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Pore water pressures and hydraulic conductivity in a clayey earthflow: experimental data in the landslide body, in the slip band and in the stable soil

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Abstract

The Costa della Gaveta earthflow occurs in a structurally complex clayey formation of the Italian southern Apennines. The slip band detected by inclinometers reaches 40 m depth. Sliding localized on a thin slip zone, under conditions of constant soil discharge, is the current prevailing mechanism of movement. Over the last 15 years, the displacements have occurred at almost constant average yearly rate, with seasonal variations ascribable to the hydrologic conditions. The total stress being constant, rain can influence displacements by an influence on pore water pressures. Pore water pressures were monitored by Casagrande piezometers and vibrating wire cells in three different zones of the subsoil: stable formation, landslide body and slip band. The experimental data show that along the shear band the response of pore water pressures to the site hydrological conditions is far faster than in the landslide body and in the stable formation. Furthermore, the deep displacement rates of all the inclinometers crossing the slip surface seem to be strictly correlated to pore water pressures in the slip band. To understand why and how this occurs, the hydraulic conductivities of the three different parts of the subsoil were evaluated by the analysis of two types of field tests: falling head tests in the Casagrande piezometers, and localized seepage measurements in test wells equipped to this aim. The experimental data show that in the slip band, the hydraulic conductivity is much higher than that in the landslide body which, in turn, is higher than that of the stable formation. Piezometric measurements support the hypothesis that such permeable zone is connected to the atmosphere.

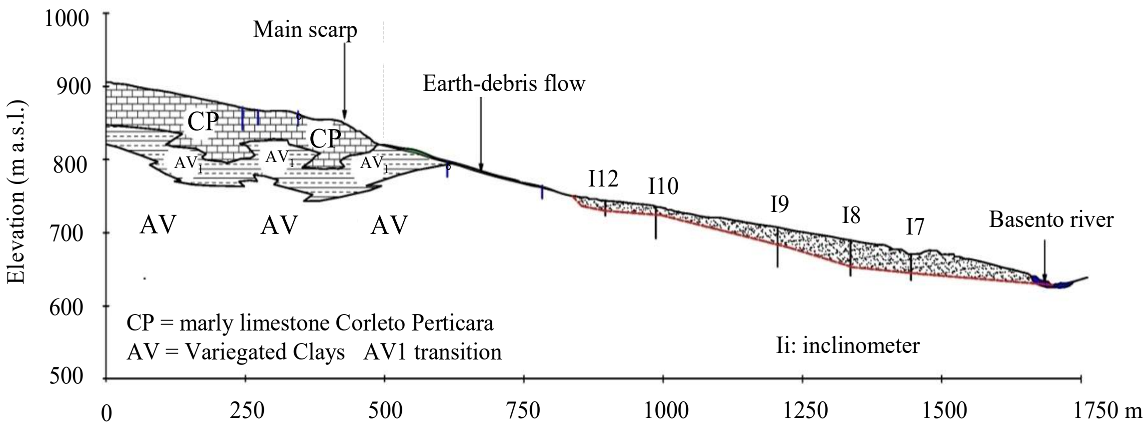

Figure 1. Geological section of the *Costa della Gaveta* earthflow occurring in the structurally complex clayey formations of Variegated Clay and Corleto Perticara marly limestone (Di Maio et al., 2017).

