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Twenty-year monitoring of the Orvieto overconsolidated clayey slope (Italy)

Vingt ans de monitorage des talus argileux surconsolidées de Orvieto (Italie)

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ABSTRACT

In addition to landslides of different types and extent, the clayey slope of the Orvieto hill is affected by extremely slow movements at relatively high depths (up to 33 m) and by very slow movements at shallower depths (up to 10 m). These movements are strictly related to rainfall regimes and to the consequent pore pressure distribution inside the hill. The influence of rainfall regimes on the hydraulic conditions and movement rates was reconstructed by means of piezometric and inclinometric measurements performed over the last twenty years.

RÉSUMÉ

Autre que par des glissements de différents type et extension, les talus argileux sous-jacents la falaise pyroclastique de Orvieto sont affectés par des mouvements soit extrêmement lents à une profondeur relativement elevée (jusqu'à 33 m), soit lents à plus faible profondeur (jusqu'à 10 m). Les mouvements sont strictement relatés aux variations des pressions interstitielles dans le talus et par conséquent aux régime des pluies. L'influence des précipitations sur les conditions hydrauliques et sur la vitesse des déplacements a été reconstruite à l'aide des mesures piézométriques et inclinométriques éffectuées dans les derniers vingt ans.

1 INTRODCUTION

Natural slopes in overconsolidated clays are often affected by slow movements occurring along pre-existing slip-surfaces.

Movements involve buildings and infrastructure rising on the clay slope and may accelerate, leading to even generalized failure when human activities alter pore pressure and/or stress conditions.

At Orvieto, similarly to many other ancient towns of Central Italy built on top of soft rock slabs overlying clayey formations, movements in the clay slope also influence the stability of the margins of the slab. Relentless deformation of the clay at the cliff foot induces severe tensile and shear stresses in the margins of the slab which lead to fracturing and eventually to failure.

Even though many authors have shown that slow movements are controlled by pore pressure variations and in turn by the rainfall regime, detailed insights into the relationships between these parameters have rarely appeared in the geotechnical literature. This paper offers a contribution based on twenty years of monitoring of the northern slope of the Orvieto Hill, which is part of a wider research on the geotechnical problems of this ancient town.

2 THE NORTHERN SLOPE OF THE ORVIETO HILL

Orvieto is built on top of a pyroclastic slab, delimited by subvertical cliffs, that overlies an overconsolidated clayey substratum. Between the two formations a high permeability layer is interposed which hosts a permanent perched groundwater (Albornoz formation).

The northern slope of the Orvieto hill is represented in Figure 1. Investigations have been carried out partly inside the area involved in the huge 1900 Porta Cassia slide and partly in an outer zone adjoining the western flank of the slide. The slope extends over a length of 500-600 m between 220 and 120 m a.s.l. with an overall dip of 11°-12°.

2.1 *Geotechnical stratigraphy of the slope*

Borehole logs and excavations have indicated that the same succession of slope materials characterizes the entire investigated area. Local variations in the thickness of the different slope materials have been produced by the repeated landslides that have occurred at different elevations in the course of time. A typical stratigraphic and geotechnical log is shown in Figure 2.

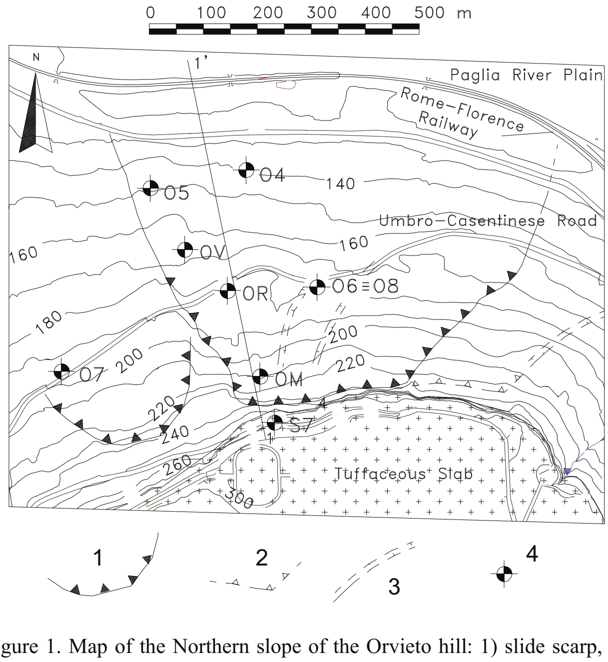

Figure 1. Map of the Northern slope of the Orvieto hill: 1) slide scarp, 2) limit of the area affected by minor deformations of the 1900 Porta Cassia slide, 3) limit of kinematically independent portions inside the 1900 Porta Cassia slide body, 4) instrumented borehole.

