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AMRA:
Final Report 2008

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Abstract:

The report summarises the main results of the research activity directed by AMRA in 2008.

Keywords: rainfall, infiltration test, numerical analysis, threshold, test case

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1. Foreword

In 2008 A.M.R.A. S.c.a.r.l. has directed and managed the research activity concerning the geotechnical part of the general programme jointly established with C.M.C.C. having as goal the prevention and protection against the risk of landslide due to extreme meteorological events.
The main concern of such an activity until now has been the setting up of procedures for the prediction of slope failure in pyroclastic soils based on precipitation forecasting.
All the results of the research carried out in 2008 have been carefully described in some Technical Reports concerning single activities. After a very general framework of the research programme, here the main aspects of single activities constituting the conceptual chain short-time weather forecasting–analysis of rain water infiltration–analysis of slope response until to failure, are briefly summarised and discussed with the aim to highlight some points and address the prosecution and conclusion of the programme.

2. General framework

Rainfall is one of the most important causes of slope failure in the world and is by far the most important one for unsaturated soil deposits. In fact, water infiltration is responsible for increase of the water content and the degree of saturation of soil, leading to increase of the unit weight and decrease of the suction, thus of the cohesion. In particular, the contemporaneous increase of the unit weight and decrease of the cohesion can quickly trigger slope failure, especially in the case of shallow covers on impervious bedrock.
This is a crucial problem within the whole volcanic area around Naples and a much wider area around it, where steep hills and mountains rise, covered by the products of eruptions in the last tens thousands of years (essentially granular pyroclastic soils). 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 but also in depth, everywhere a more pervious layer rests on less pervious soils. Combined with local slope morphology and other soil properties (primarily the friction angle), such transient conditions may lead to slope failure. If crucial factors, such as soil brittleness and slope morphology, present critical values, soil failure may turn into a large and fast landslide with potential severe consequences for people and other exposed elements.
Summing up, there can be a combination or even local factors which may trigger catastrophic events. The probability of these events could increase in the next years because of apparent incoming climatic changes (increasing hazard). On the other side, the tremendous increase in exposure occurred in the last tens of years, especially after the Second World War (increase of population, of infrastructures and of economic activities), makes the risk of landslide higher and higher because of the combination of a constant, or even slightly increasing hazard, and of the dramatic increase in exposure and vulnerability.

This is what is happening in Campania, which in the last eleven years has been hit by eleven killer events[1] (and by a much higher number of large and fast landslides) which caused the loss of about 180 lives.
This situation requires an extraordinary societal effort aimed at a general increase of the knowledge about the causes and mechanisms of such events, at the dissemination of such a knowledge and the improvement of available instruments for risk mitigation.
The research programme jointly proposed by C.M.C.C. and A.M.R.A. has this goal, looking at the short-term prediction of landslides and the consequent setting-up of alert systems as an important tool for timely landslide prediction.
The main lines of the research in 2008 have been:

a) the simulation by physical modelling of the slope behaviour during infiltration;
b) the simulation of the slope behaviour in typical geomorphological scenarios, based on the implementation of a numerical code;
c) the analysis of some test cases.

Physical modelling (point a) has the goal to check and clarify the mechanisms of landslide triggering due to rainfall, through the understanding of the effects of infiltration on the state of stress and of the role played by single factors. The activity b) has a similar but more advanced role. In fact, just based on experiments (point a), a reliable model of soil behaviour may be validated and under concerned assumption about the factors which govern the slope behaviour, the consequences on the land of given inputs (rainfall) may be investigated and extended to different geomorhopological, physical and mechanical scenarios. Finally, the activity c) has the double goal to check if the understanding reached through previous investigations applies to test cases (real cases histories), and to evaluate if the numerical instruments which are being tested could have predict such events.

