Research Paper

CENTRO EURO-MEDITERRANEO PER I CAMBIAMENTI CLIMATICI

ISC – Impatti sul Suolo e sulle Coste

Coupling of meteorological forecasting and landslide triggering: development, constraints and further goals

A.M.R.A. S.c.a.r.l.

Centro Euro-Mediterraneo
per i Cambiamenti Climatici
www.cmcc.it

January, 2010, TR

Coupling of meteorological forecasting and landslide triggering: development, constraints and further goals

Summary: The modern society needs reliable instruments for the prediction and prevention of extreme natural events which can produce casualties and damage. For instance, severe hydrogeological phenomena are periodically caused by critical weather conditions. Because of the strong improvement of sensors and numerical tools capable to correctly predict the weather, integrated approaches for the prediction of weather-induced landslides and the assessment of the role of long-term climate changes on land stability can be confidently used. This is a base for the development of warning systems and the setting up of long-term programmes for land management and maintenance.

Keywords: landslide, debris flow, analysis, numerical code, short-term weather forecasting, long-term climate scenario, flume test, test site,

JEL Classification:

Address for correspondence:
Luciano Picarelli
Full professor
A.M.R.A. S.c.a.r.l.
Via Nuova Agnano, 11
80125 Napoli
E-mail: luciano.picarelli@amracenter.com

CONTENTS

1. Foreword

A.M.R.A. S.c.a.r.l. is the partner of C.M.C.C. in the development of a research programme whose goal is the prediction of rainfall-induced landslides due to meteorological events. The basic instrument of the research is the coupling of weather forecasting with the analysis of its effects on slope stability. The two principal topics of the research are: i) the timely prediction of landslide triggering based on short-term forecasting of incoming storms; ii) the development of reliable hydrogeological scenarios created by the future climatic changes.
The results obtained up to now are summarised in specific technical reports carried out by researchers working under the joint scientific of C.M.C.C. and A.M.R.A. Here the main aspects of such activity are briefly discussed to highlight some crucial points, to specify the constraints of the complex conceptual chain leading to prediction of hydrogeological weather effects, and to address the development of more advanced research programmes.

2. Role of weather on slope stability

Rainfall is one of the most important landslide triggers. In unsaturated soils, water infiltration leads to the increase of the water content (and of the degree of saturation) thus of the unit weight of soil, and the decrease of the suction thus of the cohesion. In saturated soils, the effect of infiltration is the increase of pore pressure and the consequent decrease of the effective stress thus of the frictional component of the shear strength. An opposite process is evapotranspiration which tends to subtract water from the subsoil, leading to the increase of both shear strength components. When infiltration prevails, the shear strength of soil decreases because of the decrease of cohesion (in unsaturated soils) or friction (in saturated soils), sometimes leading to slope failure. When evapotranspiration prevails the shear strength increases as well the safety conditions.
All sloping deposits generally present a unsaturated cover, which is sometimes very thin (especially in clayey soils) and collects or looses water, governing the process of infiltration or of evapotranspiration, thus the pore water regime, in the underlying saturated layers. Infiltration or evapotranspiration in such layers are in turn regulated by their structure (stratigraphy, discontinuity sets), the boundary conditions and both the hydraulic conductivity and stiffness of soil. Finally, a not negligible role is played by the vegetation which can absorb water. Therefore, weather is a prominent regulator of slope stability conditions.
Rainfall may trigger landslides through infiltration. In wet seasons the hazard is higher being governed by both the duration and the intensity of rainfall, but also by the external temperature, humidity and vegetation, which play an important role through the amount of infiltrating or evaporating water. In contrast, the hazard is lower in dry seasons when the amount of rainfall drastically decreases and both high temperature and low humidity subtract water from the subsoil.
A correct land management should account for the effects of weather on slope stability. In particular, a coupling of weather forecasting and slope stability analysis might be highly beneficial for the prediction of the evolution of the safety conditions. This may be carried out by a double way: i) through short-term weather forecasting and assessment of

potential local failures caused by incoming storms; ii) through the evaluation of the future climatic scenarios and of their effects on the general physical conditions of the land.
Both approaches have been adopted in the research which has been jointly carried out by C.M.C.C. and A.M.R.A.