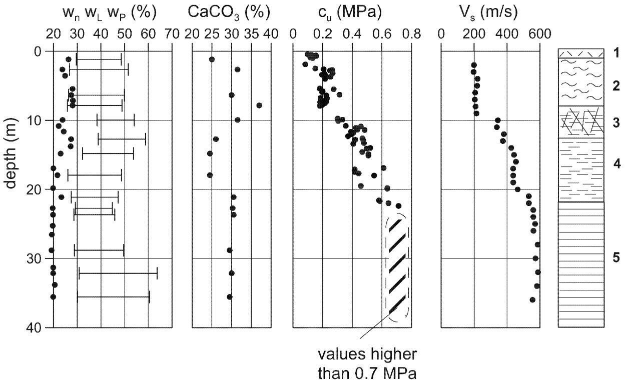

Figure 2. Typical log of the physical-mechanical properties of the slope materials (borehole O6): 1) slide debris (volcanic and clayey material), 2) slide debris (clayey material), 3) softened, fissured and jointed clay, 4) softened clay, 5) intact stiff clay.

The *in situ* clay formation is a clay and silt of medium plasticity, with an appreciable carbonate content. At depth the clay is stiff, intact and highly overconsolidated without a well-defined preconsolidation pressure. In fact, oedometer compression curves do not display any apparent drop up to vertical pressures of some 10 MPa. On the basis of its undrained strength (higher than 1 MPa at the depth of 35 m), the material can be defined as a "hard clay" (Skempton and Hutchinson, 1969).

The clay progressively softens and becomes fissured proceeding upwards, even if mechanical properties remain significantly high. At the top, the clay formation is jointed, and weathering is revealed by the oxidation of fissures and joints and also of the clay matrix.

The *in situ* clay formation is covered by slide debris consisting of remoulded clay mixed with volcanic material belonging to the tuffaceous slab.

In situ permeability was evaluated by means of falling head tests in Casagrande piezometers installed in the different clayey materials. Values of the magnitude of 10^{-11}, 10^{-10} and 10^{-9} m/s were obtained for the stiff clay, the softened clay and the slide debris, respectively.

2.2 *Instability phenomena*

Archaeological, historic and archival evidence indicates that landslides have occurred on the clayey slope since historical times (Tommasi et al, 1996).

In the 20th century, at least three failure phenomena affected the clayey slope: the huge 1900 Porta Cassia slide on the northern slope (Vinassa de Regny, 1904), having a width of some 600 m, and the 1900 and 1979 Cannicella slides on the southern slope (Manfredini et al., 1980, Tommasi et al., 1996). In two cases (the Porta Cassia and the 1979 Cannicella slides) human activities seem to have accelerated the phenomena of progressive failure of the clayey slope.

The 1900 Porta Cassia slide occurred 35 years after the completion of the Rome-Florence railway which required the excavation of discontinuous cuts not exceeding 4 m in height. These cuts may have re-activated the shallower slides at the foot of the slope which subsequently induced delayed failure in the upper part of the slope, possibly with a progressive mechanism.

At present, inclinometric measurements indicate that extremely slow movements are continuously displacing the lower two-thirds of the clay slope. Displacements occur along shear surfaces located within the softened portion of the in situ clay formation (see, e.g., slip surfaces α and β in Fig. 3).

Shallower movements, characterized by significantly higher displacement rates, develop at the contact between the clayey slide debris and the *in situ* clay formation. These movements are found to produce long-term slope deformations which can seriously damage buildings and infrastructure.

2.3 *Monitoring system*

The northern slope of the Orvieto hill has been monitored since 1982 by means of piezometers and probe inclinometers.

All the boreholes are equipped with two or three Casagrande-type cells. Two-cell boreholes allow monitoring of piezometric levels in the stiff clay and in the clayey debris. The third cell measures piezometric heads in the softened clay layer.

Monthly inclinometer readings have been taken by means of a SINCO Minitilt probe inserted in aluminum casings, with the exception of the deepest O6 tube (Fig. 1) where an ABS casing was adopted.

Daily rainfalls and temperatures have been recorded since the second decade of the 20th century at a meteorological station located on top of the slab. Rainfall concentrates mainly in October and in November and it increases significantly in February. The dry season extends from the second half of June to the first half of August.

