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Evaluation of hydraulic conductivity in the slip zone of an earthflow in clay shales

Evaluation de la conductivité hydraulique dans la surface de rupture d'un glissement de terrain dans des schistes argileux

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ABSTRACT: Discontinuities and inhomogeneities can significantly influence soil permeability. The study of such influence is very important for landslides, in which permeability controls distribution and response of pore water pressures to rain. In order to evaluate if the slip surface affects permeability distribution in clayey earthflows, field tests were carried out in the head zone of an earthflow of the Italian Apennines. In a number of boreholes, the water level was lowered and the inflowing discharge was evaluated locally, by an *ad hoc* apparatus, along the whole height of the boreholes. The results of the experimentation show that in a narrow band around the slip surface the specific discharge is much higher than elsewhere. The permeability along the shear band was evaluated by interpreting experimental data by a commercial FEM code (SEEP/W). The model was used to simulate both the localized tests and standard tests of rapid water table lowering followed by spontaneous rising. The results provide permeability values k_b for the shear band one-two orders of magnitude higher than in the landslide body k_l. The high values of permeability in the shear band are supposed to influence significantly the kinematic response of the earthflow to variations in the hydraulic boundary conditions.

RÉSUMÉ: Les discontinuités et les inhomogénéités peuvent influencer considérablement la perméabilité du sol. L'étude de cette influence est très importante dans le cas des glissements de terrain, où la perméabilité contrôle la distribution et la réponse des pressions interstitielles à la pluie. Afin d'évaluer si la surface de rupture affecte la distribution de la perméabilité dans écoulement de terre argileuse, essais in situ ont été effectués dans la zone de tête d'un écoulement de terre dans les Apennins du sud de l'Italie. Dans plusieurs forages, le niveau d'eau a été abaissé et l'écoulement entrant a été évalué localement, par un appareil *ad hoc*, sur toute la hauteur du forage. Les résultats de l'expérimentation montrent que, dans une bande étroite autour de la surface de glissement, l'écoulement spécifique est beaucoup plus élevé qu'ailleurs. La perméabilité le long de la bande de cisaillement a été évaluée en interprétant les données expérimentales à l'aide d'un code FEM commercial (SEEP/W). Le modèle a été utilisé pour simuler à la fois les tests localisés et les tests standard d'abaissement rapide de la nappe phréatique, suivis de levées spontanées. Les résultats donnent des valeurs de perméabilité k_b pour la bande de cisaillement supérieure de deux ordres de grandeur à celle du corps de glissement de terrain k_l.

Keywords: landslide; slip surface; water flow; permeability test; field permeameter.

1 INTRODUCTION

Active earthflows in tectonized clay shales are widespread in the Italian Apennines, as well as in many other countries. Their kinematics is much influenced by pore water pressure distribution which, in turn, depends on the interaction with both atmosphere and contiguous aquifers. Discontinuities of various origins can influence significantly the results of the interaction. The technical literature presents many studies on this aspect. Among others, Yin et al. (2012) studied the influence of fissures on slope stability of expansive soils. Picarelli et al. (2000), Picarelli and Olivares (2004), Picarelli and Di Maio (2010) discussed the role of fissures, discontinuities and inhomogeities at various scales on the behaviour of stiff clays and clay shales. The clay fissuring and the fractured rock interbeddings have been recognised by Cotecchia et al. (2015) as sources of larger field permeabilities in tectonized clayey turbidites. By interpreting the behaviour of some large landslides, the authors hypothesized that high permeability values along discontinuities predispose the slopes to infiltration rates down to large depths higher than those expected for homogeneus and intact clays, thus influencing the slope stability. While investigating pore pressure distribution in stiff fissured clays, Alonso et al. (2014) too discussed the role of existing discontinuities on slope permeability and on the effect of rainfall on the stability of slopes. Urciuoli et al. (2016 and references therein) recognized the important and unaspected role of fissures and discontinuities in the response of pore pressures to rain in several clayey landslides.

The slip surface is an important discontinuity in slopes affected by landslides, and the shear band can act as an inhomogeneity in the subsoil. In order to evaluate the occurrence of preferential paths of water flow, or pore water pressure propagation, along the slip surface, several permeability field tests were carried out in the *Costa della Gaveta* earthflow by using a field permeameter *ad hoc* realized. The permeability along the shear band was evaluated by simulating the observed processes by means of the FEM software SEEP/W.

