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MOVEMENTS IN A TECTONIZED SOIL SLOPE: COMPARISON OF MONITORING DATA AND MODELLING RESULTS

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ABSTRACT

The slope deformation processes described in the paper, define a typical example of unstable behaviour for a tectonically active chain area in Italy, where slopes are formed of highly tectonized soils and rocks. Monitoring data compared to numerical modelling results show the existence of two interconnected mechanisms of deformation in the slope: a fast shallow mechanism (slump-earthflow) and a deeper and slower deformation process (deep-seated creep). This mechanism is fundamentally due to the poor mechanical properties of the deep soils, which are at yield and therefore undergo significant plastic deformations for even limited changes in loading.

INTRODUCTION

The present paper discusses the mechanisms of deformation active in an unstable slope, the Vadoncello slope, located beneath the town of Senerchia (Figure 1) in the upper Sele River Valley (southern Apennines, Italy), where the epicentre of the November 1980 earthquake (M_s=6.9) occurred. The deformation behaviour of this slope exemplifies that of many others in the area. The soils in the slope are highly tectonized, being crossed by both shear surfaces and discontinuities, and they include intensely fissured clay shales and scaly clays, the latters being formed of millimetric hard scales (Esu 1977; D'Elia et al. 1999). In particular, the allochthonous Variegated Clay Formation, which outcrops on the slope (Figure 1), includes grey-green scaly clays, varicoloured scaly clays, fractured marls, marly limestones and sandstones.

A landslide was activated on the Vadoncello slope on 29 December 1993. At its toe there is the Serra dell'Acquara landslide, a 2.5 km long slump-earthflow, which is quiescent at present but was mobilized by the 1980 earthquake, when also a subsidiary landslide was activated in the lower part of the Vadoncello slope (Cotecchia et al. 1986). No significant displacements have been observed on these slopes since the end of 1980 till December 1993, except for some slow retrogression of the rear scarp of the 1980 Vadoncello subsidiary landslide. The 1993 landslide developed as a slump at the top of the slope, with crown behind the 1980 rear scarp, and an earthflow downslope (Figure 1). Since this event ground movements have been active on the slope, which define a mechanism of deformation reconstructed by means of monitoring data compared to numerical modelling results, as discussed in the following.

GEOLOGICAL MODEL OF THE VADONCELLO SLOPE

In situ investigation and monitoring of the Vadoncello slope was financed by the European Community within a research project lasting from December 1994 to the end of 1996 (EEC Project Report 1996). The location of the continuous coring boreholes, which were drilled on the slope and equipped with either inclinometers (I) or piezometers (P), is shown in Figure 1. Topographic displacements were monitored by means of both topographic and GPS surveying (EEC Report 1996).

The schematic lithological section of the slope is shown in Figure 2; the section line is drawn in Figure 1. The figure also reports the changes in slope profile since 1981 till summer 1995, showing the effects of the important 1993 event and of the significant landslide activity during 1995. This activity has caused the collapse of the back wall of a house sitting on the top of slope, as shown in the figure. Defined alternations

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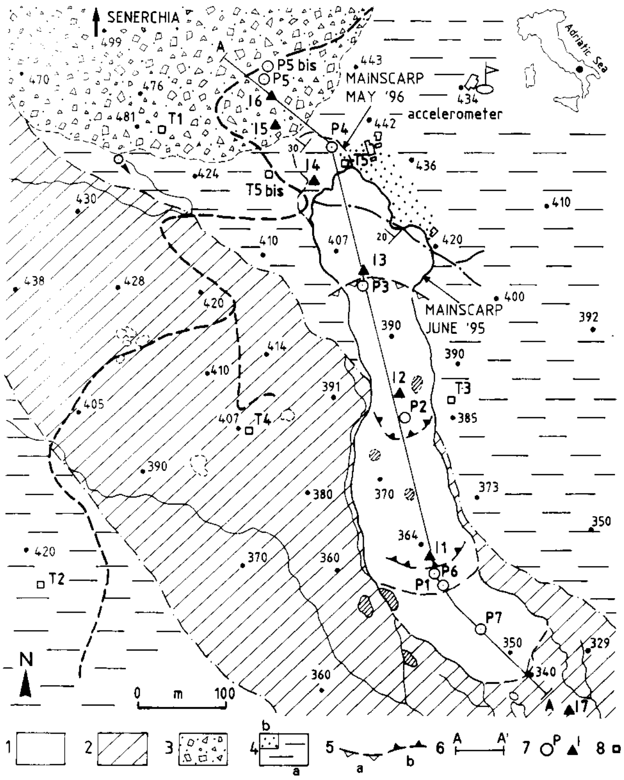