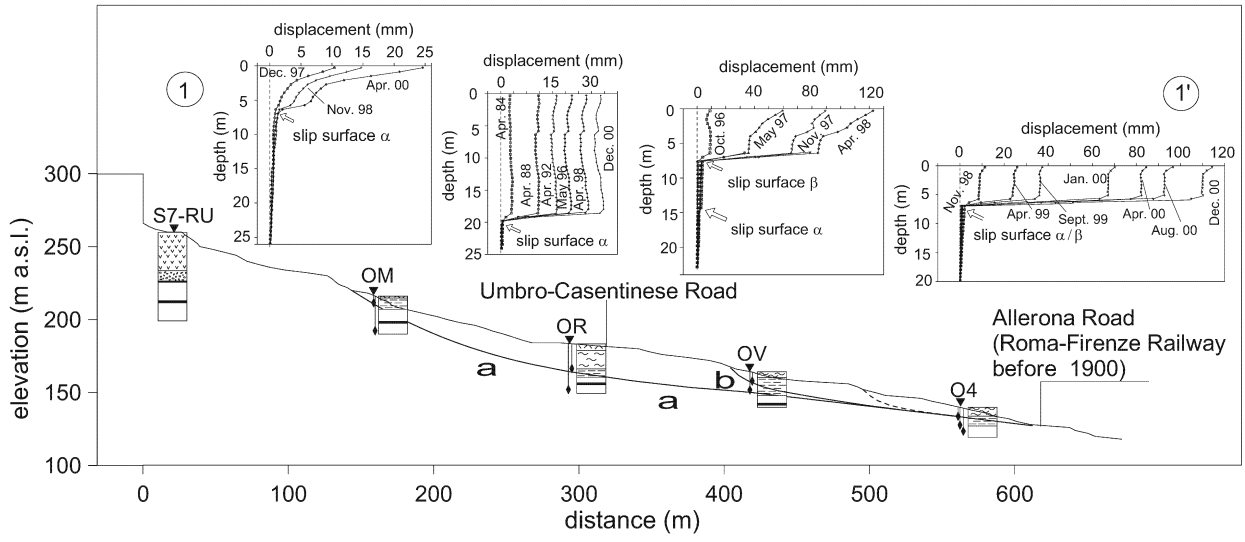

Figure 3. Displacements within the softened clay detected by inclinometers OM, OR, OV and O5 (section 1-1', see Figure 1).

3 RELATIONSHIP BETWEEN MOVEMENTS, PIEZOMETRIC LEVELS AND RAINFALL REGIME

3.1 *Shallow movements*

Oscillations of the piezometric levels in the clayey debris are characterized by sharp annual excursions generally ranging between 2 and 4 m (Fig. 4). The higher values are typical of piezometers installed in the coarser debris.

Maximum values of piezometric levels are generally observed between January and March (in some years two peaks are recorded during the same wet season) showing a delay of 2÷3 months with respect to the maximum values of rainfall which typically occur between October and November. A considerably good agreement between piezometric levels and rainfall distribution during the hydrologic year can be found by considering the rainfall cumulated over a 60-day period, P_{60}.

Minimum recordings of piezometric levels occur between August and September thus displaying a delay of 1÷2 months with respect to minimum rainfall.

The relationship between piezometric levels and displacement rates recorded in the inclinometers inside the clayey debris is quite significant. The magnitude of the displacement rates strongly depends on the amount of rainfall during the year. When P_{60} exceeds the value of $\overline{P}_{60}$ (calculated by assuming for each day of the year the average rainfall during the last 50 years) a sharp seasonal increase in the displacement rate is apparent. However, even if P_{60} is lower than $\overline{P}_{60}$, the inclinometers detect extremely low relentless displacements.

