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Hydrodynamics and Rheology: Key Factors in Mechanisms of Large Landslides

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Abstract

When checking the behaviour of large landslides, deterministic stability analysis has little sense. Stability coefficients can only be seen as the relationship between acting and reacting forces. In fact, large landslides simply move in any case, more or less quickly. When stable, the displacements are actually so small that they aren't detectable. Thus the so called security factor could always be set to unity, and the computations performed as back analysis. The transition from a very slow viscous displacement to a catastrophic failure is better described in a change of rheological behaviour than in an overtaking of a stability coefficient. Actors of such changes are in most cases the hydrodynamic and hydrogeological conditions, related to external factors such as climatic changes, weathering, natural or artificial deforestation, etc. Two cases located in the south Alps, one in Switzerland and the second in Italy, involving weathered metamorphic rocks are taken as illustrating examples.

Introduction

The use of stability analysis with deterministic methods, based on the balance between driving and braking forces, is commonly used. Driving forces are ruled by gravity and geometry of the instable body and the assumed surface where shear occurs. Resisting forces derive from friction, cohesion, pore pressure, manmade supports, etc. Sometimes supplementary forces are introduced in the models to simulate dynamic conditions due to earthquakes or blasting. This so called limit equilibrium condition approach is depends on a certain number of assumptions, realistic for small slopes, but which cease to be legitimate when examining large slope instabilities.

The first fundamental assumption is that all the physical phenomena that are considered in the calculation are limited to the slide surface, or eventually also in the interface separating slices of the modelled geometry. Nothing is supposed to happen inside the slide mass. Another assumption is that all distinct bodies (slices) of the models are rigid. Further, the limit equilibrium approach uses exclusively static rules, as said above, for earthquake or blasting influence, where dynamics are translated in statics.

For large landslides, all these assumptions are not respected, and alternative physical models are necessary for a realistic analysis of the phenomena. Unfortunately, official codes and rules tend to introduce compulsory safety factors for reclaim designs to be approved. This is dangerous in the sense that large landslides, especially by reactivation of ancient slides, can only have safety factors very close to unity. If presented with factors reaching 1.3, the calculation cannot describe the reality in an affordable way. The two cases presented hereby are used to sustain this motion.