Figure 1: Geomorphological map of the slope - 1, 1993-‘95 Vadoncello landslide; 2, Serra dell’Acquara earthflow; 3, debris slab; 4, a) Variegated Clay Formation, b) calcareous detritus; 5, a) 1980 crown, b) internal toes; 6, line of section in Figure 2; 7, piezometers (P) and inclinometers (I); 8, topographic control stations (after EEC Report 1996, modified).

and/or successions of strata are distinguished as soil complexes, which are described in the figure and discussed in detail by Santaloia et al. (1999).

Complex G represents the earthflow debris of the 1993 to 1995 landslide events. Although the degree of remoulding of the soils in this complex is less intense below 6-7 m depth, the soils at depth are still significantly disturbed and neither a bedrock nor a shear surface defines the base of this complex. Complex H is the 1980 Vadoncello landslide debris and complex I is the debris of the 1980 Serra dell’Acquara landslide. The soils not subject to dislocation, the «in-situ» soils, have been distinguished into complexes A to F, generally part of the Variegated Clay Formation, except for complex A, that is part of a calcareous debris slab which also underlies the town of Senerchia. The set-up of the strata in complexes B to F is chaotic. Fractured and discontinuous lapideous strata merge with marls and scaly clays, which can be as disturbed as the landslide soils of complexes G to I. On the whole the in-situ complexes seem to be verging up-slope.

MONITORING DATA

The displacement rates monitored at the surface on the Vadoncello slope were similar within each of the three areas distinguished in Figure 3, that are the source area A, the earthflow channel (area B) and the earthflow accumulation zone with the toe of the slope (area C). In the figure the displacement rates and directions are shown for each of these areas in the periods of maximum landslide activity within 1995. It appears that the fastest displacements have occurred in the earthflow channel; the second fastest displacements have been in the source area and defined a retrogressive slipping mechanism.

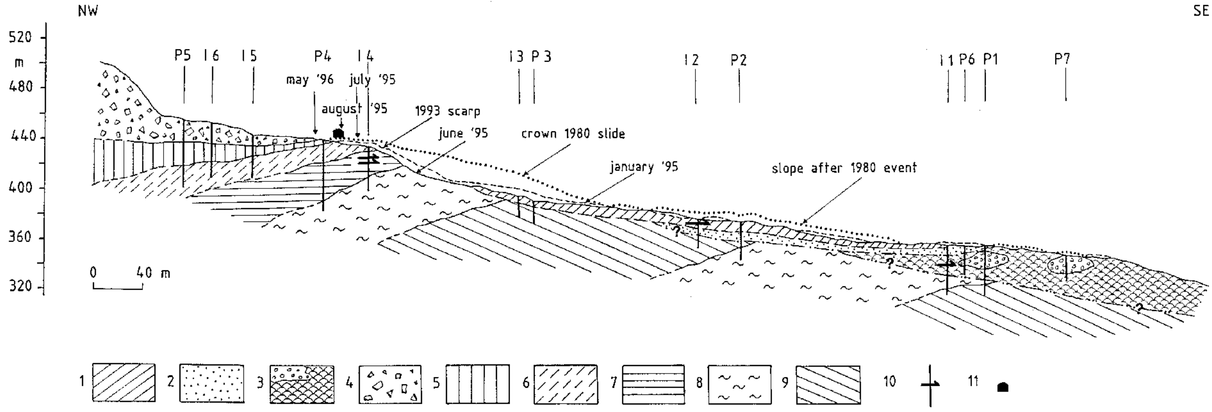

Figure 2 : Cross section A-A’ of Vadoncello slope - 1, Complex G; 2, Complex H; 3, Complex I with calcareous blocks floating in it; 4, Complex A; 5, Complex B: scaly marly clays with interbedding marls and marly limestone; 6, Complex C: scaly clays with marls and siltstone strata; 7, Complex D: scaly clays with calcareous marls; 8, Complex E: clays, marly clays, marls, marly limestones and silty sandstones; 9, Complex F: scaly clays with marly strata and siltstone layers; 10, depth of shear of inclinometer; 11, house.