3. Short-term landslide triggering

3.1 Generalities

The short-term landslide prediction is a crucial problem, especially when incoming storms can trigger fast landslides. In this case the risk is high because of the difficulty to prevent the consequences of the slope failure, which are often severe because of the long run-out and high kinetic energy possessed by the landslide body, especially if its volume is large enough. These problems threaten mainly developing countries within the Circum Pacific Region (Aleotti and Chowdhury, 1999), especially in the Far East and in Southern America. Serious problems concern also some developed countries, such as Italy and Japan.
In the case of fast landslides, the risk mitigation includes different approaches such as: a) construction of passive structural works able to protect the exposed goods; b) evacuation of the risk areas; c) early warning systems (temporary evacuation and saving, when possible, of a part of the exposed goods through special emergency plans).
The construction of passive works is expensive and cannot be carried out everywhere for different reasons such as: a) the lack of areas available for the construction of such works (f.i. large retention basins); b) difficulties often related to the morphology of such areas; c) high costs; d) environmental reasons.
The evacuation of inhabited areas is often impossible for the strong link between people and their native settlements, for the density of population or for the lack of areas to exploit for new settlements.
Early warning systems theoretically represent a cheap and effective procedure, but the difficulty to develop reliable procedures able to avoid missing alarms or excessive false alarms is still very high. Nevertheless, this procedure will be more and more adopted in the near future; in fact, the research in this field well is already very active.
One of the criteria which should support this procedure is to link the meteorological forecasting to the analysis of slope stability. Such a procedure is still in a very initial phase and the literature is very poor in this respect. Generally, only very rough qualitative approaches are adopted (Picarelli et al., 2009). The effort to carry out in the near future is then to develop and calibrate a quantitative meteorological-hydrogeological chain based on the assessment of the location, duration and intensity of incoming precipitations and the analysis in real time of their physical-mechanical effects on land.
The effectiveness of such an approach has been investigated in this research referring to the case of the fast debris flows in the unsaturated loose pyroclastic soils which outcrop in Campania Region (Cascini et al., 2000; Olivares and Picarelli, 2003).

3.2 Main hydrogeological problems in the Campania Region

A large part of Campania, especially around the districts of Napoli, Salerno and Caserta, is covered by the products of eruptions occurred in the last tens thousands of years, essentially consisting of granular pyroclastic soils, tuff and lava. The part of the Region covered by pyroclastic soils is much wider than the others consisting in tuff or lava

outcrops. Being rather pervious when saturated, such covers cannot host aquifers, but during transient phases of intense precipitation, they may experience a strong increase in the water content up to ephemeral formation of water pondings on the ground surface or in depth. Depending on local slope morphology, stratigraphy, boundary and initial conditions and soil properties, such transient conditions may lead to slope failure. If crucial factors, such as soil brittleness and slope morphology, present critical values, soil failures may turn into relatively large and fast landslides (debris flows) with potential severe consequences for people and other exposed elements (Picarelli, Olivares, 2006). On the other side, the tremendous growth in the exposure occurred in the last tens of years due to the growth of population, of infrastructures and economic activities, makes the risk of landslide higher and higher because of the combination of an even constant, or slightly increasing hazard, and of a dramatic increase in exposure.
Another very large part of Campania, the one which develops along the Apennines chain in the districts of Avellino and Benevento, is occupied by argillaceous formations, generally very stiff and fissured, where very large landslides occur, much slower than the debris flows in pyroclastic soils, but subjected to long-lasting movements which in the long-term can cause damages and different problems in the use of structures and infrastructures (Picarelli Russo, 2004). On the other side, every first-time landslide may be fast enough to cause significant damages to any work rising in the area affected by failure, before than any intervention can be set up.
The hydraulic conductivity of such materials is very low in both unsaturated and saturated conditions thus only long wet periods and continuous rainfall can determine significant infiltration and increase in pore water pressure, especially at high depths. Nevertheless, the land stability problems due to weather are diffuse and the consequences on man-made works, heavy. Therefore, a clear framework about the relevance of the problem with special reference to the effects of incoming climate changes is necessary.
The general problems concerning the two geomorphological contexts described above, i.e. the one of unsaturated pyroclastic granular soils and the one saturated stiff fissured clays, require an extraordinary societal effort in order to increase the knowledge on the causes and the mechanisms of landslides, to provide a wide dissemination of such a knowledge and to favour the improvement of reliable instruments for risk mitigation. Furthermore, it is worth to mention that such two basic scenarios are representative of simila geomorphological contexts all over the Mediterranean basin, thus the results of the research can be used as paradigmatic references to be followed for such contexts.

