability (case 1) of the slope, while increasing the piezometric level and decreasing coherence and friction coefficient were found to favour instability (cases 2-5). One of the findings was that after heavy rain and with the basin level at 710 m both profiles are very close to instability, but still stable. However, lowering the level down to 700 m causes the safety factor to go below the critical threshold of 1 (case 6), which reflects the last sequence of the historical facts leading to the collapse of the slope on 9th October 1963.

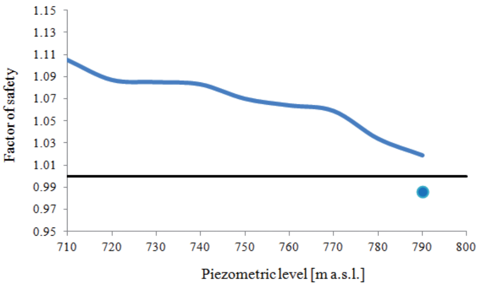

Fig. 12 - *Trend of F for case 6, profile 1. See caption of Fig.11 for further details*

The analysis we have performed is still preliminary and needs both an extension (analysis of more profiles) and a validation of the geotechnical parameters that have been used to study instability. It seems that the angle of friction is by far more influential than the cohesion for the stability analysis of this case, and therefore more specific studies should be addressed to a better determination of its values and how they can change in the transition from dry, unsaturated and saturated rocks. It is worth noting that the hypothesis of a heterogeneous slide surface with the west side differing from the east side (see Tabs 1 and 2) is corroborated by the dynamical study of the Vajont slide performed by Zaniboni *et alii* (2013) where it was found that the friction coefficient has to be much smaller on the west than on the east to obtain a good fit between the numerical results and the observations (namely slide deposit and peak velocity).

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REFERENCES

ARYAL K., GRANDE L. & SANDVEN L. (2006) - *A study on interslice force function and line of thrust in slope stability analysis.* In: SCHWEIGER (ED.). *Numerical methods in geotechnical engineering.* Taylor & Francis Group, London: 497-500.

BISHOP A.W. (1955) - *The use of the slip circle in the stability analysis of slopes.* Geotechnique, **5**: 7-17.

BROILI L. (1967) - *New knoledge on the geomorphology of the Vaiont Slide slip surfaces*. Rock Mechanics & Eng. Geol. Jour. Int. Soc. Rock Mechanics, **V** (1): 38-88.

BUSETTO & GAIANI (1964) - *Commissione parlamentare d'inchiesta sul disastro del Vajont. I gruppo di lavoro: Nota sugli studi tecnico scientifici connessi alla concessione delle acque e alla costruzione dell'impianto del Vajont* (in Italian).

CARLI M. (2011) - *Thesis of Geological structural mapping and geoelectrical investigation of the North-occidental portion of the Vajont landslide in the Venetian Prealps.* Dipartimento di Scienze Geologiche, Università degli Studi di Padova.

CARLONI G.C. & MAZZANTI R. (1964 b) - *Aspetti geomorfologici della frana del Vaiont.* Riv. Geogr. It., **71**: 201-231 (in Italian).

CRAWFORD B.R., FAULKNER D.R. & RUTTER E.H. (2008) - *Strength, porosity, and permeability development during hydrostatic and shear loading of synthetic quartz-clay fault gouge.* Journal of Geophysical Research, **113**.

FAULKNER D.R. & RUTTER E.H. (2000) - *Comparisons of water and argon permeability in natural clay-bearing fault gouges under high pressure at 20°C.* Journal of Geophysical Research, **105**: 16415-16426.

FELLENIUS W. (1936) - *Calculation of the stability of earth dams.* Proceedings of the 2nd Congress on Large Dams, **4**: 445-463.

FREDLUND D.G. & RAHARDJO H. (1993) - *Soil mechanics for unsaturated soils.* Wiley, New York.

FREDLUND D.G. & XING A. (1994) - *Equations for the soil-water characteristic curve.* Canadian Geotechnical Journal, **31**: 521-532.

