Application of a numerical model for slow moving landslides to the Valerio landslide in the Italian Appenines and the Super Sauze mudslide in the French Alps

Applications of a numerical model for slow moving landslides to the Valoria landslide in the Italian Apennines, and the Super Sauze mudslide in the French Alps.

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ABSTRACT: This research shows applications of the dynamic SLOWMOVE model to the Valoria case study located in the northern Apennines (Italy) and the Super-Sauze landslide in the southwestern Alps (France). The SLOWMOVE model is based on the Navier-Stokes equations with one-phase material, homogeneous and constant rheological properties and cancellation of the inertia term. At the Valoria case study site a 3.5 km long earth slide/flow with materials comprised of disaggregated Flysch, Marl and Claystones resumed activity in 2001 after a suspended phase. The landslide is characterized as earth slides in the upper slope, and as earth flows in the main track following complete disaggregation of the materials in the source areas. During reactivations, the earth flows can reach velocities up to 10 m h-1. Repeated acceleration events show a strong season control and continuous activity since 2001 more than 15 million cubic meters of material have been transferred down-slope. The Super-Sauze landslide is triggered in Callovo-Oxfordian black marls and is composed of a silty-sand matrix mixed with moraine debris. It extends over a horizontal distance of 850 m with an average 25° slope implicating a volume of 560,000 m³. The complex paleo-topography covered by the landslide is made by successions of crests and gullies which plays an essential role in the mudslide behavior by creating sections with distinct kinematical, mechanical and hydrological characteristics. The mudslide kinematics are characterized by a spatially heterogeneous displacement field with velocities ranging from 0.01 to 0.40 m day-1. For the Valoria landslide, the performance of the 1D approach of SLOWMOVE was analyzed on a representative landslide cross-section from the main track zone down to the toe zone. A large set of surface displacement data obtained since March 2008 through continuous monitoring in conjunction with multi-temporal Lidar surveys allowed for evaluation and calibration of the numerical implementations in terms of velocity and displacements and in terms of event-induced morphological changes. For the Super Sauze mudslide, the 2.5 D approach is used to simulate the heterogeneous displacement field of the mudslide. The performance of the model is evaluated on multi-temporal and spatially distributed datasets of landslide displacements for the period of summer 2009.

1 INTRODUCTION

Mass movements characterized by flow-like processes pose a serious hazard and require sound modelling approaches. A large number of experimental studies demonstrated the wide range of hydrogeological slide - flow conditions as well as the inherent complexity of physical processes involved in these phenomena (Iverson & Major, 1987; Hungr, 1997, Mangeney et al. 2007, van Asch et, 2007, Iverson, 2007). Due to this complexity, the run out depending on hydro-mechanical processes is often difficult to forecast. It is quite widely acknowledged that sliding and flowing is primarily controlled by topography, groundwater, residual shear strength, cohesion, viscosity (Sassa 2003; Hutchinson 1986; Comegna et al., 2007). Dynamic processes such as undrained loading during movements, basal erosion, development and dissipation of excess pore and transition from active to passive Rankine's states in compression and extension areas may also play a significant role (Picarelli et al. 2005, Hungr,1995). A mathematical model describing excess pore pressure generation and dissipation by dilation or contraction of a water saturated basal shear zone of a landslide was proposed by Iverson (2005). The displacement rate is then controlled by pore pressure generation during failure which can cause fluidization of the sliding materials. Van Asch et al. (2006) propose that excess pore pressure is generated by compression or extension as result of differential velocities of the landslide mass. The approach is convenient due to its sufficient degree of simplification and was shown to produce accurate results. Also in van Asch & Malet (2009) a conceptual mechanism describing the development of excess pore pressures as a result of kinematic deformation of a sliding material is used. In this study the basic equations of this concept are adapted and modified assuming the case of slow landslide motion that is controlled by pore water pressure dissipation. To validate the approach tha model is applied to different case studies in the Italian Apennines and the French Alps characterized by slow moving gravitational flows.

2 METHODOLGY

2.1 *Numerical simulation of slow-moving landslides*

For this study we modified a model concept for slow moving landslides (van Asch & Malet, 2009) which focuses on the complex processes related to excess pore pressure development. The main assumptions of the so-called SLOWMOVE model used in this work are

(1) it is based on the theory of infinite slopes,
(2) the sliding mass is assumed to behave as an incompressible fluid,
(3) undrained loading,
(4) viscoplastic material behavior,
(5) development of strains due to pore water pressure dissipation.

The fluid flow is described by the following equations. Mass conservation is given by equation 1

$$\frac{\partial h}{\partial t}+\frac{\partial h}{\partial x}v=0 \qquad (1)$$

where h is the thickness of the flow or the height of a slice respectively, t is the time and x is the horizontal distance. The conservation of momentum is based on the Navier-Stokes equations (Begueria et al. (2009)).

$$\frac{\partial v}{\partial t}+\frac{\partial v}{\partial x}v=g\cos\alpha\left[\sin\alpha+k\frac{\partial h}{\partial x}-S_f\right] \qquad (2)$$

In this model approach the momentum equation is simplified by setting the left side, i.e. inertia equal to zero (equation 3). The possibility of neglecting inertia in the simulation of slow moving landslides is discussed in van Asch et al. this issue. The landslide behavior depends on the balance between driving forces and resisting. The first term on the right defines the gravitational driving stress component that is dependent on topography. the second term reflects lateral stress that depends on the earth pressure coefficient k and the gradient of lateral force difference within the flow. The third term S_f includes the Mohr-Coulomb resisting stress, depending on cohesion and friction and a viscous resisting stress (equation 3).