3.3 Lines of the research programme developed by C.M.C.C. and *A.M.R.A.*

The strict relation between rainfall and debris flows in unsaturated granular pyroclastic soils is well known and very well documented through a number of papers. However, very poor has been so far the knowledge about the mechanics of such phenomena. Only in the last ten years, i.e. just after the catastrophic events of Sarno (1998), the research has significantly covered some lacks of knowledge.
As a first research topic, C.M.C.C. and A.M.R.A. contributed to partially fill such a gap through some instrumented flume tests which enabled to investigate on the hydrological response of small scale slopes consisting of uniform or layered pyroclastic soils. As a successive topic, some 2D numerical models working either at the slope either at regional scale have been tested in order to assess their capability to simulate the effects of rainfall with particular reference to the process of infiltration until to failure. The quite good results obtained encouraged to reproduce some real test cases. Finally, a new GIS based 3D

model has been developed and tested in order to check the feasibility of short-term predictions at the slope scale.

3.3.1 Flume tests
The flume tests have been carried out to investigate the hydrological response of model slopes set up with volcanic ashes taken from risk sites, which have been subjected to artificial rainfall. The slopes have been heavily instrumented through classical and advanced sensors which enabled to investigate the pore pressure regime, the water content and the displacement fields.
The detailed results of the experiments are reported in a technical report. It has been shown that infiltration causes a progressive increase in the water content from the top of the layer to its bottom, whose rate depends on the permeability function of soil, in turn depending on its water content. Intermediate layers can modify the saturation rate of the slope: in particular, pumice layers slow down the infiltration process in the underlying ash layers. Another important result is that the presence of a pervious bedrock is more favourable to slope stability than the presence of an impervious bedrock. However, even being rapid in the very first phase of infiltration, saturation then proceeds rather slowly, delaying the stage of complete saturation.
Precipitation intensity seems to play an important role as well: for low rainfall intensity and relatively pervious soils, these do not reach a full saturation, thus the continuous presence of an even very small suction can assure the stability of thin relatively steep covers; however, in the case of impervious bedrock located at a relatively small depth, saturation can start when the humid front reaches the bedrock, rising from the base of the layer upward until to failure of the entire cover. In contrast, high rain intensity tends to saturate very soon the shallowest layers causing their premature failure. This has of course important consequences on the risk.
Such phenomena can be easily simulated by existing or purposely built numerical models, which in fact have been extensively adopted.

3.3.2 Numerical modelling of infiltration by 2D existing codes
The numerical analysis had the role to provide a general framework of the response to rainfall of unsaturated pyroclastic soils.
The slope behaviour has been investigated by: i) a set of analyses based on the simple model of infinite slope resting on either pervious or impervious bedrock (scenarios of slope behaviour); ii) simulation of some test cases.

3.3.2.1 Analysis of representative scenarios
Typical geomorphological situations consisting of thin covers of pyroclastic soil deposited on fractured limestone (pervious bedrock) or altered ash, tuff or clay (impervious bedrock) have been analysed. The investigated slope angle ranges between 20° and 45° and the thickness of the cover between 0.5 and 4 m, corresponding to the majority of situations in which liquefied debris flows (i.e. the most catastrophic landslides) have been triggered in the past. Regarding soil properties, both relatively pervious ash, representative of the phlaegrean zone (West to Naples), and relatively impervious ash, representative of a wide area located to East to Naples, have been considered.
An initial uniform suction ranging between 19 and 95 kPa has been assumed: it corresponds to relatively dry (typical of late spring or late fall) to very dry situations (hot summer). Moreover, constant precipitation with intensity comprised between about 1 mm/h

and 100 mm/h has been considered. The computations have been conducted through the numerical code SEEP, under 2D conditions.
A detailed description of all considered cases is reported in a specific technical report.
The results obtained suggest that the permeability function has a prominent role on the time to failure and on the process of infiltration; therefore, without a correct measurement of the permeability function, no reliable thresholds can be obtained. Prediction cannot neglect a number of hydraulic and mechanical factors including morphology, initial and boundary conditions, stratigraphy, which strongly affect the slope response whose prediction is a really complex and heavy task. As shown by flume tests too, the presence of an impervious bedrock is a unfavourable factor for stability.
The mechanism of failure depends on different factors; for instance, failure can be either superficial or deep as a function of permeability function, thickness of the cover and rain intensity: as shown by flume tests too, the analysis shows that failure may be shallow for relatively low soil permeability and high rain intensity; the opposite mechanism (i.e. deep failure) takes place for relatively pervious covers and low rain intensity; in the last case, a full saturation may occur only in depth or across the entire layer, depending on the same factors listed above. Naturally, the risk of shallow landslides is relatively lower because of the thinner volume of triggered landslide; in addition, potential subsequent larger events can be predicted based on the simple indicator due to spreading of mud at the toe of the slope as a consequence of first shallow failures. In the case of deep landslides, the risk is higher, because of its volume and sudden triggering which is not announced by geoindicators, as the spreading of mud before the rupture of the entire cover.
As shown by flume tests, it is worth to note that saturation favours soil liquefaction, giving rise to very fast movements.