In area C the displacements have been much smaller, though still significant, even in the part of the area overlapping the Serra dell'Acquara landslide body. In addition, here the displacements have direction equal to the main direction of the Serra dell'Acquara slope, in contrast to the North-South direction of the displacements in the other areas. The Serra dell'Acquara landslide itself has been moving at rates between 0.003 and 0.05 m/month (see point T4, Figure 3). These data give evidence to the two fast shallow failure mechanisms on the slope, a rotational slipping at the rear scarp and earthflowing downslope, and to a much slower mechanism of deformation affecting the soils at the toe, in continuity with the Serra dell'Acquara landslide soils (Santaloia et al. 1999).

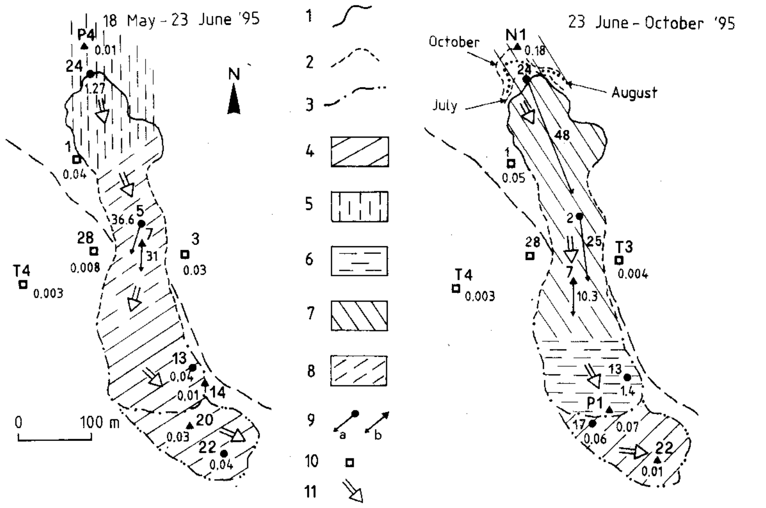

Figure 3: Horizontal displacement rates (m/month) - 1, area A; 2, area B; 3, area C; 4, 0.02÷0.2; 5, 0.2÷0.4; 6, 0.4÷10; 7, 10÷20; 7, > 20; 8, max. (a) and min. (b) rates; 9, other topographic control stations; 10, displacement directions; 11, Serra dell'Acquara earthflow.

Inclinometers I2 and I3 in the channel area were soon broken at shallow depths due to the very fast shallow soil displacements. On the contrary both inclinometer I4 at the top and I1 at the toe of the slope revealed the existence of deeper and slower movements. Significant relative displacements were logged at 15 m depth in I4 and 16-17 m depth in I1; in the latter inclinometer tube also some relative displacement was logged at 24 m depth. The depths of final shear failure for these two inclinometers are shown in Figure 2. These data suggest that the fast shallow mechanisms of deformation on the slope overlie a deeper and slower deformation process, which is likely to be connected to the deformations of the Serra dell'Acquara landslide soils. These slow displacements occur below the earthflow body (complex G) and downslope its toe. Thus the morphological evolution of the Vadoncello slope takes place as superimposition of fast, shallow and large deformations onto deep slow deformations spreading outside the Vadoncello slope itself. This slow mechanism of deformation is classified as a deep-seated creep by Santaloia et al. (1999).

