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Abstract:

The Portalet landslide is a large, active slope failure located on the upper part of the Gállego River valley, in the Central Spanish Pyrenees (Sallent de Gállego, Huesca). The landslide is located on a southwest-facing hillside of Petrasos Peak, close to the ski resort of Formigal. The dimensions of the landslide are 500 m long and up to 700 m wide at the toe extended over an area of 0.35 km2 that shows superficial cracking and distinct ground displacements. Displacements are quite important (several cm in a month) from summer 2004 when the construction of a parking area was carried out by digging the foot of the slope. Field observations show a close relation between ground movement and rainfall intensity. Monitoring and predicting the landslide behaviour is necessary to guarantee the safety of this ski resort area. Monitoring was performed with four differential GPS (DGPS) campaigns between May and November 2006 and installing a novel ground based SAR (GBSAR) monitoring system. GBSAR measurements were recorded continuously for 47 days, from the 5th of October 2006 to the 21st of November 2006, providing up-to-date displacement maps of the landslide area at a rate of 1 per hour. Two numerical models have been proposed to forecast the recorded movements directly from rainfall intensity. A simple 1D infinite slope model solving the momentum equation gives a first approximation. The model includes a viscoplastic behaviour and takes into account directly the known daily rainfall intensity and the dissipation of the excess pore-fluid through a simple consolidation equation. A fully coupled hydro-mechanical finite element analysis in plane strain conditions using an elastoplastic constitutive model has also been performed. The results show that prediction of slope behaviour is feasible if data parameters are well documented.

*Keyword*s: GBSAR monitoring; 1D infinite slope model, viscoplastic model, consolidation model, coupled hydro-mechanical finite element modelling

1. Introduction

Two broad categories of models can be pointed to predict landslide mobility: the phenomenological models and the physically based models. The former employ empirical relationships, statistical or probabilistic approaches and artificial neural networks to relate soil movements and their causes; the latter provide relationships taking into account the

mechanical behavior of the soil. A summary of the different methods proposed in the literature can be found in Federico et al. (2004).

Physically based models have been mostly used in practical cases to estimate landslide occurrence and stability conditions for a given scenario through a stability factor based on limit equilibrium analysis. In the present paper, a simple 1D infinite slope model assuming a pre-existing slip surface where the shear strength is at residual conditions and including a viscoplastic behaviour (Vulliet and Hutter 1988) is used for predicting the movements of Portalet landslide. The movements are concentrated within a relatively narrow shear zone above which the sliding mass moves essentially as a rigid body. This model was also used by other authors (Van Ash and Van Genuchten 1990, Corominas et al. 2005). In their studies the hydrologic contribution is directly given from groundwater level changes measured by piezometers. Here, no precise information about the position of the groundwater level was available, a simple improvement is proposed to overcome this limitation and make prediction directly from the recorded daily rainfall intensity. Leaning on the observed velocity given by the monitoring data a dissipation model of the excess pore-fluid through a simple consolidation equation is proposed. The main advantage of such a procedure lies in its relatively simple applicability.
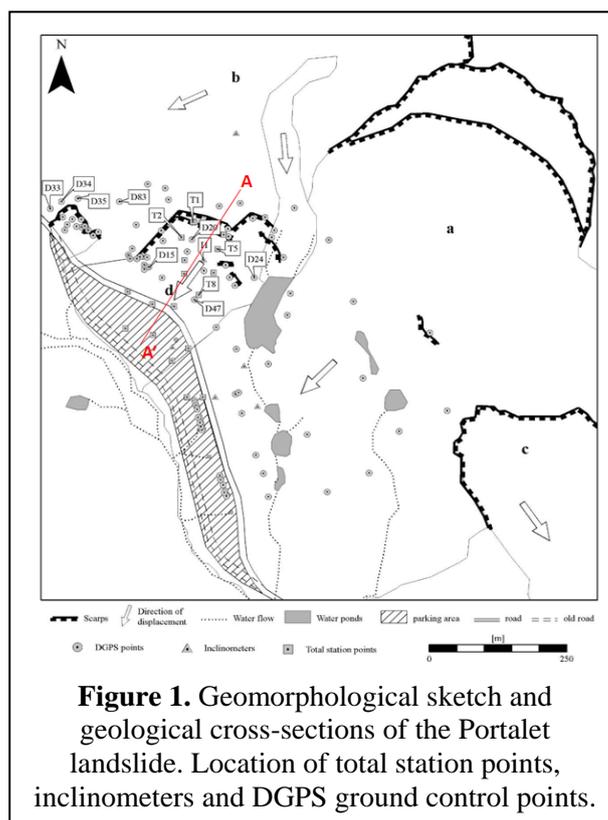
Not to mention earthquake study, time dependent analysis is requested when hydrological conditions change as in the case of rainfall, when resistant parameters reduce as in the case of strain softening and weathering processes or when creep behaviour is taken into account. Complex numerical models as the finite element method can provide a good understanding of the mechanism of failure in these cases as they can correctly reproduce the fully coupled hydrogeological and mechanical behaviour, moreover, advanced constitutive laws, complex 3D geometries and spatial variations in soil properties can be used. Many numerical modelling case studies of landslides mechanics have already been published focussing on strain localization (Dounias et al. 1988, Troncone 2002), visoelastoplasticity (Desai et al. 1995, Vulliet 2000) or hydromechanical coupling in large landslides (François et al. 2007).