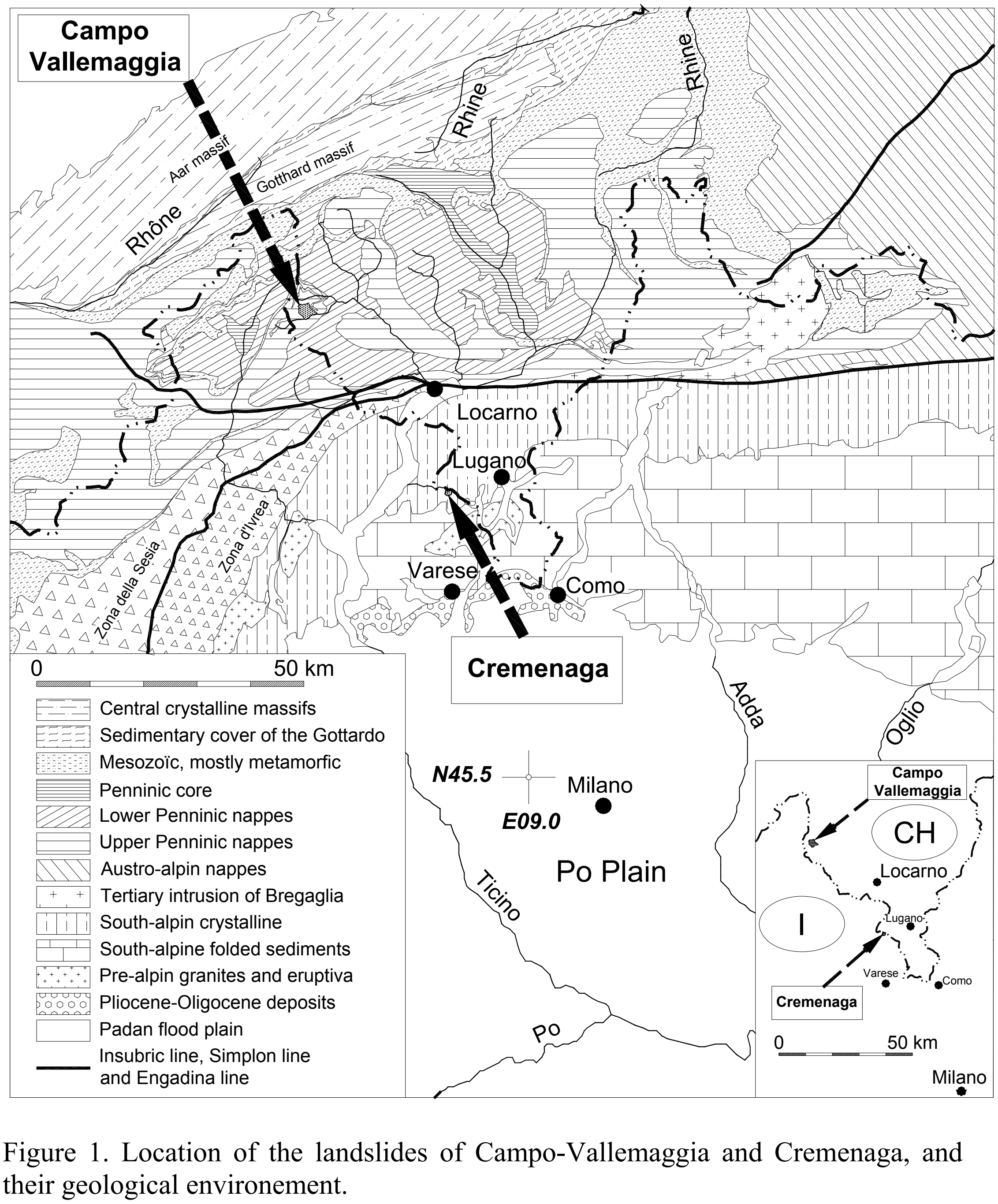


Figure 1. Location of the landslides of Campo-Vallemaggia and Cremenaga, and their geological environement.

	Campovallemaggia	Cremenaga
Total volume (cubic meters)	800'000'000	5'000'000 (approx.)
Maximun depth (meters)	300	120
Average velocity (cm/years)	5	'ca 10
Surge velocity (cm/day)	'ca10	Unknow

Table 1. Main Characteristics of landslides of Campovallemaggia (CH) and Cremenaga (I).

The slide of Campo Vallemaggia

The Campo Vallemaggia landslide is located in the crystalline Penninic nappes of the southern Swiss Alps, in the Italian speaking Canton of Ticino (see Figure 1). This deep-seated, creeping landslide is very large. It reaches depths of up to 300 m and a volume of about 800 million m^3. The body of the slide mass is subdivided into several blocks by sub-vertical fault zones varying in thickness from a couple of metres to tens of metres, with sub-horizontal slip zones developed along lithological boundaries, foliation or zones of differentiated weathering. As a result of this complex geometry (see Figure 2), its movements are complex and difficult to describe with simple geomechanical models.

Recorded observations in the villages go back 200 years, and geodetical observations about hundred years, which is a rare opportunity for information. The horizontal displacement of the slide mass has reached approximately thirty metres between 1892 and 1995. In the same period, the vertical displacements has reached 7 meters.

The analysis of the deformations showed a pulsing or “stick-slip” behaviour. The average displacements was of about 5 cm/year. Accelerated movements were usually associated with periods of intense precipitation, but a clear correlation between rainfall and displacement is not evident. It seems that the slide "charge" itself over a period of a couple of tens of years. Than, a relatively modest meteorological event could trigger a dramatic acceleration of up to many centimeters every day. Afetr a short time, background velocities are again observed, even if new heavy precipitations occur.

The investigations have clearly demonstrated that the Campo-Vallemaggia Landslide is beeing controlled by high pore pressures (Bonzanigo, 1999, see Figures 2 and 3). The importance of water embedded in the slide was recognized as early as more than a hundred years ago (Heim, 1892), but the loss of abutment due to erosion was seen for a long time as responsible for the consequent damages.

Between 1993 and 1996, a drainage adit in the bedrock under the slide, equipped with borholes reaching the instable mass stopped the slide, as far as the residual displacements are below the resolution of measurements (Bonzanigo, 2000, Bonzanigo et al., 2006).

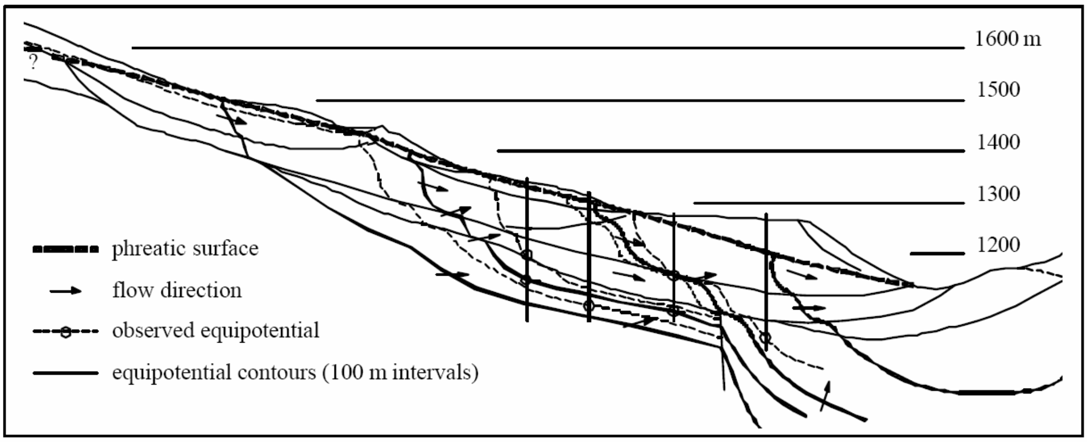


Figure 2. Geometry with pore pressure and flow pattern in the Campovallemaggia landslide, as reconstucted on the basis of observed heads.

