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Modelling of a rapidly evolving rockslide: the Mt. de la Saxe case study

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Abstract. To model the temporal evolution of complex landslides, a 1D pseudo-dynamic visco-plastic approach, based on Perzyna's theory, has been conceived. In the original version of the model the viscous nucleus has been assumed to be bi-linear: irreversible deformations develop uniquely for positive yield function values whereas, in a more general case, even for negative values. In this work the model has been enriched by considering: i) an exponential viscous nucleus, ii) a strain-rate softening to reduce friction angle as sliding velocity increases and iii) block interaction forces to cope with complex 3D geometries for the sliding mass. The application of the proposed model to the La Saxe rockslide (Italy) clearly shows how a relatively simple model can be applied to a complex landslide by considering a spatial discretization of the sliding mass.

1. Introduction

In order to model complex sliding masses subject to continuous slow movements related to water table fluctuations it is quite convenient to: i) model the time-dependent mechanical behaviour of the materials by means of a viscous-plastic constitutive law ; ii) assume the water table fluctuation as main input to reproduce time acceleration; iii) consider, the 3D constrains by maintaining a high level of simplicity such to allow implementation into EWS (Early Warning System) for risk management.

In this paper a previously presented 1D pseudo-dynamic visco-plastic model (Secondi et al. 2011), based on Perzyna's theory is applied. The sliding mass is considered as a rigid block subject to its self weight, inertial forces and seepage forces varying with time. All non-linearities are lumped in an interface thin layer positioned between the rigid block and the bedrock. The mechanical response of this interface is assumed to be visco-plastic. The viscous nucleus is assumed to be also exponential, so that irreversible strains develop for both positive and negative values of the yield function; the friction angle is assumed to reduce with strain rates; the sliding mass is discretized in blocks to cope with complex rockslide geometries.

To validate the improvements introduced in this paper one case study is presented. It refers to the recent La Saxe rockslide movements (Aosta valley; Italian Western Alps) widely described in Crosta et al. (2013).

It will be shown that, in its modified version, the mode satisfactorily fits the La Saxe displacements triggered by the fluctuation of the water ground levels induced by snow melting and that the blocks discretization confirms the model suitability in case of complex 3D rockslide.

2. 1D Viscous plastic model

As is well known, a simple static limit equilibrium analysis is not suitable for modelling and correctly reproducing the time depentent mechanical response of sliding masses triggered by water table fluctuations. A dynamic, or, at least, pseudo-dynamic, analysis should be adopted, and a delayed-plastic constitutive approach employed. The first issue can be addressed by evaluating the inertial effects on the soil mass by using a pseudo-dynamic approach, as that introduced by Newmark (Newmark, 1965) for dams under seismic actions, whereas, viscous components can be described by employing the visco-plasticity theory introduced by Perzyna (1963).
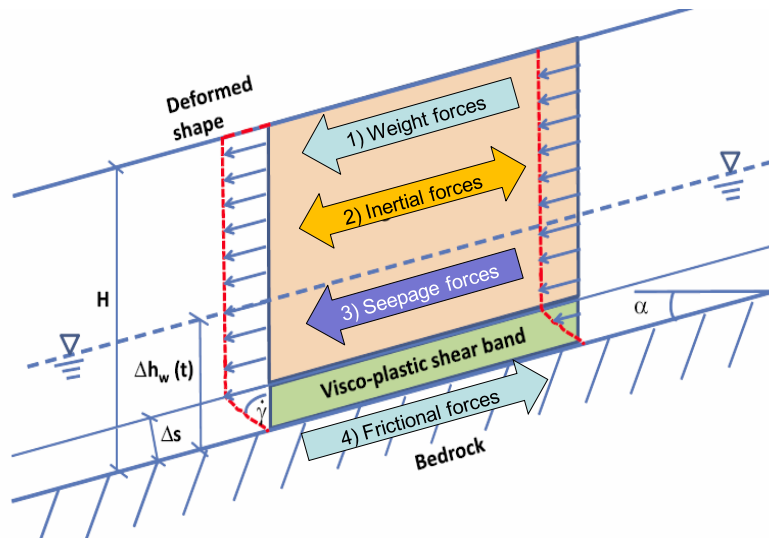

Figure 1. 1D block model with main geometrical elements.