$$0=\rho hg\left\{\begin{matrix}\overbrace{\sin\alpha\ \cos\alpha}^{\text{Shear Stress (D)}}\ +\overbrace{\frac{k}{\rho hg}\frac{\partial h}{\partial x}}^{\text{Lateral Stress (P)}}- \\ \left[\underbrace{\cos^2\alpha\ \tan\varphi'}_{\text{Frictional Resist. (S)}}+\underbrace{\frac{1}{\rho gh}\left(\tau_c\right.}_{\text{Cohesive Resist. (C)}}+\underbrace{\left.\eta\left(\frac{\partial v}{\partial z}\right)\right)}_{\text{Viscous Term (N)}}\right]\end{matrix}\right\} \qquad (3)$$

In the frictional term the apparent friction angle *φ'* is used that results from the pore water pressure ratio r_u and the residual friction angle *φ*.

$$\tan\varphi'=(1-r_u)\tan\varphi \qquad (4)$$

Equation 3 is solved for velocity (van Asch & Malet, 2009, van Asch et al., this issue) and differential strains are calculated. Since we assume the development of excess pore water pressure due to undrained loading the calculated velocities and strains are referred to as virtual velocities ($\bar{v}$) and virtual strains ($\bar{\varepsilon}$). From the virtual strains stresses are computed using Newton's viscosity law

$$\Delta\sigma=\frac{\eta}{\Delta t}\Delta\bar{\varepsilon} \qquad (5)$$

where η is the viscosity [kPa s]. Pore water pressures *p* are computed by Skempton's law that is a function of *A*, the Skempton parameter usually between 0.5 and 0.7 for fine grained soils, and of the stress *σ*. Real strains evolve due to pore water pressure dissipation. Many constitutive laws based on Terzaghi's one dimensional theory of consolidation exist (Lambe & Whiteman, 1979, Inverson, 1997). We use a dissipation law developed by Hutchinson (1986) to calculate the amount of pore pressure that is dissipated p_{diss}.

Pore water pressures and the lateral stresses are conserved using equations 4 and 5:

$$\frac{\partial p}{\partial t}+\frac{\partial p}{\partial x}v=-(1+A)\frac{\eta}{\partial t}\frac{\partial v}{\partial x} \qquad (6)$$

$$\frac{\partial P}{\partial t}+\frac{\partial P}{\partial x}v=-\frac{1}{\rho h}\frac{\eta}{\partial t}\frac{\partial v}{\partial x} \qquad (5)$$

The numerical scheme is based on a finite difference solution (fixed time-steps, 2D Eulerian space with Cartesian coordinates) was implemented in 1D using Microsoft Excel and in 2.5D using PC Raster, a GIS scripting language.

2.2 1 D application to the Valoria landslide

2.2.1 Objectives

The main motivation for the adaption of the concept to this case study is the complete reactivation of the Valoria landslide located in the Northern Apennines of Italy. The entire landslides has been active since in autumn of 2001 (Ronchetti et al. 2007). With the ongoing activity it poses a threat to numerous structures, such as a methane pipeline, houses and a bridge that traversed the landslide and was recently inaugurated. A reliable reconstruction and forecast of the landslide development requires the knowledge of the hydro-mechanical processes that are responsible for the landslide activity. Using the SLOWMOVE approach it is analyzed if pore pressure dissipation is a relevant process at this site.

2.2.2 Site description

The Valoria landslide, a complex and composite earth slide – earth flow is positioned in the Northern Apennines of Italy in province of Modena (Figure 1). The total affected are is about 1.6 km² and an estimated volume of as much as 20-30 million m³ of clay-rich debris are involved (Corsini et al., 2009). Main parameters of the landslide are summarized in Table 1.

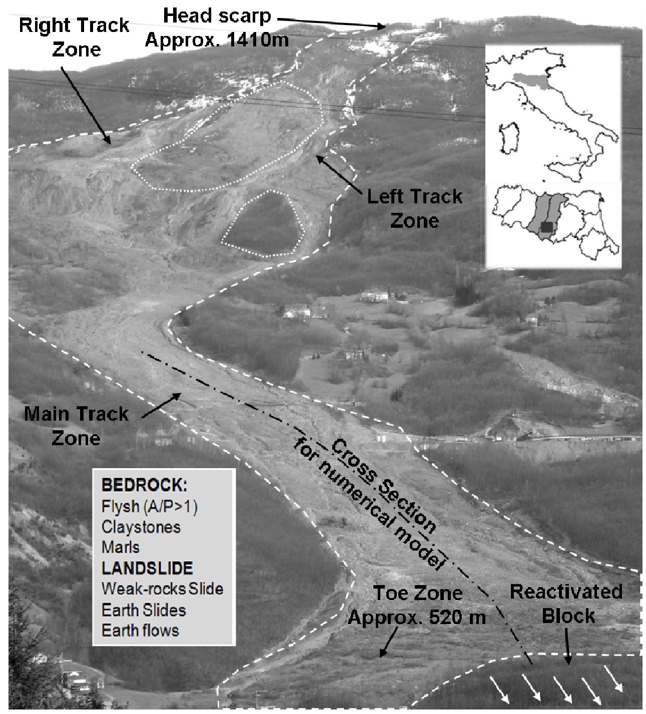
Table 1. Main Parameters of Valoria landslide

Properties	Description
Location	Northern Apennines, Italy
Classification	Complex earth-slide – earth-flow
Elevation	1413 m to 520 m
Length	3500 m
Area (active)	1.2 km²
Area (pot total)	1.6 km²
Volume	20-30 Mm³
Depth Max	40 m
Mean slope	14°

