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Volume thématique : Issues in landslide process monitoring and understanding

Techniques, issues and advances in numerical modelling of landslide hazard

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Key words. – Landslide, Hazard assessment, Modelling, Pre-failure, Failure, Post-failure, Research directions

Abstract. – Slope movements (*e.g.* landslides) are dynamic systems that are complex in time and space and closely linked to both inherited and current preparatory and triggering controls. It is not yet possible to assess in all cases conditions for failure, reactivation and rapid surges and successfully simulate their transient and multi-dimensional behaviour and development, although considerable progress has been made in isolating many of the key variables and elementary mechanisms and to include them in physically-based models for landslide hazard assessments. Therefore, the objective of this paper is to review the state-of-the-art in the understanding of landslide processes and to identify some pressing challenges for the development of our modelling capabilities in the forthcoming years for hazard assessment. This paper focuses on the special nature of slope movements and the difficulties related to simulating their complex time-dependent behaviour in mathematical, physically-based models. It analyses successively the research frontiers in the recognition of first-time failures (pre-failure and failure stages), reactivation and the catastrophic transition to rapid gravitational processes (post-failure stage). Subsequently, the paper discusses avenues to transfer local knowledge on landslide activity to landslide hazard forecasts on regional scales and ends with an outline how geomorphological investigations and supporting monitoring techniques could be applied to improve the theoretical concepts and the modelling performance of physically-based landslide models at different spatial and temporal scales.

Techniques, état de l'art et avancées dans la modélisation numérique de l'aléa « glissement de terrain »

Mots-clés. – Glissement de terrain, Evaluation de l'aléa, Modélisation, Pré-rupture, Rupture, Post-rupture, Directions de recherche

Résumé. – Les mouvements de versant (*i.e.* glissements de terrain) sont des phénomènes dynamiques, au comportement complexe dans le temps et dans l'espace et contrôlés par des facteurs (hérités et actuels) de prédisposition et de déclenchement. A l'heure actuelle, il n'est ni possible d'évaluer les conditions qui conduisent à la rupture du versant, à la réactivation d'un glissement déclaré ou à une accélération forte, ni de simuler leur comportement transitoire et multidimensionnel, bien que des avancées considérables sur l'identification des variables de contrôle et des mécanismes élémentaires, et sur le développement de modèles à base physique aient été effectuées. Ainsi, l'objectif de ce manuscrit est d'effectuer un état de l'art critique sur la connaissance des processus « glissement de terrain » et d'identifier des directions de recherche pour le développement de modèles numériques utiles pour l'évaluation de l'aléa gravitaire dans les prochaines années. Le manuscrit a pour clé d'entrée la nature variée des mouvements de versant et les difficultés associées à la simulation de leurs comportements temporels dans des modèles numériques à base physique. Le manuscrit analyse successivement les challenges scientifiques associés à l'identification des déformations lentes et des ruptures initiales (stades de pré-rupture et de rupture), des réactivations de glissements déclarés et à leur transformation catastrophique en mouvement gravitaire rapide (stade de post-rupture). Puis, le manuscrit discute la problématique du transfert d'échelle, de la connaissance de l'activité d'un glissement de terrain à l'échelle locale à la connaissance et à la prévision de l'aléa à l'échelle régionale. En conclusion, le manuscrit souligne l'intérêt des observations géomorphologiques (en complément des techniques d'investigation et de surveillance) pour améliorer la performance de nos modèles conceptuels et numériques à plusieurs échelles spatiales et temporelles.

INTRODUCTION

The sustainable development of mountainous areas and assured safety to their citizens require sophisticated and reliable analyses of hazardous processes and consequent risks. A major threat arises from all types of slope movements (e.g. falls, topples, slides, lateral spreads, flows to which we refer as landslides from here on) which are triggered in these areas and which represent one of the most destructive natural hazards on earth [Brabb, 1991]. Human casualties are imperative and economical losses may reach 1 or 2% of the gross national product in many developing countries [Schuster and Highland, 2001]. As stated in 2006 by the United Nation University, Asia suffered 220 catastrophic landslides in the

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past century – by far the most of any world region – but those in North, Central and South America have caused an equally astounding toll in deaths and injuries while those in Europe are the most expensive – causing average damage of almost $23 million per landslide – [OFDA/CRED, 2006]. Moreover, landslide activity seems to increase because of global warming and anthropic actions [Schuster, 1996]. Analysing, evaluating and mitigating the hazard and risk associated to slope movements pose therefore a challenge to many earth scientists, engineers and decision-makers.

The quantitative analysis of the slope movement hazard requires that both the spatial and temporal probability of occurrence and the intensity of all types of landslides are forecasted [Aleotti and Chowdhury, 1999; Bonnard *et al.*, 2003]. The spatial probability of occurrence, often within an undefined, implicit time span, is called susceptibility [Varnes, 1984]. Occurrence probability is the explicit probability that a certain phenomenon will occur within an area over a specified period of time. Intensity is a measure of the destructive potential of a phenomenon, based on a set of physical parameters, such as velocity, thickness of the displaced debris, volume, energy and impact forces. Intensity varies with location along and across the travel path of the material and therefore it should ideally be described spatially.

Given the present state of knowledge, understanding, forecasting and controlling the hazard associated with landslides is still an empirical task. It involves qualitative and quantitative analyses, including model simulations, from various disciplines (geomorphology, structural geology, engineering geology, hydrology, hydrogeology, geophysics, geotechnics, civil engineering). Analysis can be performed at several spatial and temporal scales according to the objective of the hazard assessment [Aleotti and Chowdhury, 1999; van Westen *et al.*, 2006]. Accordingly, the methods and tools used for the analysis are radically different; empirical or statistical techniques (*e.g.* multivariate analysis) are generally applied to predict landslide susceptibility at regional scale, more process-based approaches (*e.g.* limit-equilibrium methods, numerical deformation methods) are applied at the local scale.

The objective of this article is to present the techniques, issues and advances in landslide hazard assessment. We limit ourselves to the quantitative assessment of landslide hazard at the local to regional scale over human timescales (< 100 years) and we focus on physically-based or process-based approaches. The paper does not review the various techniques and methods available at the regional scale for susceptibility and hazard evaluation [see for instance van Westen, 1994; Guzzetti *et al.*, 1999]. Moreover, the focus is restricted to the analysis of the literature concerning slide and flow processes.

– First, the complex nature of slope movements is discussed in relation to difficulties in simulating their time-dependent behaviour in numerical models. The utility of physically-based modelling in understanding landslide processes and the evaluation of scenarios for hazard assessment is also outlined.

– Second, some of the major problems in analysing the mechanisms at the local scale are summarized on the basis of an extensive literature review. The mechanisms are subdivided according to the stage in landslide development (*e.g.*, pre-failure stage, failure stage, post-failure stage) and possible avenues for improvement are outlined.

– Third, procedures for hazard assessment and mapping at the regional scale with physically-based modelling are discussed.

– Finally, sources of supporting information to improve our modelling efforts are proposed (geomorphology, monitoring techniques).

For this overview of the state-of-the-art in our understanding of slope movements and to identify those areas that require the attention from the landslide modelling community over the coming years, we draw from recent available reviews of slope stability models [Bromhead, 1996; Brunsden, 1999; Vulliet, 2001; Vulliet and Dewarrat, 2001] and recent Conference Proceedings on landslides and debris flows over the past 10 years, as well as recent research papers published in International Journals. Our choice of papers is limited for practical reasons; only papers describing conceptual, theoretical or numerical studies are included here and detailed case studies have been ignored. We are ourselves aware that both the scope and extent of the paper necessitates many choices, often subjective, and that we are not able to cover the entire field of landslide modelling. Notwithstanding, we belief that we are able to paint the broad picture of the present state-of-art, to reveal its general composition and to highlight the essential details that will dominate the field of landslide modelling for the coming years.

SPECIAL NATURE OF SLOPE MOVEMENTS AND AVAILABLE PHYSICALLY BASED METHODS

Slope movements and controlling factors

In both the geomorphological and the geotechnical literature [Dikau *et al.*, 1996; Cruden and Varnes, 1996], the term slope movement characterizes all varieties of ground failure and downslope movement of earth material controlled by gravity. One of the simplest methods of classification (fig. 1) is that initially proposed by Varnes [1978] and extended by Vaunat *et al.* [1994] and Leroueil [2001]: they classify slope movements according to the type of movement, the type of material and the movement phase or state of activity (*e.g.* the rate of development over a period of time [Dikau *et al.,* 1996]).

Five principal types of movements are distinguished according to the geomorphological classification proposed by Cruden and Varnes [1996] and Dikau *et al.* [1996] (table I). These five principal types sometimes combine or cascade in time and space, resulting in ‘complex movements’, which consists of more than one type (*e.g.* a rotational-translational slide) or those that evolve from one type into another (*e.g.* slump-earthflow). Many slope movements are complex, although one type of movement generally dominates over the other at a particular point in time and space. Since few landslides except falls and topples are first-time movements, it is therefore important to identify the initial phenomena in order to understand present-day deformation patterns.

Another important qualitative criterion in identifying the type of landslides is to characterize their size and especially their thickness. Varnes [1984] categorizes the slope movements as shallow (less than 2 m thick), medium (between 2

TABLE I – The five principal types of slope movement.
TABL. I – *Les cinq principaux types de mouvements de versants.*

Type of movement	Definition
Fall	A slope movement for which the mass in motion travels most of the distance through the air, and includes free fall movement by leaps and bounds and rolling of fragments of material. A fall starts with the detachment of material from a steep slope along a surface on which little or no shear displacement takes place.
Topple	A slope movement that occurs due to forces that cause an over-turning moment about a pivot point below the centre of gravity of the slope. A topple is very similar to a fall in many aspects, but do not involve a complete separation at the base of the failure.
Lateral spreading	A slope movement characterized by the lateral extension of a more rigid mass over a deforming one of softer underlying material in which the controlling basal shear surface is often not well-defined.
Slide	A slope movement by which the material is displaced more or less coherently along a recognisable or less well-defined shear surface or band.
Flow	A slope movement characterized by internal differential movements that are distributed throughout the mass and in which the individual particles travel separately within the mass.

and 5 m) and deep-seated (deeper than 5 m). The thickness is difficult to estimate from the surface using solely geomorphological criteria and it calls for detailed site investigation.

The behaviour of slope movement is highly controlled by the nature of the material and its physical, hydrological and geotechnical properties have to be established. In the geotechnical classification (fig. 1b), the types of material are gathered into ten main classes: hard intact rocks, hard fissured rocks, soft rock, structurally complex formations, stiff clays, post-glacial clays, silts and fine sands, debris and coarse materials, and other unsaturated materials such as residual soils. By nature, slope material is largely discontinuous, anisotropic, inhomogeneous and a non-elastic medium. The material is also a fractured or porous medium containing fluids (in either liquid or gas phases), under complex *in-situ* conditions of stresses, temperature and fluid pressures.

Finally, the behaviour of slope movement is time-dependent [Flageollet, 1996; Qin *et al.*, 2001], and the movement phase is split into pre-failure, failure and post-failure stages with the possibilities of occasional reactivation (table II). All types of movements at a given stage are associated with specific controlling variables that are subdivided into preparatory and triggering factors.

Movement is resisted by the shear strength of the material (cohesion and effective inter-particle friction in case of effective stress analysis) that can be mobilized along the slip surface. Hence, the ratio between the available shearing resistance (resisting forces) and the shear stress (disturbing forces), or safety factor F, is conventionally taken as the measure for the stability of a slope [Bromhead, 1992; van Beek, 2002]. As the shear stress approaches the maximum available shear strength, the safety factor becomes one and failure is imminent. If the slope is destabilized by triggering factors (*e.g.*, earthquake, rainfall), the apparent increase of the shear stress over the available shear strength is equivalent to the acceleration of the sliding mass. Hence, it may be useful to visualize slopes as existing in one of the following three stages (fig. 2):

- stable, $F > 1.5$: the margin of stability of the slope is sufficiently high to withstand all destabilising forces;
- marginally stable, $1.0 < F < 1.5$: the slope is likely to fail at some time in response to destabilising forces reaching a certain level of activity;

TABLE II – The three phases of movement and their associated specific control variables.
TABL. II – *Les trois stades de mouvement et leurs variables de contrôle.*

Movement stage	Definition
Pre-failure stage	Includes all the deformation precursory to failure. It is controlled by preparatory factors that ultimately determine the types and values of triggering factors.
Failure stage	Is initiated by the occurrence of one or more triggering factors and coincides with the full development of a continuous (localized or diffuse) shear surface through the entire mass; failure can occur along discrete, pre-existing surfaces or arise from the global deformation of the slope and is generally reflected in an increase of the displacement rate.
Post-failure stage	Starts with the detachment of landslide mass from the base of the shear zone with an initial acceleration. It is interrupted by a definitive or temporary halt. Post-failure movement can develop into different types, *e.g.*, slow of long-duration, or very rapid and of limited duration. It may continue to experience occasional reactivation and crisis (*e.g.* acceleration of the rate of movement due to a significant modification of the triggering factors).