As was previously suggested, according to this approach, the rockslide is interpreted as a rigid block (Figure 1), where the active forces taken into account are (i) the weight, (ii) the inertial forces and (iii) the seepage force deriving from the water table level which is a function of time, $\Delta h_w(t)$. All non-linearities are lumped in a shear band of thickness Δs positioned between the rigid block and the bedrock. All the details and the analytical formulation of this model are reported in Crosta el al. (2013). Thus, the main equations controlling this model are:

Visco-plastic strain rate definition

$$\dot{\gamma}^{vp} = \tilde{\gamma} \cdot \phi(f) \tag{1}$$

Sliding mass displacement rate:

$$\dot{x} = \Delta s \dot{\gamma}^{vp} = \tilde{\gamma} \, \Delta s \, \phi(f) \tag{2}$$

Yield function definition

$$f = \frac{\tau - \tau_{res}}{\sigma'_n} \tag{3}$$

Active shear stress

$$\tau = \tau_{stat} - m^* \ddot{x} \tag{4}$$

$$\tau_{stat} = \left(W \left[\Delta h_w(t) \right] \sin(\alpha) + J \right) \big/ A \tag{5}$$

Failure criterion

$$\tau_{res} = c' + \sigma'_n \tan \phi'_{res} \tag{6}$$

where f is the yield function, $\tilde{\gamma}$ a constitutive viscous parameter, $\phi(f)$ the viscous nucleus, $\dot{x}$ the sliding displacement rate of the mass m, A the total contact area, W' the soil buoyant weight, J the total seepage force, $\Delta h_w(t)$ the groundwater table level varying with time t.

In case f is positive, by substituting equations. (2), (3) and (4) into the expression of the viscous nucleus, and by introducing the geometrical and constitutive parameters, we obtain an equation of the following type:

$$a\ddot{x} + b\dot{x} + c = 0 \tag{7}$$

where coefficients a, b and c depend on time and can be derived from the previous equations. The improvements of the model are presented in the following sections.

3. 1D Viscous nucleous

As is sketched in Figure 2, two different formulation for the viscous nucleus have been considered. The first, proposed in the original version of the model (Secondi et. al. 2011), is a bilinear function (Figure 2a) defined as:

$$\phi(f) = \langle f \rangle \tag{8}$$

where brackets imply the viscous nucleus to coincide with the yield function for $f > 0$ and to be nil for negative values of f (equation 3).

The second expression is an exponential law (Figure 2b) defined: according to the following equation

$$\phi(f) = e^{\alpha \cdot f} \tag{9}$$

The exponential law is also enriched by parameter α, governing the shape of the viscous nucleus (Figure 2b).
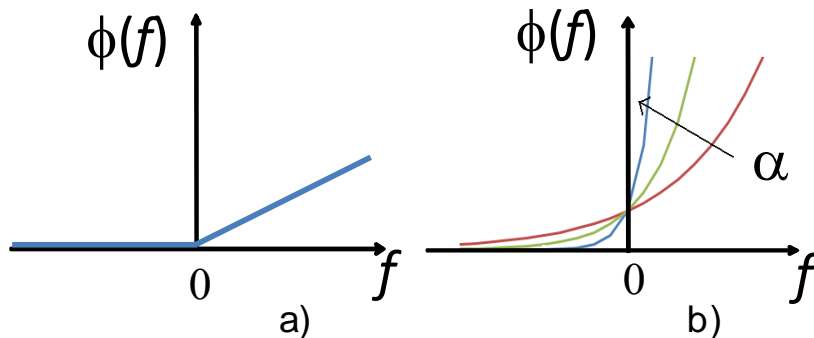

Figure 2. a) bilinear viscous nucleous; b) exponential viscous nucleous

4. Friction weakening

As a preliminary way to simulate the transition from the initiation to the propagation of an unstable rock mass, a friction weakening is here after considered. An increase in the localized shear strain rate (i.e. slip velocity) is thus assumed to produce a slight reduction in the friction angle:

$$\|\dot{x}\| > \dot{x}_w$$

$$\tan\phi'(\dot{x}) = \frac{\tan\phi'_0 - \tan\phi'_w}{\|\dot{x}\| - \dot{x}_w} + \tan\phi'_w \tag{10}$$

otherwise,

$$\tan\phi'\,(\dot{x}) = \tan\phi'_{\,0}$$

where ϕ'_o and ϕ'_w are the static and the weakened friction angles, respectively, and $\dot{x}_w$ is a threshold characteristic velocity for the weakening to occur.