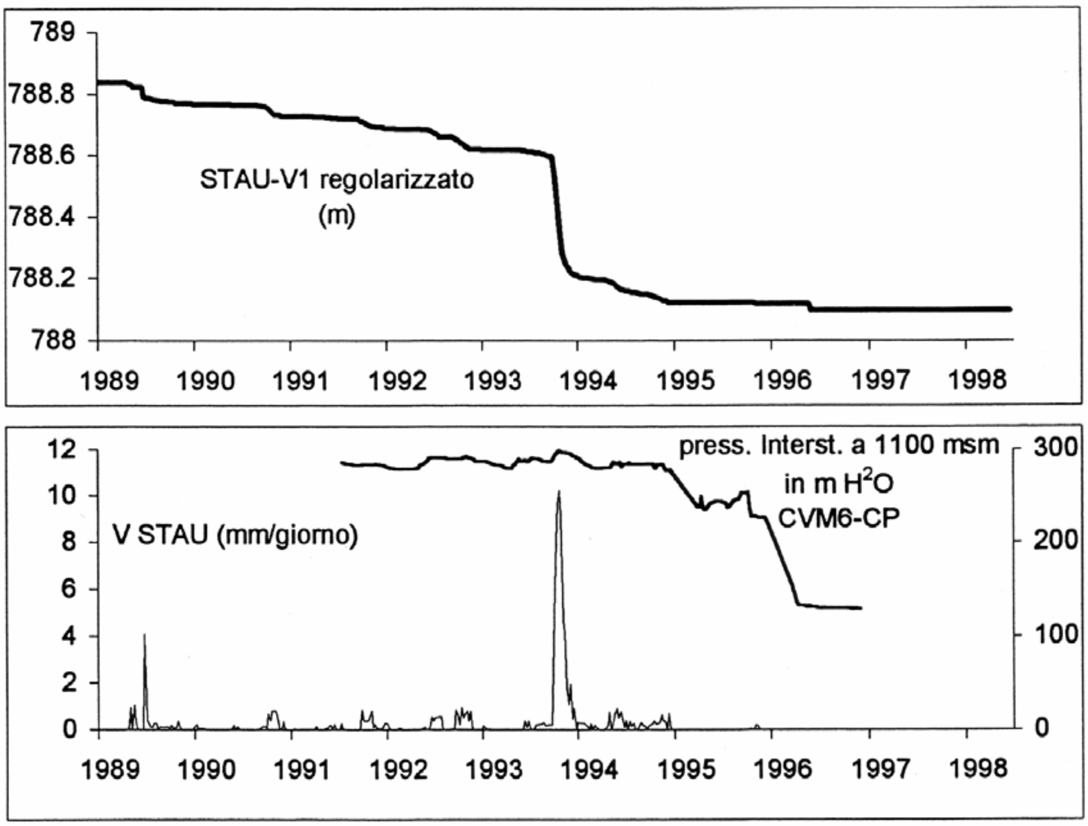


Figure 3. Evolution of pore pressure measured in a borehole and displacement velocity, before and after the drainage.

The slide of Cremenaga

Not very far from Campovallemaggia, another slide present some analogies, but at reduced dimensions. It is situated along the river Tresa which constitute the border between Switzerland and Italy (see Figure 1). At the toe of this landslide, an important road was cut with severe inconvenience to local and international connections.