The aim of the article is to use the monitoring data obtained by the continuous GBSAR measurements to calibrate the proposed models and to predict the Portalet landslide mobility directly from the recorded rainfall intensity.

2. Portalet landslide description

The landslide subject of this paper is located in Central Spanish Pyrenees (Sallent de Gállego, Huesca). This slope is composed mainly by slates and shales, all of which are of Carboniferous and Devenian age, characterised by an intense weathering and a high plasticity.

The landside, which extends over an area of 0.35 km2, presents a steep cliff that corresponds to the main scarp and it is of the rotational kind with unidirectional movement from a global point of view (zone a in Figure 1). The mass movement was triggered by the excavation of a parking area damaging a connexion road to France. Constructive solutions were carried out to minimize the slope displacement rate. The

Figure 1. Geomorphological sketch and geological cross-sections of the Portalet landslide. Location of total station points, inclinometers and DGPS ground control points.

landslide has generated several blocks sliding between each other along pre-existing slip surfaces (zone d in Figure 1); section AA' has been chosen for the modellisation and previous stability analysis exhibited a nearly translational behaviour of this slide.

A total of four DGPS campaigns were performed in the Portalet landslide between May and November 2006 involving around 100 benchmarks. Overall, during this period maximum displacements of 22 cm were observed in 180 days.

A GBSAR sensor (Nofirini et al. 2007) was installed at a distance of about 600 m from the main body of the landslide on a hill overlooking the parking area, providing automatically one displacement map per hour continuously along 47 days (over 1000 maps) involving around one million pixels with a resolution of 2 x 2 m. During this monitoring campaign a maximum displacement of 14 cm was estimated with an error in the range of millimetres.

The analysis of the monitoring data measured with conventional techniques in different time periods, and particularly of the continuous GBSAR displacement temporal evolution has allowed understanding some of the characteristics of the Portalet landslide mechanism. It has been established that the rate of displacement is very sensible to rainfall. From this we infer that there is a rapid, almost instantaneous response of the ground water level to rainfall events.

3. Modelling using a simple viscoplastic sliding-consolidation model

Several authors (Van Ash and Van Genuchten 1990, Corominas et al. 2005) have used a simple 1D infinite slope model to predict slow landslides mobility directly from groundwater level changes. The model includes a viscoplastic behaviour (Vulliet and Hutter 1988) of the landslide but seems to be too simplistic since neither 2D and 3D effects are taken into account nor elastic deformation is predicted. Nevertheless, the model can give a first approximation of the landslide kinematics and can be used to reproduce the ground displacements and velocities measured with the GBSAR and DGPS techniques.

The landslide is assumed to be as a translational infinite slide with constant depth h and constant slope α, in this case the equilibrium over a unit surface can be described with the simple equation:

$$\mathbf{F} - \mathbf{F}_r = \mathbf{F}_i + \mathbf{F}_v$$

Where F represents the destabilising force equal to the weight of the considered volume, F_r is the resisting force that can be estimated with a Mohr–Coulomb criterion, F_i is the inertial force and F_v represents a viscous force usually dependent of the strain rate of the shear zone that can be evaluated using a Bingham model. The momentum balance equation can be written over the slope direction as:

$$\tau - \left[c + \left(\sigma_n - p_w(t) \right) \tan \phi \right] = m\, a(t) + \frac{\eta}{d} v(t) \qquad \text{or}$$

$$m\, a(t) + \frac{\eta}{d} v(t) = mg \cdot \sin \alpha \cos \alpha - \left[c + \left(mg \cos^2 \alpha - p_w(t) \right) \tan \phi \right] \qquad (1)$$

where τ is the destabilising shear stress, σ is the normal stress, ϕ is the friction angle, c is the cohesion, m is the mass $= \rho \cdot h$, ρ being soil density and h the height of the landslide, η is the viscosity, d is the thickness of the shear zone, $p_w(t)$ is the pore water pressure $p_w(t) = z(t) \cdot \gamma_w \cdot \cos^2 \alpha$ assuming a parallel flow to the slope surface, z is the position of the groundwater level, γ_w is the specific weight of water, $a(t)$ is the acceleration and $v(t)$ is the velocity.