Many authors (e.g. Rice R. J., 2006, Beeler et al 2008; Kuwano and Hatano, 2011; Vardulakis, 2000; Veveakis et al. 2007) proposed specific studies and theoretical interpretations to justify the frictional weakening as a consequence of multiple mechanisms. Here the authors introduce equation (10) only as one possible ways to simulate, within the adopted 1D model, the acceleration usually recorded before the run-out process. No specific theoretical justification are given; equation (10) should be therefore considered as a macroscopic strength reduction as sliding velocity increases towards catastrophic failure.

5. Discretization

The proposed model can be employed to reproduce the evolution of a non-deformable mass sliding on an inclined rigid plane. A 3D complex landslide a priori does not satisfy all the hypotheses behind the model. To overcome this limitation and to tentatively apply the proposed model to complex 3D landslide settings, a two steps methodology has been developed.

5.1. Splitting the displacement function

In general, the rockslide displacements can be expressed as a vectorial function $\boldsymbol{u}\,(x, y, z, t)$ defined in space and time. At any instant this function should be properly evaluated from the monitoring. For the sake of simplicity, by assuming:

i) the direction of displacements to be constant within the area considered and to be determined by a unit vector $\boldsymbol{u}'$. This also implies that the dispersion in direction of the velocity within the domain $\hat{\boldsymbol{u}} = \boldsymbol{u}\,(x, y, z) - \boldsymbol{u}'$ is negligible with respect to $\boldsymbol{u}'$;

ii) the evolution of displacement with time to be independent of space.

The function $\boldsymbol{u}\,(x, y, z, t) \in C^{0}$ can be written as the product of three elementary functions:

$$\boldsymbol{u}\,(x, y, z, t) = \boldsymbol{u}'\,\overline{f}_1\,(x, y)\,\overline{f}_2\,(z)\,g\,(t) \tag{11}$$

where

$$\overline{f}_1\,(x, y) = f_1\,(x, y)\big/u_p\,(x_p, y_p, z_p, t_0) \tag{12}$$

$$\overline{f}_2\,(z) = f_2\,(z)\big/u_p\,(x_p, y_p, z_p, t_0) \tag{13}$$

In particular (see Figure. 3):

- $\overline{f}_1\,(x, y)$ can be considered as a non-dimensional shape function of the spatial superficial distribution of t displacements. This could be evaluated, for example, from GB-InSAR measurements divided by the displacement at a selected point, P, and reference time, t_0;

- $\overline{f}_2\,(z)$ is the shape function in depth of the displacement at any point on the ground surface (Figure 3) of the rockslide assumed to be time independent. This can be obtained from inclinometer data at a chosen point P by dividing it by the ground displacement measured in P. This function is crucial in order to verify the model assumption of a rigid block sliding on a shear band.

- Function $g(t)$ can be considered as the displacement evolution with time of a representative "pivot point" P.
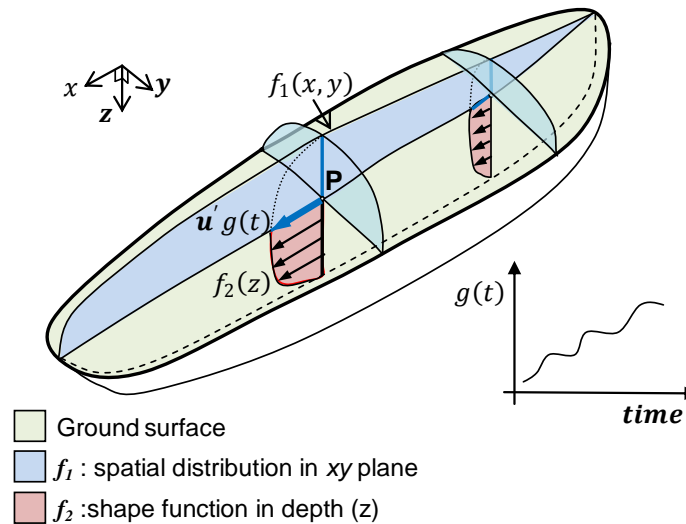

Figure 3. a)Suggested elementary function of $\boldsymbol{u}(x, y, z, t)$ of a rockslide mass.