The Valoria landslide affects Cretaceous to Miocene rock masses such as sandstone-dominated flysch and silty-to-clayey shales dipping into the slope (Plesi et al. 2002). As a result of the convergence of the European and Adriatic plates that formed the Northern Apennines during the Tertiary the rocks are deformed by overthrusts and faults (Bettelli & De Nardo, 2001), favoring the decomposition of underlying bedrock along pre-marked discontinuities and weak zones. In the crown zone the landslide affects bedrock by developing listric shear-surfaces through the highly fractured rock masses mainly comprised of clayshales and weak sandstones. In the head zone blocks of bedrock in the scale of some meters are After the blocks are completely dismembered, a silty-clayey matrix with sparse rock blocks is formed encompassing earth-flow materials in the head zone, as well as in the track and toe zones. Using a wood fragment collected close to the bedrock interface in the landslide toe the total age of the landslide was estimated to be about 7800-7580 cal yr BP was obtained for zone (Bertolini, 2003).

In recent history, the landslide was mobilized partially or totally several times in the last 60 years (1950, 1951, 1956, 1972, 1984, 2001, 2005, 2006, 2007, 2008, 2009) (Manzi et al. 2004; Ronchetti et al. 2007). Following the 2001 reactivation the precarious stability conditions have contributed to an increased frequency of acceleration events. From 2005 onward reactivations occur several times per year, even in presence of non-exceptional rainfall.

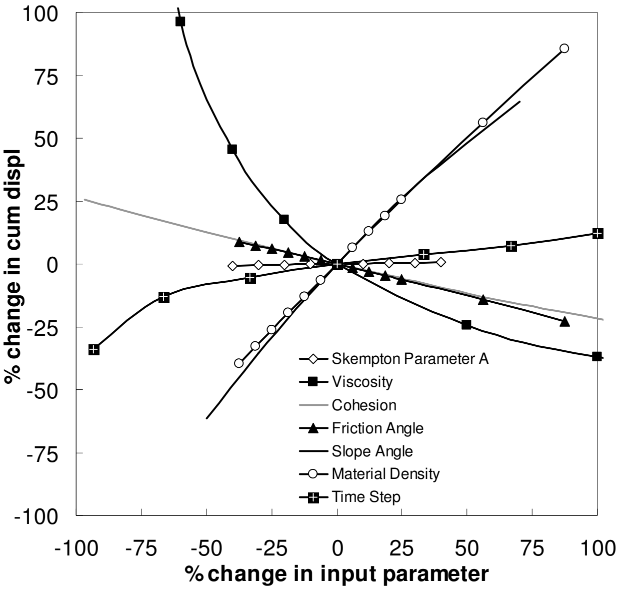
Figure 1. The Valoria landslide as seen from the west looking east. The active area is outline (white dashed line) on the image from 2009. A cross section for use with a numerical model is also marked.



2.2.3 Model Parameters and Setup

The one dimensional solution of the model was implemented using a spreadsheet software. A sensitivity analysis was conducted to evaluate the responsiveness of the model to parameter changes (Figure 2). From the formulation of the model we can infer that it is strongly depended on changes in viscosity. Further crucial and highly responsive parameters are given by the underlying topography and material density. On a trail-and-error basis we utilized three model outputs for calibration (1) mass transfer (change in topography), (2) velocity, (3) cumulated displacements. Table 2 shows reasonable ranges for all input parameters and a range of possible velocities and displacements that we obtained through a topographic monitoring system that obtains every three hours measurements from targets placed inside the landslide.

Figure 2. Results from the sensitivity analysis. We tested all input parameters of the numerical model and found that the model is highly sensitive to changes in viscosity density and slope angle.



Through analysis of geophysical data and topographic data we were able to extract a representative cross section that we used as basis for a back analysis of the topographic development between 2003 and 2007 (Figure 1).

Table 2 shows reasonable ranges for all input parameters and desired model results. Maximum displacements show two scenarios; a) for short term monitoring of active event and b) for long-term multi event observations

Properties	Description
Involved Materials: Claystones, Clayshales, Sandstone blocks	
Residual Friction Angle φ	12° -18°
Cohesion (c)	5-15 kPa
Viscosity (η)	$5x10^{10}$ Pa·s
Density (ρ)	1800 kg/m³ - 2000 kg/m³
Consolidation Coefficient (Cv)	0.1-1 m²/h
Skempton Parameter (A)	0.5-0.7
Pore Pressure Ratio (r)	0.5-0.8
Time Step (Δt)	0.1 days
Monitoring data	
Max Cumul. Displ. (Main flow)	a) 56 m in 2 months b) 164 m in 7 months
Avg. Cumul. Displ. (main flow)	50 meters in 2 years
Max velocities (main flow)	8-12 m/day
Avg. velocities (main flow)	0.1 m/day