1 INTRODUCTION

Earthflows in structurally complex clayey formations are widespread in the Italian Apennines. After the first failure, they are generally characterized by alternate phases of rapid and very slow movement (Urciuoli et al., 2016, Guida and Iaccarino, 1991). In the hill slopes facing the Basento river, many of such earthflows, of different ages and sizes, occur. Among them, the Costa della Gaveta earthflow and the Varco d'Izzo landslide system, in the so-called Varicoloured Clay formation, are the most important for their extension. Since the landslides extend from the top of the hills to the river valley, railways, highways and pipelines must necessarily cross them. Furthermore, during the phases of very slow movements or quiescence, the instable areas have been, and still are, urbanized. Thus, although slowly, the involved structures and infrastructures undergo damage, thus requiring continuous maintenance with high social and economic costs. In order to understand the landslide mechanism and to design effective measures of risk reduction, many studies are funded by public and private institutions. Several of these studies refer to the influence of rain on the landslides behaviour. In fact, although the high clay component makes the hydraulic conductivity of these landslides generally very low, and although the slip surfaces are very deep (some ten meters) the hydrological regime seems to play an important role. Many authors recognized the role of discontinuities as preferential flow paths that facilitate the propagation of pore water pressure associated to rain (Brundsen, 1999; Shao et al. 2015; Boogard and Greco, 2016; Belle et al. 2018; Sidle et al., 2019). The influence of discontinuities was also discussed by Hencher, (2010), Vitone and Cotecchia (2011), Cotecchia et al. (2015). Di Maio et al (2020) investigated the role of the slip zone as a discontinuity able to facilitate pore water pressure propagation. This paper shows some results of a long-term monitoring of pore water pressure distribution in the *Costa della Gaveta* earthflow, east of Potenza city, Italy (Figures 1-2a). Furthermore, the paper presents the results of an investigation carried out to evaluate the hydraulic conductivity of the zones of the subsoil characterized by different fabric: the stable soil, the landslide body and the slip band.

2 THE EARTHFLOW

The *Costa della Gaveta* earthflow occurs on a slope of the Basento river valley in the Variegated Clay Formation (Lower Miocene) (Figure 1). The Formation is constituted by clays, marly shales, cherty marls and marly clays, gray and polychrome, with interbedded layers of calcareous marls, jasper, calcilutites and turbiditic biocastic calcarenite with fossils and with chert (Di Maio et al., 2017). System of faults with orientations NW-SE and NE-SW control the slope evolution.

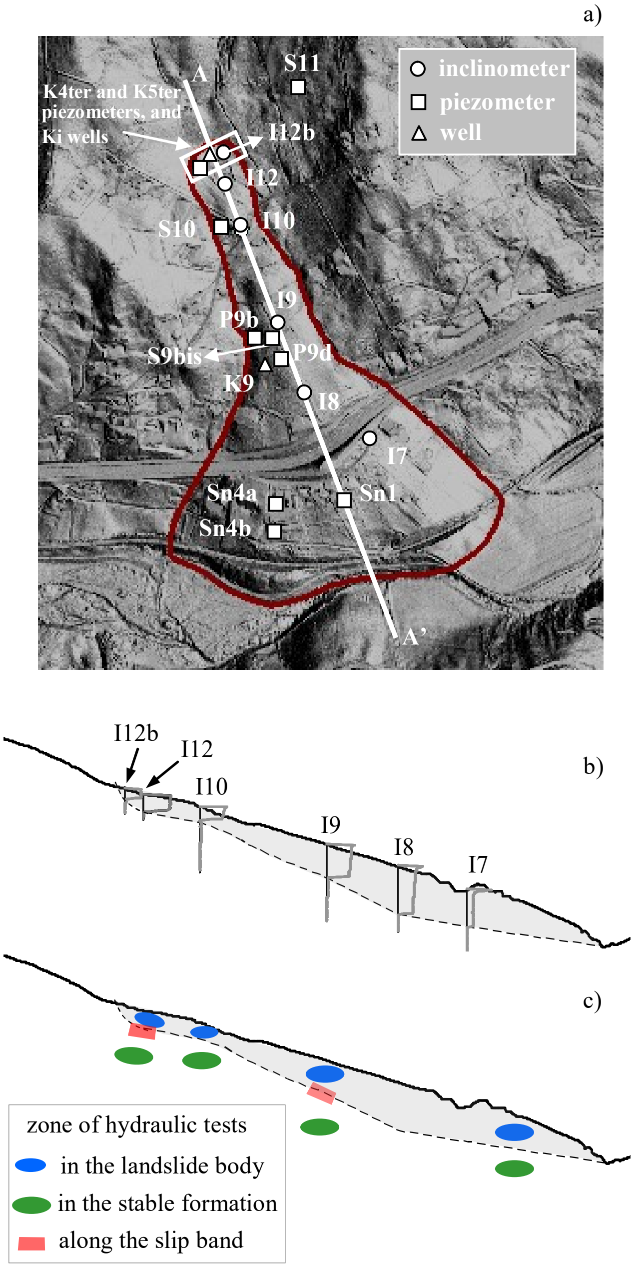

Figure 2. Map of the *Costa della Gaveta* eartflow and location of piezometers and inclinometers (a), section AA' with the slip surface hypothesized on the basis of inclinometer measurements (b), section AA' with indication of the zones where pore water pressures were monitored and permeability tests were carried out (c).