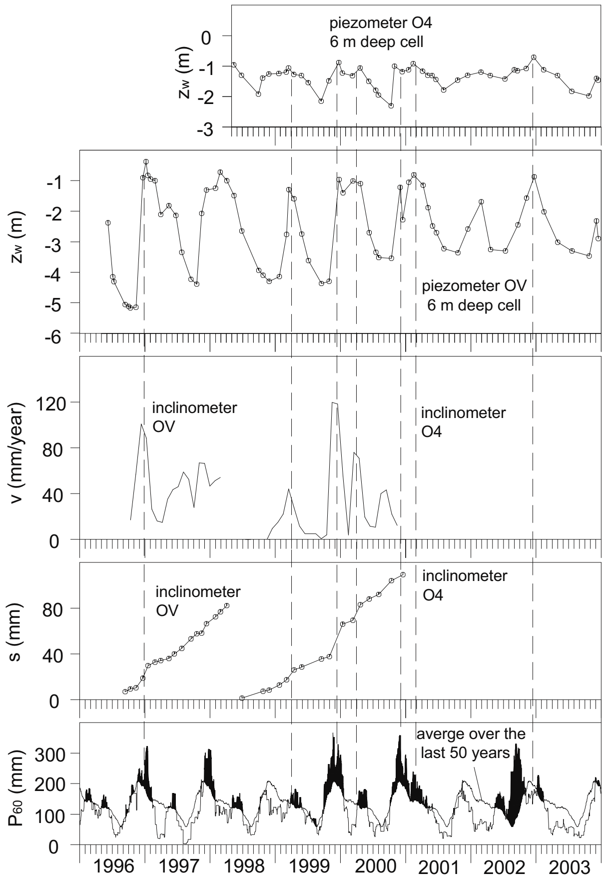

Figure 4. Rainfall regime, piezometer levels and displacements of the shallow movements in the slide debris (boreholes OV and O4).

3.2 *Deep-seated movements*

Figure 5 shows the relationship between the rainfall regime, piezometric levels and deep-seated movements occurring at the contact between the intact clay and its softened portion.

Piezometric oscillations are remarkably smaller than those observed in the clayey debris. Maximum piezometric levels are observed between March and May while minimum levels are attained between September and October.

A reasonable agreement between piezometric levels and daily rainfall is obtained by considering rainfall values cumulated over long periods of time (e.g., over 120 days in Fig. 5), thus indicating that only prolonged rainy periods can significantly change the pore pressure distribution at depth.

The displacement trend shows multi-year periods of extremely scarce activity alternating with periods characterized by higher average velocity.

Periods of inactivity (e.g., during the years 1995-1996) always take place during less rainy wet seasons, i.e., when P_{120} is lower than the corresponding value $\overline{P}_{120}$ assuming the average daily rainfall of the last 50 years. Furthermore, in these conditions the actual piezometric levels z_w are lower than the seasonal component $z_w - \overline{z}_w$, estimated through the regression of piezometric data using a periodical polynomial (Tommasi et al., 1996). Also seasonal increases in the displacement rate are in good agreement with the rainfall and piezometric distribution over the wet season.

Peaks of the displacement rate correspond to excesses of cumulated rainfall P_{120} with respect to the average values $\overline{P}_{120}$. They are found to constantly occur about 2 months before peaks of the piezometric levels. This can be related to different factors: the time-lag typical of Casagrande-type piezometers, (whose time-lag can be estimated in about 1 month for permeability of the order of 10^{-11} m/s; Terzaghi and Peck, 1967), the possible reactivation of movements on the slip surface for pore pressure values that are even lower than the maximum value and, for the special case of borehole OR, the greater depth of piezometer OR with respect to that of the slip surface (located at a depth of about 20 m).

4 CONCLUSION AND CURRENT RESEARCH ACTIVITY

The Orvieto overconsolidated clayey slope is affected by deep-seated movements involving the entire upper softened part of the clay formation down to a depth of some 33 m, and by shallower movements at the bottom of the slide debris.

Rainfall, piezometric and inclinometric data show that displacement rates of both shallow and relatively deep movements are strongly correlated with pore pressure and rainfall regimes.

A different influence of piezometric levels and rainfall on displacement rates characterizes shallow and relatively deep movements. In fact, in order to produce a significant rise in pore pressures able to reactivate movements, rainfall has to accumulate over longer time periods (of up to 180 days) and is to be in excess with respect to average values (Fig. 5).

On the contrary, rainfall produces relatively fast changes in pore pressure in the more permeable shallow materials (slide debris and uppermost jointed and softened part of the clay formation), so that the rate of displacement of shallower movements is better correlated with the rainfall cumulated over 60 days (Fig. 4) and may exhibit more than one velocity peak per year reflecting the double-peak rainfall distribution.