2.3 2.5 D application to the Super Sauze mudslide

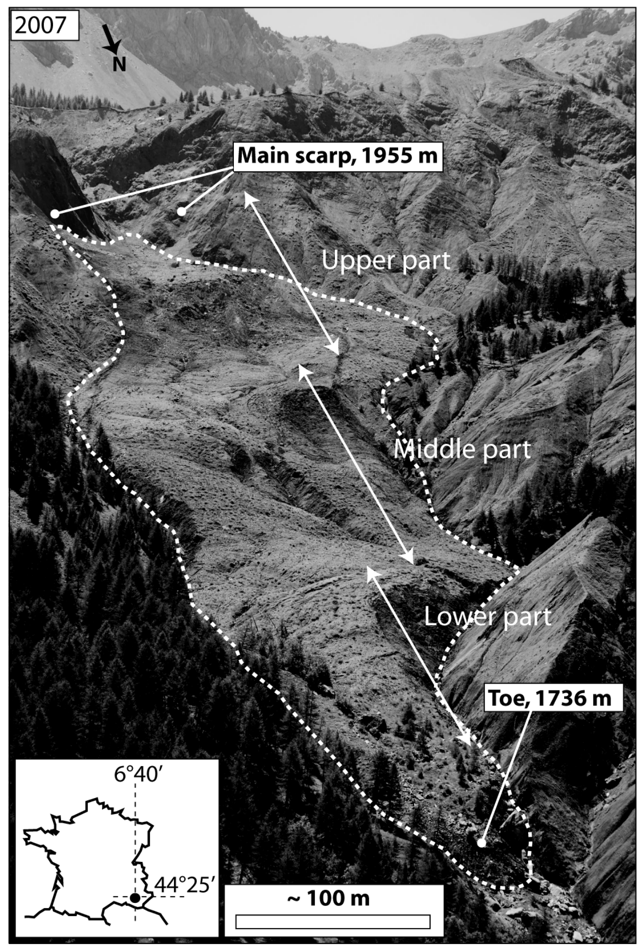
2.3.1 Objectives

The main objective of this 2.5 D application is to model spatial distributed displacements and to analyze the influence of the 3D basal topography on the mudslide propagation. In modeling complex 3D geometries benefit is derived from the simplicity of the SLOWMOVE model. The model is implemented in the GIS scripting language PCRaster which is especially adapted for iterative spatio-temporal environmental models (Karssenberg et al., 2001).

2.3.2 Site description

The Super-Sauze mudslide is located in the upper part of the catchments basin of the Sauze torrent characterized by a badland type morphology (Figure 3). Geomorphologic, geologic, geophysical, geotechnical and displacement monitoring studies have been conducted over 15 years in order to monitor the landslide dynamic. These investigations allowed also a good identification of the main structures.

Figure 3. View of the Super-Sauze mudslide from the North



2.3.3 History of development

Before the destabilization event in the 1960s, the scarp area was probably affected by a deep seated slope deformation controlled by regional faults which initiated the slope collapse. In the 1960s, additional shallow failures occurred in the scarp area. They mainly consist in successive plane and wedge failures affecting the crests. The collapsed material of rocky panels progressively transformed into a silty sandy matrix integrating marly fragments of heterogeneous size through successive drying/wetting and freeze/thaw cycles. In the late 1970s, the mobilized material started to accumulate in the gullies. From the 1970s until today, the mudslide is gradually covering the torrential stream located downstream. In 2007, the mudslide extent over a distance of 920 m between an elevation of 2105 m at the crown and 1736 m at the toe with an average width of 135 m and a average slope of 25°. The total volume is estimated at 560,000 m^3 (Travelletti & Malet, submitted).