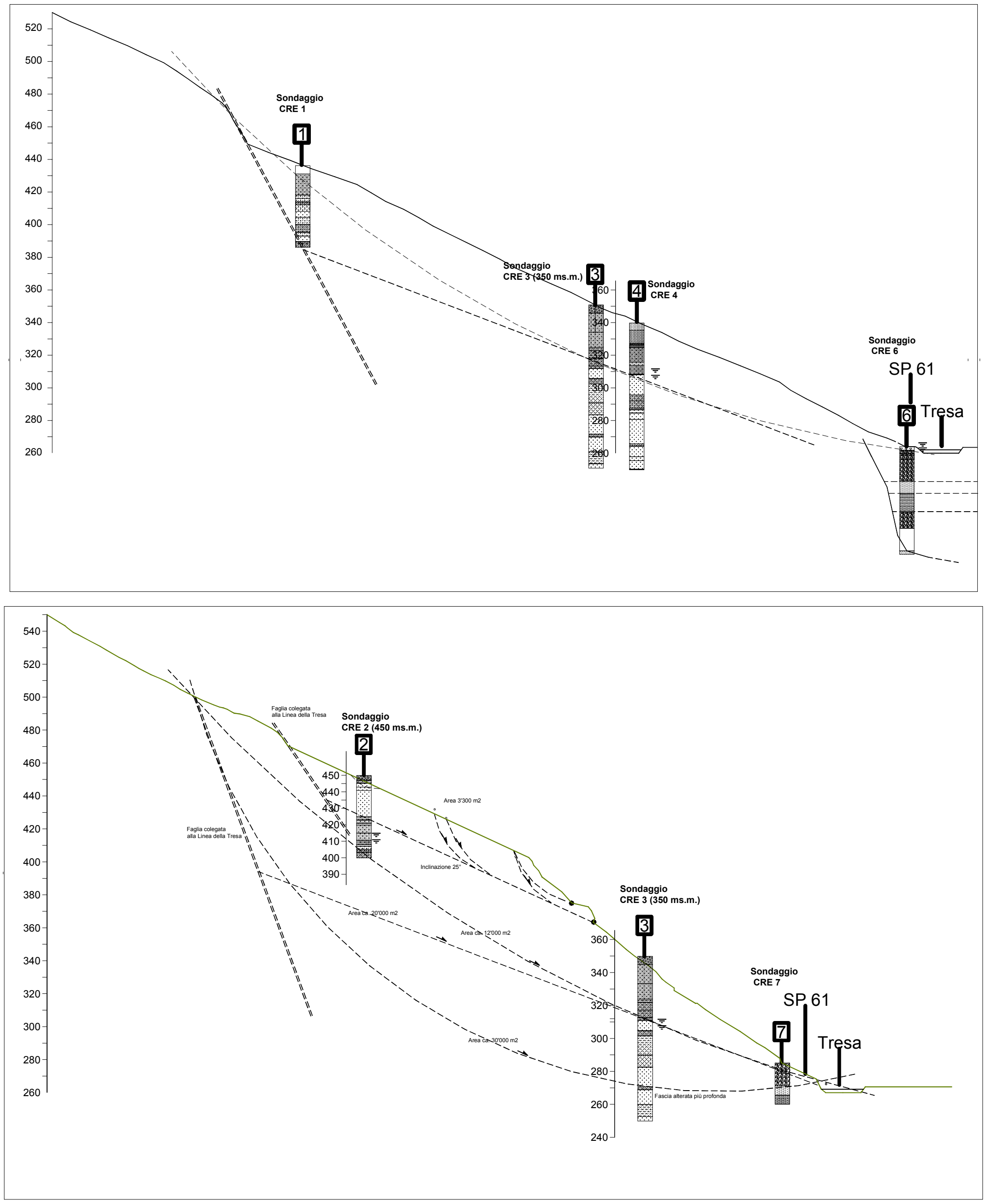
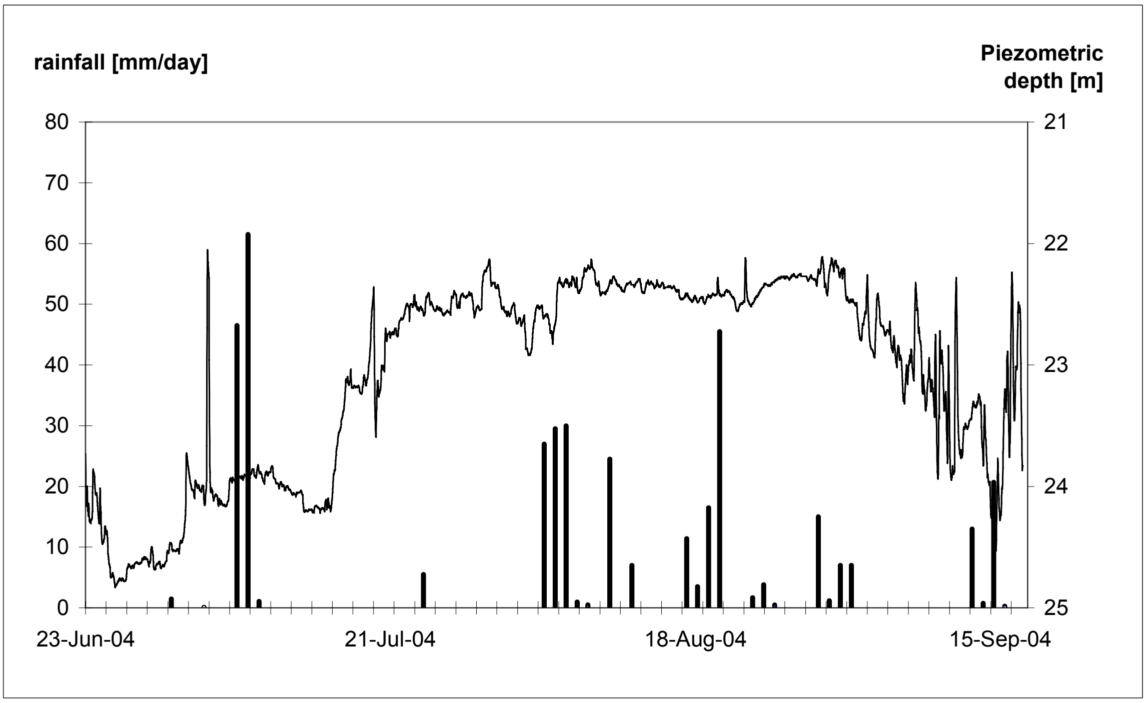


Figure 4. Cross sections of the landslide of Cremenaga. Artesian heads of water pore pressure has been encountered in the boreholes (above, lower borehole).