The response of shallow and deep-seated movements to pore pressure changes and, in turn, to variations in rainfall regime depends on the groundwater flow in the hill, that is largely controlled by the differences in hydraulic conductivity of the slope

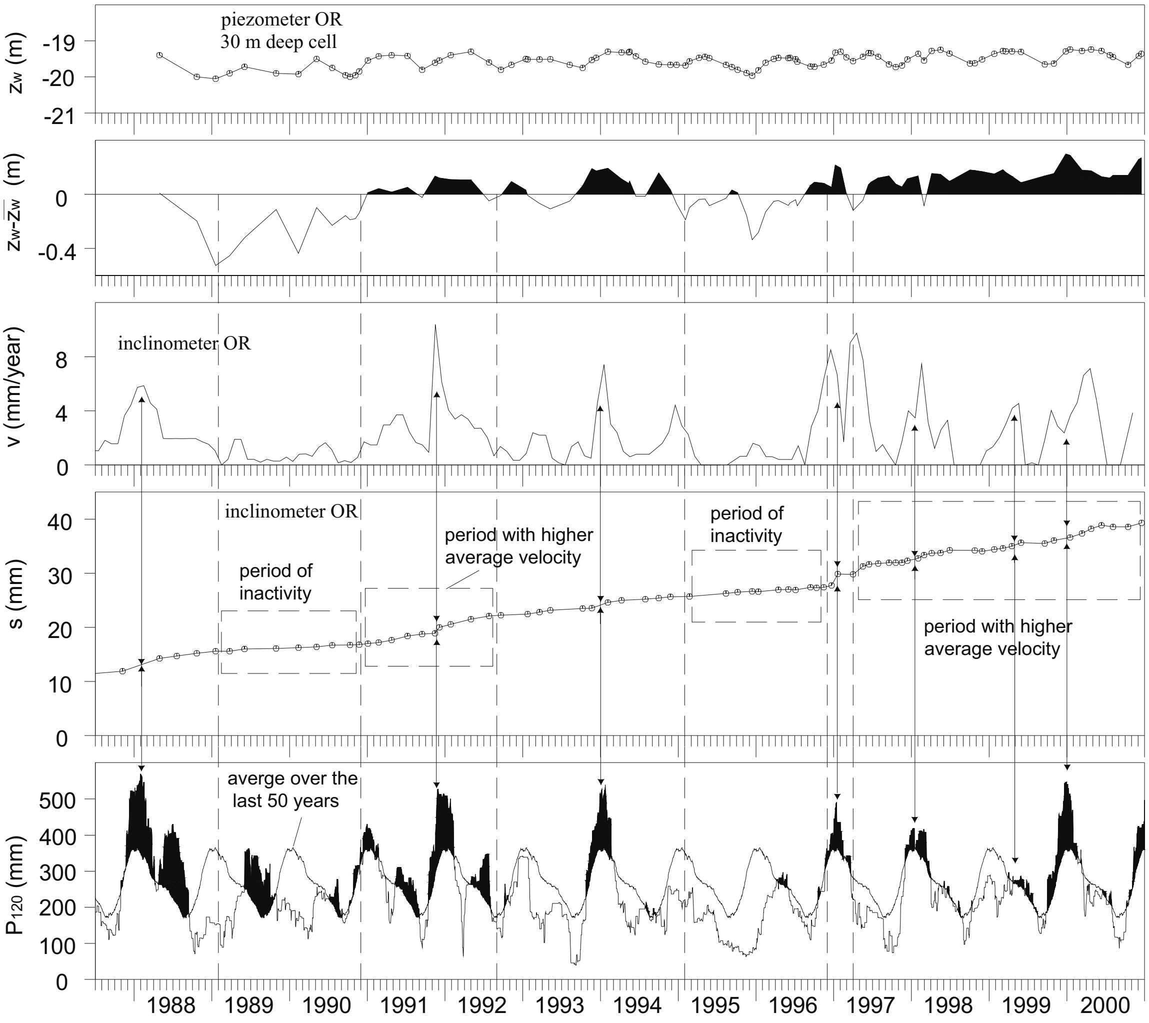

Figure 5. Rainfall regime, piezometer levels and displacements of the deep-seated slide (borehole OR).

materials and by the permeability contrast between the slab and the underlying clay. Both the shallower slope materials and the in situ clay are partly connected to the perched groundwater at the slab bottom , but different drainage paths, permeability values and infiltrated rainfall determine two distinct groundwater flow regimes which affect distribution and variations in time of pore pressures.

A better understanding of the response of groundwater circulation to rainfall variations will surely be achieved by modeling the transient groundwater flow, that has been recently started. The model is based on the geotechnical stratigraphy of the slope reconstructed by means of boreholes, in situ permeability tests and saturation-suction relationships obtained by means of laboratory tests (Cafaro et al., 2005). A further contribution will come from a more refined reconstruction of the rising and descending time series of piezometric levels, provided by miniature pressure transducers inserted in the tubes of the Casagrande cells.

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