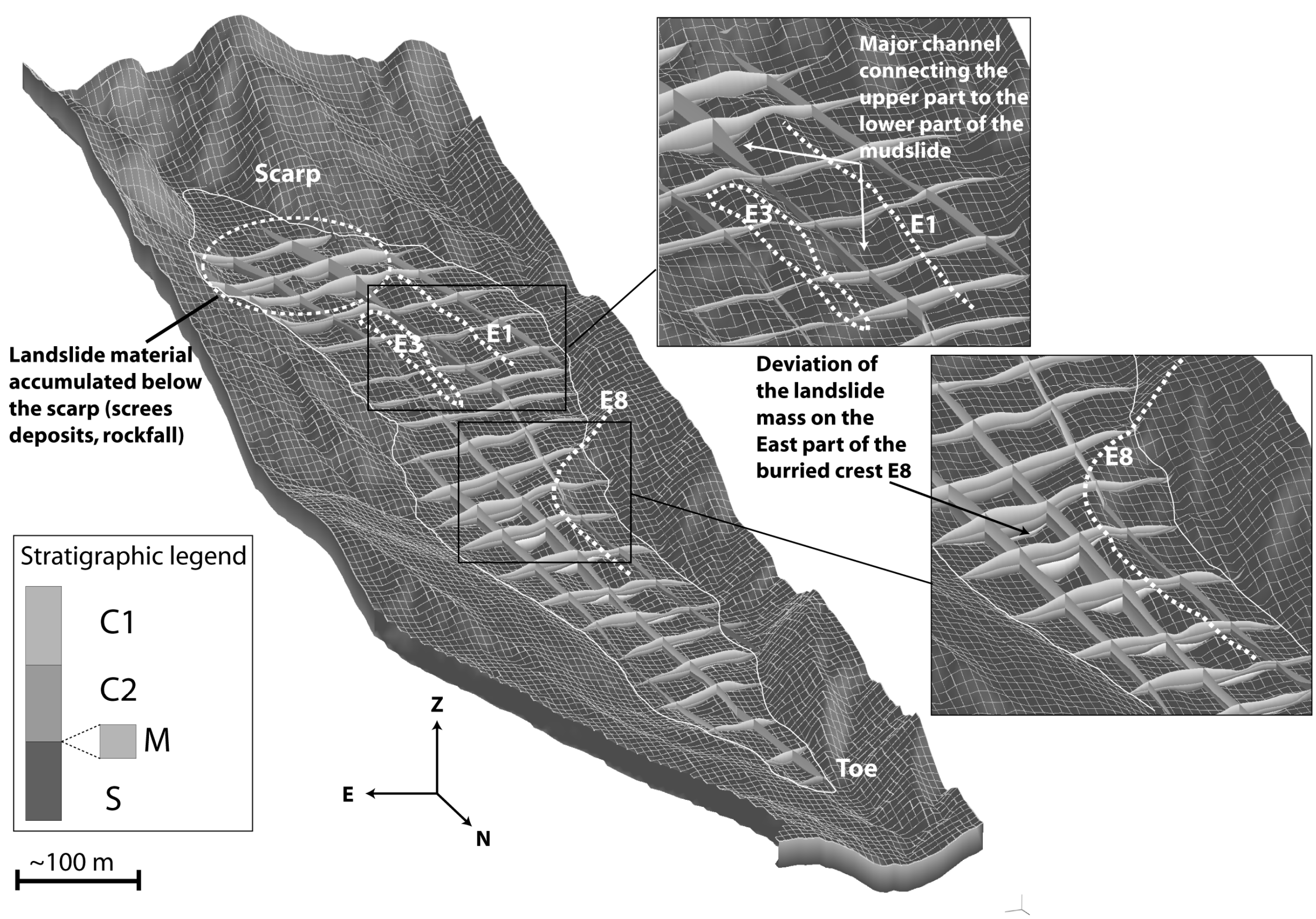
2.3.4 Geometry and Internal layering

The topography covered by the mudslide is composed of sub-parallel crests and gullies in the accumulation zone. Some of them emerge out of the mudslide others are located a few meters below the ground surface. A three-layer structure characterized by distinct mechanical properties has been proposed to define the internal structure. This characterization is based on the type of material, inclinometer measurements and dynamic penetration tests (395 dynamic penetration tests along 19 cross-sections) (Figure 4). A detailed description of the geomechanical and hydrological characteristics of the internal structure can be found in Flageollet et al. (2000) and Malet et al. (2003).

The vertical layering of the mudslide can be summarized in:

- A superficial unit “C1”with a thickness ranging between 5 to 325 9 m (cone tip resistance Qd < 10 Mpa, pressiometric modulus EM < 15 Mpa, velocity greater than 5 m.y-1). A shear surface is identified at a depth between 5 and 8 m.
- A deep unit “C2” with a thickness ranging between 5 to 10 m. According to inclinometer measurements and pressiometric tests (EM > 15 Mpa, pressure limit Pl > 4 Mpa), this unit is considered as impermeable and very compact. Inclinometer measurements showed that this unit is characterized by very low to null displacement rate. It is associated to a “dead body” as it is observed on the Slumgullion earthflow and on the La Valette mudslide (Colat and Locat, 1993). The ancient torrent channel can be partially filled by significant thickness of morainic deposits “M” (several meters) before the landslide event (Weber and Hermann, 2000)
- s “M” (several meters) before the landslide event (Weber and Hermann, 2000)
- The stable substratum “S” composed of intact black marls (Qd > 20 MPa)

Figure 4. 3D geometrical model of the Super-Sauze mudslide



2.3.5 Kinematics

Terrestrial laser scanning, DGPS measurements and permanent camera monitoring system (Travelletti et al., this issue) are used to measure the intensity of short and long term movements. The distribution of the landslide kinematics at the ground surface vary temporally and spatially with typical range of velocity between 1 to 3 cm.d^{-1} and acceleration peak until 40 cm.d^{-1} in the spring season during snowmelt. Thus indicates that a main driving force of the movements is the variations of pore-water pressure in the slope. The development of compression zone leading to changes in pore pressure under (partly) undrained conditions is a mechanism that has to be considered (van Asch et al., 2007).

For long and short term kinematics, one can observe a decrease of displacements rate from the upper to the lower part of the slope and a strong influence of the basal topography, especially in the vicinity of nearly emergent crests.

2.3.6 Mesh and boundary conditions

The finite difference geomechanical calculations are carried out in the PCRaster environmental modeling language (Wesseling et al., 1996; Karssenberg et al., 2001). The model is implemented in an explicit finite dif-ference (Eulerian) mesh, i.e. the flow is described by variation in the conservative variables at points of fixed coordinates as a function of time. The mesh is defined as a regular grid with a size s=Δx=Δy of 5 m, in accordance with the grid format common to most GIS platforms. Because the most active layer C1 is mainly responsible for the displacements ob-served on the ground surface (Malet, 2003), the in-terface between C1 and C2 is considered as the slid-ing surface. This interface does not change in time. This interface is the first input file for the model provided in the form of a DEM. The DEM defines also the computation domain and the mesh size (Be-gueria et al, 2009). The mudslide is not allowed to go outside the spatial limit of the DEM (close boundary). The second input is the map of the thickness of the layer C1.

A twenty-day runout with a constant time step Δt of 0.1 day is simulated to analyse the coherence of the simulated displacements pattern with the observed one.

3 PRELIMNARY RESULTS AND DISCUSSION

3.1 Valoria

Table 1 summarizes the parameters that we found to achieve a reasonable degree of fit for a first estimate of the model's performance. Starting from the topographic profile in 2003 the model was used to simulate a time span of 1000 days. This time window approximately covers the period between the topographic profiles we developed for the years 2003 and 2007 and used to evaluate the performance of the mdel. The concept model has predicted a surface that is significantly lower then the topography observed in 2007 (Figure 5). of the Although the velocity values are realistic (Figure 6 and Table 4), the suggested topography deviates noticeably starting at 500 m in the crossection Lower viscosity values resulted in a longer runout distances without significant improvement in degree of fit of the topography.