Santaloia et al. report the existence of both a shallow and a deep hydrogeological complexes in the slope. The shallow one occurs within the most disturbed earthflow soils and includes a non-steady flow, with base about 7-9 m depth below ground level. In the second one there is a steady flow relating to a water table between 12.8 and 15 m below ground level, which has never been significantly affected by the rainfall events in the monitoring period, in contrast to the piezometric levels of the top hydrogeological complex. Thus only the pore water pressures in the earthflow soils are affected by rainfalls, which have probably contributed directly to the shallow displacements in 1995. The deep displacements instead are probably kept active by the intermittent loading due to the seismic activity in the area and the changes in soil weight at shallow depths consequent to rainfall infiltration. In addition, the changes in morphology resulting from these deep displacements can in turn reactivate the deep displacements and have negative effects on the stability of the slope. The origin of these deep displacements is further investigation later.

The study of the cumulative daily rainfalls before December 1993 (Santaloia et al. 1998 and 1999) has shown that these were of very low return period, less than 10 years. Therefore rainfalls could not be the fundamental cause of the 1993 landslide event, although they added to the negative effects on the slope stability of the slow changes in morphology resulting from the deep-seated creep.

SOIL PROPERTIES AND GEOTECHNICAL MODEL

The in-situ clayey soils, parts of complexes B to F (Figure 2) are generally of high plasticity and no difference has been recognized between the index properties of the in-situ and the landslide soils (complexes G to I; EEC Report 1996; Santaloia et al. 1999).

Oedometer compression curves are shown in Figure 4 for high depth undisturbed scaly clay samples from complexes B and C and for the same soils reconstituted in the laboratory. The location of the undisturbed soil compression curves in the e-σ_v' plane, to the left of the reconstituted normal compression curves, is indicative of a highly disturbed structure for the natural soils. These appear to have gross yield states to the left of the normal compression curve. Therefore the natural scaly clay is weaker than the reconstituted clay, which has larger state boundary surface (Santaloia et al. 1999). The weakness of the natural soil is the result of the severe disturbance that it has undergone in its geological history due to tectonics and past landsliding.

Triaxial (EEC Report 1996; Fearon 1998) and direct shear tests (Santaloia et al. 1999) have confirmed the very poor strength properties of the scaly clays in the slope, as also found by other authors for other scaly clays (Guerriero et al.1995; Picarelli and Olivares 1998). Specimens consolidated to states about gross yield before shear exhibit a contractant behaviour, in contrast to the dilative behaviour exhibited by highly overconsolidated specimens, as generally is the case for either reconstituted clays and sensitive natural clays (Burland 1990; Cotecchia and Chandler 1997). Dilation in shear has been observed for the shallow samples consolidated to their in-situ stresses. These exhibit peak friction angles between 20° and 30°, if c'=0. Deep samples consolidated to the in-situ stresses are contractant and exhibit maximum strength at large shear strains, when reaching a “pseudo-critical state”, characterized by both zero volumetric strain and strength increment and very low friction angles, generally in the range 13°-20°. Therefore, the mechanical properties of the clayey soils are seen to be very poor and not to improve with depth. These soils are likely to be at gross yield and subject to plastic flow as result of even limited shear load increments, which may cause large plastic straining even at significant depths in the slope. Thus the mechanics of the in-situ soils is seen as a critical inherent cause of the instability of the Vadoncello slope and seems to be consistent with the hypothesis of a deep-seated creep in the slope.

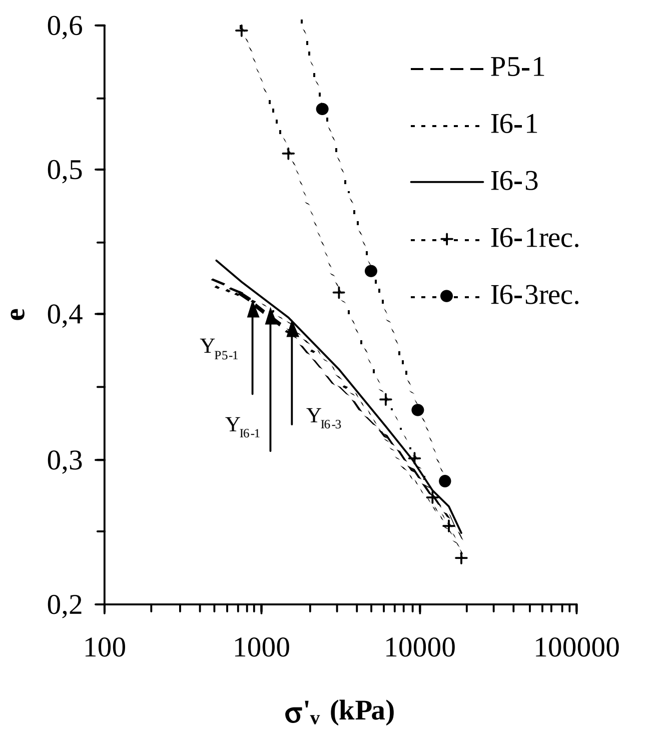

Figure 4: Natural and reconstituted samples: oedometer test results.