Once shape functions $\overline{f_1}(x, y)$ and $\overline{f_2}(z)$ are known, it becomes possible to provisionally evaluating the displacement of a complex landslide by simulating or predicting the ground movement at a specific representative point P with respect to time but uniquely defining function $g(t)$.

5.2. Spatial discretization

If the rockslide prevalently slides parallel to the average slope inclination, the outlined model can be a priori employed by assuming for instance both f_1 and f_2 (Heaviside step function) simply describing a rigid block sliding along a plane and variable $\hat{z}$ to coincide with the normal to the average slope inclination (in this case a rotation of the reference frame is suggested, so that $\boldsymbol{u}'^T [1, 0, 0]$). For complex 3D rockslides a more refined subdivision of the sliding mass is required. This will be based on a set of criteria employed to identify from monitoring data, geomorphological and geometrical observations, homogeneous displacement zones. Once the rockslide mass is split into subzones, the same subdivision can be applied to the groundwater table, so that for each zone a time dependent oscillation $\Delta h_{w,i}(t)$ can be evaluated. Each zone is then treated has a rigid block resting on a shear band with a viscoplastic behaviour (Figure 1). In order to take into account the interaction between the blocks, equation (5) becomes

$$\tau_{stat,i} = \left(W_i \left[\Delta h_{w,i}(t) \right] \sin(\alpha_i) + J_i + F_i^{rel} \right) \Big/ A_i \tag{14}$$

where F_i^{rel} stands for the resultant of both the forces transmitted by the lateral boundaries of each block and the forces transmitted by the uphill blocks to the downhill ones; index i refers to the current block.

6. Case study: the la Saxe Rockslide

During the last decade, a large rockslide along the NW slope of the Mont de la Saxe (Courmayeur, AO - Italy) showed a significant increase in the rate of activity in conjunction with snow melting periods and more recently with important amount of rainfall (see Figure 4).

The 8 Mm^3 rockslide affects a heavily tectonised and intensely fractured mass of black schists, for a surface area of about 150'000 m^2. The rockslide failure surface is typically located at depths of 60 to 80m b.g.l. Because of the highly valuable exposed elements, regional authorities commissioned a comprehensive ground investigation and monitoring campaign, as well as theoretical and numerical analyses, in order to assess slope stability conditions, the possible evolution and the suitable stabilization and mitigation countermeasures (see Crosta et al 2013). Here we briefly present the recent rockslide evolution, recorded in the spring and summer of 2014 and then with the aim to validate the 1D visco-plastic model, the results of a series of simulations considering interacting blocks are presented.
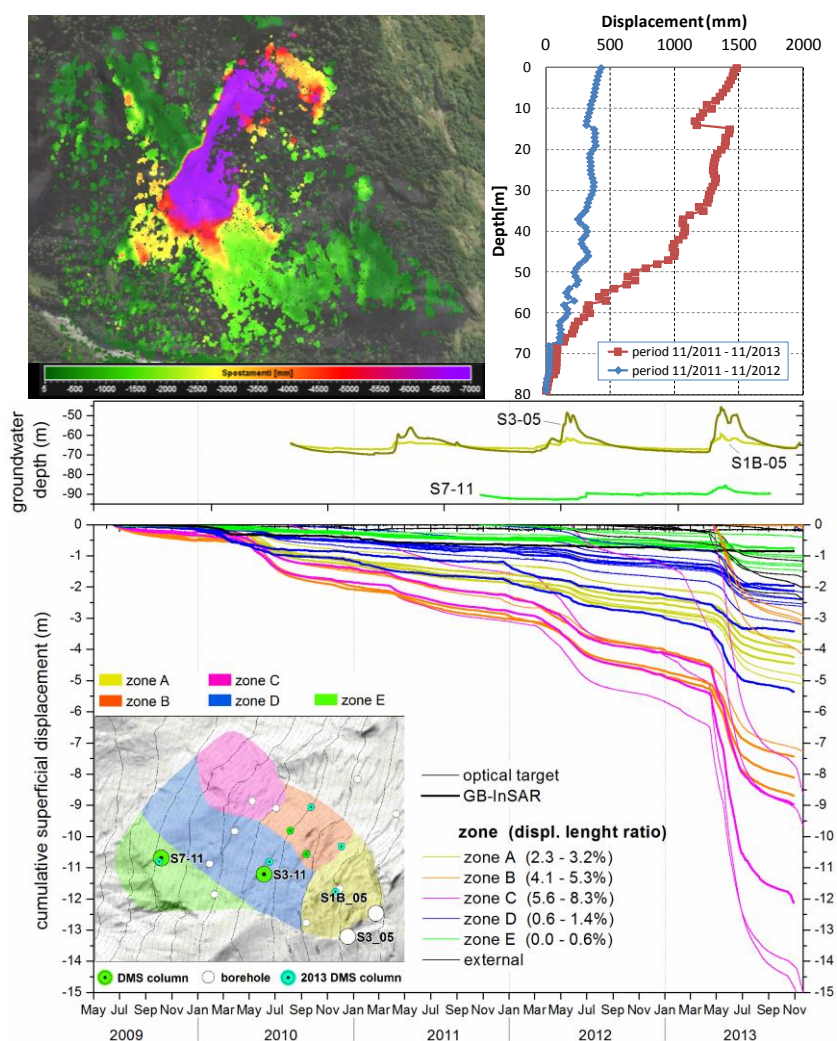