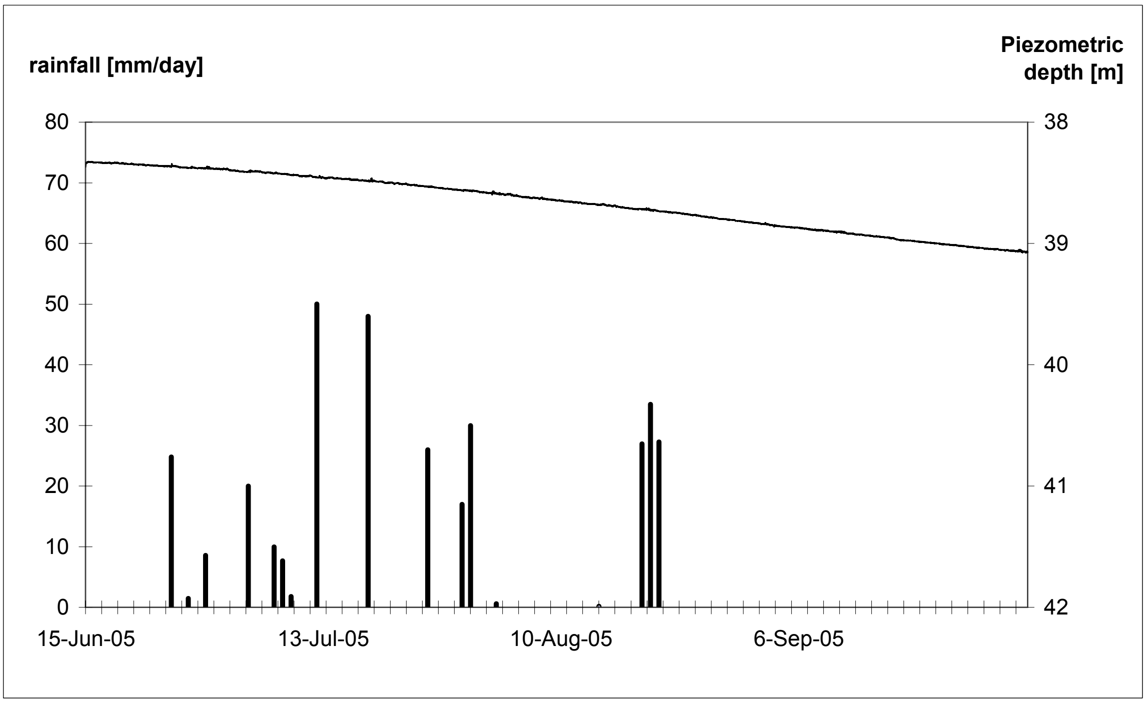


Figure 5. Precipitations and variation of head in two boreholes, showing a small or no direct correlation. The hydrogeological conditions are complex, as usual in crystalline weathered rockmasses.

The sliding mass is composed of weathered schists and biotitic schistous gneisses, metapelites with staurolites, garnets and kyanite, and some anfibolitic layers. They plunge between 15 and 35 degrees toward WSW to W, but localy steeper or pluging more to South.

From the boreholes that were drilled it was observed that also in this case high pore pressure is entrapped in the deep acquifers, and at one of the boreholes, even with artesian character (see Figure 4). The investigations are still in progress, and we yet do not dispose of enough information to draw an affordable head-flow pattern as for Campovallemaggia, but a similar hydrogeological situation is likely, even if not identical.

Rheology

When calculating the stability of a slope, the failure mechanism considered in the sense of the limit-equilibrium approach doesn't consider any rheology. Under Fs = 1 no displacement are theoretically possible. When Fs > 1 the displacements are not restriced and could occur at any velocity. In fact, at the very beginning of the failure, depending of the type of involved terrains, it can be very fast, as in the case of a rock failure in a steep slope, or it can flow very slowly, as in the case of a mud flow in soils.