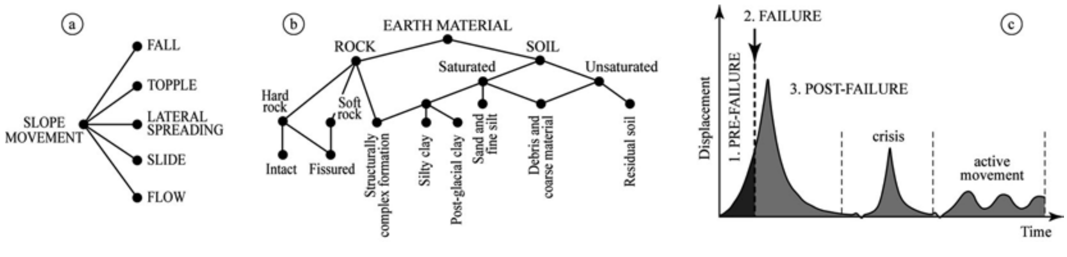

FIG 1. – Classification of slope movements according to the movement types (1a), the material types (1b) and the movement phases (1c) [modified from Vaunat *et al.*, 1994].
FIG 1. – *Classification des mouvements de versants en fonction du type de mouvement (1a), du matériau déplacé (1b) et des stades de mouvement (1c) [modifié de Vaunat* et al.*, 1994].*

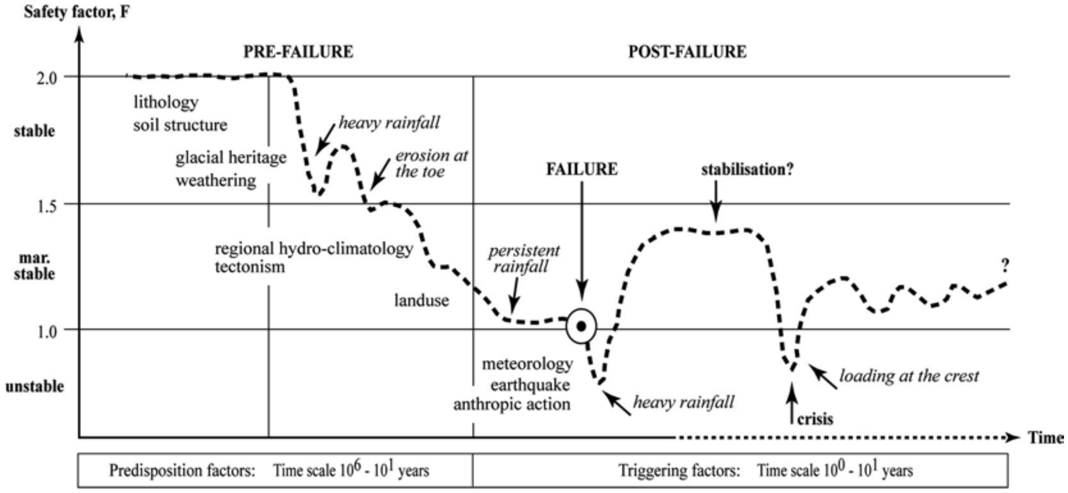

FIG. 2 – Time influence of predisposition and triggering factors on instability.
FIG. 2 – *Influence du facteur temps sur les facteurs de prédisposition et les facteurs de déclenchement d'instabilités gravitaires.*

- actively unstable, F~1.0: destabilising forces produce acceleration of the sliding mass (continuous or intermittent movements).

These three stages provide a useful framework for understanding the causal factors of landsliding. It can be seen that short-term variations in safety factor may occur due to seasonal variations in groundwater levels and pore pressures, while longer term trends may reflect the influences of weathering, glaciation cycles or longer term changes in regional groundwater conditions. This conveniently emphasizes that landslides may not be attributable to a single control factor, but always respond to a combination of preparatory and triggering factors. Thus, the preparatory factors change most times only gradually over time whereas the triggering factors are transient [Crozier, 1986; Leroueil, 2001]. It is often difficult or even impossible to isolate the true causes of a landslide. Triggering factors may either increase the shear stress, decrease the shearing resistance of the material or both. Table III summarizes the most common triggering factors of slope movements.

Strategy for hazard assessment: concepts, available modelling tools and methods

Although some qualitative answers to important questions can be made using best engineering or best geomorphologic judgment, human reasoning alone is inadequate to synthesize the conglomeration of factors involved in analyzing complex slope stability problems in many instances [van Westen *et al.*, 2006]. The best tool to help slope stability engineers meet the challenge of analyzing and forecasting the hazard is a mathematical model describing explicitly the relations between the preparatory and triggering causes (model inputs) and the responses of the slopes (model outputs). However in many cases, building an effective mathematical model is very difficult due to the specific nature and the 4-D pattern (space and time) of slope movements, as outlined in the former section.

Hazard assessment supposes a conceptualisation of the slope and of the elementary mechanisms controlling instability, which are idealized representations of the way material will move under loading [Hutchinson, 1988]. To understand such slope movement mechanisms is fundamental for the regionalisation of the knowledge and the key to a quantitative assessment at several scales [Brunsden, 1999]. A synthesis of the fundamental failure mechanisms and post-failure mechanisms can be found in Terzaghi [1950], Morgenstern and Sangrey [1978], Hutchinson [1988, 1993] and Picarelli *et al.* [2000] and used to define analytical or numerical models. Respectively, these mechanisms include among others sliding over an existing, discrete surface or across a shear zone, progressive plastic deformation of the material and formation of a shear zone, rotation of the principal stresses at the base of the moving mass, static liquefaction, undrained loading [Hutchinson and Bhandari, 1971; Sladen *et al.*, 1985; Urcioli, 2002] and grain-crushing, rheofluidification, vibration energy [Sassa, 1998; Iverson *et al.*, 1997]. To adequately represent slope movements in mathematical models, it is necessary to include the following features or *models* in the model concept:

TABLE III – Common triggering factors of slope movements [modified from Popescu and Sève, 2001].
TABL. III – *Principaux facteurs de déclenchement de mouvements de versants [modifié de Popescu et Sève, 2001].*

Increase in shear stress
• Erosion and excavation at the toe of the slope • Subterranean erosion (piping) • Surcharging and loading at the crest (by deposition or sedimentation) • Rapid drawdown (man-made reservoir, flood, high tide, breaching of natural dams) • Earthquake • Volcanic eruption • Modification of slope geometry • Fall of material (rock and debris)
Decrease in shearing resistance
• Water infiltration (rainfall, snowmelt, irrigation, leakage of drainage systems) • Weathering (freeze and thaw weathering, shrink and swell weathering of expansive soils) • Physico-chemical changes • Fatigue due to static/cyclic loading and creep • Vegetation removal (by erosion, forest fire, drought or deforestation) • Thawing of frozen soils
Possible increase in shear stress and decrease in shearing resistance
• Earthquake shaking • Artificial vibration (including traffic, pile driving, heavy machinery) • Mining and quarrying (open pits, underground galleries) • Swinging of trees

– the *geometrical model* characterising the local geometry and internal structure (*e.g.* layering, discontinuities) of the slope in order to define the probable extent of the slope movement;

– the *morphostructural model* identifying eye-witness evidences of localized movements (*e.g.* kinematic fractures, lobes, scarps, horst/graben structures, etc) in order to define the probable state of activity of the slope movement. This model is constructed through photo-interpretation of multi-source documents and field work;

– the *kinematic model* specifying the key controlling variables over time at a frequency consistent with the rate of movement of the landslide (*e.g.*, rainfall, air and soil temperature, soil moisture content, water level at many points, surface and in-depth displacement at many points, etc.). This also characterizes the pre-existing state of stress within the slope;

– the *geotechnical model* characterising the physical and hydro-mechanical properties of the material, reflecting its heterogeneity and anisotropy and considering any scale-dependence or hysteresis in order to define time/rate-dependent behaviour of the slope movement;

– the *geomechanical model* that merges these sub-models and their supportive data in order to identify the probable mechanism of movement into consistent descriptions of the relevant physical processes in mathematical form.

Figure 3 explains the relationships between the controlling variables and the constitutive mathematical equations of a process-based landslide model. The figure highlights the relations for rainfall-induced landslides for which the dynamics are simulated by a hydrological model (R-U relationship) coupled to a mechanical model (U-S-F-V relationship) described by a constitutive law of material behaviour embedded in an equation of motion.

The extent to which these features are captured for the investigated slope as well as the objective of the study, will determine the physically-based modelling approach to be used, its extent (2D or 3D, constant or time-dependent simulations) and the representation of the mass (discontinuous or equivalent continuum approach). The main problem with the discontinuous approach is to determine the location and geometry of the natural discontinuities, while the main problem with the continuum equivalent approach is the evaluation of the hydro-mechanical properties of the material at the slope scale, which cannot be readily determined in the by field or laboratory experiments.

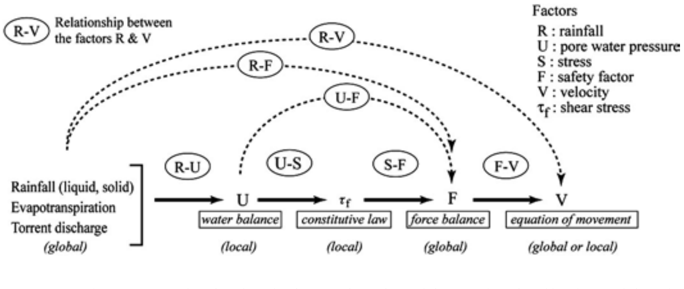

FIG. 3 – Phenomenological relations simulated in a physically-based landslide model assuming an explicit approach [in Malet, 2003; modified from Leroueil, 2001].

FIG. 3 – *Relations phénoménologiques simulées dans un modèle à base physique de glissement de terrain avec une approche explicite [in Malet, 2003 ; modifié de Leroueil, 2001].*

To discretize slope mechanisms in space and time and space dimensions, most mathematical models revert to the limit-equilibrium method (LEM), the finite element method (FEM), the boundary element method (BEM) and the finite difference method (FDM) for the continuum equivalent approach and to the distinct element method (DEM) for the discontinuous approach. LEMs do not allow the evaluation of stress and strain conditions in the slope and are incapable to reproduce the crucial role played by deformability in slope movements [Bromhead, 1996; Griffiths and Lane, 1999]. FEMs and FDMs, on the one hand, are the most flexible methods because of their ability in handling material heterogeneity, non-linearity and boundary conditions, but due to their internal discretization they cannot simulate infinitely large domains and the computation time can be prohibitive. BEMs, on the other hand, require discretization at the boundary of the solution domains only, thus greatly simplifying the input requirements, but are impractical when more than one material must be taken into account. It is the most efficient technique for fracture propagation analysis. DEMs represent a discontinuous medium as assemblages of blocks formed by connected fractures in the problem domain, and solve the equations of motion of these blocks through continuous detection and treatment of contacts between the blocks. Handling large displacements including fracture opening and complete detachments is therefore straightforward in these methods although they are less suitable to model plastic deformation.

Hence, any simulation will contain subjective judgements and be a compromise between conflicting detail of process descriptions and practical consideration. From our point of view, the challenge at hand is not to develop truly fully (thermo-hydro-mechanical) coupled physically-based models that would continue to be hampered by shortcomings in the knowledge of the geometrical and physical properties of slopes. Rather, it is essential to define guidelines for the development of physically-based models that perform satisfactorily for a given problem: the model does not have to be complete and perfect, it only has to be adequate for the purpose of hazard assessment.