Figure 4. Monitoring data: a) Cumulative GB-InSAR from 2009, b) DMS S3 displacements for two different time intervals; c) GB-streaming points and optical targets data subdivided according to 5 different zones

The rockslide is subject to accelerations every spring due to the combined effect of snow melting and rainfall that implies an increase in the groundwater level (Figure 4). Due to the complexity of the rockslide, this can be subdivided in sub-areas characterized by different geometrical properties (i.e. depth of surface failure, groundwater elevation, Figure 5). This complexity affects the overall rockslide behavior. The 5 blocks discretization (Figure 5b) subdivides the overall rockslide into different sub-areas so that each block has its own basal inclination, height, width length and shear

band thickness. The interaction between the blocks has been taken into account by assuming lateral and normal forces (Crosta et al., 2013).
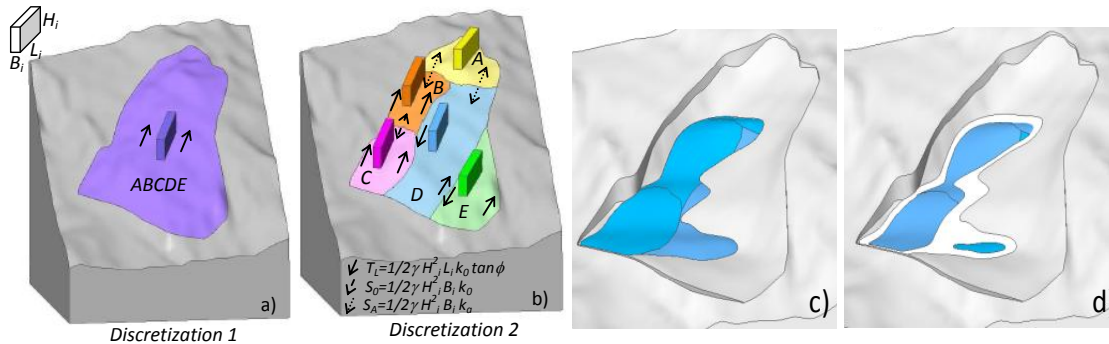

Figure 5. Landslide discretization in 1 (a) and 5 blocks (b). The lower panels show the wet and dry season groundwater table (light blue) above the failure surface.