3.3.2.2. Test cases
The analysis of test cases concerns three events, two of them occurred on the Camaldoli hill, in Naples, the third one in the Nocera Inferiore area. In both sites, two different computation procedures have been carried out. The first procedure has been applied to a much wider surface than the failed slope, that has been analysed by the numerical code TRIGRS (Baum et al., 2002), which assumes 1D seepage conditions and can be used at a regional scale. The second procedure has been just limited to the failed slope, for which the 2D SEEP code has been used.
In the Camaldoli site, relatively small landslides occurred twice in two consecutive years, 2004 and 2005. In Nocera Inferiore, a larger event occurred in 2005, killing three people. The covers, which have been assumed to be uniform, are relatively well known, thus their characterization has been based on reliable data concerning similar materials. Initial suction comes from the hypothesis of steady-state conditions. Even though the rainfall history at the two sites is known, a simulation of the presumable precipitations has been carried, based on weather forecasting by the COSMO-LM code at the time preceding the events.
The results obtained for the Camaldoli site confirm the crucial role of some parameters as the initial suction profile and the precise depth of the bedrock. As a consequence, presently, the use of such analyses as a predictor of slope failure can lead to a unacceptable number of false alarms. In fact, based on the obtained results, the two critical events should have triggered further landslides besides those which were actually mobilised. On the other side, the location of the real failures has been correctly

recognized. Similar considerations held for the Nocera Inferiore test case for which TRIGRS has been also used.
The same events have been investigated through "local" analyses carried out with SEEP. Measured rainfalls in the month before the landslide events as well as those which could have been predicted through the COSMO-LM programme have been used as input data. Following this approach, a slope failure along the steepest part of the Camaldoli slope has been predicted in both analysed events, even though the real landslide was larger than the predicted one, covering a longer surface downslope. The analysis carried out using as input the meteorological forecast do not enable to predict the same failure.
In the Nocera Inferiore test case, further considerations have been made concerning the differences between the results obtained with 1D and 2D analyses, the role of the permeability of the bedrock and especially the role of the rainfall history which is appreciable even for rainfalls occurred months before the event. This suggests that a correct analysis cannot neglect a significant part of the rainfall history and that empirical thresholds based on the present rainfall can lead to significant mistakes in the prediction, at least for soils having the thickness, the slope angle and the permeability of the considered geomorphological context.

3.3.3 Numerical modelling of infiltration through a home made 3D code
In the last year an original home-made numerical code has been set up in order to perform 3D infiltration analyses starting from a Digital Terrain Model and accounting for the conditions of partial saturation of soil through the use of the water retention curve and permeability function. The code is described in another technical report.
The model includes a 3D volume finite algorithm (I-MOD3D) developed in VBA application for ARCOBJECTTM/ARCGIS 9.2TM to automate the mesh-generation starting from the Digital Terrain Model (Olivares and Tommasi, 2008). As mentioned above, the code covers the conditions of partial saturation of soil and very frequent morphological situations characterised by the presence of gullies, that available commercial codes do not consider. This enables to perform more correct analyses than with other codes at the catchment scale.
The model has been calibrated using either data from laboratory tests on natural soil samples or from infiltration tests on small scale slope models (section 3.3.1). It has been validated also through back-analysis of in situ suction measurements using initial and boundary conditions obtained from site monitoring.