PRE-FAILURE BEHAVIOUR: INFLUENCE OF PREPARATORY FACTORS

The necessity of understanding long-term preparatory mechanisms

Pre-failure deformations form the ouverture to first-time landslides and their recognition is paramount to the success of hazard assessments and early-warning system in particular. Therefore, preparatory factors controlling the long-term evolution of the slopes have to be investigated. This long-term evolution is related to the rate of chemical and mechanical weathering of the rock and soil material and to cyclic loading by earthquakes, leading to progressive damage. All these processes results in the development of a population of cracks and in the possible changes of groundwater composition that will weaken the material. Equally, slope evolution, which arises from a variety of processes working with different intensity depending on the climatic conditions, alters the loads acting on a potential landslide and ultimately affect its equilibrium [Brunsden, 1999].

The evolution of the fracture system, which is inherited from the tectonic and hydrogeological history in rocks, has to be investigated to forecast first-time failures in rock material. Thermo-mechanical and chemical processes induced by circulating water in the preferential fissure system may enhance the propagation of the fracture system [Peng, 1973; Boukharov *et al.*, 1995; Kilburn and Petley, 2003]. Circulating water alters the parent material chemically and pore pressures, root growth and ice wedging lead to fracture growth and the deterioration of its surfaces. The damage process can therefore be characterized by a hydro-chemical signature as the increase in exposed surface leads to a higher reactivity of the rock/water interface. This hypothesis is in agreement with laboratory observations [Ojala *et al.*, 2003; Bruderer-Weng *et al.*, 2004; Song *et al.*, 2004] and provides a possible mechanical interpretation of *in-situ* observation of the correlation between slope deformation and chemical composition of flowing water [Cappa *et al.*, 2004; Charmoille *et al.*, 2005].

The life-time and strain rate observed theoretically and experimentally during brittle creep are sensitive to the temperature, water saturation and effective pressure [Scholz, 1968; Kranz, 1980; Kranz *et al.*, 1982; Masuda, 2001]. As the water flow is related to the state of damage through the permeability, water flow through the fractured rock mass constitutes a positive feedback and may worsen the first-order response of the material to pore pressures as a result of a decrease in effective strength.

The external influence of rock and soil weathering is imposed on the intrinsic effect of fractures on the bulk strength of the material; the initial distribution and the progression of cracks over time due to loading and unloading control the path to failure and the formation of individual cracks as well as their population at the meso-scale should be considered [Kranz, 1980; Masuda, 2001; Amitrano *et al.*, 1999; Amitrano, 2003; Kemeny, 2005; Amitrano, 2006].

Challenges and future research directions

Advances in our ability to model pre-failure deformation require the realization of laboratory and controlled field experiments that are coupled to the development of numerical models that describe the development of discontinuities; attention should be paid to the changing stress distribution in rocks imposed by external loads, pore pressure fluctuations, temperature gradients, and hydro-chemical exchanges. This approach will provide crucial information for the physical interpretation of the *in-situ* observations, particularly for identifying the deformations that precede slope failure.

Over longer time-scales, the fracturing and deterioration of rocks has been often modelled by either a discontinuous media containing propagating cracks [Costin, 1983; Cowie *et al.*, 1993; Scavia, 1995; Scavia and Castelli, 1996] or a continuous material subjected to a bifurcation phenomenon [Rice, 1976]. An intermediary approach consists in considering the material to be continuous at the meso-scale. The cracking is then taken into account through elastic damage (reduction in the apparent elastic modulus). In this way, it is possible to model both macroscopic plasticity [Zapperi *et al.*, 1997] and macroscopic brittleness [Tang, 1997; Tang and Kaiser, 1998]. Some applications of this approach have been developed mainly for underground mining failure. Amitrano *et al.* [1999] proposed a model able to switch continuously from macroscopic plasticity, with diffuse damage, to macroscopic brittleness, with localized damage. These numerical results appear to be in good agreement with laboratory experiments and earth crust observations [Amitrano, 2003], but have not been applied to rock slope movements until recently. Following this meso-scale approach and considering the sub-critical growth of a population of cracks, Amitrano and Helmstetter [2006] simulated the brittle creep phenomenon, *e.g.* the three stages of creep (primary, secondary and tertiary creep) associated to different stages of the spatial damage distribution (diffuse to localized). The tertiary creep appears to be associated to both strain and seismic acceleration in accordance with *in-situ* observations of muddy slope failures [Voight, 1988; Petley *et al.*, 2002] and of precursors to chalk cliff collapse [Amitrano *et al.*, 2005]. Figure 4 presents this model approach for an idealized, initially intact rock slope. It shows the propagation of damage within the slope and the final state of damage, which could be compared with field data, *e.g.*, from geophysical prospecting. For a better representation of a real slope, the model has to include the tectonical setting, erosion history and material heterogeneity.

Over shorter time scales, the extent, timing and run-out of a potential failure have to be assessed. Conventionally, stability calculations are made from analytical and numerical models based on limit-equilibrium or stress-strain relationships or established by expert opinion from monitored slope displacements [Bhandari, 1988; Zvelebil and Moser, 2001; Petley *et al.*, 2002; Petley *et al.*, 2005]. Acceleration of the displacements can be described by a power law [Saito and Uezawa, 1961; Kennedy and Niermeyer, 1971; Voight, 1989; Fukuzono, 1990] or an exponential law [Petley *et al.*, 2002]. Various authors tried to explain the character of the curves by creep processes measured in the laboratory, by theoretical damage models for fractured rock [Voight, 1989] or by a slider-block model [Scholz, 1998; Helmstetter *et al.*, 2004]. Comprehensive reviews of these methods are provided by Federico *et al.* [2002] and Crosta and Agliardi [2003]. These phenomologically-based methods generally overlook the causes and the mechanisms of failure, and do not integrate external perturbations (*e.g.*, climatic, hydrologic, tectonic, seismic, human-induced) in the evolution to failure [Voight, 1989; Fukuzono, 1990; Qin *et al.*, 2001]. It should also be noted that the previously mentioned studies all involved back-analyses of slope movements; reported cases of forward prediction are few [Zvelebil, 1984; Hungr and Kent, 1995]. Different techniques (NDS: nonlinear dynamical systems techniques; ANNs: artificial neural networks) may provide alternative means to analyse these multi-source data and to forecast the influence of external factors on the failure pattern of the slopes [Mayoraz *et al.,* 1996; Mayoraz and Vulliet, 2002].

FAILURE BEHAVIOUR: THE ROLE OF HYDROLOGY AS A DYNAMIC TRIGGER

The necessity of understanding hydrological triggering mechanisms

Worldwide rainfall-triggered landslides occur more frequently than earthquake-triggered landslides. In general terms, infiltration and the resultant transient changes in the hydrological systems are the most common triggers of

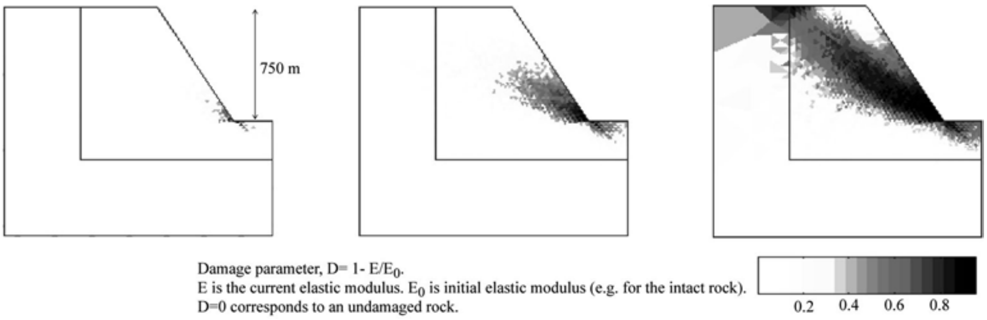

FIG. 4 – Simulation of the progressive damage of an idealized rocky slope based on brittle creep theory [from Amitrano, 2005].
FIG. 4 – *Simulation de l'endommagement progressif d'un versant rocheux par la théorie du fluage fragile [in Amitrano, 2005].*

landslides [van Asch *et al.*, 1999]. There are many main types of hydrological triggering mechanisms dependent on the state of the system, which defines the thresholds for first-time failure and landslide reactivation.

The more well known triggering system occurring in shallow as well as deeper landslides is related to an increase in pore pressures resulting in a decrease in effective stress and strength. However, infiltration may have other effects both before and after slope failure. Especially, on steep slopes in shallow soils (fig. 5), landslips can be triggered by a rapid drop in the apparent cohesion following a decrease in matric suction when a wetting front descends into the soil, without generating positive pore pressures [van Asch and Sukmantalya, 1993; Terlien *et al.*, 1995; Fredlund *et al.*, 1996; Sun *et al.*, 1998; Brooks *et al.*, 2004]. Another important but quite different hydrological trigger is the rotation of the principal stresses at the base of the soil caused by a rise in the groundwater table, favouring the development of potential failure planes [Picarelli *et al.*, 2000; Urcioli, 2002]. Also, surface runoff following high-intensity rainfall in steep catchments can infiltrate into accumulated debris and trigger debris flows [Blijenberg, 1998] or provide a localized source of infiltration on a landslide body.

Surprisingly, modelling of these hydrological triggering factors has been curiously slow to gain acceptance [Bromhead and Dixon, 1984], compared to rainfall-runoff modelling or catchment hydrological modelling. Nevertheless, this aspect has been gaining ground in recent years as geotechnical, geomorphological and hydrological models are drawn closer together [Picarelli *et al.*, 2005; Malet *et al.*, 2005]. The research frontiers are connected with the complexity of real landslides, the difficulty to monitor groundwater levels or soil moisture contents in unstable terrain, and the difficulty to understand the water pathways within the landslide bodies [Brunsden, 1999]. Many authors have shown that the quality of the hydrological model had a greater influence on the general performance of the model than the geomechanical model [Okunushi and Okumura, 1987; Haneberg, 1991; van Asch *et al.*, 1999].

Consequently, the occurrence of rainfall-triggered landslides is evaluated in many cases by empirical threshold methods or multivariate statistical techniques [Caine, 1980; Corominas, 2000*;* Fan *et al.,* 2003]. However, such approaches may have limited validity if a variety of landslide types within an area responds in a different way to the meteorological input [Malet *et al.*, submitted]. Moreover, historical datasets linking meteorological data to failure events to derive such thresholds are rare [Coe *et al.*, 2004]. It is obvious that for the assessment of meteorological thresholds, shallow landslides (1-2 m) require different meteorological information than deeper landslides. For deeper landslides a large windows of antecedent precipitation of weeks or months, including any losses to evapotranspiration, will determine the threshold for failure. For shallow landslides one has to consider only a few rain events or even one, with known intensity and duration, to forecast failure [van Asch *et al.*, 1999]. Consequently, a relevant hazard analysis requires that the hydrological system is studied diligently and that the transient nature of the unsaturated and saturated zone is reflected [van Asch *et al.*, 1999; Iverson, 2000].

Challenges and future research directions

Hydrological model results are very sensitive to the initial conditions, which are probably the most significant input for the modelling effort. Obtaining accurate initial conditions requires a significant number of field observations possibly supplemented by modelling to extrapolate between observations [Iverson, 2000; Wilkinson *et al.*, 2002]. Steady-state situations are most times used but more elaborate analyses are appropriate to take the role of the unsaturated zone with its highly non-linear behaviour and its buffering

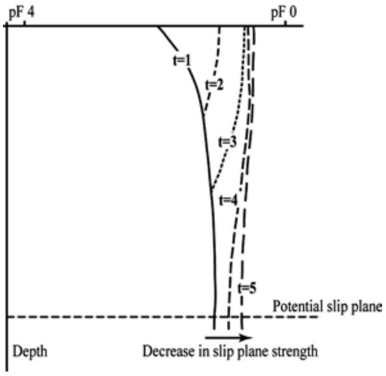

FIG. 5 – Hypothetical graph showing transient percolating water in an unsaturated soil profile. The decrease in matrix suction related to an increase in soil moisture over time (matric suction represented by pF, 10log of the matric suction in centimeters) results into a decrease in cohesion with depth, which may induce failure in steep slopes or slopes with cohesive soils.
FIG. 5 – *Concept indiquant l'écoulement transitoire de l'eau dans un sol non saturé. La diminution du potentiel de succion matricielle en fonction d'une augmentation de la teneur en eau du sol avec le temps (succion matricielle représentée par pF, 10log de la succion matricielle en centimètres d'eau) conduit à une diminution de la cohésion du sol avec la profondeur, qui peut déclencher des ruptures dans les versants à pente forte ou dans les versants à sols cohésifs.*

capacity into account [Ng and Shi, 1998; Bogaard and van Asch, 2002].