Prediction of ground motion is obtained by solving equation (1) given the geometry of the landslide (h, α and d parameters), material properties (ρ, ϕ, c, η parameters) and initial and time variation of the ground water level $z(t)$. The parameters are obtained by field observations, in-situ tests and laboratory tests. If one of these parameters is not available it can be estimated by back analysis in a fixed period of time, in this case prediction must be

made in a different period of time. If more than one parameter is not available, the prediction is analyzed for given scenarios or providing reasonable estimates. In the present study 2 parameters are not determined: the viscosity η and the position of the ground water level $z(t)$.

Section AA' defined in Figure 1 has been chosen for the modelisation, the average inclination of the section is α=14º. Information from inclinometer I1 and borehole S1, located on the section, indicates that the depth of the failure surface is located at h=12m and the thickness of the shear zone is d=0.4 m. Tests on undisturbed samples (ICOG 2005) assign an average density of the material ρ=2310 kg/m^3 and an estimate shear strength ϕ=18º, c=0 t/m^2 for the fragmented slate material located in the shear band.

No precise information about the position of the groundwater level was available, due to environmental constraints no piezometer was installed. The equilibrium state (zero velocity and zero acceleration) corresponding to a zero value of the right hand side of equation (1) is achieved when the groundwater level is at z=6.499 m. An initial state $z(0)$=6.5 m is postulated. The results are very sensitive to the initial conditions, small variations of this value have a strong effect on the final response of the landslide mobility.

A simple model is now proposed to make prediction directly from the known daily rainfall intensity and not from groundwater level changes. In this case, the effect of the snow melting during the spring season cannot be considered.

R.M. Iverson 2000 presented a complete mathematical model based on Richards's equation to evaluate the hydrological process during rain infiltration in saturated material. In the present study, measured displacements show that the landslide reacts almost immediately to rainfall inputs. This rapid response is likely due to the presence of superficial cracks and preferential drainage pathways. Changes in groundwater level have been taken directly proportional to the rainfall intensity through:

$$dz = \frac{I_{\text{rainfall}}/1000}{n}$$

where the rainfall intensity is recorded in mm/m^2/day and n is the material porosity supposed to be constant equal to 0.15. No runoff is contemplated when rainfall intensity exceeds the infiltration capacity.

Following the work done by Hutchinson 1986 and Pastor et al. 2002, describing the variation of excess pore-fluid pressure during flow slides, an attempt was made to reproduce slow consolidation process in the Portalet landslide. Assuming a parallel flow to the slope surface, the dissipation of the excess pore-fluid pressure in the saturated layer of length h_s is governed by the Terzaghi's one dimensional consolidation theory, one solution is given by:

$$ep_w(t) = ep_{w0} \cdot e^{\frac{-t}{T_v}}$$

where ep_{w0} is the initial excess pore pressure, T_v is a time factor defined by $T_v = \dfrac{4h_s^2}{\pi^2 c_v}$ and

c_v is the consolidation coefficient. T_v controls the dissipation time of the excess pore-fluid pressure, two values have been considered, T_v=1s corresponding to an instantaneous dissipation and T_v =5.e6s corresponding to a slow consolidation process.

The viscosity has been determined by back analysis during the period of time from October, 5th to November, 21st 2006 corresponding to the GBSAR campaign. Table 1 summarizes the set of values taken in the different computations done.

| Set of parameters	$z(0)$ in m	T_v in s	η in Pa.s
Computed 1	6.5	1.	7.5 e9
Computed 2	6.5	5.e6	6.5 e10

Table 1. Values taken in the different computations done

Figure 2 presents the comparison between GBSAR measured and computed displacements and velocities for the "computed 1 and 2" set of parameters from the 5th of October to the 21st of November 2006. For the "computed 1" analysis, the velocity is directly proportional to the rainfall intensity and it is constant equal to 0.07 cm/day during the dry periods. In the "computed 2" analysis slow consolidation process is taken into account, the velocity pattern shows a smoother response of the landslide to rainfall input.