Table 3. Parameters calculated from back analysis for the development of topography of Valoria between 2003 and 2007.

Properties	Value
Friction Angle φ	15°
Cohesion (c)	15 kPa
Viscosity (η)	9x10^{10} Pa·s
Density (ρ)	1800 kg/m³
Consolidation Coefficient (Cv)	0.2 m²/h
Skempton Parameter (A)	0.5
Pore Pressure Ratio (r)	0.7
Time Step (Δt)	0.1 days

Figure 5. Results of topographic reconstruction after 1000 days. The SLOWMOVE acronym represents the implemented numerical model.

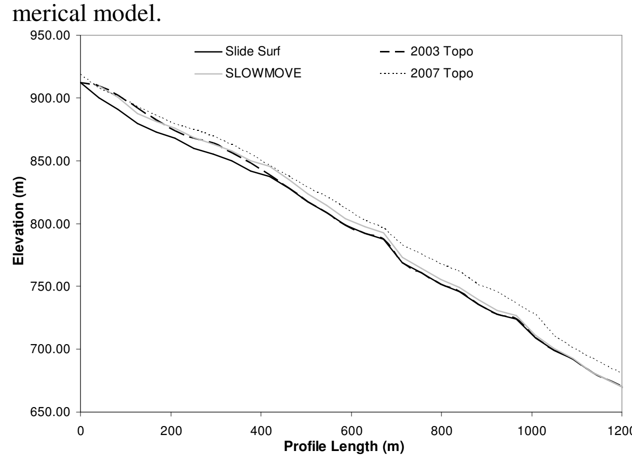


Figure 6. Results of topographic reconstruction after 1000 days. The SLOWMOVE acronym represents the implemented numerical model

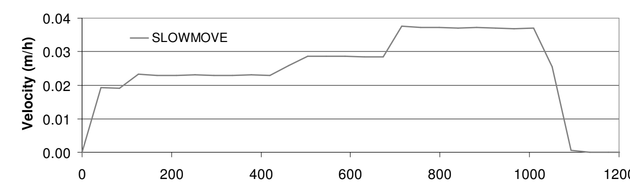


Table 4. Results of a simulation of a cross section of the Valoria landslide (1000 days) .

Properties	Value
Max velocities (first 50 days)	2.4 m/day
Avg. velocities (first 50 days)	2.0 m/day
Avg. velocities (50-1000 days)	1.0 m/day
Runout distance	1080 m

Furthermore, the flow advancement in the first 50 days was found to coincide with real observations, as the mass had closed a gap extending from a dormant lobe (at about 400 m) to another block of landslide material farther downslope (at about 550 m). This indicates that the cumulative displacements predicted by the model are realistic for the first phase of the model execution. An further increase in strength parameters, i.e. residual friction angle, cohesion or in the viscosity can yield a better fit but it becomes compulsory to increase the period of simulation to far beyond 1000 days and strength parameters are no longer representative for the Valoria landslide. Another possibility would be introducing a source of mass that feeds new material into the model, thereby increasing the rate of mass transfer. Further calibration is necessary to improve a better fit. Overall we speculate concurring with our observation at the Super-Sauze mudflow that the main drawback of the SLOWMOVE concept is the limitation to a one phase rheological model. Using state dependent parameters (shear strength, viscosity) better reflecting real world conditions could help to overcome this drawback.

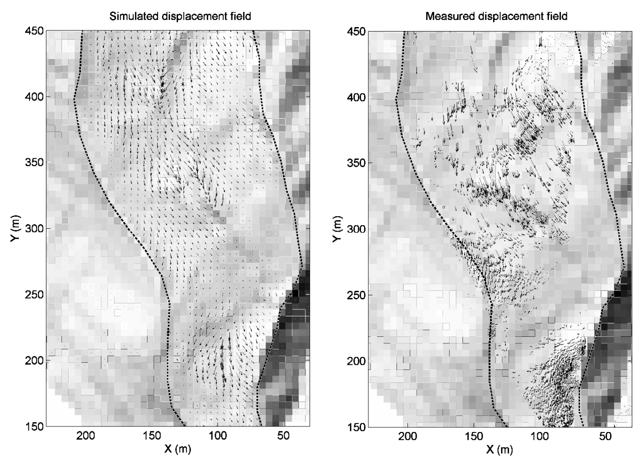
3.2 *Super-Sauze*

A set of parameters in a reasonable range according to the mudslide rheology is chosen (Table 5). The results are very sensitive to small variation of the viscosity. This parameter mainly controls the mudslide velocities while the cohesion mainly acts on the amount of material being transferred. High viscosity values are necessary to obtain displacements and velocities comparable with observed one. Globally, the horizontal displacement pattern is coherent with the reality, especially for the middle and the lower part of the mudslide (Figure 7).

Table 5. Parameters used for the simulation of Super-Sauze.