A geotechnical model of the slope in 1995 is shown in Figure 5, which implements all the soil complexes in Figure 2 and distinguishes dilative and contractant zones for each of them. The model soils are characterized by Mohr-Coulomb effective strength parameters, which are c'=0 and $\phi'=\phi'_{cs}$ in the contractant zones. In the dilative zones curved peak strength envelopes are used, with $c'$and ϕ' values in the ranges reported in the figure. Also shown in the figure are the water tables of the two hydrogeological complexes.

MODELLING RESULTS

The behaviour of the Vadoncello slope has been modelled making use of the geotechnical model in Figure 5 extended upslope of about 500 m, and by means of the finite difference numerical code FLAC 3.30. All the soils have been assumed to have linear elastic-plastic behaviour with Mohr-Coulomb yield locus and strain softening post-yield. The yield loci used are defined by the c'-ϕ' parameters in Figure 5, yield being reached at about 10% shear strain. Post-yield the soils have been modelled to strain soften to a final yield locus defined by the residual strength parameters c′=0 and ϕ'_r=5.5° (ring shear test results, Fearon 1998). The residual state is assumed to be reached at 50% shear strain.

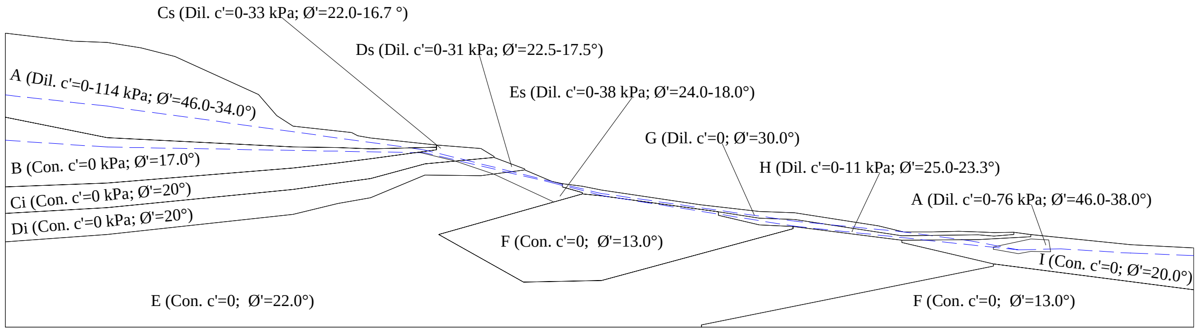

Figure 5 : Geotechnical model of Vadoncello slope; Dil.=dilative; Con.=contractant.

Seepage has been assumed to occur within two separate hydrogeological complexes with water tables as shown in Figure 5. For comparison, the slope behaviour has been modelled also assuming saturation, but zero pore water pressures. In a first stage the movements normal to all the boundaries have been locked, whereas the movements parallel to the boundaries have been left free. In a second stage the vertical boundary at the toe of the slope has been assumed to translate horizontally of 0.60 m over the whole integration time, in order to simulate the displacements of the Serra dell’Acquara landslide.