Figure 3 shows the relation between the predicted water table height evolution and rainfall intensity. In the case of "computed 1" the water level is constant in dry periods and varies instantaneously when it rains. On the contrary, the "computed 2" water table height is higher than "computed 1", because the excess pore-fluid pressure has no time to dissipate between two following rain events.
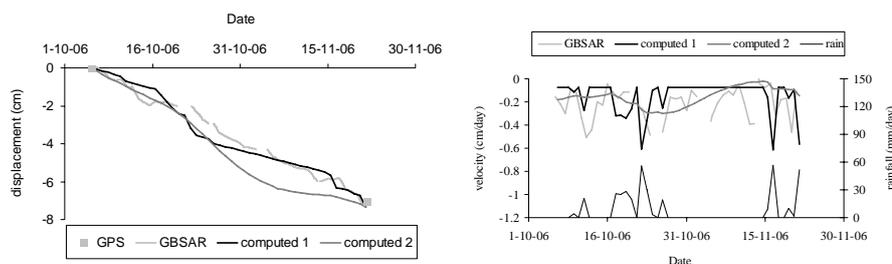
Figure 2. Measured and computed displacement and velocity from the 5th of October to the 21st of November 2006
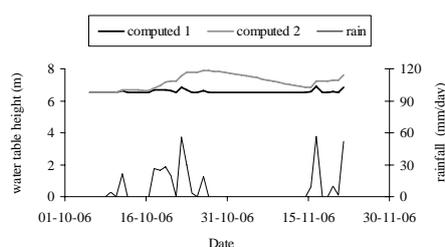
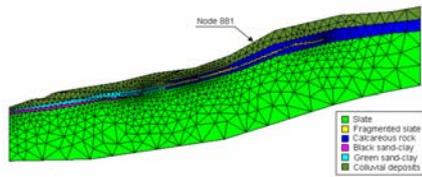

Figure 3. Predicted water table heights and rainfall intensity from the 5th of October to the 21st of November 2006

4. Modelling using a 2D coupled hydro-mechanical finite element model

A fully coupled hydro-mechanical plane strain finite element analysis has been performed to overcome limitations of the simple viscous model. The finite element code GeHoMadrid (Pastor et al. 1998) for transient Biot's equation resolution has been used.

The geological structure of the landslide has been obtained by means of geological, geomorphological assessment and drilling data (ICOG 2005). Section AA' has been discretized using quadratic triangular elements (6 nodes for displacement degree of freedom and 3 nodes for pore pressure degree of freedom). The mesh is composed by 2151 triangles and 3975 nodes, Figure 4.

Material behaviour has been represented with a Drucker-Prager constitutive model using material parameters defined in Table 2. Saturated condition is taken in all the materials.

Material	γ (Kg/m³)	E (N/m²)	ν	φ (°)	c (N/m²)
Colluvial deposit	2100.	15.e6	0.2	29.	0.
Green sand-clay	2040.	14.e6	0.2	18.	0.
Black sand-clay	2220.	25.e6	0.2	30.	0.
Calcareous rock	2170.	40.e6	0.2	38.	0.
Fragmented rock	2170.	20.e6	0.2	25.	20.
Slate rock	2770.	4000.e6	0.2	31	640

Figure 4. Finite element mesh and geological structure

Table 2. *Material parameters*

Two important factors have an influence on the slope stability: initial stress condition and ground water level position. Initial conditions have been treated in a first attempt modelling the construction process of the parking area described in section 2. Excavation process induced local instability near the toe of the excavated slope. The local collapse was also observed on the field and an immediate repair solution was carried out by replacing the excavated material. Consequently the final executed profile has been chosen as the studied geometry.

No information about the position of the ground water level was available. The initial hydraulic condition has been chosen performing an initial static stability analysis. The transient response taking into account rain condition has been performed in a second analysis.

4.1. Stability analysis

Stability analysis is performed in two phases: in the first one, gravity is progressively applied using a high value of suction on the upper boundary keeping the slope in a stable state. This condition is equivalent to imposing a water table parallel to the surface at a depth of 10 metres. In the second one, suction on the upper boundary is progressively reduced performing successive static equilibrium analysis, the water table is progressively raised to the surface. Plastic deformation develops along a shear surface until failure occurs for a given boundary suction condition.