In Figure 6 the results of the 1D viscoplastic model simulations are reported. The results for the single block discretization (Figure 5a) obtained by assuming averaged geometrical properties for the entire rockslide, are shown in Figure 6b. From this single block discretization the groundwater level results to lay always below the average failure surface with the consequence that the model is unaffected by its oscillation.This clearly suggests that the single block discretization is too poor to reproduce the 3D complex behavior. In contrast, the 5 blocks discretization (Figure 5b) shows the model capability of reproducing the monitored displacements in different subareas of the rockslide (Figure 6c).
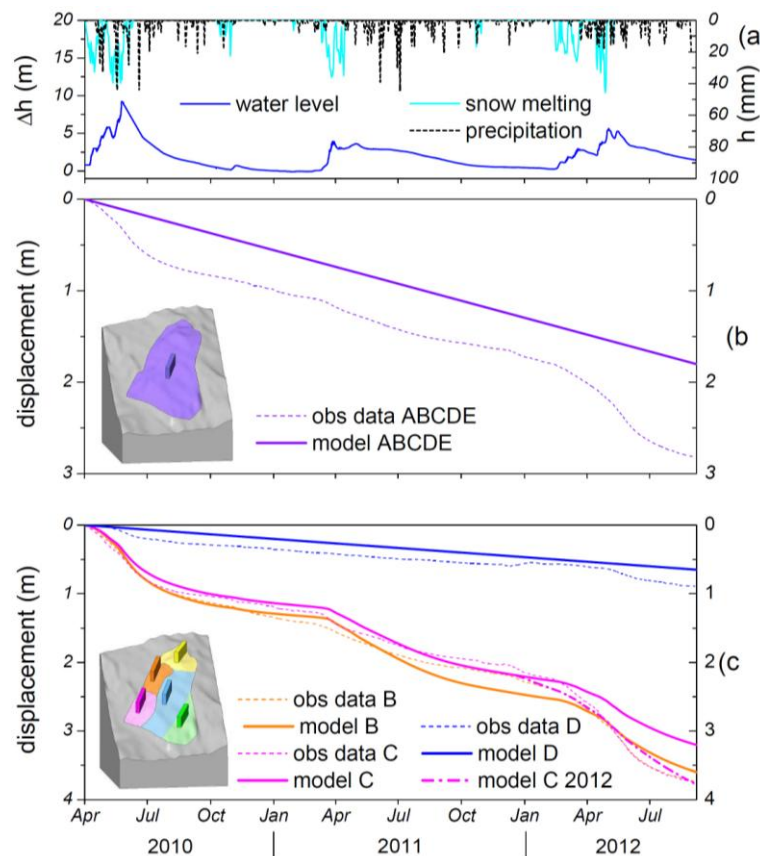

Figure 6. Model simulations in term of $g(t)$ functions: a) ground water level fluctuation; b) simulation for Discretization 1; c) simulation for Discretization 2.

Since March 2014 a sector corresponding with Zone C in Figure 5b and involving about 400.000 m3 underwent a strong seasonal reactivation. As a consequence, the landslide mass in this zone reached displacement velocities up to about 0.9m/h and a cumulative displacement of about 30 metres in less than 3 weeks. It is worth noticing that this sector of the landslide, already described as the most sensitive and active one, became every year more and more sensitive to seasonal perturbations.

Among the possible causes and controlling factors for such a behavior and exceptional acceleration, we can list:

a) snow melt contributing to the groundwater recharge favoured by a progressive fracturing of the rock mass nd a consequent increase in permeability;

b) progressive degradation of the rock mass by large displacement, opening of fractures and shear zones till a condition typical of a granular mass;

c) further contribution to groundwater recharge from the neighboring areas.

To understand the landslide behavior and to improve our capabilities to predict landslide displacement we tried to simulate the observed displacements starting from the parameters calibrated on previous time series (2009-2013) and other field observations (Figure 4). In this simulation the depth of the failure surface below the ground surface is reduced to an average value of 30 m.