The landslide presents a chaotic fabric with a clayey matrix incorporating rock fragments, blocks and disarranged strata. The earthflow has an average inclination of about 10°, it is 1250 m long, from 100 to 600 m wide. The maximum depth of the slip surface provided by the inclinometers is about 40 m (Figure 2b).

The landslide movements have been monitored by inclinometers since 2004. The inclinometer profiles show that sliding localized along a thin slip zone is the prevailing type of movement (Di Maio et al., 2010; 2013; 2015). Figures 2 and 3 show that the average yearly displacement rates decrease in the downslope direction. In particular, Figure 3 shows that the average yearly deep displacement rates can be considered constant over the monitoring time. Figure 4, which compares cumulated deep displacements to cumulated rain, shows that the displacement rates undergo seasonal variations which seem strongly correlated to the hydrological regime (Vassallo et al., 2015). Vassallo et al. (2016), by means of the data driven model EPRMOGA, showed the existence of a strong correlation between contemporary rain and displacement rates. In the case under study, in which total stresses can be considered constant over the year, the rain regime can influence the displacement rate through an influence on pore water pressures. Such an influence is not obvious in the case of the *Costa della Gaveta* earthflow, because of: i) the depth of the slip surface, ii) the high clay fraction, and iii) the low hydraulic conductivity of the undisturbed material. To investigate the hydraulic role of fabric and discontinuities, pore water pressures were monitored and the hydraulic conductivity was evaluated in several different locations of the landslide and at different depths from the ground surface, namely in the stable formation, in the landslide body and along the slip band.

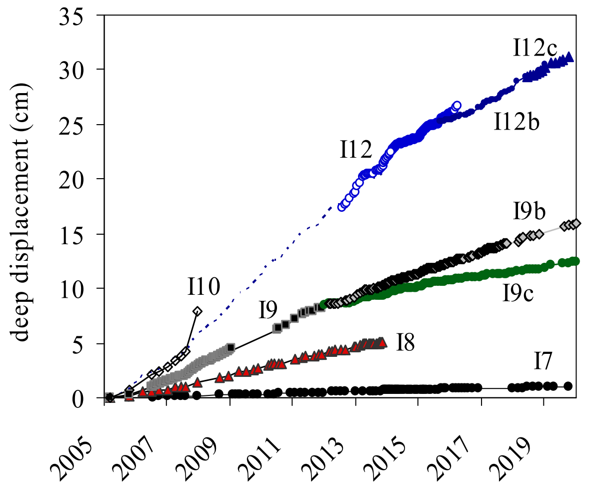

Figure 3. Deep displacements AB against time (Di Maio et al., 2020).

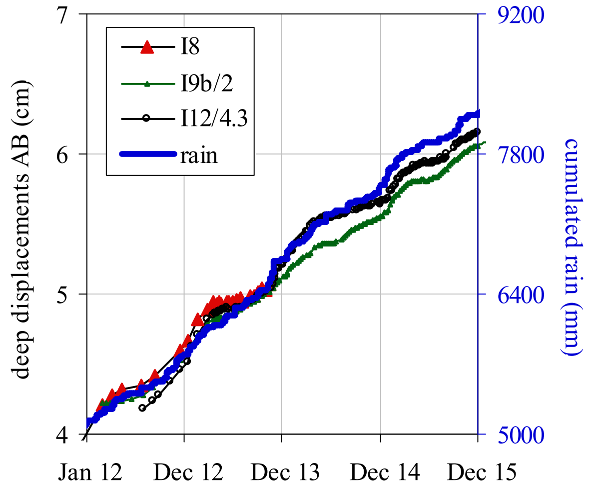

Figure 4. Cumulated rain and cumulated deep displacement against time (Vassallo et al., 2016).