3. Simulation of slope behaviour though physical modelling

Physical models can greatly help in the understanding of complex mechanical phenomena, especially when site monitoring cannot apply. Monitoring is extremely useful in the case of the most landslides in fine-grained soils whose pre-failure and post-failure behaviour can be easily recognized and investigated in depth, because they are slow enough to allow a proper installation of instruments and the consequent recording of the main factors (pore pressures, displacements) which govern and reveal the slope behaviour. As a matter of fact, the present knowledge about triggering and evolution of landslides in fine-grained soils is mostly based on the interpretation of in-situ monitoring and consequent theoretical development and numerical analysis.
The use of monitoring as a powerful tool for the development of the knowledge and the setting up of new theories is not possible in the case of landslides in rocks and in coarse-grained soils, because failure is generally sudden and post-failure movements very short and fast. In such cases, physical modelling can be highly beneficial in spite of its intrinsic limits due to the small scale of the model and the difficulty in reproducing local inhomogeneities in soil structure and properties.

[1] Pozzano and Nocera Inferiore in 1997; Sarno, Quindici, Bracigliano, Siano and San Felice a Cancello in 1998; Cervinara and San Martino Valle Caudina in 1999; Nocera Inferiore in 2004 and Ischia in 2005

For this reason several experiments have been carried out. Such experiments have been described in the Technical Report “Laboratory experiments on the response of model slopes subjected to rainfall”, concerning the behaviour of uniform or layered slopes with angles ranging between 0 and 40°. Due to its relatively small thickness (generally 10 cm) compared to length (110 cm), the model slope can be considered “infinite” according to the geotechnical meaning, i.e. characterized by a uniform state of stress along any plane parallel to the ground surface. The soil adopted in the experiments is air-fall volcanic ash taken from two different sites (Cervinara and Monteforte Irpino).
Two series of experiments have been carried out:

a) a number of tests on a uniform 10 cm thick 40° model slope resting on impervious surface, which has been led to failure;
b) some tests on a 20 cm thick model slope, consisting of two ash layers with an embedded pumice layer, laid down on a pervious surface; in this case the slope angle has been gradually increased from 0 to 40°, but failure has not been attained.

In the first case, the slope has been subjected to constant rainfall (around 50 mm/h). In the second case, alternating phases of rainfall and evaporation have been imposed.
The detailed results of the experiments are reported in the above mentioned technical report. Some very general considerations suggested by such experiments are reported in the following:

1) the complex atmosphere-slope interaction and the slope response to water infiltration can be successfully investigated through physical modelling, revealing highly beneficial for the understanding of the deformation-failure processes of natural slopes;
2) even though the real slope response depends on a number factors which have not been completely investigated, such as its morphology (an example is the role of water pondings which may form on the ground surface in non-sloping zones), structure (continuity, location and thickness of different soil layers), boundary conditions (f.i. pervious or impervious bedrock), soil properties (water retention curve, permeability function, stiffness and strength) and features of rainfall (continuity, duration and intensity), the experiments provide a lot of information which are very useful for the setting up of numerical modelling;
3) based on the results of experiments, the numerical tools which are today available for the analysis of infiltration and consequent slope failure, appear rather sound: as usual, the major problem is in the selection of the appropriate parameters for their implementation;
4) depending on different factors such soil thickness, layering and permeability of the base, in most cases infiltration causes a progressive increase in the water content from the top of the layer to its bottom (essentially 1D infiltration), whose rate depends on the permeability function of soil, in turn depending on void ratio; intermediate layers can either accelerate either slow down the saturation of the lowermost part of the slope: in particular, experience shows that embedded unsaturated pumices slow down the process;
5) the presence of a pervious bedrock may strongly govern the seepage process and is more favourable to slope stability than the presence of an impervious bedrock;

6) suction decrease is rapid in the very first phase of infiltration, then it proceeds rather slowly; therefore very steep slopes or slopes consisting of relatively poor soils (i.e. slopes characterised by a low initial safety factor) or even including less pervious layers (which favour the development of flow parallel to the slope), may fail early; if the slope does not fail in the first stage of infiltration, it can remain stable for a relatively long while;
7) rainfall intensity seems to play an important role, more than expected: for low 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 covers; however, in the case of impervious bedrock located at a relatively small depth, saturation can start when the humid front reaches the bedrock, prosecuting from the base of the layer upward, until to failure of the entire cover; an important issue is the degree of saturation of soil at failure (which affects the potential of liquefaction), since full saturation of the entire cover could be most dangerous than saturation of the lowermost part only;
8) high rainfall intensity tends to saturate very soon the shallowest layers causing their premature failure.