In hydrological models a coupling between unsaturated and saturated flow is essential to forecast the pore pressure distribution and its time delay to the meteorological input signal adequately. Unsaturated flow is more complex than that in saturated soil because of the initial degree of saturation of the soil profile which relates directly to the matric suction, controls the hydrologic conductivity and the available storage capacity [Torres *et al.*, 1998]. Relationships between degree of saturation, matric suction and hydrologic conductivity are not simple [Fredlund and Rahardjo, 1993]. Wang and Thomas [2000], Ng *et al.* [2001], Bogaard [2001] and Bogaard and van Asch [2002] have demonstrated the complex non-linear response of the groundwater on rainfall (fig. 6).

The local topography (e.g. stress relief) further confounds the development of pore pressures in initially unsaturated soils [Bromhead and Dixon, 1984; Hulla *et al.,* 1984; Torres *et al.,* 1998], the influence of the vegetation on water losses by evapotranspiration [Eigenbrod and Kaluza, 1999] and the influence of preferential flows within fissures, desiccation cracks, root holes and animal burrows [Beven and German, 1982]. Especially, the complex morphology of landslides and the presence of fissure systems may result into complex and inter-connected hydrological subsystems. For instance, the stability of deep-seated landslides in varved clays in France is controlled by a perched groundwater table in the morainic top layer that feeds into the deeper fissures [van Asch *et al.,* 1996]. From a detailed analysis of the Super-Sauze mudslide, Malet *et al.* [2005] have shown that incorporating a conceptual (grey-box) model of fissure flow in a physically-based infiltration model describing matrix fluxes can lead to more accurate simulations of the soil moisture contents in the unsaturated zone (fig. 7).

Yet, it remains extremely difficult to quantify the influence of preferential flows on soil stability, especially because the architecture of the fissures and the flow processes in the fissures are difficult to detect. The challenge is to describe, experimentally and mathematically, the hydraulic behaviour of water in fissures and the interaction with the soil matrix, and to upscale these concepts to the slope scale [van Beek and van Asch, 1998]. Interesting information can be gained from the monitoring of electric signals (e.g. the soil electrical streaming potential) by innovative geophysical techniques at the laboratory scale as well as in the field [Sailhac *et al.*, 2004], and from the use of chemical tracing techniques to quantify the water fluxes at different scales [Di Pietro *et al.,* 2003; Weiler *et al.,* 2003].

The hydrology of low permeability deposits (especially clays) has also to be studied. The water flows in saturated clayey soils are controlled by the swelling/consolidation coefficients of the material, and possible presence of anisotropy, like for instance layering in stiff varved clays [Nieuwenhuis, 1991]. Accordingly, the seasonal variations of pore pressures at the boundaries of a clay deposits may not be reflected throughout the entire deposit [Picarelli *et al.,* 2000].

All in all, our modelling capabilities are limited to model hypothetical scenarios. A thorough understanding of the hydrological processes and a clear definition of the initial conditions are needed to forecast occurrences of failure induced by climate and land use changes [Bonnard and Noverraz, 2001; Bogaard and van Asch, 2002; van Beek, 2002]. It is also apparent that a hydrological record of substantial length is essential to detect a wide range of meteorological and piezometric conditions, preferably including the more extreme events that may trigger instability.

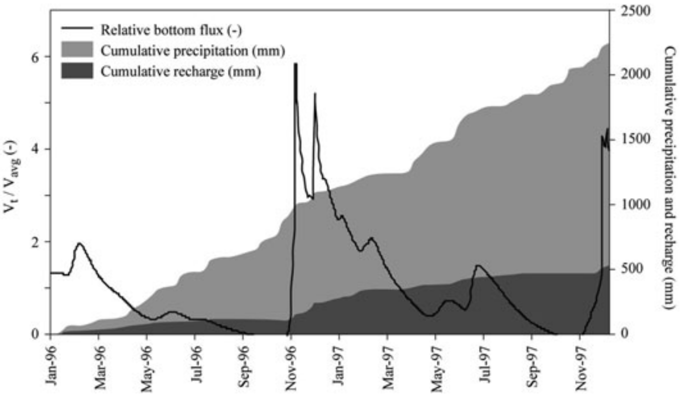

FIG. 6 – Cumulative precipitation, groundwater recharge and the simulated relative bottom flux, Vt/Vavg, of the unsaturated zone for the Salins-les-Bains landslide (Jura, France). Above a certain rate of cumulative rainfall, the soil moisture deficit is overcome and recharge to the groundwater increases markedly (e.g., November 1996), whereas the recharge halts and the soil moisture deficit deepens gradually over summer (e.g., July-October 1996) [modified from Bogaard, 2001].

FIG. 6 – *Précipitation cumulée, fluctuation piézométrique et flux d'eau relative à la base du profil de sol non saturé, Vt/Vavg, du glissement de Salins-les-Bains (Jura, France). Au-delà d'un certain taux de précipitation cumulée, le déficit de teneur en eau du sol est comblé et une recharge de la nappe phréatique intervient (i.e., Novembre 1996), alors que pendant l'été la recharge piézométrique est interrompue et le déficit de teneur en eau augmente graduellement (i.e., Juillet-Octobre 1996) [modifié de Bogaard, 2001].*

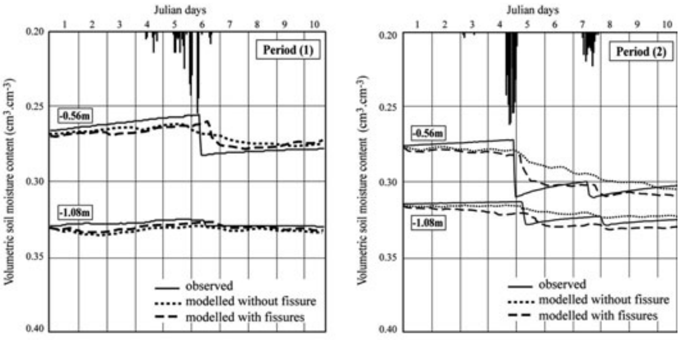

FIG. 7 – Influence of fissure flow on simulating rainfall infiltration in the unsaturated zone of the Super-Sauze mudslide for two periods [modified from Malet *et al.*, 2005]. The graphs indicate the observed and simulated variations of volumetric soil moisture contents at two depths (-0.56 m; -1.08 m) using a physically-based model with and without fissure flow, which was represented by a conceptual model of direct flux of rain water to the bottom of the fissures, bypassing the unsaturated zone.

FIG. 7 – *Influence d'écoulements préférentiels en fissures sur la simulation du processus d'infiltration dans la zone non saturée du glissement-coulée de Super-Sauze pour deux périodes [modifié de Malet* et al.*, 2005]. Les graphes indiquent les variations observées et simulées de la teneur en eau volumique à deux profondeurs (-0.56 m; -1.08 m) avec un modèle hydrologique à base physique avec ou sans écoulement préférentiel représenté par un flux direct d'eau de pluie à la base des fissures, sans interactions avec la zone non saturée.*

POST-FAILURE BEHAVIOUR: SLOW AND RAPID MOVEMENT

Controls on slope movement and the potential for catastrophic acceleration

An essential part of any landslide hazard risk assessment is a quantitative estimate of post-failure motion defining distance, material spreading and velocity. Some slope movements are slow and ductile, other slope movements are brittle, meaning that, after a certain prelude of slow deformation or as the result of sudden loading, they accelerate and potentially fluidize (e.g., gradual deformation vs. rapid run-out). The essence of modelling post-failure behaviour should therefore revolve around the accurate reproduction of the deceleration and acceleration of landslide bodies and, in particularly, a reliable forecast of the potential transformation towards catastrophic, extremely rapid surges.

Post-failure movement of landslides is controlled by a complex interaction between mechanical and fluid properties and states and reflects spatio-temporal trend in the effective strength and rheological properties of the material [Vulliet, 1997; 2000]. Excess shear stress is partly counteracted by the intrinsic viscosity of the shear zone and, in landslides with an intermittent moving pattern, strength regain by consolidation may occur during period at rest [Nieuwenhuis, 1991; Bertolini and Pellegrini, 2001; Angeli *et al.*, 2004]. But landslides are not rigid moving bodies and zones of compression and extension will be generated caused by heterogeneity of the moving pattern. This will create undrained loading effects leading to the generation of excess pore pressure [Giusti *et al.,* 1996, Picarelli *et al.,* 1995; fig. 8). Undrained loading can equally be invoked as an explanation for the hysteresis (fig. 9) in the velocity pattern during the rising and falling limb of the groundwater [Leroueil *et al.*, 1996; Malet, 2003; van Asch, 2005]. Alternatively, the development of negative excess pore pressure during movement may have a controlling effect on movement; Keefer and Johnson [1983] attributed variations in the mobilized shear strength during movement not to the intrinsic viscosity but entirely to pore pressure effects developed by a porous elastic solid, sliding over an ondulating slip surface, with destabilising positive and stabilising negative pore pressures developing as the result of compression and dilation at respectively the proximal and distal sides of bumps. Van Genuchten and van Asch [1988] found similar feedback mechanisms in intermittently sliding blocks of the La Mure landslide. Movement was initiated by a groundwater rise after rainfall but decelerated prior to a fall in the groundwater levels and this mechanism was ascribed to the formation of negative pore pressures in the wake of irregularities in the slip surface (*e.g.*, large stones, boulders), thus lowering the mean pore pressure along the slip surface.

Due to these complex interactions, the parameterization of hydrological and geomechanical factors by field and laboratory tests is not sufficient to describe the post-failure movement patterns of landslides [Vulliet, 2000; 2001] and not all the processes can be included in detail in the simulation. Not only do the deformations lead to changes in the fluid-mechanic interactions, they also affect the hydrological system itself, for example by the opening and closing of fissures as mentioned above. This may drastically change the rate in discharge and drainage of the groundwater body and the pore pressures that govern slope stability [Laloui *et al.*, 2004; Malet *et al.*, 2005; Tacher *et al.*, 2005].

Different mechanisms have been identified, which explain the dangerous transition from intermittently or gradually

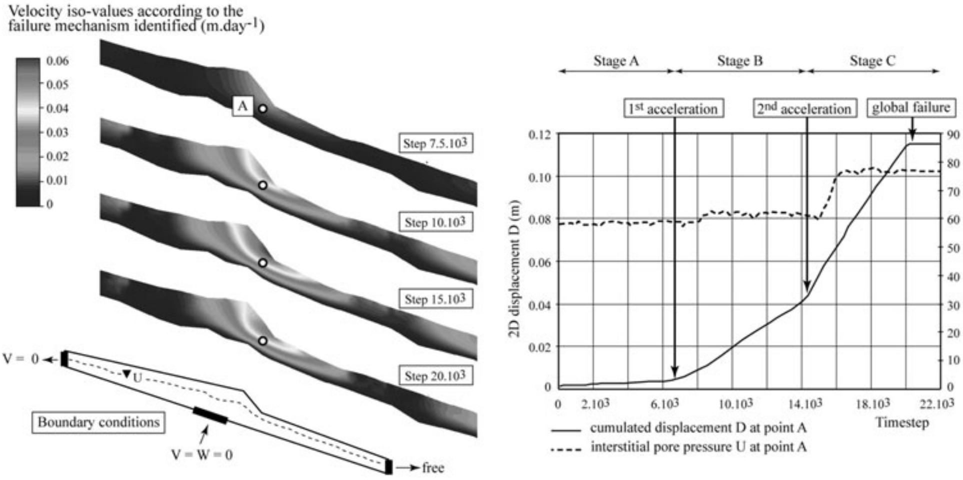

FIG. 8 – Fully coupled hydro-mechanical simulation of an acceleration of the Super-Sauze mudslide, South French Alps with the GefDyn finite-element code. The soil is described as an elasto-visco-plastic Hujeux material [Hujeux, 1985]. At the start, the overall safety factor is 1.2. A pore pressure increase from 56 to 62 kPa over 5 days leads to a partial acceleration of the soil mass (stage A). Consequent undrained loading and ongoing infiltration lead to a second acceleration (stage B). This local failure is rapid enough to generate excess pore pressures, causing the global failure of the secondary scarp of the mudslide (stage C). This type of analyses allows to investigate the interaction between landslide movements and the development of pore pressures induced by both infiltration and undrained compression of the soil [modified from Malet, 2003].