For very large landslides, lets say larger than five to ten millions of cubic meters, it is observed that in most cases the trigger of the instability is not a single event, when an equilibrium between acting and reacting forces are overtaken, but the simultaneous occurance of different circumstances. The limit equilibrium approach is too limited to describe the complex interactions between weathering, aging, stress histories of different types in different locations inside the distinct instable bodies of the landslide. Limit equilibrium stability analysis can be calculated only as general check or for back analysis purposes (Bonzanigo, 1999, Bonzanigo et al, 2000, 2001). Very large landslides, when they are detected, are in most cases already active since a long time, and eventually reactivated as consequence of changes of climatic conditions or exeptional events. In some cases the cause of reactivation is anthropogenic. The hydrogeologic conditions are usually very sensitive, and even small variations of them lead to strong variation in the behaviour of the slide.

Further, the large landslides are often "self healing" in the sense that the deformations lead to an improvement of the reacting forces, due to the drop of pore pressure following increase of dilatance and thus of permeability. At least it can be considered that once the overall possible displacements are achieved, the consequent self-abutment of the groving toe tend to add reacting forces. It is nevertheless frequent to have a river at the toe of a large landslide, and the self-abutment is empeached by the progressive erosion. For that reason erosion is sometimes wrongly individuated as the cause of the slide instead of the consequence, even when evidences of internal hydrogeological particularities are observed. Accurate correlation between rainfall, pore pressure and displacements allow for a better understanding of the triggering mechanisms, or best said, the tuning parameters that control the displacement velocity.

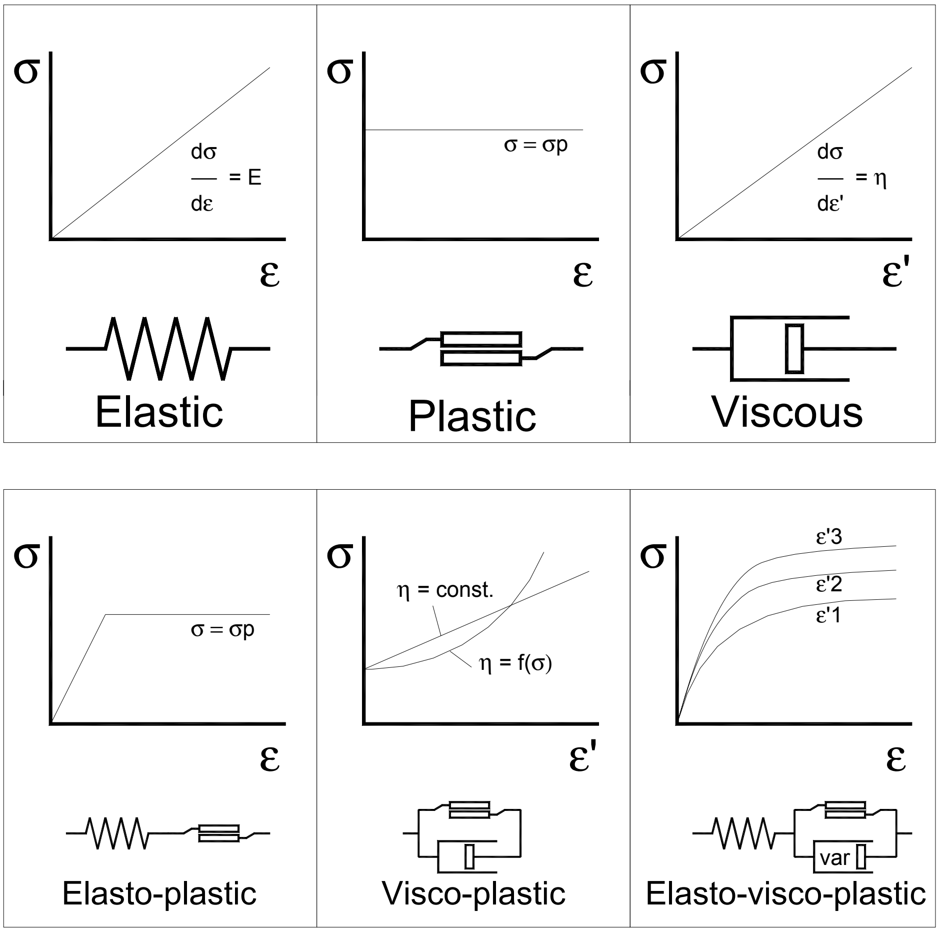


Figure 6. Definition of rheological models, terminology and symbols (Bingham models). To analyse time dependent deformation, the viscosity must be considered.

From the rheological point of view, the theoretical mechanism of a failure only considered with pure limit equilibrium approach is in fact equivalent to an infinite plastic behaviour (see Figure 6). No deformation should occur until the failure condition is reached, when the safety factor equals to unity. Above, the deformation could have any amount, because it is not defined. For rock falls or other catastrophic instabilities, or when it is the matter of small slopes in almost homogeneous terrains, this model can be sufficient. But in situations where the acting forces are controlled also by the amount of deformation, and the distribution of hydrogeological conditions is complex, the pure infinite plastic model is not sufficient to correctly describe the behaviour. Viscosity must be introduced in the model, and so far, time dependent parameters. Viscosity doesn't describe the amount of deformation, but its derivate, the velocity of displacement (see Figure 6). A constant value is true if the relation between stress and velocity is linear, but this is seldom observed. To analyse the behaviour of large landslides, or even single portions of them, a relatively simple approach has been proposed, relating usual geotechnical parameters like friction and cohesion to velocities in different hydrodynamic conditions (see Figure 7, from Bonzanigo, 1999).