4. Scenarios of rainfall-induced lanslides

The numerical analysis had the role to provide a general framework of the response to rainfall of sloping unsaturated granular pyroclastic soils through a theoretical model of slope behaviour which has been validated by comparison with laboratory experiments.
The slope behaviour has been investigated by a set of analyses based on a simplified, but realistic assumption about the morphology of the slope. As a matter of fact, only the case of infinite slope consisting of a thin cover resting on either pervious or impervious bedrock has been investigated. This simple model is consistent with reality. As a matter of fact, typical geomorphological situations in Campania consist of thin and long covers of pyroclastic soil presenting a relatively constant thickness over the most of their length, deposited on fractured limestone (pervious bedrock) or altered ash, tuff or clay (impervious bedrock). The slope angles adopted in the analysis range between 20° and 45°, which reproduce the majority of real situations.
In almost all analyses the cover has been considered uniform, with a thickness comprised between 0.5 and 4 m, but a single case of non-uniform deposit including a pumice layer interbedded between two ash layers has been investigated as well. Soil properties have been taken from available files concerning such materials. In particular, two different soils have been considered: a relatively pervious ash representative of the phlaegrean zone (West to Naples), and a relatively impervious ash, representative of a wide area located to East to Naples, which is mantled by air-fall soils and has been the geological context of occurrence of the most destructive landslides in the last fifty years. It is worth to mention that in each area volcanic ashes present rather uniform characteristics (Picarelli et al., 2008).
Selection of the initial conditions is the most delicate phase of the analysis. Since the principal scope of the investigation is the drawing of a general scenario of slope response, special cases have been neglected, and initial steady-state conditions have been considered. In particular, a uniform suction has been assumed at the ground surface. The

selected values of suction correspond to different rainfall histories and initial values of the safety factor, the lowest value (19 kPa) being more or less representative of the beginning of the wet season, the highest one (95 kPa) representing a hypothetical peak in the dry season. Moreover, constant precipitation has been considered in the analysis, with values of the intensity comprised between about 1 mm/h and 100 mm/h.
The computations have been conducted by means of the numerical code SEEP, under 2D conditions.
A detailed description of all considered cases is reported in the Technical Report A3D1: “Numerical analyses on the response of slopes subjected to rainfall - Typical geomorphological scenarios in Campania Region”. They cover a number of typical situations and inputs, providing useful information on the slope response and behaviour.
In order to calibrate the results of the analyses with available data, empirical values of the time to failure for different rainfall intensities based on data concerning recent landslides (Guadagno, 1991; Calcaterra et al., 2000), have been compared to calculated values.
The trends are similar. However, it has to be stressed that the number of factors which are ignored by the empirical thresholds is too high and some of them too significant to be neglected. In fact, the thickness and the permeability function of the cover strongly affects the time to failure since both control the rate of suction decrease, especially at the base of the slope. The absence of any consideration about soil strength, especially cohesion, is another serious lack of empirical thresholds; finally, initial conditions, i.e. the recent rainfall history, play a role which cannot absolutely be neglected. Naturally, in relatively uniform areas (in terms of geomporphological slope features) and for given periods of the year, empirical thresholds could anyway work quite well.
For all these reasons, a general virtual framework about the features of the precipitations which could trigger a landslide in different scenarios can be obtained only based on numerical analyses. Besides providing thresholds associated with given precipitations and given initial conditions, the performed analyses offer further important elements about the evolution of the state of soil during the pre-failure stage (changes in void ratio, permeability and cohesion) and about the mechanisms of infiltration and rupture. Other significant information contained in the technical report can be summarised as follows:

1) the permeability function, which is not so frequently measured in the laboratory, 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 (as shown by Olivares and Tommasi, 2008, flume tests enable to obtain a correct characteristic curve, which appears different from the one provided by lab tests, then a better assessment of the associated permeability function);
2) as discussed before, prediction cannot neglect a number of hydraulic and mechanical factors as well as data about morphology, initial and boundary conditions, which strongly affect the slope response, thus it is a very complex and heavy task;
3) the presence of an impervious bedrock is a unfavourable factor for stability because it leads to the establishment a 2D flow parallel to the base of the cover following formation of water ponding; the opposite occurs for pervious bedrock which favours the development of a 1D vertical flow: this is confirmed by both flume tests discussed above and by data from site investigations (Picarelli et al., 2008);
4) 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, 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.