FIG. 8 – *Simulation hydro-mécanique couplée d'une accélération du glissement-coulée de Super-Sauze, Alpes françaises du Sud, avec le code éléments finis GefDyn. Le sol est décrit comme étant un modèle rhéologique élasto-visco-plastique de type Hujeux [Hujeux, 1985]. Au début de la simulation, le facteur de sécurité du versant est 1.2. Une augmentation de pression interstitielle de 56 à 62 kPa sur une période de 5 jours conduit à une accélération partielle du massif de sol (stade A). Le chargement non drainé consécutif ainsi qu'une infiltration d'eau continue dans le temps conduisent à une deuxième accélération (stade B). Cette rupture locale est assez rapide pour générer des surpressions interstitielles qui conduisent à la rupture globale de l'escarpement secondaire du glissement-coulée (stade C). Ce type d'analyse permet d'étudier les interactions entre les mouvements de la masse glissée et de développement de pressions interstitielles [modifié de Malet, 2003].*

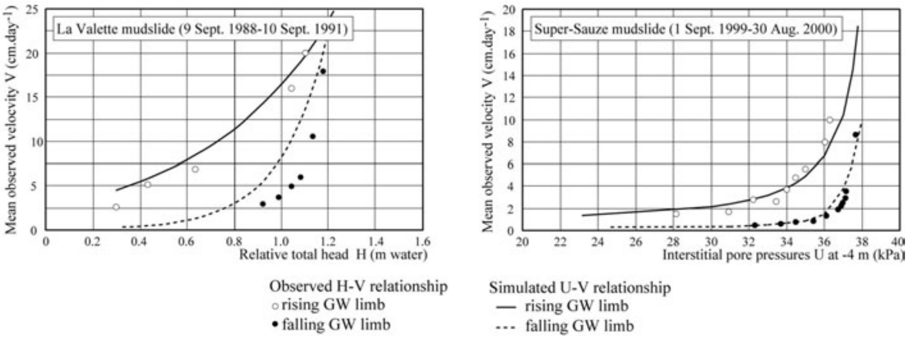

FIG. 9 – Observed and simulated hysteresis in the velocity pattern during a rising and falling limb of the groundwater in two slow-moving mudslides due to compression and undrained loading. Data from La Valette mudslide and Super-Sauze mudslide in the South French Alps (modified from Malet [2003]; van Asch [2005]).

FIG. 9 – *Hystérèse observée et simulée du champ de vitesse de deux glissements-coulées pour un période de drainage et de recharge de la nappe d'eau, par compression et chargement non drainé. Données des glissements-coulées de La Valette et Super-Sauze, Alpes Françaises du Sud (modifié de Malet [2003]; van Asch [2005]).*

moving landslides to catastrophic movements. Most observations concern loosely packed material, which contracts during shear failure inducing a catastrophic rise in pore pressure and subsequent fluidisation [Yoshimi *et al.*, 1989; Anderson and Reimer, 1995; Iverson *et al.*, 1997; Dai *et al.*, 1999]. However, liquefaction phenomena have also been observed in denser soils, which dilate during shearing. The processes that govern liquefaction of denser soils are still poorly understood and should be the subject of fundamental research: it may be generated by simple undrained loading (fig. 10) caused by a changing stress field during initial failure [Baum and Fleming, 1991; Picarelli *et al.*, 1995; Giusti *et al.,* 1996; Klubertanz *et al.*, 2000; Picarelli *et al.*, 2005; van Asch *et al.*, 2006] or, alternatively, deformation of the toe of the landslide may increase the effective stress so that the material may pass the critical state line and transform from a dilative towards a contractive state [Reimer, 1992; Gabet and Mudd, 2006]. Initial porosity appears crucial for the development of rapid flows through liquefaction in sliding material [Iverson *et al.*, 2000] and field investigations on liquefaction combined with geomechanical analyses of the deformation characteristics for the involved material will reveal under what conditions dense materials will liquefy.

Rapid developments of slope movements (fast gravitational flows)

Rapid gravitational processes, like mudflows, debris flows and rockfalls, are very frequent and are the most dangerous type of landslides. Several methods have been developed to analyse their travel distance and velocities, ranging from empirical (black-box) methods to physically-based approaches.

Empirical methods are based on field observations and on the analysis of the relationships between parameters characterizing the travel path (local morphology), the landslide (volume) and the run-out distance. Simple statistical analyses can be used to produce indices expressing, directly or indirectly, landslide mobility. Analyses of relevant datasets with a geometrical approach [Corominas, 1996; Finlay *et al.*, 1999; Hunter and Fell, 2003] have proposed that the angle of reach (*Farhböschung*) may be taken as the measure of the relative mobility of the landslide or as the coefficient of friction of a sliding body [Scheidegger, 1973]. Several plots of the tangent of the reach angle against the landslide volume have been proposed [Hsu, 1975; Corominas, 1996] demonstrating that large landslide (generally over a certain volume) display lower angles of reach than smaller ones. There are nevertheless large controversies on the interpretation of the volume dependence to the angle of reach [Davies *et al.*, 1999; Hunter and Fell, 2003]. These methods require comprehensive datasets with the identification of both source point and end point, and useful to create GIS-based susceptibility zonation maps of probability of debris arrival [Michael-Leiba *et al.*, 2003; Dorren, 2002]. However, the underlying distributions are not specified and may reveal large scatter [van Westen *et al.*, 2006] and they are not able to provide an estimate of the flow velocities, which is important to evaluate the vulnerability of infrastructures and buildings and their occupants.

Physically-based models, most of them solved numerically, model movement using constitutive laws of solid and fluid mechanics. Three main groups of models have been developed [Hungr, 1995]: lumped-mass approach, 2-D models looking at a typical velocity profile of the moving mass, and 3-D models treating the flow over irregular topographic terrains. Most models are simplified by integrating the internal stresses in either vertical or bed-normal directions to obtain a form of Saint-Venant or Navier-Stokes equations (*shallow water assumption*) [Iverson, 2005]. Derivations of the constitutive relationships using the theory of frictional grain flow [Savage and Hutter, 1991; Hutter *et al.*, 1995] or the theory of mixture flow [Iverson, 1997; Denlinger and Iverson, 2004; Iverson *et al.*, 2004] have also been investigated. A review of these methods has been recently presented by Hungr *et al.* [2005].

To simulate one-phase constant-density flows, most models use the semi-empirical approach called "equivalent fluid method" introduced by Hungr [1995] assigning simple constitutive relationships judged appropriate for a given material. The rheologies used in most models are the frictional-turbulent Voellmy resistance relationship (proposed initially for snow avalanches) and applicable for granular cohesionless material with or without the presence of a pore fluid, and the visco-plastic Bingham (or Herschel-Bulkey) resistance relationship applicable for fine plastic clay-rich material [Soussa and Voight, 1991; Laigle and Coussot,

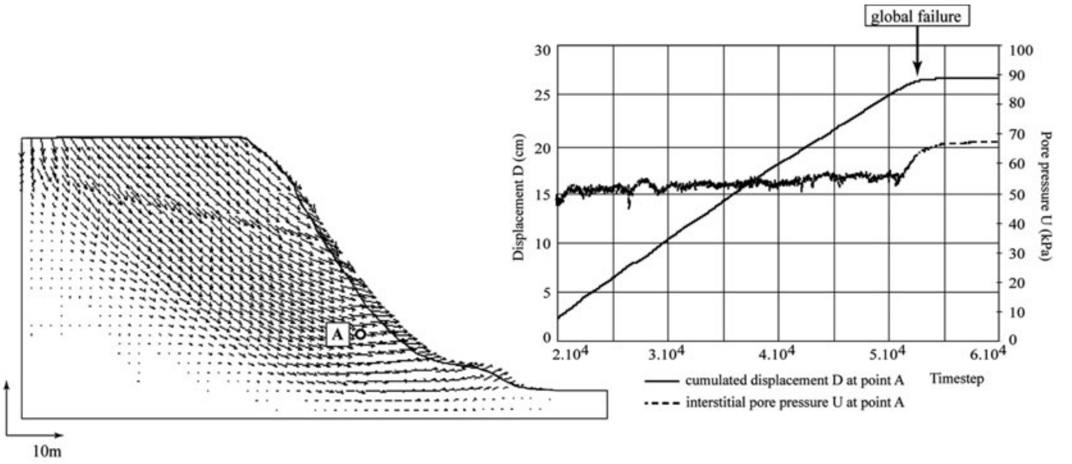

FIG. 10 – Geomechanical simulation of the failure of the secondary scarp of the Super-Sauze mudslide, South French Alps, by undrained loading assuming an elasto-platic material with the code FLAC-2D [hcITasca, 2004]. Starting from a critical slope with a safety factor F=1.0, incipient deformation leads to undrained loading that affects the short-term stability negatively. Movements translate into a noisy but gradual increase in pore pressure that in turn leads to an ongoing deformation than that required to accommodate the unbalanced force within the grid. Once a new equilibrium is maintained, pore pressures stabilize at a higher level due to the cumulative displacement and may dissipate ultimately to return a new long-term stability for the slope.

FIG. 10 – *Simulation géomecanique avec le code FLAC-2D [hcITasca, 2004] de la rupture de l'escarpement secondaire du glissement-coulée de Super-Sauze, Alpes françaises du Sud, par chargement non drainé et pour un sol au comportement élasto-platique. La simulation débute avec un facteur de sécurité de F=1.0 ; de faibles deformations conduisent à charger le sol de manière non drainé, ce qui affecte la stabilité à court-terme. Les mouvements de la masse deformée conduisent à une augmentation, bruitée mais régulière, des pressions interstitielles qui entretiennent les déformations. Une fois qu'un nouvel équilibre est atteint, les pressions interstitielles se stabilisent à un niveau plus élevé à cause des déplacements cumulées de la masse en mouvement, et peuvent se dissiper à long-terme pour engendrer un nouvel état de stabilité du versant.*

1997]. More complex rheologies have also been proposed such as the Coulomb-viscous model [Johnson and Rodine, 1984], the bi-linear constitutive equation [Locat, 1997], the generalized viscoplastic equation [Chen, 1988], and a dilatant rheology for modelling the run-out of mudflows [Takahashi, 1991].

Flow velocity largely depends on the resistance term of the material, which may be highly variable, or likely to change during the flow itself [Savage and Hutter, 1991; Takahashi, 1987; Hungr and Evans, 1996; GDR MiDi, 2004]. The processes involved in the motion of fast gravitational flows are very complex. Direct measurements of key variables such as pore-pressure and viscosity are impossible in full-scale events. Rheological properties (yield stress, viscosity) determined from laboratory small-sale samples may not be representative at the slope scale. The parameterisation for a given rheological model (fig. 11) is therefore most times determined by back-analyses of observed event [Malet *et al.*, 2004; Hungr *et al.*, 2005]. Back-analysed parameterisations are, however, not unique and figure 11 demonstrates that information on the distribution of sediment along the track, as well as the temporal velocity during run-out are indispensable to bracket the model parameters within physically realistic ranges. Pore pressure remains an important factor. Following initial failure, excess pore pressures may be generated and help to maintain momentum but they will eventually dissipate during the run-out process and the movement slow [Major and Iverson, 1999; Major, 2000; Iverson, 2003].