A nearly linear behaviour is observed during the first phase corresponding to the gravity activation. A more marked plastic behaviour can be observed during the second phase corresponding to the decreasing suction boundary condition. Collapse is reached when the suction is equal to 34105. Pa, it is equivalent to a water table located at 3.48 m below the surface, plastic deformation and displacement contours at this moment are presented in Figure 5. The computed location of the rupture surface agrees very well with field observations. The observed scarps, Figure 1, are located at the same position on the upper part of the slope. Besides, rupture surface located at 12 m given by borehole 1 fits in with the computed rupture surface.
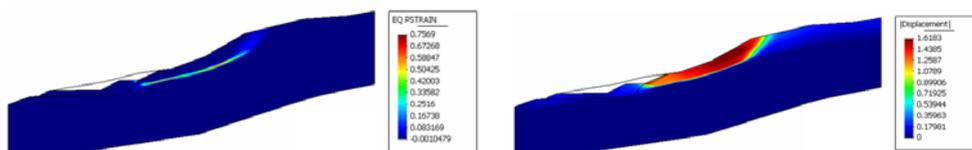
Figure 5. Equivalent plastic deformation contour and displacement contour (in m) at failure

4.2. Transient analysis with hydrological changes

The initial condition of the transient analysis is chosen from the stability analysis. The equilibrium state corresponding to a ground water level located 6 meters below the surface has been chosen. The choice of this initial state has an influence on the transient analysis,

states corresponding to the highest values of the ground water level can induce sudden collapse for small variations of pore pressure.

Rain is modelled using an input flow condition on the upper boundary. This condition supersedes the initial given hydraulic prescription, to do this an equivalent flow condition must replace the suction prescribed condition.

Different values of permeability (k_w=1.e-5m/s, k_w=2.e-5m/s, k_w=3.e-5m/s) constant over the domain, have been postulated. Figure 6 presents a comparison between GBSAR measured and computed displacement and velocity at node 881 during the autumn 2006 campaign. Permeability has an important influence on time response, further investigations must be carried out to correctly determine this parameter in each material as it can give also a different mechanical response in different zones of the slope profile.

It can be seen how motion is governed by rain infiltration. The model allows prediction of swelling process during no rain periods corresponding to the excess water pressure dissipation. The highest values of computed velocity coincide with long time rain periods, when excess pore pressure has no time to be dissipated. The observed discrepancy: the difference in the gradient of the measured and computed displacement curves and the zero computed velocity during no rain period can be reduced with a viscoplatic model.
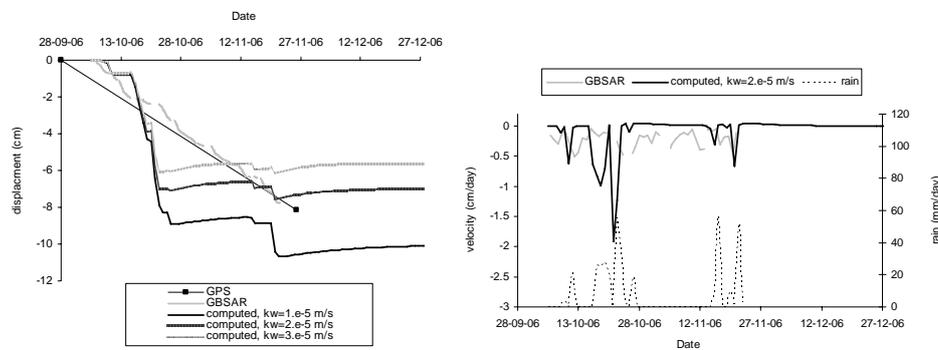

Figure 6. Measured and predicted displacement and velocity at node 881

5.   Conclusions

An attempt was made to model the slope mobility directly from rainfall intensity trough a simple 1D infinite model. The model includes a viscoplastic behaviour and takes into account directly the recorded daily rainfall intensity and the dissipation of the excess pore-fluid through a simple consolidation equation. In spite of the simplistic hypothesis done and undetermined parameters, the model can give a first approximation of the landslide kinematics.

A fully coupled hydro-mechanical finite element model overcomes limitations of the 1D model as it includes multidirectional behaviour, elastic response and delayed answer due to consolidation. A forthcoming analysis, taking into account viscoplastic behaviour and using the GBSAR data that are being collected will give a better approximation within an extended period of time.

After calibrating the unknown model parameters by back analysis in a fixed period of time, these models can be used to predict the landslide mobility in another period of time using scenarios of rainfall events with different return periods, or snow melt events.

Such local scale models can also be used to define danger criteria, for example when computed velocities reach unacceptable values or when velocities increase more and more for a same hydraulic solicitation. These models are useful tools for quantitative risk assessment and management strategies for landslides.

ACKNOWLEDGEMENTS

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