3 PORE WATER PRESSURES

Pore water pressures are being monitored since 2005 by Casagrande piezometers and by some vibrating wire cells (Figure 5a). In 2018, new instruments have been installed (Figure 5b). Figure 5a shows the time evolution of data of the older instruments in terms of depth of water level from the ground surface. Negligible seasonal variations in pore water pressures ascribable to rain can be observed both in the stable formation and in the landslide body. Figure 5b shows that even the vibrating wire cells installed at about 8 m and 4 m depths, in the accumulation and in the head zone respectively, besides the deeper ones, do not show a seasonal response to rain. Figure 6a shows the results obtained by the piezometers installed in the slip zone. Besides the values of the Casagrande piezometers K4ter, K5ter, and P9D, the figure shows the data of the open tube K9 (30 m deep), and of other open tubes Ki in the tests field, all deeper than the slip surface (location in Figure 2). It can be observed that pore water pressures vary quickly with rain on the slip band at 8 m depth in the landslide head (K4ter, K5ter) and even at 25 m in the channel (P9D). As shown by the next section, because of the subsoil permeability ratios, also the data obtained from the open tubes Ki and K9 can be representative of the hydraulic conditions in the slip zone, and in fact their water level time trends are in good agreement with all the other data.

The rates of deep displacements were evaluated by fixed-in-place and mobile inclinometer data. Figure 6b reports the deep displacement rates in some different verticals against time. Each curve was obtained by dividing the displacement rate by a constant which makes comparable the average yearly rates of the different verticals. It can be observed that the rates' variations are very similar to pore water pressure variations on the slip band (Figure 6a).

4 PERMEABILITY TESTS

The soil hydraulic conductivity was evaluated by two types of field tests: localized seepage in test wells and falling head tests.

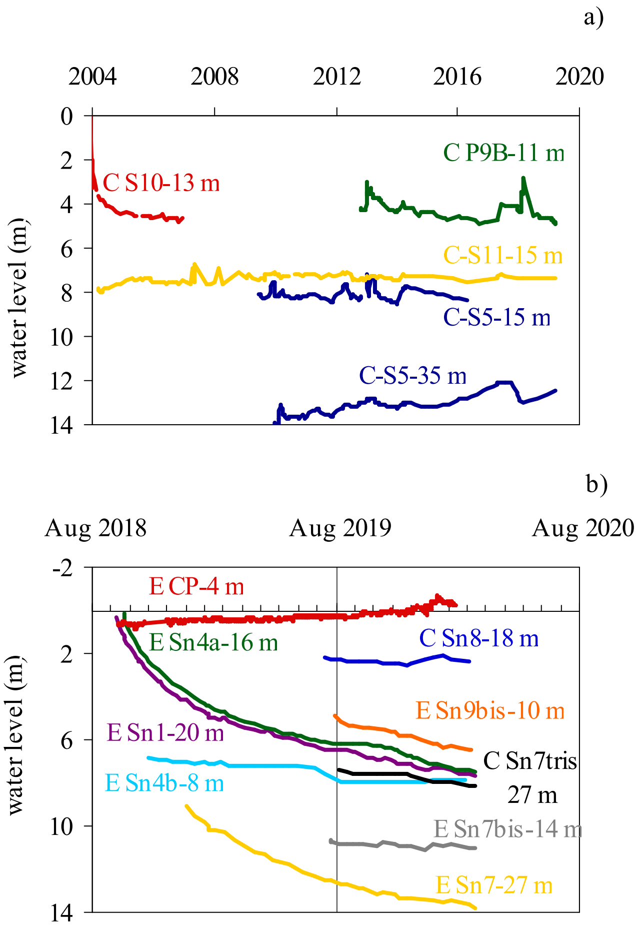

Figure 5. Pore water pressures evaluated by different types of piezometers at different depths: since 2004 (a) and since 2018 in new installations (b). Casagrande piezometers are indicated with the letter C and electric cells with the letter E (re-drawn from Di Maio et al., 2020).