Under the shallow water assumption, 2-D and 3-D solutions of fast gravitational flows can be derived from the momentum equation for unsteady fluid flow, evaluating the dynamic equilibrium for a single column (or voxel in 3-D) isolated from the flowing mass and integrating the stresses in the bed-normal or vertical direction. Several forces diagrams can be used to solve the equilibrium of the column [Iverson, 2005]. Eulerian and Lagrangian solutions of these governing equations have been developed [Hungr, 1995]. Non-hydrostatic internal tangential stress has been introduced by Savage and Hutter [1991] and Hutter *et al.* [1995] assuming that the moving mass is frictional and undergoes plastic deformation according to the Rankine theory. The most well-known Lagrangian algorithm for 2D integrated modelling is the DAN "Dynamic ANalysis" model [Hungr, 1995] validated on

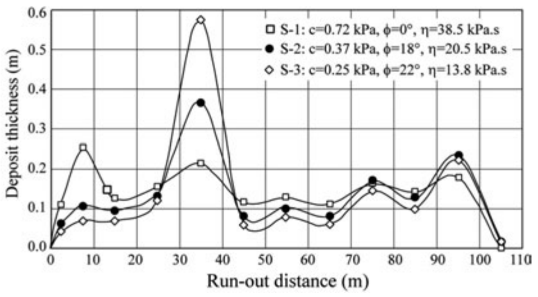

FIG. 11 – 1-D run-out modelling of 15 m^3 volume of debris material along a run-out track at the Super-Sauze mudslide, South French Alps, showing the effect of material properties, for a fully cohesive Bingham material (scenario S-1) and a frictional Coulomb-viscous material (scenario S-2 and S-3). The three rheological models are equally capable to simulate the run-out distance but in the first case the flow depth and slope angle are the limiting factors, in the latter two only the slope angle controls displacement [modified from van Asch *et al.*, 2004].

FIG. 11 – *Simulation 1-D de la distance de parcours de 15 m^3 de matériau dans une ravine du glissement-coulée de Super-Sauze, Alpes Françaises du Sud, indiquant l'effet des propriétés rhéologiques pour un matériau au comportement visco-plastique de type Bingham (scénario S-1), et un matériau au comportement frictionnel-visqueux (scénario S-2 et S-3). Les trois modèles rhéologiques sont capables de reproduire les distances de parcours observées; dans le scénario S-1, l'épaisseur de l'écoulement et l'angle de la pente sont des facteurs limitants ; dans les scénarios S-2 et S-3, seul l'angle de pente contrôle les déplacements [modifié de van Asch* et al.*, 2004].*

laboratory experiments and against multiple case histories [Hungr and Evans, 1996; Pirulli *et al.*, 2004; Revellino *et al.*, 2004], and for which Chen and Lee [2000] and M^{c}Dougall [2006] have developed 3D extensions. Another interesting approach is the generalization of the Savage-Hutter theory, proposed by Iverson [1997] and based on grain-fluid mixture theory to account explicitly for viscous pore fluid effects. This approach has been implemented in a 2-D Lagrangian sheme [Iverson, 1997], in a 3-D conventional Eulerian scheme [Denlinger and Iverson, 2001; Iverson and Denlinger, 2001] and in a unique hybrid Eulerian-Lagrangian scheme [Denlinger and Iverson, 2004].

3-D solutions have also been developed using Eulerian schemes implemented on fixed rectangular grids. These fluid dynamic models need to consider fluid discharges (and associated momentum fluxes) across the domain and its boundaries. Lave2D [Laigle and Coussot, 1997] and Flow-2D [O'Brien *et al.*, 1993] are the few existing models that have been used on real cases, and for practical work [Laigle *et al.*, 2003; Garcia *et al.*, 2003]. 3-D solutions assuming non-hydrostatic lateral stresses have been developed recently [Gray *et al.*, 1999; Iverson and Denlinger, 2001; M^{c}Dougall and Hungr, 2004] especially to take into account of the bed-parallel strain in the flow and to provide realistic simulation of the internal stress state. A 3-D kinetic scheme incorporated in an unstructured finite-volume mesh have been proposed by Mangeney-Castelnau *et al.* [2003] to solve the 3D Savage-Hutter equations, and modified by Pirulli [2005] to account for irregular terrain.

Alternative solution have also been investigated such as coupling the numerical methods of Cellular Automata and Smoothed Particle Hydrodynamics [Bursik *et al.*, 2003], or using variable time step, time-forward, second-order accurate finite differences scheme implemented in a GIS environment [Beguería-Portuguès, 2007]. This latter approach is a simple 2-D numerical model based on one phase, depth averaged flow in the XY-plane in which flow is described by the Bingham and Voellmy constitutive equations (fig. 12). The model has been essentially designed for simulating the deposition of debris over low-gradient surfaces (typically alluvial fans) for which particular attention has to be given to the forces diagrams used. This simple model has been verified against the more complex hydraulic Lave2D model developed at Cemagref [Laigle and Coussot, 1997; Laigle *et al.*, 2003].

The development of these techniques necessitates detailed topographic information on both the travel paths and the deposition areas. This constitutes a problem because of the lack of accuracy in the available DTMs and the stochastic changes in topography during depositional process. However, major improvements can be expected from airborne laser scanning techniques, such as LIDAR, which will be beneficial for many aspects of landslide hazard modelling [Glenn *et al.*, 2006].

Finally, it should be noted that relevant estimates of run-out distance are associated to relevant estimates of initial volumes of failed material. If the material is delivered by a slide, the volume can be estimated as that bounded by the slip surface. This approach requires also an estimate of the amount of rainfall or groundwater heights triggering failure and an assumption of the mechanism of fluidization (*e.g.*, compaction, undrained loading and/or deformation) [Wang and Sassa, 2003]. Yet, other processes may be involved in the triggering of fast gravitational flows. Debris material accumulated in gullies in the source areas can be entrained by runoff or fail once saturated and turn into debris flows [Bardou *et al.*, 2003; Remaitre *et al.*, 2005]. Also, debris material can be delivered in the source area by erosion in steep gullies [Hessel, 2002], or collapse of gully walls during high water discharges. Scouring of *in-situ* bed material during the flow event in the run out track is also of paramount importance [Hungr *et al.*, 1984; Chen, 1987; Jakob *et al.*, 2000; Hungr and Evans, 2004] and entrainment capabilities have to be included in the numerical models for instance through erosion/deposition rate formulas incorporated implicitly [Takahashi, 1991; Hungr and Evans, 1997; Brufau *et al.*, 2000; Egashira *et al.*, 2001; Ghilardhi *et al.*, 2001] or explicitly [Naaim *et al.*, 2003]. Nevertheless, in such instances it is difficult to forecast which process is dominant, especially because of the stochastic nature of the processes involved [Blijenberg, 1998].

In the forthcoming years, an important feature in the physically-based modelling of fast gravitational flows will remain the necessity to account for erosion/deposition, *e.g.* the ability to entrain or depose material from the path of the flow (torrent bed, torrent reach), as well as to take into account associated changes in the rheology. Attempts to simulate successfully these processes have been made by Hungr and Evans [2004] by introducing a user-specified quantity of entrainment (*e.g.* erosion depth) along the path, and by De Joode and van Steijn [2003]. Major inputs can be expected here from detailed geomorphological mapping of the run-out paths [Remaître *et al.*, 2005; Veyrat-Charvillon and Meymier, 2006], mass balance calculations, and from the capacity to measure velocity, depth, discharge, pore pressure distribution, grain size distribution and sediment concentration during flow events in instrumented catchments [Genevois *et al.*, 2000; Tecca *et al.*, 2003; Lavigne, 2004]. Geophysical techniques to measure the hydrodynamics of the flows should be extended [Lavigne and Suwa, 2004] and seismometers combined to video recording have proven their worth [Suwa, 1988; Zhang and Chen, 2003]. Consequently, an effort should be made to monitor zero-order catchments and torrents subject to frequent debris flows to quantify the microclimate, morphometry and material conditions as well as their kinematics. Controlled laboratory experiments in small and large flumes will be equally valuable to improve our understanding of the governing mechanisms [Iverson, 2003]. Particularly the entrainment of material within the moving mass and the influence of the front volume on the dynamic behaviour of the total volume have to be studied experimentally. Models based on *SPH* (Smooth Particle Hydrodynamics), in which spatial gradients can be calculated without a reference grid and the resolution can be arranged and changed automatically, may prove to provide a novel way to account for the dynamics of fast gravitational flows [Lachamp *et al.*, 2002].

EXTENDING LANDSLIDE HAZARD FORECASTS TO THE REGIONAL SCALE

Many statistical techniques have been developed and applied successfully to landslide susceptibility assessment and mapping in the last ten years using bivariate or multivariate approaches, probabilistic approaches (like Bayesian inference

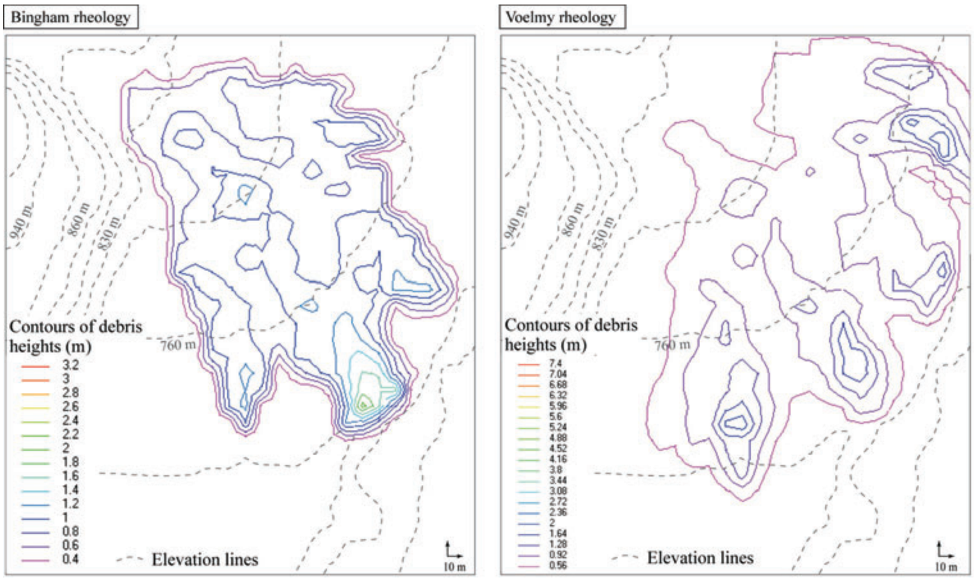

FIG. 12 – 2-D run-out modelling of 5000 m^3 volume of debris material on an alluvial fan showing the effect of material rheology (viscoplastic Bingham rheology, frictional Voellmy rheology) on the spatial distribution of material. The black lines represent the elevation curves of the digital elevation model and the coloured lines represent the thickness of the material deposits.

FIG. 12 – *Simulation de l'étalement de 5000 m^3 de débris sur un cône alluvial soulignant les effets de la rhéologie du matériau (comportement viscoplastique de type Bingham, comportement frictionnel de type Voellmy) sur la distribution spatiale du matériau. Les tiretés gris représentent les courbes de niveau du modèle numérique de terrain, et les lignes de couleur représentent les contours d'épaisseurs de matériau.*

or logistic regression) and artificial neural networks approaches [Carrara, 1983; Carrara *et al.*, 1991; Fabbri and Chung, 1996; Guzetti *et al.*, 1999; Ermini *et al.*, 2005]. Such techniques are capable to predict the spatial distribution of landslides adequately with a relatively small number of conditioning variables [Coe *et al.*, 2004; Zêzère *et al.*, 2004a; van den Eeckhaut *et al.*, 2006]. Nevertheless, these techniques lack the support and skill to evaluate temporal probabilities, transient effects and long-term changes in landslide activity.