The triggering causes listed above can be introduced into the 1D model considering the increase in water level above the failure surface associated to the snow melt contribution or lateral inflow, and we also take into account for the seepage force. Rock mass degradation can be simulated by considering an increase in thickness of the shear band and/or a progressive decrease in the average friction angle along the shear zone, due to changes of state characteristics of the material (progressive grain size reduction of black schist and calcschist).
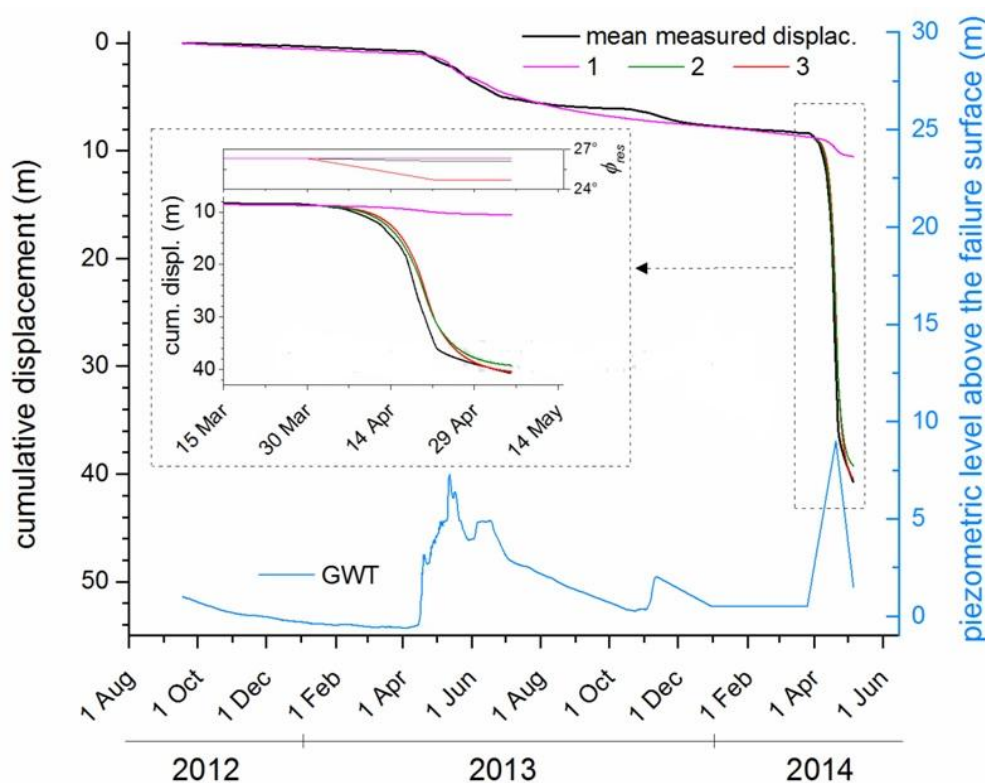

Figure 7. Results of the 1D visco-plastic simulation of the 2013-2014 period. 1) constant friction angle (26.8°, see inset), shear band thickness Δs =1m; 2) friction angle changes linearly (26.8→26°, see inset), shear band thickness Δs =5 m; 3) friction angle changes linearly (26.8→24.7°, see inset), shear band thickness Δs = 1m. Piezometric level (GWT) changes in the same way for all the models.

To accomplish these analyses we carried out a series of simulations by changing different parameters under the above slightly different assumptions:

1. Groundwater recharge with a simplified oscillation comparable to the one observed in the previous year (April-May 2013) and without any change in the material properties (see curve 1 in Figure 7) and shear thickness with respect to previous simulations ($\square$s = 1 m);

2. The change in groundwater level was imposed as in 1) but we progressively decreased the friction angle (26.8$\rightarrow$26°, see inset in Figure 7) since the beginning of the acceleration phase and assigned it to a thicker shear band ($\square$s = 5 m);

3. The change in groundwater level was imposed as in 1) but we progressively decreased the friction angle (26.8$\rightarrow$24.7°, see inset in Figure 7) since 2013 till the beginning of the 2014 deceleration phase and assigned to a 1 m thick shear band.

Model 1 in figure 7 performs well till the seasonal reactivation occurring on April 2013 but it is unable to replicate the sudden acceleration recorded on April 2014. This last reactivation stage is reproduced by models 2) and 3) thanks to the imposed changes in the mechanical characters (shear zone thickness, friction angle) through simple linear state relationships (see Figure 7) for the friction angle or the increase in shear band thickness. In all the simulations the viscous parameters are maintained constant.

Even if these simulations and their results cannot be used directly for prediction of future evolution, because of the inherent difficulty in collecting the real values of controlling variables, some conclusions can be drawn. In fact it seems possible to state that the groundwater recharge and associated piezometric level oscillation and/or the change in frictional properties associated to material destructuration could be useful predictors to be tested in the laboratory and monitored in situ.

7. Conclusion

A 1D rigid-viscoplastic model has been modified for what concerns the expression of the viscous nucleus, the friction strain-rate weakening and extended to simulate the response of systems of multiple interacting blocks to model 3D complex rockslides . The La Saxe rockslide were chosen in order to show the capability of the proposed model of reproducing the displacement time series triggered by groundwater table fluctuations by adopting an interacting block discretizaton.

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