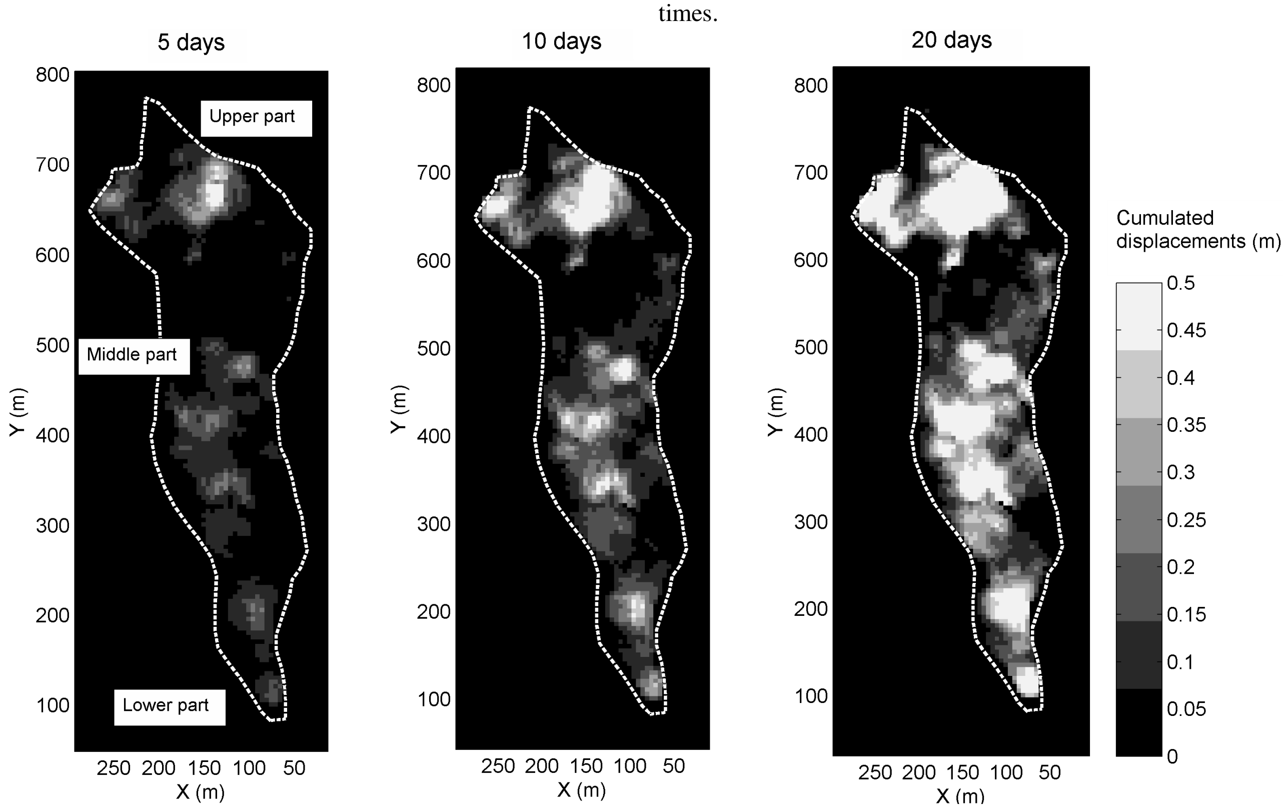
Properties	Description
Friction Angle φ	28°
Cohesion (c)	20 kPa
Viscosity (η)	2×10^{11} Pa·s
Density (ρ)	1800 kg/m³
Consolidation Coefficient (Cv)	0.2 m²/h
Skempton Parameter (A)	0.5
Pore Pressure Ratio (r)	1
Time Step (Δt)	0.1 days

Figure 7. Comparison between simulated displacement field and measured displacement field.



Major cumulated displacements are directly correlated with areas where the thickness of the layer C1 is important (Figure 8) (middle part and lower part).

Figure 8. Cumulated displacements maps for three different times.



The influence of the buried crest E8 is also particularly visible in the middle part. However some incoherencies concern the upper part of the mudslide exhibiting unexpected significant horizontal displacements. On the opposite, the simulation fails to reproduce high velocities in areas where the bedrock is close to the surface topography as it is the case in the middle part. Therefore different rheological proprieties should be assigned in these areas. Analogous to the application of the concept to the Valoria landslide we find that a change in rheological properties during the simulation would help to overcome low displacement in areas where the bedrock is close to the ground topography for example. In this way the mass transfer could be more accurately predicted for the lower portion of the slope.

4 CONCLUSIONS

In this study a model approach is proposed that assumes pore water pressure dissipation as a possible mechanism that controls slow landslide motion. The modified model concept of van Asch & Malet (2009) is applied as one and 2.5-dimensional formulation. The application to the Valoria landslide using the 1D model shows that the SLOWMOVE approach is not sufficient to reconstruct the real slope behavior. However the numerical scheme is successfully implemented in 2.5 dimensions and applied to the Super-Sauze landslide where the main objective was to model spatially distributed displacements. The main drawback of SLOWMOVE lies in the limitation to one-phase materials with constant properites, i.e. constant shear parameters, constant viscosity and pore water pressure dissipation. We found that this does not accurately reproduces such complex behaviour as in the cases of Valoria and Super-Sauze with regard to longterm mass transfer. Further development is needed to include transient pore pressure conditions, i.e. in response to groundwater changes and spatially distributed rheological properties. Another possibility is an improvement of the pore pressure dissipation function which mainly is the main controlling mechanism in the models present configuration. In conclusion we would like to point out that the capabilities of the current setup of SLOWMOVE are limited to predictions of short term (1D) and spatially distributed displacements (2.5D) since an accurate prediction of long-term mass transfer rates is still insufficient.

5 REFERENCES

Beguería, S. Van Asch, Th.W.J. Malet, J.-P. & Grondahl, S. 2009. A GIS-based numerical model for simulating the kinematics of mud and debris flows over complex terrain. *Nat. Hazards and Earth Syst. Sci.*, 9 : 1897-1909.

Bertolini, G. 2003. Frane e variazioni climatiche nell'Appennino emiliano. Tesi di Dottorato inedita, *Università degli Studi di Modena e Reggio Emilia*: 215 pp.