2 COSTA DELLA GAVETA SLOPE AND TEST FIELD

The *Costa della Gaveta* earthflow (Fig. 1) is located east of the city of Potenza in the southern Italian Apennines. It occurs in a geological formation, Varicoloured Clays, constituted by a tectonized clay-marl system of Upper Cretaceous - Lower Miocene. The earthflow (about 3 millions m^3, up to 40 m thick) moves very slowly, with almost constant yearly displacement rates. Along the axis, such rates vary from 2-3 cm/yr at the head to about 1 mm/yr in the accumulation (Di Maio et al., 2013; 2017).

The decrease of Na$^+$ concentration in the pore solution has been hypothesized as one of the important causes of soil deterioration which contributes to the landslide activity (Picarelli and Di Maio, 2010; Di Maio et al., 2015; Di Maio et al., 2017).

Laboratory data show that exposure of the Varicoloured Clays of the site to concentrated KCl solutions causes ion diffusion towards the pore fluid and a great increase in the soil shear strength (Di Maio et al., 2017). In order to evaluate the possibility of improving the landslide soil, an experimentation has been initiated some years ago in the head zone of the *Costa della Gaveta* earthflow (De Rosa et al., 2016). In a test field of about 300 m^2, several boreholes have been driven for the installation of KCl wells, piezometers, inclinometers, and for the monitoring of water and ion flows (Fig. 2). The results of field tests suggested that: *a)* ion propagation occurs mainly for advection, and *b)* advection is controlled not only by the high hydraulic gradients of the zone but also and mainly by more permeable bands which work as preferential flow paths. This paper presents the results of the hydraulic part of experimentation.

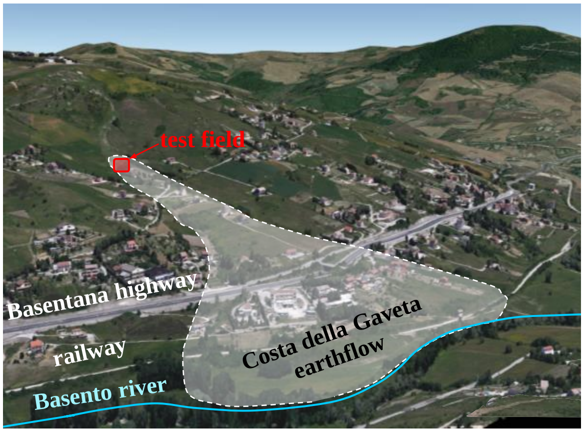

Figure 1. Costa della Gaveta earthflow with indication of the test field

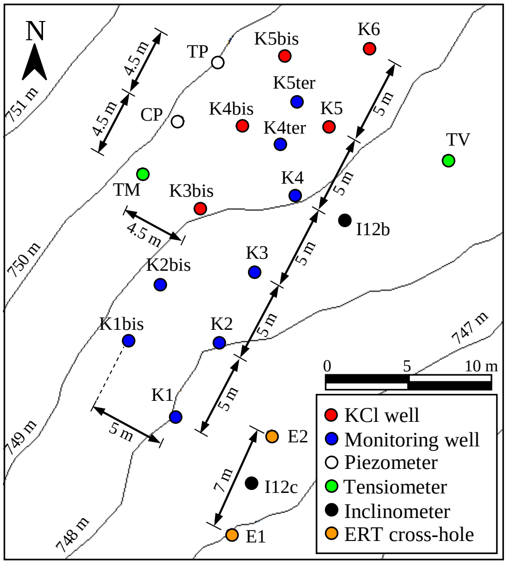

Figure 2. Plan of the test field

3 FIELD PERMEABILITY TESTS

3.1 Localized permeability tests

In October 2015, eleven boreholes, 5 m mutual distance and 11 m - 15 m depth (Fig. 2), were drilled and stabilized by jacket slotted tubes. In the experimentation, still in course, some boreholes are being filled with granular KCl, while the others are used to induce and/or monitor water and ion flows (Fig. 2).

The Varicoloured Clays at Costa della Gaveta are heterogeneous, anisotropic and present numerous discontinuities that influence the hydraulic conductivity, making it vary by several orders of magnitude from area to area of the slope. To obtain a reliable estimate of the hydraulic properties of the subsoil, a local evaluation of hydraulic conductivity is therefore necessary.