The last consideration is very important since in these two cases the risk is very different. For shallow landslides it 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 general failure of the entire cover after full saturation (deep landslides) the risk is higher, because of the sudden triggering of a large landslide. In addition, as a consequence of saturation the cover may liquefy, giving rise to fast movement.

5. Test cases

The analysis of test cases concerns three events (two events 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: such an analysis has been carried out by the GIS supported numerical code TRIGRS (Baum et al., 2002). The second procedure concerns a “local” analysis, just limited to the failed slope, for which the 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 large catastrophic event occurred in 2005 killing three people. Both sites are mantled by pyroclastic soils, the Camaldoli hill being covered by phlaegrean ash, the Nocera Inferiore area by air-fall vesuvian ash. Such materials, which have been assumed to be uniform along the slope and in depth, are relatively well known, thus the hydraulic and mechanical soil characterization adopted in the analyses can be considered reliable. Rainfall history up to the onset of slope failure is known, because in both sites rainfall gauges are located not far from the concerned sites. However, a simulation of the presumable precipitations fallen at the time of failure just on the investigated slopes has been carried out using the COSMO-LM code, which covers a grid 2.8 km long. Such analysis has been carried to check if weather forecasting can support criteria for prediction of the landslide behaviour.
The first type of analysis, which has been carried out under 1D seepage conditions, required several hypotheses about unknown parameters such as the exact depth of the bedrock all over the examined area, the initial conditions and the distribution in depth of pore pressures. Hence, the analysis must be considered only as a first attempt to check if correct predictions can be made on macroareas helping in the activation of emergency plans, and to recognize the limits of such analyses.
The results obtained for the Camaldoli site confirm the crucial role of some parameters (as the initial suction profiles and the depth of the bedrock) which cannot be ignored, but require a precise assessment for a correct prediction. 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 other test case, concerning the Nocera Inferiore landslide.
The same events have been investigated through “local” analyses. Initial suction one month before the events has been estimated. The corresponding pore pressure profiles come from the hypothesis of steady-state conditions. Measured rainfalls in the month before the landslide events as well as those which could have been predicted through the COSMO-LM programme were used as input data. In fact, such in data enabled to compute the consequent variations in suction and their effects on slope stability.
Following this approach and performing 2D analyses for infiltration, 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. It is likely that the real landslide was caused by the interaction (due to undrained loading or progressive failure) between the part of the slope which failed first (the one located upslope), and the part which, following the analysis, appears stable (located downslope). It is worth mentioning that 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 concern several other aspects of the analysis, as the differences between the results obtained with 1D and 2D analyses, the role of the permeability of the bedrock and especially the one 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 considered volcanic ash.

6. Summary and conclusions

The research carried out in 2008 under the direction of A.M.R.A. s.c.a.r.l. shows that a sound link can be established between rainfall forecasting and prediction of the effects of rainfall on slope stability. In fact, data provided by meteorological forecasting can greatly help in the short-term prediction of landslides, especially of those events which, for their magnitude and velocity, can be responsible for destruction and loss of lives.
The “geotechnical side” of the research concerned the development of a complete understanding and modelling of slope response to rain water infiltration based on: i) the interpretation of the physical and mechanical effects of infiltration; ii) the analysis of the possible scenarios of rainfall-induced landslides through simple numerical models; iii) the extension to real cases of the numerical models for the analysis of the slope response to given precipitations. This last approach includes “regional analyses” using GIS based 1D models and local analyses using 2D models.
The slope response to rain infiltration is now quite clear based on a number of flume tests on model slopes, and the extension to such a understanding to typical geomorphological scenarios is quite easy and reliable. Naturally, the application to real cases is not always satisfying because of problems associated with the complex slope response due to the variability of soil structure and properties, and to local inhomogeneities in morphology,

initial conditions and rain features. In spite of such problems the adopted procedure appears encouraging.

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