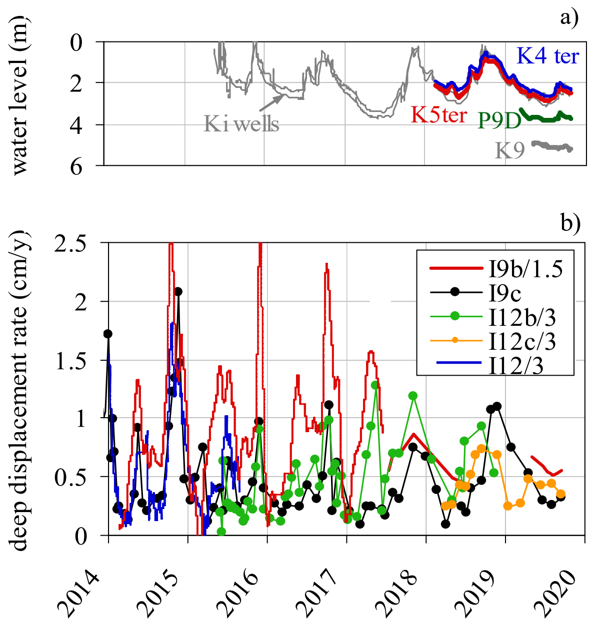

Figure 6. Pore water pressures evaluated along the slip band (a) and deep displacement rate against time (b) (re-drawn from Di Maio et al., 2020).

4.1 Localized seepage measurements

The tests were carried out in the test field described by Di Maio et al. (2017). Eleven test boreholes, Ki, were drilled crossing the slip zone (Figures 2), and were stabilized by jacket slotted tubes. The localized seepage measurements were carried out by a permeameter, constructed *ad hoc*, with a cylindrical cell, 7 cm diameter and 15 cm height, provided of two sealing rubbers. The cell is fixed at the end of a series of hollow rods which allow the insertion of the galvanometric probe (Figure 7a). The test procedure consists in lowering the water surface below the slip surface until steady-state seepage conditions are reached; then the cell is installed at the desired depth and the volume of the inflowing water is measured and monitored for several days. The specific discharge draining from the well walls is thus evaluated (Di Maio et al., 2020). The procedure is applied with continuity along the height of the same borehole, and of all the other boreholes with the same type of stabilization, thus obtaining the profiles of specific discharge in steady-state conditions shown by Figure 7b.

The data show that the greatest inflows occur in narrow bands about 0.2 m – 0.5 m thick at depths varying with the boreholes between 7.5 m and 9 m, i.e. in the range of depths where the nearby inclinometer tubes undergo concentrated deformations.

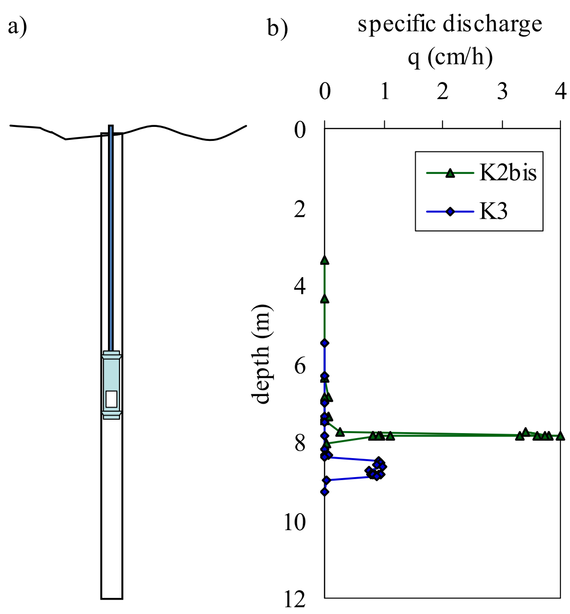

Figure 7. Scheme of installation of the permeameter (a) and specific discharge profile (b).