The localized tests have been performed by using a permeameter *ad hoc* designed (Fig. 3). The cylindrical cell, 7 cm diameter and 15 cm height, is provided of two rubber strips which garantee the hydraulic seal. The cell is mounted at the end of a series of hollow rods inside which the galvanometric probe can be inserted. The apparatus is installed at the desired depth after the borehole has been emptied. The measurement of inflowing water is carried out by keeping, in the wells, free water surface below a given depth (about 8 m in this zone) until steady-state conditions are achieved (about 10 days in the average). The time trend of free water surface level in the cell is monitored and, thanks to the calibration scale, it is possible to estimate the volumes of water inflowing from the well wall between the seals.

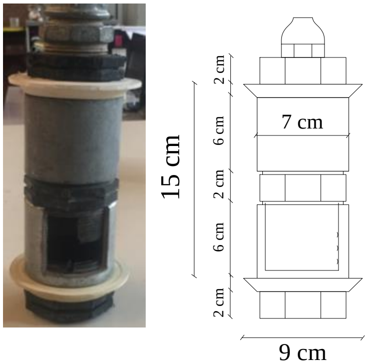

Figure 3. Cell of the field permeameter

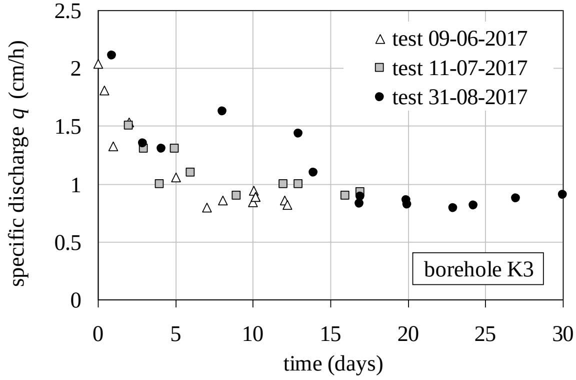

Figure 4. Specific discharge in the localizd tests against time, at 8.5 m depth, in the transient induced by water level drawdown

The rate of the transient induced by the lowering of the free water surface depends on various factors: stratigraphy, hydraulic conductivity, hydraulic head, compressibility of the soil. Figure 4 shows the time trend of the specific discharge flowing in the cell during such transient. The cell was installed at a depth of 8.5 m, and the test was repeated three times. It can be observed that: *a)* the results of the tests are very similar to each other, *b)* the specific discharge *q*, initially in the order of a few cm/h, decreases with considerable gradients for about 5 days. Subsequently, the *q(t)* gradients decrease and finally, about 10 days after the beginning of the test, a constant *q* value is obtained.

At different depths and in other boreholes, the stationary conditions have been reached at different times. In some cases about ten days, in other cases some tens minutes. In any case, the tests have been carried out until stationary conditions all along the borehole height, so as to evaluate *q(z)* profiles of specific discharge as accurate as possible.

The profiles of Fig. 5 show that the greatest water inflows occur in a very narrow band, and that inflows are negligible above and below this band. The figure also shows the experimental data relative to non-stationary conditions, taken in different seasons. In transient conditions, the values of *q* do not give rigorous quantitative indications, but they reveal anyway that the greatest inflows always occur at depths between 7.5 m and 9 m. At these depths, inclinometer profiles exhibit concentrated deformations (Di Maio et al., 2017).

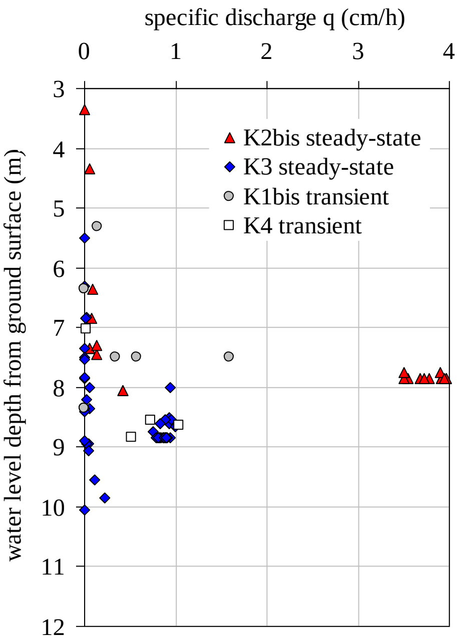

Figure 5. Specific discharge evaluated in steady-state (K2bis and K3) and transient (K1bis and K4) conditions

3.2 *Standard well permeability tests under variable hydraulic head*

The standard tests were carried out by lowering the free water surface to a given depth, in about ten minutes, and then by monitoring its spontaneous rising *h(t)*.