GENEVOIS R. & GHIROTTI M. (2005) - *The 1963 Vaiont Landslide.* Giornale di Geologia Applicata, **1**: 41-53.

GHIROTTI M. (1993) - *Nuovi dati sulla frana del Vaiont e modellazione numerica.* Geol. Rom., **30**: 207-215 (in Italian).

GIUDICI F. & SEMENZA E. (1960) - *Studio geologico del serbatoio del Vajont.* Unpublished report for S.A.D.E.

HENDRON A.J. & PATTON F.D. (1985) - *The Vaiont slide, a geotechnical analysis based on new geologic observations of the failure surface.* I, II, Technical Report GL-85-5. U.S. Army Eng. Waterways Experiment Station, Vicksburg, MS.

JANBU N. (1957) - *Earth pressure and bearing capacity calculations by generalised procedure of slices.* Proceedings of the 4th International Conference, SMFE, London, **2**: 207-12.

JANBU N. (1973) - *Slope stability computations. Embankment dam engineering.* Casagrande Volume: 47-86.

KANEKO H., TANAKA H. & KUDOH Y. (2009) - *Slope stability consisting of two different layers caused by rainfall.* In: OKA, MURAKAMI & KIMOTO (EDS.). *Prediction and simulation methods for geohazard mitigation*. Taylor & Francis Group, London.

KIM J., JEONG S., PARK S. & SHARMA J. (2004) - *Influence of rainfall-induced wetting on the stability of slopes in weathered soils.* Engineering Geology, **75**: 251-262.

LEE S.G. & DE FREITAS M.H. (1989) - *A revision of the description and classification of weathered granite an its application to granites in Korea.* Quarterly Journal of Engineering Geology, **22**: 31-48.

MÜLLER L. (1964b) - *The rock slide in the Vaiont valley.* Felsmech. Ingenieurgeol., **2**: 148-212

MÜLLER L. (1968) - *New Considerations on the Vaiont Slide.* Rock Mech. Eng. Geol., **6**: 1-91.

ROSSI D. & SEMENZA E. (1965) - *Carte geologiche del versante settentrionale del M. Toc e zone limitrofe, prima e dopo il fenomeno di scivolamento del 9 ottobre 1963, Scala 1:5000.* Istituto di Geologia, University of Ferrara, Ferrara (in Italian).

SEMENZA E. (1965) - *Sintesi degli studi geologici sulla frana del Vajont dal 1959 al 1964.* Memorie del Museo Tridentino di Scienze Naturali, **16**: 1-52 (in Italian).

SEMENZA E. & GHIROTTI M. (2000) - *History of 1963 Vaiont Slide. The importance of the geological factors to recognise the ancient landslide.* Bull. Eng. Geol. Env., **59**: 87-97.

SPENCER E. (1967) - *A method of analysis of the stability of embankments assuming parallel interslice forces.* Geotechnique, **17**: 11-26.

TERZAGHI K. (1943) - *Theoretical soil mechanics.* John Wiley & Sons, Inc., New York, N. Y.

TINTI S. & MANUCCI A. (2006) - *Gravitational stability computed through the limit equilibrium method revisited.* Geophysical International Journal, **164**: 1-14.

TINTI S. & MANUCCI A. (2008) - *A new computational method based on the minimum lithostatic deviation (MLD) principle to analyse slope stability in the frame of the 2-D limit-equilibrium theory.* Nat. Hazards Earth Syst. Sci., **8**: 671-683.

VAN DE REEP (2009) - *Permeability of limestone-dolomite composite fracture surfaces.* Honour Thesis

VEVEAKIS E., VARDOULAKIS I. & DI TORO G. (2007) - *Thermoporomechanics of creeping landslides: the 1963 Vaiont slide, northern Italy.*

Journal of Geophysical Research, **112**: F03026

Zaniboni F. & Tinti S. (2013) - *Numerical simulations of the 1963 Vajont Landslide, Italy: Application of 1D Lagrangian Modelling.* Natural Hazards, submitted.

Zaniboni F., Paparo M.A. & Tinti S. (2013) - *The 1963 Vajont landslide analysed through numerical modeling.* In this volume.