Almost all materials can behave in viscous manner at very slow deformation processes. The elasto-plastic behaviour is tipical of rupture of intergranular pattern of rock matrix, or along joint surfaces, at low temperatures. But the forming of microfractures leads to a change of geomechanical characteristics and in rheology, and the appearance of residual shear and compression resistance (Eberhardt et al, 1999). The elasto-visco-plastic model applies well to most crystalline terrains and to soils, provided that a large variation of ruling parameters is considered. At low temperature, a massive metamorphic or magmatic rock shows elevated elasticity modules and yield threshold, and viscosity coefficient playes no sensitive role. But under conditions of high stress or greater temperatures, the viscous behaviour take the upper hand. We still don't know what exactly happens along the slip surfaces with the energy that is dissipated by the displacements, and very local rise in temperature is possible, that could play a role in the control of the viscous behaviour.

Viscous approach for analysis of landslides

The concept of the analysis of large landslides is based on the definition of a viscosity model, as proposed by Vuillet et al (1988). The viscous approach for large landslides was already attempted earlier (Haefeli, 1953; Ter-Stepanian, 1963; Huder, 1976). The main rule of viscosity can be expressed by:

$$\frac{d\varepsilon}{dt} = f(\tau)$$

with ε being the angular deformation and τ the shear stress along the zone where the deformation occur. The funtion f can be a very simple expression, like a unique viscosity coefficient, but also a complex relation involving all parameters that are considered having an influence. The shear velocity can be reduced to a displacement velocity, if considered across a unitary thickness of the shear zone. One of the possible practical approaches is to introduce the Mohr-Coulomb theory in the controlling factors of $f(\tau)$, as for instance:

$$v = B\frac{1}{(c + \sigma' \tan\varphi)^n}\tau^n$$

where v is the displacement velocity, c and σ' the usual geotechnical parameters of cohesion and friction. B represent a refence velocity, and n a factor of sensitivity. When n is small, the velocity tend to be independent from the shear stress. If n = 1, at the equilibrium the velocity will be equal to B. If n is great, the velocity under the Mohr-Coulomb equilibrium will be very small, above it will be very fast. The factors B and n are thus the controlling parameters of the viscous behaviour, and can at their turn depend on other factors.