The tests were repeated several times to evaluate the reliability of the results. With reference to the rising rate, two different behaviours were observed (Fig. 6) and the boreholes were distinguished in "slow" and "fast". Higher rates occurred where the thickness of the permeable band was lower. Both the processes occurring in the two rate conditions were simulated.

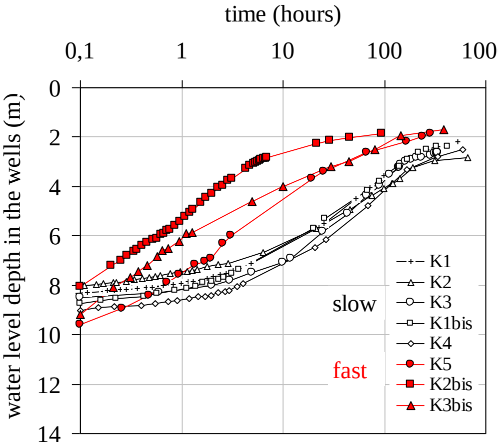

Figure 6. Free water surface depth against time

3.3 FEM simulation

The observed processes were simulated by the FEM code SEEP/W, in an axisymmetric scheme. The domain was subdivided in three regions: landslide, stable formation and a more permeable band at the depth of the highest experimental specific discharge (Fig. 7). The boundary conditions were: *i)* null unit flux on the ground surface and at the domain base, *ii)* hydraulic head on the lateral domain surface equal to that determined experimentally in the nearby wells 5 m far, *iii)* potential seepage condition along the well wall (in the steady-state process), *iv)* volume-head function, a special function of the code, along the well wall (for the transient process). Permeability values of $4\cdot10^{-9}$ m/s and 10^{-10} m/s, obtained by piezometer tests, were attributed respectively to the landslide and to the stable formation. Volumetric compressibilities obtained by oedometer compression tests were considered.

The thickness *s* of the permeable band was different for different boreholes, and equal to the one determined experimentally with the localized permeability tests. Permeability k_b was evaluated by successive approximations, seeking the values which allowed the best fitting of both the experimental *q(z)* profiles obtained by stationary tests and the *h(t)* curves of standard well permeability tests. Figs. 8a and 8b compare experimental and numerical data for the borehole K3. For the considered well, *s* = 50 cm, the best data fitting is obtained with 10^{-8} m/s < k_b < $3\cdot10^{-7}$ m/s. For K2bis, *s* = 20 cm, values of $6\cdot10^{-8}$ m/s < k_b < $5\cdot10^{-7}$ m/s were evaluated (Fig. 9). Thus, the permeability of the considered band varies from vertical to vertical, but it is

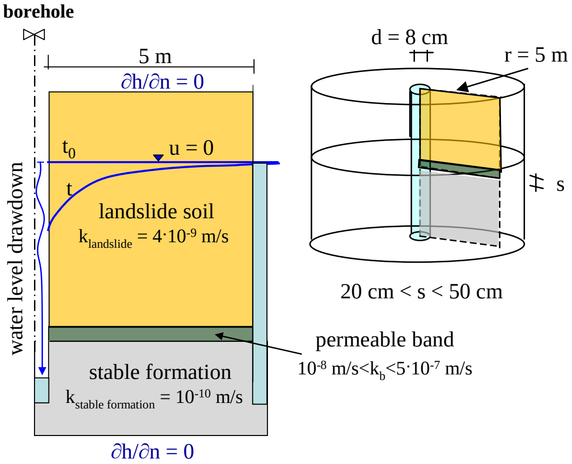

Figure 7. Axisymmetric domain of the FEM analysis

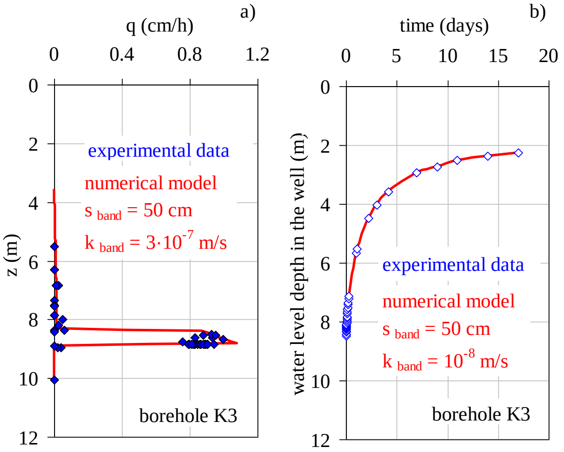

Figure 8. Experimental and calculated specific discharge along borehole K3 (a) and time trend of the water level after a rapid drawdown (b)