Bettelli, G., De Nardo, M.T. 2001. Geological outlines of Emilia Apennines (Italy) and introduction to the rock units cropping out in the areas of landslides reactivated in 1994-1999 period. In: Bertolini, G., Pellegrini, M., Tosatti, G. 2001. Le frane della regione Emilia-Romagna, oggetto di interventi di Protezione Civile nel periodo 1994-1999. *Quaderni di Geologia Applicata* 8 (1): 1-26.

Chen, H. & LEE, C.F. 2000. Numerical simulation of debris flows. Canadian Geotechnical Journal 37: 146-160.

Colat G., Locat J. 1993. Glissement et coulée de La Valette dans les Alpes de Haute-Provence. Présentation générale et modélisation de la coulée. Bull. Liaison Labo. P. Et Ch. 187: 19-28.

Corsini, A., Borgatti, L, Cervi, F., Dahne, A., Ronchetti, F., Sterzai, P. 2009. Estimating mass-wasting processes in active earth slides – earth flows with time-series of High-Resolution DEMs from photogrammetry and airborne LiDAR. *Natural Hazards and Earth Systems Sciences* 9: 433-439.

Flageollet, J.-C, Malet, J.-P, Maquaire, O. 2000. The 3D structure of the Super Sauze Earthflow: A First Stage Towards Modelling its Behaviour. Physics and Chemistry of the Earth 25 (9), 785-791.

Hungr, O. & McDougall, S. 2009. Two numerical models for landslide dynamic analysis. *Computers & Geosciences* 35: 978–992.

Hungr, O. 1995. A model for the runout analysis of rapid flow slides, debris flows and avalanches. *Canadian Geotechnical Journal* 32: 610-623.

Hutchinson, J. N. 1986. A sliding-consolidation model for flow slides. *Can. Geotech. J. 23*: 115–126.

Iverson, R.M. 1997. The physics of debris flows, *Rev. Geophys.* 35: 245-296.

Iverson, R.M., & Major, J.J. 1987. Rainfall, groundwater flow, and seasonal movement at Minor Creek landslide, northwestern California: Physical interpretation of empirical relations. *Geological Society of America Bulletin*, 99: 579‐594.

Iverson, R.M., 2005. Regulation of landslide motion by dilatancy and pore pressure feedback. Journal of Geophysical Research: 110 F02015, doi.10.1029. 16 pp.

Karssenberg, D., Burrough, P. A., Sluiter, R., and de Jong, K.: The PCRaster Software and Course Materials for Teaching Numerical Modelling in the Environmental Sciences, Transactions in GIS, 5(2), 99–110, 2001.

Lambe, T. W. & Whitman, R. V. 1979. *Soil Mechanics, SI Version,* John Wiley, New York, 553 pp.

Malet, J.-P. 2003. Les glissements de type écoulement dans les marnes noires des Alpes du Sud. Morphologie, fonctionnement et modélisation hydromécanique. PhD Thesis in Earth Sciences, Université Louis Pasteur, Strasbourg, 364 p.

Picarelli, L., Urciuoli, G., Ramondini, M. & Comegna L. 2005. Main features of mudslides in tectonised highly fissured clay shales. *Landslides* 2(1): 15-30.

Picarelli,L., Urucioli, G., RUSSO, C. (2000) – Keynote Lecture. Mechanics of slope deformation and rupture in stiff clays and clay shales as a consequence of cycling pore pressures. In: BROMHEAD E.N., DIXON N. & IBSEN M.-L., Eds., Landslides in Research, Theory and Practice: Proc. 8th Int. Symp. on Landslides, Cardiff, UK – Thomas Telford, London. Keynote lecture, CD_ROM.

Plesi, G., Daniele, G., Palandri, S., Balatri, R. 2002. *Legenda Foglio 235 Pievepelago.* Bologna.

Sassa K. 1985. The mechanism of debris flows. Proceedings, 11th International Conference on Soil Mechanics and Foundation Engineering, San Francisco, 1: 1173-1176.

Savage, S.B. & Hutter, K. 1989. The motion of a finite mass of granular material down a rough incline. *Journal of Fluid Mechanics* 199: 177-215.

Travelletti J and Malet J-P. Characterization of the 3D geometry of flow-like landslides: a methodology based on the integration of multi-source data. Submitted in Engineering Geology.

van Asch Th. W.J., Van Beek L. P. H., Bogaard T.A. 2007. Problems in predicting the mobility of slow-moving landslides. Engineering Geology 91: 46-55.

van Asch, T. W. J., Malet, J.-P., and van Beek, L. P. H. 2006. Influence of landslide geometry and kinematic deformation to describe the liquefaction of landslides: some theoretical considerations, *Eng. Geol.*, 88 (1–2): 59–69.

van Asch, Th.W.J., Malet, J.-P. 2009. Flow-type failures in fine grained soils: an important aspect in lanslide hazard analysis. *Nat. Hazards and Earth Syst. Sci.* 9: 1897-1909.

Wang, G., & K. Sassa 2003. Pore-pressure generation and movement of rainfall-induced landslides: Effects of grain size and fine-particle content, *Eng. Geol.* 69: 109–125.

Weber, D., Herrmann, A. 2000. Contribution de la photogrammétrie numérique. l'étude spatio temporelle de versants instables: l'exemple du glissement de terrain de Super-Sauze (Alpes de Haute-Provence, France). Bulletin de la Société Géologique de France.

Wesseling, C. G., Karssenberg, D., Van Deursen,W., and Burrough, P. A.1996. Integrating dynamic environmental models in GIS: the development of a Dynamic Modelling language, Transactions in GIS 1: 40–48.