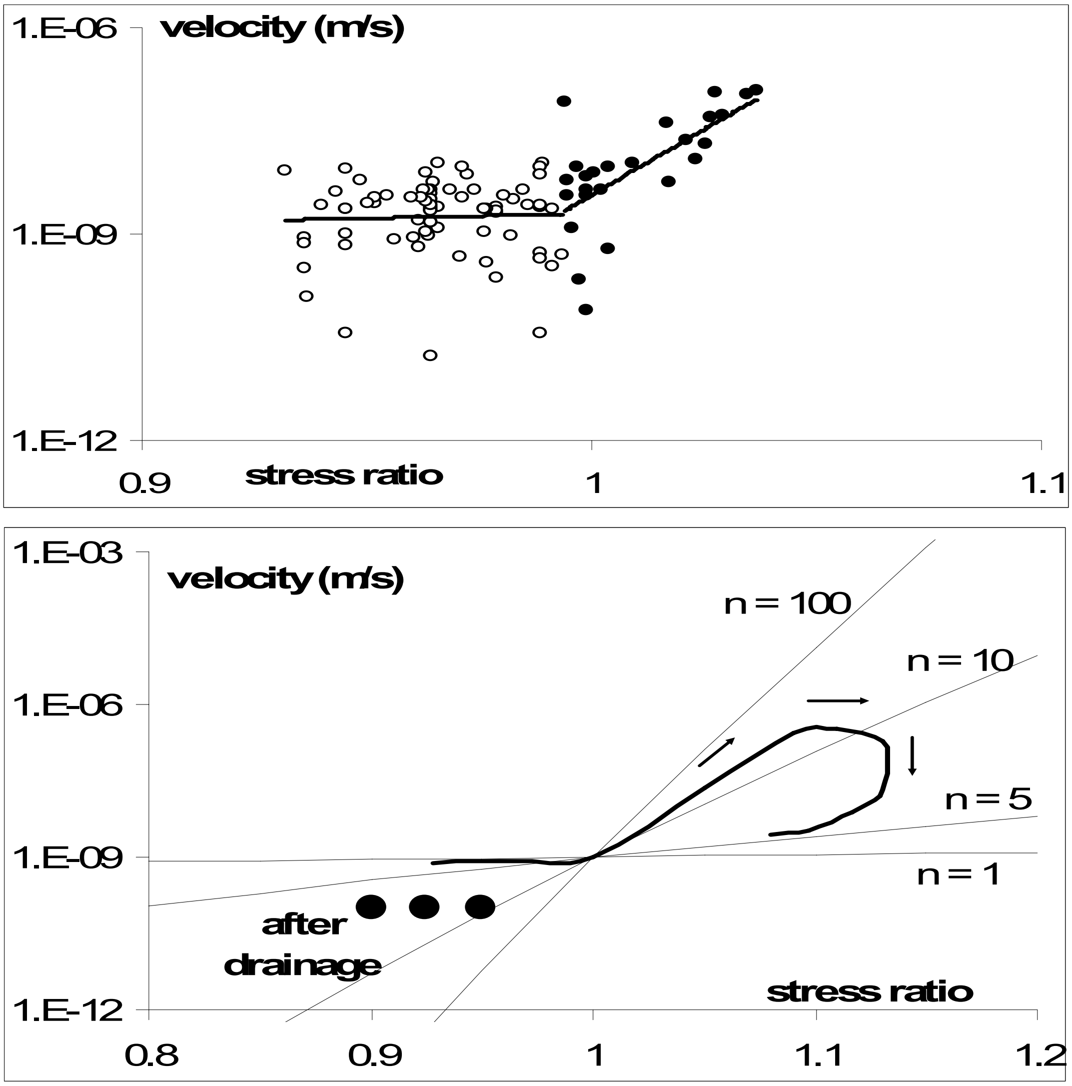


Figure 7. Plot of observed velocities at Campovallemaggia versus pore pressure, in form of a stress ratio., showing changes in rheological behaviour of the landslide. The center point at s=1 correspond to the coefficient "B" and is a reference velocity. The exponent "n" describe the degree of sensitivity. The factors "B" and "n" can depend in their turn depend on hydrogeological conditions.

If a stress factor is simply defined as the ratio between shear stress and Mohr Coulomb limit, the relation can be simplified like:

$$s = \frac{\tau}{c + \sigma' \tan\varphi} \qquad v = Bs^n$$

The analysis of the behaviour of the landslide can be performed plotting v versus s. The Figure 7 shows an example for Campovallemaggia, where c and φ has been backcalculated with a modified Janbu method, and σ' estimated with the known thickness of the landslide and the measured pore pressures in the boreholes.

Obviously, such an approach needs sufficient datas to be performed, which is unfortunately rarely given. This emphasies, if needed, the importance of the collection of datas, like water heads and geodetical measures. In the case of Cremenaga, the records of displacements are still in progress at present date (May 2006). Affordable velocities will be available only after a sufficient number of measurements under different hydrogeological and activity conditions, and the data, in order to be used, have to be cleaned on a statistical basis from instrumental errors.

With such an approach we do not consider the landslides as stable or unstable but more or less active. Velocities in the range of 10^{-12} m/s (about 30 micron per year) are no more measurable, even over long periods, and the landslide can be in practice be seen as inactive. The range of 10^{-9} m/s (about 3 cm/year) is caracteristic of most deep seated creeping landslides, and the eventual evolution in catastrophic events could be analysed in that way with benefit. Fast flow movements are in the range of 10^{-6} m/s (about 9 cm/day).

Conclusion

Large landslides in crystalline rockmasses are not seldom, and most of them present parent behaviours (see for instance: Blanc et.al., 1987, Riemer et.al., 1988, Gillon at. al., 1991, Beetham et.al., Moore et.al., 1995, Newton et al, 1992, Bonzanigo et al. 2000, 2001, 2005). They usually do not have a simple geometry that can be described by circles or a single slip surface under a unique sliding mass. If larger than the order of the million of cubic meters, they split of in several parts, with interdependent mechanisms (Cronin, 1992). The classical limit equilibrium approach is insufficient for practical analysis of the behaviour or large landslides. It is only useful for back-analysis purposes, or for very initial overview of the general hydromechanical conditions. Limiting the analysis to the search of a safety factor can lead to dramatic mistakes, because modelled large landslides should show anytime a factor close to unity. Values of more than 1.3, as unfortunately required by some official regulations, are unrealistic. Large landslides move anyway. When stable, the velocity of deformation is so small that no damage or measurable displacements are observed. When active, they usually move slowly, but enough to induce severe damage to roads, houses or other manufacts, with severe economic weight. Seldom they develop as a whole in catastrophic events. Fast movements are usually limited to the toe, but can involve very large quantities of material

To post safety arguments in support of technical, political and investement decisions for reclaim, the use of time-dependent analysis is needed, introducing rheological models involving viscosity. Similar approaches are complex and unusual in practice of engineering, but some simplified ways are possible. The main condition is that a sufficient amount of data is needed. Frequent displacement measurement with geodetical precision and accurate water head at different depths in boreholes are nowadays possible without unreasonnable investments. Authorities should be advised in this sense.

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