3.4 Considerations about the potentialities and the constraints of short-term landslide prediction
Since the near future will require an extensive use of early warning systems for people protection from any type of natural or anthropogenic hazard, this research line has a crucial value; this is still more evident when the present trends of the research in the world are considered. In particular, that is a primary need for the case of the hydrogeological hazards.
The short-time prediction of rainfall-induced triggering should be a prominent component of any early warning system aimed at the mitigation of the risk of landslide. Such systems should include a modulus for weather forecasting and another one for assessment of the hydrological effects of the storms of highest magnitude. In many countries such systems do exist, but the hydrogeological chain is very rough, consisting of a weather forecasting at large scale and of a qualitative assessment of the potential landslide triggering based on

empirical thresholds. These generally cover wide areas independently on their local geomorphological and geotechnical features. Therefore, more accurate systems are needed for more reliable predictions at local scale.
The research carried out by C.M.C.C. and A.M.R.A. shows that a consistent and reliable link can be established between rainfall forecasting and prediction of the precipitation effects on slope stability, if the most advanced systems for weather forecasting and landslide triggering prediction are used.
The increasing quality and reliability of the procedures for weather forecasting is well known. Regarding the geotechnical side (i.e. landslide prediction), the rapid growth of the knowledge is confirmed by both the results of the tests on small scale model slopes subjected to artificial rainfall (section 3.3.1) and the performance of advanced numerical codes aimed at the analysis of rainfall infiltration coupled to slope stability analysis (sections 3.3.2 and 3.3.3). Therefore, an accurate use of such instruments can provide reliable scenarios of rainfall-induced landslides.
As shown above, at the moment, the main problem concerns the scale to which a reliable prediction can be performed. In fact, the scale of interest should be very local (slope), since alerting of extensive areas is socially and economically very heavy, but the difficulty to obtain an exact solution growths as the reference scale decreases. The number of virtual false alarms deduced from analyses of test cases (section 3.3.2.2) represent a clear indication of the problems which could be encountered using the described meteorological-hydrogeological chain. The problem concerns either the weather forecasting and the geotecyhnical analysis.
It is not a task of A.M.R.A. to stress the problems of weather forecasting, which is quite reliable at scales much greater than the local one undergoing a strong decrease in the reliability as the reference scale decreases. In any case, it is clear that the quality of the results can be improved using more powerful monitoring sensors and numerical codes.
Regarding the geotechnical side, the prediction of landslide triggering at the local scale is not yet satisfying because of the problems associated with the variability of the soil structure and properties, and to local inhomogeneities in morphology, initial conditions and rain features. These constraints are such that, at the moment, only a very good stratigraphic and mechanical soil characterization and the continuous monitoring of pore pressures providing the initial conditions can support an effective landslide prediction.
Accounting for previous considerations, presently, the hydrological chain could be developed only under the following constraints:

a) pre-selection of the most risky (critical) areas in a given country, leaving aside the other less critical areas;
b) performing detailed investigations for the definition of the stratigraphic and mechanical soil characterization and the installation of instruments for pore pressure monitoring in the selected areas (for the identification of the initial conditions);
c) weather forecasting at the regional scale (which is quite precise) and first regional alerting, based on qualitative geotechnical data (which do not enable to perform quantitative reliable predictions);
d) landslide prediction and alarming only in the selected critical areas where a careful geotechnical characterization and monitoring has been carried out.

In order to mitigate the risk of false or missing alarms the future perspective is to use the theory of decision. In addition, statistical and probabilistic methods should support the forecasting of incoming storms at local scale and the elaboration. At the same time the prediction of landslide triggering should be integrated using geoindicators such as pore pressure, water content or displacement sensors installed in the critical areas, in order to: i) validate the results of the geotechnical analyses; ii) indicate and confirm if a slope failure is likely (for instance, through developing soil deformations).
If data regarding the local scale miss, prediction should be limited to the regional scale establishing the initial conditions through an analysis of the recent rainfall history (Pagano et al., 2010).