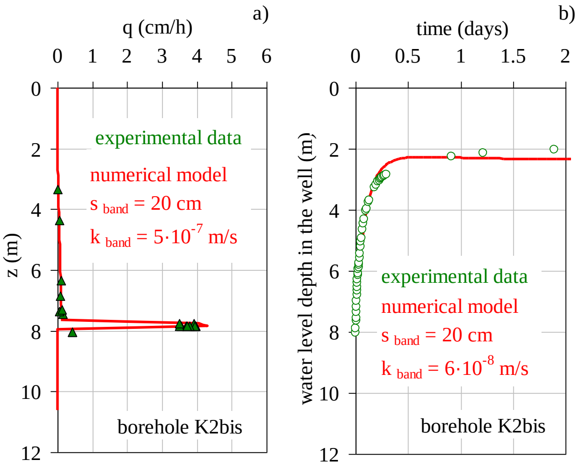

Figure 9. Experimental and calculated specific discharge along the K2bis borehole (a) and time evolution of the water level after a rapid drawdown (b)

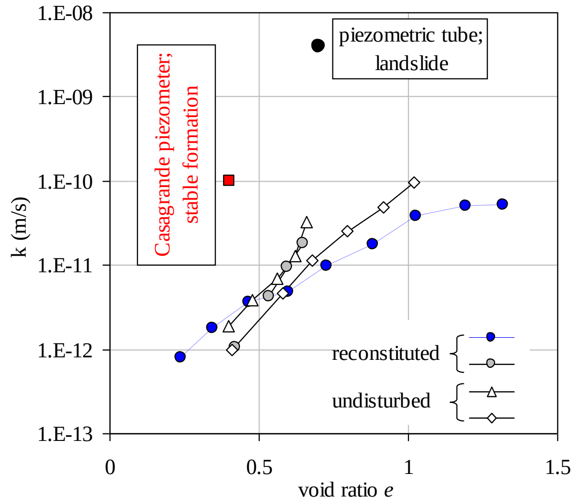

Figure 10. Hydraulic conductivity values determined in situ and by laboratory tests

anyway higher than the permeability of the landslide body.

The hydraulic conductivity was evaluated also by laboratory tests, by interpreting the oedometer consolidation curves with the Terzaghi model. Fig. 10 shows the curves *k* - *e* (permeability - void ratio) thus obtained on reconstituted and undisturbed soil specimens. The figure also shows the values of permeability obtained by piezometer tests carried out in the landslide body and in the stable formation. At the same void ratio, *in situ* permeability is 2-3 orders of magnitude higher than that determined by laboratory tests. The large difference can be ascribed to the field discontinuities and inhomogeneities.

The permeable band seems to coincide with the slip band surrounding the slip surface. Since this latter intersect the ground surface all along the boundary of the landslide, it can constitute a path of rapid pore water pressure propagation during rain events. In order to evaluate if this occurs, two more piezometers have been recently installed across the band. As matter of fact, the first results of monitoring show that the response of these piezometers to rain is faster than that of the piezometers in the landslide body or in the stable formation.

4 CONCLUSIONS

In an experimental field, in the head zone of *Costa della Gaveta* earthflow, several boreholes were drilled. Some of them were used to monitor water flow. Numerous permeability tests have been carried out under various hydraulic conditions, also with *ad hoc* equipment, to evaluate the permeability distribution along the entire height of the boreholes.

The results show that preferential water flow occurs in a very narrow band, which develops at the depth where the inclinometers show a concentration of deformations. The hypothesis that the permeable band coincides with the slip band is supported by numerous experimental evidences, among which the discontinuities of soil samples extracted from numerous boreholes.

The finite element analyses show that the different types of permeability tests are well interpreted by permeability ratio equal to 10 between landslide and stable soil, and equal to 100 between the permeable band and landslide.

This inhomogeneity in hydraulic conductivity has important consequences on the behaviour of the landslide. In some areas, in fact, the response of pore water pressures to rain can occur faster and therefore more intensely, as suggested by Urciuoli et al. (2016) for other types of discontinuities.

Moreover, the first experimental results seem to show that the higher flow also produces a faster reduction of ion concentration in the pore solution, with possible negative consequences on shear strength (Vassallo et al., 2015; Di Maio et al., 2017).

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