A particular problem to the application of time-dependent assessments is that, contrary to the historical and reconstructed records used by paleo-seismologists and paleo-hydrologists, most records cover only a short period [Glade *et al.*, 2001] and a small geographical area [Chung and Fabbri, 1999]. Scarcity of supporting temporal information on the meteorological or seismic triggering events prevents the definition of reliable magnitude-frequency curves at the regional scale [Guthrie and Evans, 2005]. Moreover, records do seldom contain information on the date of occurrence or reactivation of the slope movement, the volume mobilized or even the type of movement [Ibsen and Brunsden, 1996; Hungr *et al.*, 1999; Coe *et al.,* 2003] and, to confound matters further, different landslide types are merged into one training dataset which obscures the influence

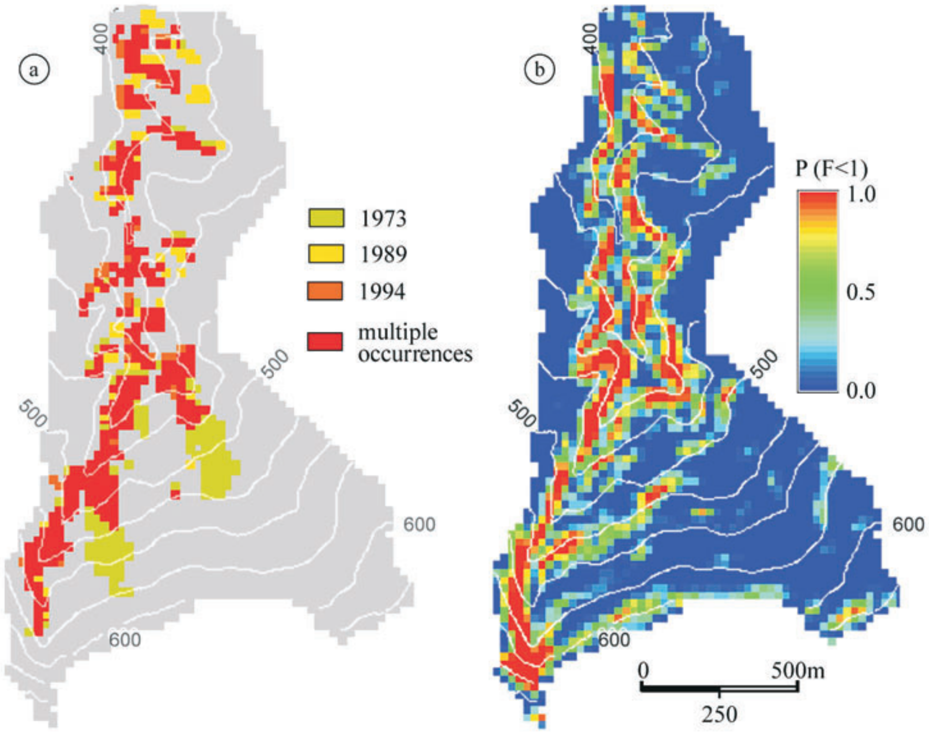

FIG. 13 – Landslide occurrence observed over the period 1973-1994 for a catchment in the Valles de Alcoy, Southeast Spain (13a) and simulated maximum probability of failure (13b) [modified from van Beek and van Asch, 2004].

FIG. 13 – *Occurrences de glissements de terrain observées sur la période 1973-1994 dans n bassin-versant de Valles de Alcoy, Sud-Est de l'Espagne (13a) et simulations de la probabilité de rupture maximale (13b) [modifié de van Beek et van Asch, 2004].*

of different controlling factors [Malamud *et al.*, 2004; van Westen *et al.,* 2006].

Therefore, the challenge in the forthcoming years is to use new strategies to add a temporal dimension, as well as information on the magnitude of events, to the already available susceptibility assessments in order to produce real hazard maps. The use of deterministic (physically-based) methods [Dietrich *et al.*, 2001; Chen and Lee, 2003; Savage *et al.,* 2003] in combination with probabilistic statistical techniques should theoretically be able to overcome these problems [van Beek, 2002; Casadei *et al.*, 2003] and complement any spatial and historical databases that are already available. To forecast landslide hazard outside the boundaries of existing active landslides, simulations based on probabilistic models as well as event-tree methods [Oboni 1988; Giasi *et al.,* 2003; Dai and Lee, 2003; Hsi and Fell, 2005] are the tools of preference to extend the knowledge gained at the scale of individual slopes to a larger area and to obtain occurrence probabilities and magnitudes for different types of slope movements [Aleotti and Chowdhury, 1999; Haneberg, 2000; Wong, 2005].

Some advances in this direction have recently been made. Coe *et al.* [2004] analysed a very detailed database of rainfall-triggered landslides in Seattle, United States, using a Poisson statistical model to estimate the probability of future occurrence of individual landslides, and a binomial statistical model to estimate the probability of having a group of one or more landslides within an individual year. Each model application produces a map showing landslide densities (number of landslide per given area) or landslide cluster densities (number of years with one or more landslides) as well as mean recurrence intervals and exceedance probabilities.

Dussauge-Pessier *et al.* [2002] and Hantz *et al.* [2003] used a multi-scale approach to derive frequencies of rock falls based on volume ranges in the Chartreuse Massif (French Alps). These frequencies allow transforming the spatial probabilities of the potential location of the unstable masses into occurrence probability and, thus, hazard. Spatial probabilities (or susceptibility) are calculated through statistical and geo-mechanical analyses, and occurrence probabilities are calculated from inventories at different time scales. In this way, probabilities can be obtained for a given volume. A similar approach has been used by Guzzetti *et al.* [2003, 2004].

Zêzère *et al.* [2004] integrated the spatial and temporal probability of shallow landslide occurrences in the Fanhões-Trancao area in the north of Lisbon (Portugal). The authors used logistic regression algorithms (for unique terrain units) on a landslide inventory that was classified by type and time of occurrence to obtain spatial probability estimates. They combined these spatial probabilities with the known return periods of rainfall-event that triggered the different landslide types to derive an integrated spatio-temporal landslide probability map.

When information on the temporal distribution of landslides is scarce, information on the spatio-temporal occurrence of landslides and on possible trends in landslide activity under changing environmental conditions can be obtained by probabilistic, physically based modelling. Van Beek and van Asch [2004] validated a daily, distributed hydro-mechanical model of shallow landslides for a catchment subject to land use change in SE Spain over a 27-year period (fig. 13). They found that the probability of failure agreed well with the observed landslide activity for different susceptibility categories but that in particular the simulated temporal characteristics were a good indicator for landslide activity. When hypothetical scenarios of land use and climate change, precipitation remaining equal, were applied to the model, only a limited change in the probability of failure was observed. More substantial changes in the simulated temporal activity were returned, however, revealing the sensitivity of the hydrological triggering mechanisms to vegetation effects and changes in climatic input.

Malet *et al.* [2007] proposed to use Probability Density Functions (PDFs) of rainfall and groundwater heights to investigate stochastically the incidence of failure within a slope by means of a deterministic coupled hydrology-hillslope stability model. The model runs were performed for many combinations of slope geometry, soil characteristics and initial hydrological conditions. This approach delivered information about the magnitude (e.g. volumes of material able to fail) and the thresholds for failure for individual or typical slopes that can be linked to a probabilistic susceptibility map. The approach necessitates detailed data on soil thickness, which may be difficult to obtain [Terlien *et al.,* 1995; van Beek and van Asch, 2004]. PDFs can also be used to handle the variability of the material characteristics [Haneberg, 2000; Hamm *et al.*, 2006].

The same type of approach provides an opportunity to investigate run-out frequencies and magnitudes of landslides in the absence of documentation of former events (volume involved, landslide travel distances). Malet and Beguería [2007] proposed a methodology to compute the characteristics of low-frequency debris flows through Monte Carlo techniques combining a deterministic 2D flow model and a probabilistic description of the model input parameters. Random inputs of flood discharges and geomechanical parameters (density, yield stress, viscosity) to the model were generated from magnitude-frequency curves for well-documented torrents and multi-variate distribution function for the material properties. From these realisations the spatial probability of occurrence (e.g. probability of a pixel being affected by material deposition) is calculated. The degree of hazard, expressed as a time probability or a recurrence interval, is computed by combining the magnitude/frequency of the discharge and the probability of occurrence. A schematic representation of the methodology is given in figure 14.

Sometimes it is practical to simulate the sequence of events which may lead to an individual slope failure or its frequency using an event-tree and expert opinion [Lee *et al.,* 2001]. This approach, common in earthquake hazard assessment, is founded on the observation of similar cases and a conceptual view of how a resulting landslide would fail and deform. Hsi and Fell [2005] used this approach to assess the hazard associated to a coal cliff in Australia. This approach is promising since at any node of the tree, conditional probabilities could be assigned to those events coming from the former node and the probabilities summed up, thus providing an approach that can deal flexibly with both “hard” and “soft” evidence in the hazard assessment procedure.

ROLE OF GEOMORPHOLOGY IN IMPROVING OUR MODELLING PERFORMANCE

Baynes and Lee [1998] discuss the role of geomorphology in landslide hazard assessment. To handle the natural variability in the controlling factors and the uncertainty in their measurement simulations encompassing both the short- and long-term slope evolution and conducted with probabilistic approaches are required if the landslide hazard is to be assessed quantitatively.

On long time scales, geomorphological analyses and modelling of slope evolution consider the weathering rate of the materials, the denudation/deposition rate of the soils and the rate of uplift/incision of the landforms by rivers or glaciers. Long-term hillslope modelling and reconstruction of landscape evolution can help to quantify the temporal evolution of predisposing factors, among them slope angle, soil depth and soil shear strength [Ahnert, 1987; Montgomery and Dietrich, 1994; Hovius *et al.*, 1997; Kirkby, 1998, 2003], and to identify the intensity of landslide activity [Cenderelli and Kite, 1998; Caine and Swanson, 1999; Korup *et al.*, 2004; Claessens *et al.*, 2006]. Nevertheless, most of the slope development models are still not detailed enough to forecast the evolution of these factors towards instability over larger spatial and temporal domains [Trustum *et al.*, 1999] and validation of such modelling efforts is severely hampered by the lack of landslide inventories that are relevant to medium to long time scales [Crozier, 1996; Martin *et al.*, 2002]. Consequently, detailed chronological analyses and dating of landslide sediment records in swamps and lakes, combined with estimates of sediment yields from landslide episodes merit our attention. The physically-based and spatially distributed models proposed by Burton and Bathurst [1998] and by Claessens *et al.* [2006] are interesting tools to estimate run-out distance from hillslope geometry and to provide maps of soil redistribution.

On shorter time scales, geomorphological observations can help to understand the type and the mechanics of movement, a stage in the investigation that is often ignored. Geomorphology may reveal the complexity of real-life landslides and thus the inevitable shortcomings of abstract models. Specific terrain vestiges enable us to reconstruct the type of processes involved and the sequence of dynamics prior, during and after failure [Geertsema *et al.*, 2006a, 2006b], information that is essential for the formulation of relevant hypotheses in the modelling of the system [Dikau *et al.*, 1996]. Distinctive geomorphological features for the identification of landslides can be found in the source area, in the development area and in the accumulation area. In the source area, the geometry of the crown and the slope of the main scarp, and the type of deformation of the topographical surface (back tilting slopes forming ponded lakes) are relevant indicators to identify the geometry of the failure surface. The topography of the development area (*e.g.* the