4. Future climatic scenarios and impact on slope stability

4.1 Generalities

As shown above, weather strongly affects the stability of slopes, essentially through its influence on the pore water pressure regime. Therefore, apparent ongoing climatic changes represented by global warming should govern the future landslide activity due to their influence on pore pressures. An evaluation of future climatic changes might then help in the assessment of general land stability.
The assessment of the effects of climate changes is very complex due to the difficulty in the long-term quantitative prediction of the modification of the climate parameters, which can be achieved only through a highly multidisciplinary approach. In addition, it is likely that the expected impact on slope stability will be different in the different countries, depending on local climate changes and geomorphological situations. Therefore, presently only a very qualitative prediction can be made based on general climatic scenarios in different geomorphological contexts.
In principle, the global warming should be responsible for an increase in the evapotranspiration which should cause a decrease in pore pressures, but an opposite effect might have any decrease in the relative humidity. Furthermore, a fundamental role will be played by the precipitation regime which in the Mediterranean area seems to be characterised by a slight decrease in the annual cumulated precipitation but, at the same time, by a potential increase in the intensity of single rainfalls due to a decrease in the number of rainy days. These phenomena might have a detrimental effect in highly pervious materials subjected to relatively low hydraulic gradients (coarse-grained soils, fractured rock) and a beneficial effect on low permeability materials (fine-grained soils). In fact, while in the first case even short rainfalls can cause significant increases in the pore pressure, in the second case, the stability of slopes should not be influenced by single rain events, which cannot determine significant increases in the pore pressure, but by the cumulated rainfall over relatively long time periods. Since the slope response after failure may be very different in different geomaterials, the goals of the analysis must be different depending on the concerned case.
Such simple considerations demonstrate the difficulty of the problem and the need for a ductile approach. This is the reason for which two geomorphological scenarios have been separately considered:

1) the one of unsaturated pyroclastic deposits outcropping in Campania, which are quite pervious for high saturation degrees;

2) the one of fine-grained soils which outcrop all along the Apennines chain in Italy and in many other regions of the Mediterranean basin.

These scenarios have been investigated through the analysis of two real cases.

4.2 Potential impact on unsaturated pyroclastic soils

The potential impacts of future climate changes on the stability of slopes in pyroclastic deposits may be obtained from the hydrogeological scenarios discussed above (section 3.2.2.1). If the general change in climate will be characterised by increasing temperature and increase in the rain intensity, the average suction increase and the general stability conditions should improve. At the same time, single intense events might cause diffuse failures involving the most superficial layers.

Some analyses have been depicted for the Cervinara area, already subjected to a catastrophic landslide (1999), accounting for the climate scenarios provided by C.M.C.C. for the time interval until to 2060. The geomophological and geotechnical features as well as the values of suction are well documented (Lampitiello, 2004; Olivares et al., 2004; 2006; Picarelli et al., 2009). Selected area is occupied by an about 2 m thick cover of unsaturated loose cohesionless pyroclastic soils, whose ashy component presents a friction angle of 38° and a saturated hydraulic conductivity of 10^{-6} m/sec, which decreases of 2 orders of magnitude for a suction up to 80 kPa. Typically, suction fluctuates in between around 2 and 60 kPa (saturation degree comprised between about 90 and 40%), depending on seasonal conditions.

The climate scenario which has been calibrated through computations based on data of temperature, relative humidity and cumulated rainfall in the last years, suggests that in the next century the temperature will increase of about one degree per 20 years following a non-linear growth. Regarding precipitations, the trend of yearly cumulated rainfall should decrease while daily rains in the range between 30-60mm/day should increase; the magnitude of the most intense events should not substantially change.

The analysis has been carried out with the I-MOD3D programme, which has been calibrated using data on suction measured in the last years. The evapotranspiration effect has been considered by the Thorntwaite (1948) formulation. The analysis has been conducted after some minor adjustment in the climate data.

The analysis carried out for the years 2059-2060 suggest higher average values of suction than today, corresponding to lower soil moisture conditions, accompanied by strong variations at shallow depths during the rainy days. An evaluation of the future stability conditions of the slope shows a global increase in the safety factors all-over the cover's depth (see concerned technical report). The critical surface should remain the deepest one even after the heaviest storms.

However, if the weather will include an increase in the intensity of rainfall (which seems to tend toward tropical scenarios), this might determine diffuse landslides, probably involving the shallowest layers, during the most intense storms. Since loose saturated soils in undrained conditions may liquefy, this can lead to fast debris flows (sections 3.2, 3.3.1, 3.3.2.1).