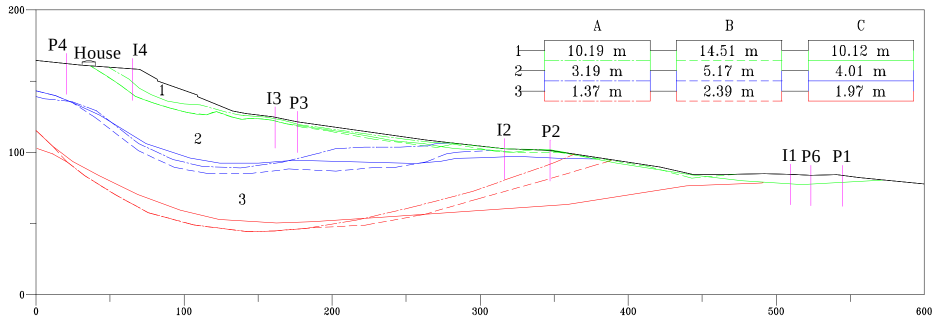

Figure 6 : Results of the numerical analysis - Areas of quasi-uniform displacement modulus (Case A: No seepage-No toe translation; B: Seepage-No toe translation; C: Seepage-Toe translation).

The numerical results are shown in Figure 6 as contours of areas (1, 2, 3) of quasi-uniform displacement modulus (average moduli in the figure) for the case of no seepage, seepage but no toe translation and seepage with toe translation.

In Figure 7 the displacement vectors are reported for the case of absence of both seepage and movement at the toe; the directions of the displacements are similar in the three cases examined in Figure 6. In all the cases the displacements give rise to a rotational slump at the top of the slope and to a translational landslide downslope, which resembles an earthflow. The depths of both the top slump (25 m maximum depth) and the earthflow (7-10 m maximum depth) are similar in both the cases with seepage. The displacements in the bottom area (3) differ of about an order of magnitude from those in the top area (1). However, the deep displacements are still significant and indicate that the deep soils are involved in a slow mechanism of deformation.

The mechanisms of deformation defined above take place both if seepage is present and if not. Therefore they are fundamentally due to the poor mechanical properties of the materials. However, both the shape and the size of the areas of uniform displacement differ between the case of presence and absence of seepage. The deep

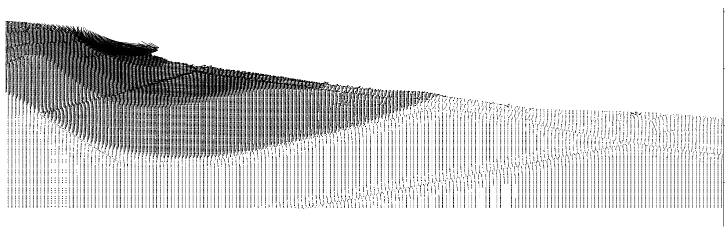

Figure 7 : Numerical analysis results - Displacement vectors

displacements configure a rotational type of mechanism of deformation, which is more extended horizontally when seepage is present. In addition the presence of seepage makes the earthflow deeper and moves its toe downslope; as such the results with seepage are closer to what observed in situ. When seepage is present, the rotational slump at the top of the slope has rear scarp crossing the edge of the house previously mentioned. Therefore it appears that both the rotational slipping and the earthflow observed in situ are simulated quite well by the numerical results in the case of seepage, both if horizontal movement of the toe of the slope is allowed for and if not. However, the numerical results in the presence of seepage but no horizontal movement at the toe boundary, do not configure the deep deformations at the toe which caused the failure of inclinometer I1. This deformation process takes place only once the toe boundary is moved horizontally (Figure 6). This movement makes the deep areas of displacement, 2 and 3, shallower and further extended downslope, and also makes the earthflow toe move further downslope. In particular, at the toe of the slope the calculated displacements are such as to shear inclinometer I1 at about 10 m depth, which is quite consistent with what observed in situ.

CONCLUSION

The numerical modelling of the slope behaviour with FLAC 3.30 appears to confirm that the mechanical properties of the soils in the Vadoncello slope, combined with the slope morphology, are such that deep soil elements are at yield and can undergo significant plastic deformations for even limited changes in loading. This condition makes the slope prone to failure, with the fastest failure mechanism being confined at shallow depths and being the combination of a rotational slump at the top of the slope and an earthflow downslope. The presence of seepage extends the failure mechanisms downslope. However, these involve the toe of the slope at depth, as observed in inclinometer I1, only if the movement of the Serra dell’Acquara landslide is allowed for. Thus the FLAC numerical application appears to have been successful in simulating the qualitative features of the complex slope failure of the Vadoncello slope.

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