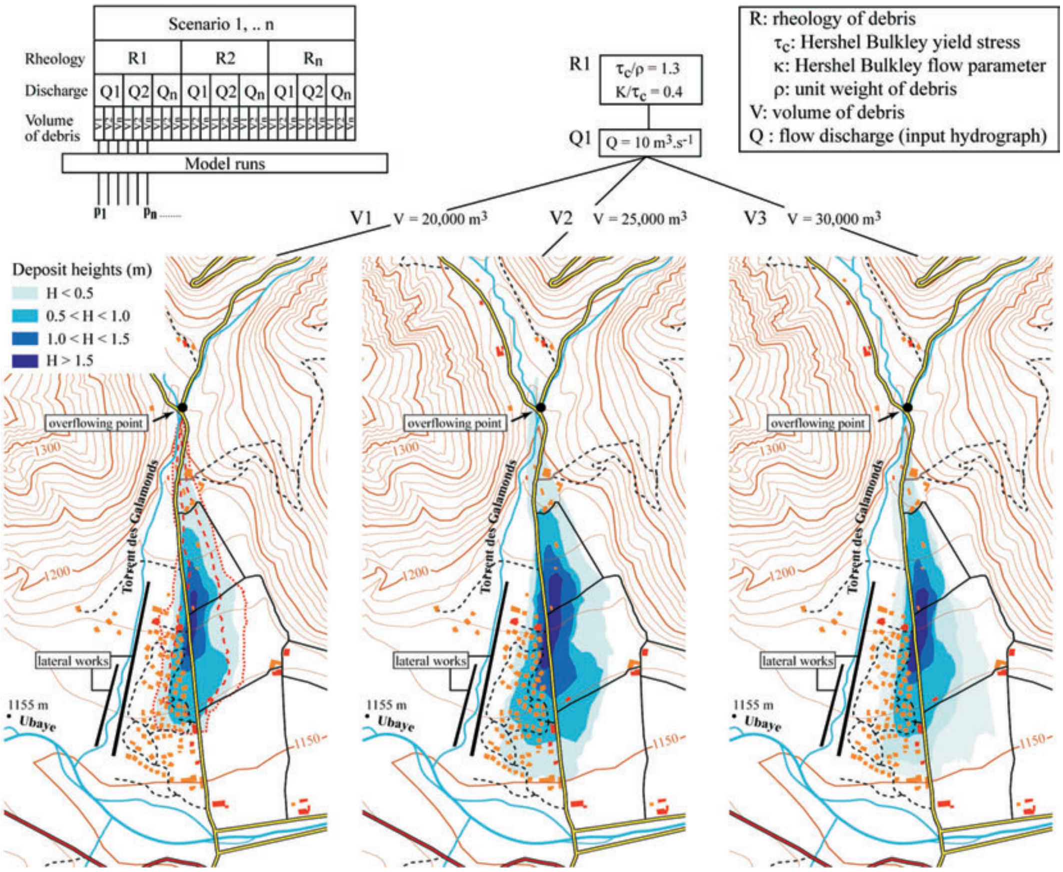

Fig. 14 – Probabilistic assessment of debris flow hazard on an alluvial fan, by combining Probability Density Function of input model parameters, Monte-Carlo simulations and model runs. Examples of Monte-Carlo simulations of debris flow heights [Malet and Beguería-Portuguès, submitted].
Fig. 14 – *Evaluation probabiliste de l'aléa lave torrentielle sur un cône alluvial, en combinant des fonctions de probabilités de données d'entrée de modèles et des simulations de Monte-Carlo. Exemples de simulation de Monte-Carlo de la hauteur de matériaux [Malet et Beguería-Portuguès, submitted].*

main body), its degree of disturbance, and the contour of the main body (elongated or strong lateral spreading) are relevant indicators to understand whether the material is sliding or flowing. The pattern of ridges and cracks and the form and steepness of the toe, give an indication of the viscosity of the landslide. The freshness of cracks, striation lines and disrupted topography and the stage in the vegetation growth are field evidences of the activity of the landslide complex [Crozier, 1986]. The two landslides of figure 15 provide interesting examples of the cascading sequence of failure as expressed by geomorphological indicators.

Geomorphological observations may also assist in the conceptualization and evaluation of the process-based models [Remaître *et al.*, 2005; Geertsema *et al.,* 2006b]. A thorough investigation and monitoring programme of an individual landslide needs therefore to combine geomorphological, geotechnical, geophysical and hydrological analyses [Bogaard *et al.*, 2000] as outlined in figure 16.

The state-of-the-art papers provided in this Special Issue address relevant recent technological developments made in the identification of landslide displacement by remote-sensing techniques [Delacourt *et al.*, 2007], in the identification of landslide geometry and internal structure by geophysical techniques [Jongmans and Garambois, 2007] and in the analysis of the hydrological system of landslides by hydrogeochemistry techniques [Bogaard *et al.*, 2007]. Still, a strong case should be made for relevant remote-sensing techniques to get accurate topographical information for both the understanding of landslide processes and as validation sets to evaluate model performance. These techniques are equally useful to support geomorphological investigations to identify the micro-relief of dormant or stabilized landslides, which are always prone to destabilisation and therefore vital areas to be identified in regional hazard assessments. Useful techniques to identify and delimit unstable areas are stereo-photogrammetric analyses of aerial air photographs [Weber and Herrmann, 2000; Chandler, 1999; Casson *et al.*, 2003], optical or radar remote-sensing [Massonnet and Feigl, 1998; Kimura and Yamaguchi, 2000; Squarzoni *et al.*, 2003; Delacourt *et al.*, 2004] or ground-based techniques like dGPS [Malet *et al.*, 2002] and terrestrial SAR interferometry [Tarchi *et al.*, 2003].

CONCLUSIONS

Forecasting both the spatial and temporal probability of occurrence and the intensity of all types of slope movements is a necessary task to quantify the landslide hazard in an area. Over the past decades, great progress has been made towards advanced, physically-based models that describe the hydrology and mechanics of landslides in detail. In our view, the task at hand would be to address the uncertainties in the parameterisation and the shortcomings in process knowledge that limit our capability to model the slope deformation throughout the life cycle of a landslide reliably.

Over longer periods, it remains extremely hard to simulate the path to failure. Slope evolution, rate of weathering, soil development and the formation of preferential pathway by mechanical and biological processes are the main preparatory agents for slope failure in rock and soil material. There are models that describe these processes but they are seldom used to explain and forecast the temporal activity of landslides because of their lack of resolution to represent these processes in complex terrain. It is important, therefore, to couple field and laboratory experiments under controlled conditions to the development of process models that describe the transitory changes in stress and resistance acting on a potential landslide.

On a short-term time scale, the most important trigger for failure and for the reactivation of slope movements is the hydrological system. It deserves more attention, and

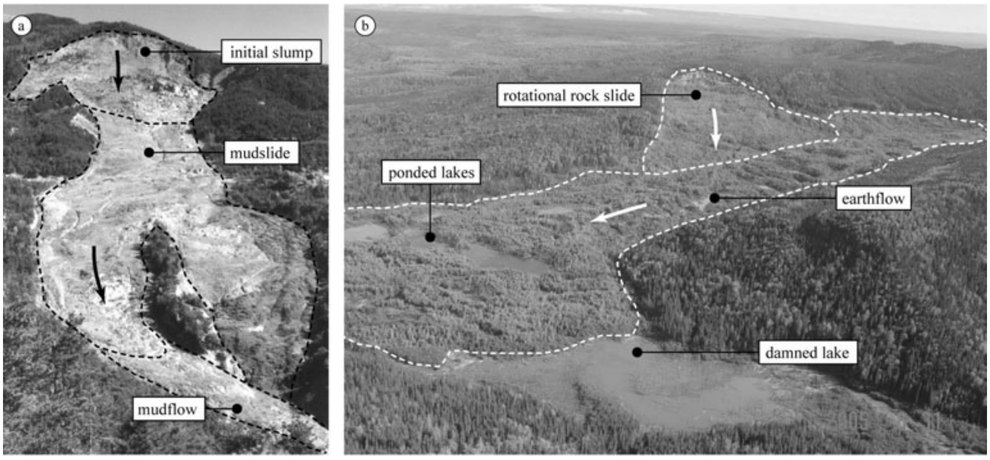

FIG. 15 – Geomorphology of complex landslides. (15a) Complex La Valette slump-mudslide in the French South Alps; (15b) Complex Muskwa slide-earthflow in North-East British Columbia, Canada. The La Valette landslide complex (fig. 15a) shows a steep scarp with a backward tilted block (initial slump) in the upper part, a less disturbed surface showing subsidence and movement parallel to the slope in the middle part, and an elongated mud track with a clear lobate form and ridges in the lower part. Figure 15b shows the Muskwa landslide with a source area with a rotational rock slide in flat-lying sandstone and shale, which triggered an earthflow in clayey till. The rotational rock slide is characterized by a distinct steep scarp and backward tilted blocks, while the flow shows transverse ridges pushed up during movement and in the lower part a lobate form with a hummocky topography with ponded lakes. The big lake at the bottom of the photograph is caused by the landslide complex damming the river. The prediction of such large earthflows from much smaller rock slides is a major challenge for terrain stability modelling in British Columbia [Geertsema *et al.*, 2006a].

FIG. 15 – *Géomorphologie de glissements de terrain complexes. (15a) Glissement-coulée de La Valette dans les Alpes Françaises du Sud ; (15b) Glissement translationnel et coulée de Muskwa slide-earthflow dans le Nord-Est de la Colombie Britannique, Canada.*

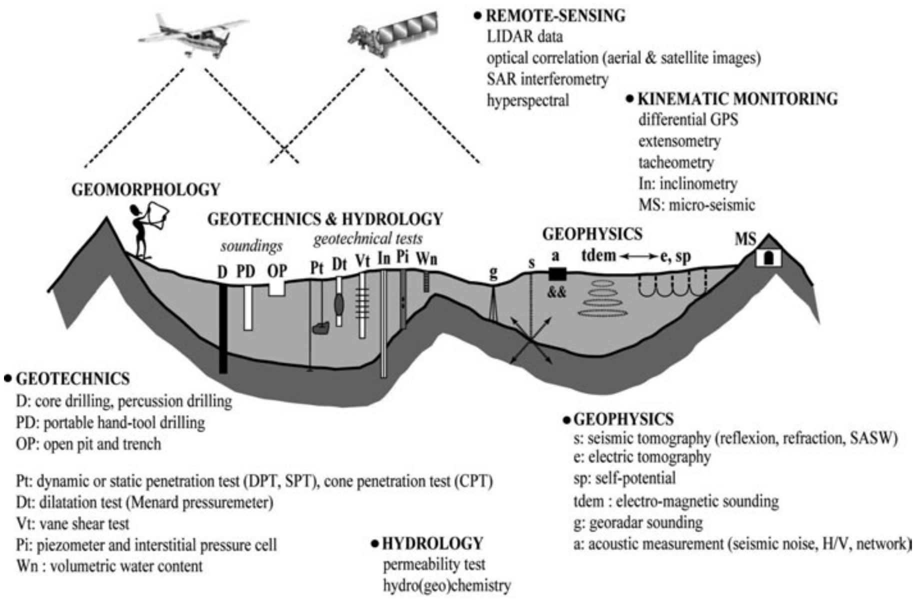

FIG. 16 – Multi-source strategy of investigation and monitoring of an active slope movement.
FIG. 16 – *Stratégie multi-source d'investigation et de surveillance d'un mouvement de terrain actif.*

especially the role of the unsaturated zone has to be highlighted. The unsaturated zone plays an important role in shallow landslides alike by controlling the groundwater recharge, which is influenced by precipitation, evaporation, interception and transpiration through vegetation, bypass flow and Darcian matric flow. Understanding of this role is paramount to any successful assessments of the effect of land use and climate change on slope stability. Due to the internal dynamics of landslides, their hydrological system tends to be more complex: preferential flow paths of different origins may be present and it is difficult to determine the extent and connectivity of these systems at any moment in time, let alone the changes over time and to quantify its interaction with the soil matrix and groundwater system.

For intermittently and gradually moving landslides, the major challenge is to forecast periods of crises. This requires a thorough understanding of the factors controlling movement. Laboratory-scale experiments are inadequate to capture the variations in the hydro-mechanical properties over time and space and a number of factors operating at the field scale have to be considered. Movement patterns that result in compressive and dilative stresses are extremely important as they may cause excess pore pressure. The transient character of these landslides is equally influenced by changes in their geometry and connectivity of the fissure system (*e.g.*, opening, clogging), which may completely change the hydrological response; pore pressure fluctuations may occur from compression (dilation) over an irregular shear surface and/or from consolidation arising from intermittent "stick-slip" movements.

Different mechanisms can play a role when sliding material liquefies and transform into rapid gravitational flows. The total amount of material that liquefies is a major controlling factor for the run-out distance of these flows. For compacted material it is difficult to forecast whether fluidisation might occur and how much material will transform into a flow. Also, erosion and transport processes on very steep slopes, generating hyper-concentrated flows with a potential to entrain material and form debris flow should be further investigated. A major problem in the run-out modelling of the rapid gravitational flows is the determination of effective rheological properties of the material, which may change during the run-out, often in response to excess pore pressure generation and dissipation. There is an urgent need to broaden our research on morphological indicators, the monitoring of rapid flows, sampling their velocity, consistency and composition, and simulating the flow behaviour under controlled conditions. In this research effort, a good balance must be sought between the increased details of the process description versus the parameterisation load if robust and trustworthy models.

Landslide hazard and risk assessment at the region scale, needed for planning purposes and cost-benefit analyses, require information on the temporal frequency and magnitude of relevant landslide processes. However, such analyses are often impaired by the lack of historical data. It is a challenge, therefore to get synthesize this information with physically-based hydro-mechanical models. The integration of these model results with hazard zonation maps remains a major issue and investigations have to be made especially on how far physically-based models are representative for the range and type of landslide processes encountered and their reliability to model the extent and frequency adequately.

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