4.3 Potential impact on saturated fine-grained soils

The response of sloping fine-grained soils to pore pressure changes is generally delayed and slow. In fact, their low hydraulic conductivity in both saturated and unsaturated state delays water infiltration at the depths where failure might occur (metres to a few tens of

metres), which is generally accomplished in some weeks or months. Therefore, in general, single intense rainfalls do not create problems higher than those caused by moderate rainfall, and is mostly the duration of the wet season the crucial factor to account for in the analysis. The main consequence is that the pore pressure fluctuations caused by infiltration are relatively slow, with a period even much longer than the period between rainy periods, leading to peak pore pressures some weeks after the rainfall peaks.
Regarding the slope response, the case of first-time landslides should be treated differently than the one of reactivated landslides, and even in that case, the first-time slope failure in OC stiff non fissured plastic clays should be treated differently than other cases. Finally, a special situation is the one of slope failures occurring in areas already occupied by softened landslide bodies, which can give rise to flow like movements (earthflows).
Highly OC stiff non fissured plastic clays experience a significant drop in the shear strength after failure, and a consequent significant acceleration of the landslide body. The same may occur in the case of softened clay bodies subjected to alimentation from upslope since the building up of positive excess pore pressures can trigger an earthflow. In such situations, the main problem is the velocity and the magnitude of the triggered movement, just as for debris flow, even though the peak velocity in clay generally does not exceed a few tens of metres per hour.
In all other cases, the ductile of moderately brittle soil behaviour causes very slow movements and the main engineering problem is to evaluate the long-term accumulated displacement which can damage structures and infrastructures putting them out of work: the scheduling of maintenance works is then the main issue. The research tried to give a partial answer to this last question through the analysis of a test case.
The study concerns a very slow mudslide (v=1÷2 cm/year) in Varicoloured Clays located along the Basento river (Southern Italy) where geomaterials very similar to those present in Campania Region outcrop. The displacement field, the pore-water regime and the climate parameters during about three years (since 2005 up to 2007) are available. Geotechnical soil properties are also available, allowing to perform the requested analysis. Collected data shows that the movement never stops and that the displacement rate grows as the piezometric level increases, attaining a peak of about 3 mm/month for a water level very close to the ground surface. A water level-velocity relationship similar to the one obtained by other researchers in other experiences fits quite satisfactorily the experimental data and enables to predict future displacements if a reliable prediction of pore pressure fluctuations can be made.
According to the climatic data in the last century the yearly cumulated rainfall shows a general decreasing trend. The C.M.C.C. group has depicted the climatic scenarios in the time interval 2005-2060: for the time interval 2005-2007 these are quite satisfying, especially concerning the cumulated rainfall; at the same time, the future trend seems to agree with the past course until 2007. Worst predictions concern the rainfall distribution during the years 2005-2007. Since the most relevant factor in the prediction is the cumulated rainfall over relatively long time, the influence of a bad prediction in the rainfall distribution is not so serious.
The analysis has been performed by the VADOSE/W code, which accounts for not only the precipitations, but also the temperature and relative humidity which govern the balance of the global infiltration and evaporation phenomena. After a calibration of the code using the data collected in 2005-2007, some statistical adjustments have been made in the future rainfall distribution and satisfactory 1D predictions providing the cumulated landslide displacement until 2060 have been performed (see the specific technical report).

The combination of the climatic effects on rainfall, temperature and humidity tends to favour the evaporative effects and so to reduce the infiltration. As a consequence, the future piezometric levels should undergo a substantially slow reduction (about -4 cm/year). Using the pore pressure-displacement relationship discussed above, the mean velocity should decrease of about 0.02 cm/year. According to this assessment, the cumulated displacement cumulated in the next 50 years should be less than 1 m.

4.4. Considerations about the potentialities and constraints of long-term predictions
A prediction of the effects of climate changes must be based on the following main steps:

- the establishment of future climatologic scenarios;
- a selection of the main factors which influence the slope behaviour;
- the validation of climatic and hydrological models required to evaluate the slope response;
- the implementation of the analysis for well defined and representative climate and geomorphological contexts.

The good knowledge attained regarding the stability of slopes in unsaturated and saturated granular and in fine-grained soils and the availability of reliable numerical codes to predict any change in the pore pressure regime due to weather assure the capability to assess the effects of climate changes on land stability. The main problem today is to establish reliable climate scenarios in the different areas of interest. The cooperation between C.M.C.C. and A.M.R.A. assures the this goal can be attained at the best accounting for the present knowledge. In particular, C.M.C.C. can develop reliable climate scenarios useful to pursue the general goal.
According to the best available long-term climate scenarios for the Mediterranean area of interest in the next century should be characterised by:

- an increase in the average temperature;
- a decrease in the relative humidity;
- a decrease in the yearly cumulated rainfall;

The combination of these climate trends should favour evaporation and so reduce infiltration. These phenomena should in turn cause a reduction in the piezometeric levels and the increase in the stability conditions all over the area investigated. Therefore, the general effects of climate changes should be a general increase in the stability conditions, i.e. a decrease in the hazard (probability of new landslides) and a decrease in the displacement rate of active landslides.
However, the potential increase in the intensity of single storms might cause fast and diffuse shallow landslides in coarse grained soils. The future situation seems more clear for fine-grained deposits, since even in the case of highest rainfall intensity this should not create critical situations, because for low pervious soils the trend in cumulated rainfall is much more important than single events. Therefore, a decrease in the displacement rate of active landslides should be a likely situation, which will determine a decrease in the costs for the maintenance of structures and infrastructures built in such areas.
An improvement of the prediction should look at a better assessment of single events at least in the case of relatively pervious soils; this can be attained only through a refinement of the future scenarios whose weakest feature is the capability to predict the intensity and

duration of the single events. On the other side, the available numerical codes for the evaluation of slope stability appear reliable accounting for the type of prediction which is necessary at the stage of evaluation. As the climatic scenarios will improve, also the hydrogeological approach should improve looking at a better evaluation of geotechnical model regarding the morphological features and stratigraphy of slopes, and the hydraulic proprerties of soils.

5. Concluding remarks

The joint research carried out by C.M.C.C. and A.M.R.A. has been aimed at developing a integrated approach in the prediction of extreme hydrogeological events (landslides) caused by weather and in the assessment of the role of long-term climate changes on land stability.
This activity has been accomplished through:

- a study of the literature and a review of existing numerical codes;
- the execution of tests on model slopes subjected to artificial rains;
- the setting up of a new GIS supported numerical code for infiltration analysis;
- the study of test cases;
- the evaluations of rainfall thresholds in some significant geomorphological scenarios;
- the assessment of potential hydrogeological scenarios for short-term and long-term predictions.

The results of such a complex investigations are reported in some Technical Reports providing a global picture of present knowledge, potentialities and constraints of an integrated meteorological-climatological-hydrogeological approach useful for short-term and long-term predictions of landslide triggering.

6. References

Aleotti, P., Chowdhury, R. (1999). Landslide hazard assessment: summary, review and new perspectives. Bulletin Engineering Geology and Environment, 58: 21-44

Baum, R.L., Savage, W.Z., Godt, J.W. (2002). TRIGRS – a Fortran program for transient rainfall infiltration and grid-based regional slope stability analysis. U.S. Geological Survey Open-File Report 02-0424

Cascini, L., Guida, D., Romanzi, G., Nocera, N., Sorbino, G. (2000). A preliminary model for the landslides of May 1998 in Campania Region. Proc. 2^{nd} Int. Symp. on The Geotechnics of Hard Soils-Soft Rocks, A.Evangelista, L. Picarelli eds., Napoli, 3: 1623-1649

Lampitiello, S. (2004). Resistenza non drenata e suscettività alla liquefazione di ceneri vulcaniche della Regione Campania. PhD Thesis, Seconda Università di Napoli

Olivares, L., Picarelli, L. (2003). Shallow flowslides triggered by intense rainfalls on natural slopes covered by loose unsaturated pyroclastic soils. Géotechnique, 53(2): 283-288

Olivares, L., Picarelli, L. (2006). Modelling of flowslides behaviour for risk mitigation. General Report, Int. Conf. on Physical Modelling in Geotechnics, Hong Kong, 1: 99-113

Olivares, L, Tommasi, P (2008). The role of suction and its changes on stability of steep slopes in unsaturated granular soils. Proc. 10th Int Symp on Landslides, From the Past to the Future, Chen Z, Zhang J, Li Z, Wu F, Ho K eds, Xi'an, 1: 203-215. Taylor&Francis, London

Picarelli, L., Evangelista, A., Rolandi, G., Paone, A., Nicotera, M.V., Olivares, L., Scotto di Santolo, A., Lampitiello, S., Rolandi, M. (2006). Mechanical properties of pyroclastic soils in Campania Region. Invited paper, Proc. 2nd Int. Workshop on Characterisation and Engineering Properties of Natural Soils, Singapore, 4: 2331-2384

Picarelli, L., Versace, P., Olivares, L., Damiano, E. (2009). Prediction of rainfall-induced landslides in unsaturated granular soils for setting up of early warning systems. Invited paper, Proc. 2007 Int. Forum on Landslide Disaster Management, Hong Kong, 1: 643-665

Thornthwaite, C. W. (1946). An approach toward a rational classification of climate. Trans. Am. Geophys. Union, 27(1)