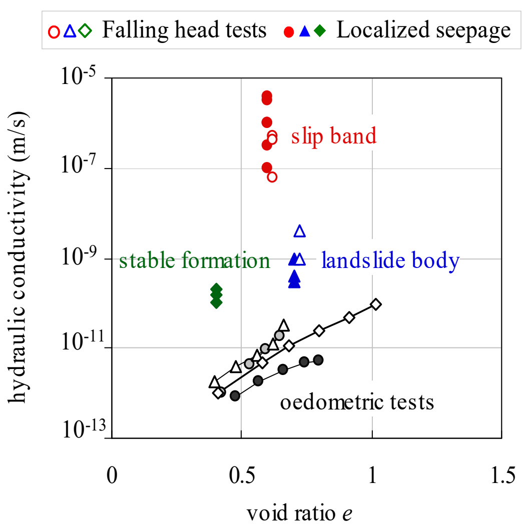

Figure 8. Hydraulic conductivity determined by different methods in situ in the landslide body, in the stable formation and along the slip band. Comparison with laboratory test results (Di Maio et al., 2020).

The tests were simulated by 2D, 3D and axisymmetric models based on finite element and finite difference methods (Grimaldi et al., 2018; De Rosa et al., 2019). Values of thickness of the more permeable band between 0.2 m and 0.5 m were considered; hydraulic conductivities corresponding to the upper limits of experimental ranges, i.e $k_{sf} = 10^{-10}$ m/s for the stable formation, and $k_{lb} = 10^{-9}$ m/s for the landslide body were assumed (both values obtained by falling head test in the piezometers). The values of the band hydraulic conductivity k_{sb} which allow the best modeling are in the range 10^{-7} m/s $<k_{sb}<10^{-5}$ m/s. Thus, on the basis of this analysis, the slip band is very inhomogeneous but anyway much more permeable, some orders of magnitude, than the other zones of the subsoil.

4.2 Falling head tests in Casagrande piezometers

In all the Casagrande piezometers installed in the slope (Figure 2), falling head tests were carried out. Some piezometers were installed in the slip band, some in the stable formation and others in the landslide body. The interpretation of the tests was carried out by using the Hvorslev model based on the assumption of Darcy's law validity and on the incompressibility of soil and water (Hvorslev, 1951). The model provides values of the slip band hydraulic conductivity k_{sb} in the range 10^{-7} - 10^{-6} m/s, for a thickness of the band in the range 0.2 - 0.5 m. Variations lower than an order of magnitude are obtained by using different reasonable values of the shape factor F. For the piezometers in the landslide body and in the stable formation, if F is considered relative to the case of homogeneous soil, the values of the hydraulic conductivity that best interpret the tests are about $k_{lb} = 10^{-9}$ m/s and $k_{sf} = 10^{-10}$ m/s respectively.

Figure 8 compares the values of hydraulic conductivity obtained by the two different types of field tests and also reports the results of laboratory tests. The figure shows that the results of the falling head tests are very similar to those of the seepage-pumping tests: both the sets of data provide hydraulic conductivity values for the slip band much higher than those of the other zones of the subsoil. The large difference in the field values relative to the three investigated zones: stable formation, landslide and slip band are reasonably due to the different fabric. The fabric is still responsible of the much lower k values obtained for the small laboratory elements of soil.

Summing up, the permeability tests provide values of k in the range 10^{-7} m/s $<k_{sb}<10^{-5}$ m/s in the slip band, 10^{-10} m/s $<k_{lb}<10^{-9}$ m/s in the landslide body, and 10^{-11} m/s $<k_{sf}<10^{-10}$ m/s in the stable formation. Thus, there are from two to six orders of magnitude differences within the same formation.

5 CONCLUSIONS

The experimental results relative to a deep and very slow earthflow in tectonized clay shales show that:

a) pore water pressures along the slip band, even at depths of about 27 m, exhibit seasonal variations almost in phase with the gradients of cumulated rain;

b) the hydraulic conductivity of the slip band is rather high, in the order of 10^{-7} m/s – 10^{-5} m/s and much higher than that of both the stable formation and the landslide body;

c) the rates of the deep displacement provided by inclinometers have time trends very similar to those of pore water pressure on the slip band.

Thus, it can be inferred that the relatively high values of hydraulic conductivity along the slip band and the connection of this latter to the atmosphere can be responsible of the kinematic response of the earthflow to rain. The continuous displacements along the slip band are probably responsible of an open fabric that facilitates water flow; this aspect is currently under examination. Besides its intersection with the ground surface, the connection of the slip surface with the atmosphere can occur by several types of discontinuities which are present in the landslide.

As final consideration, it seems reasonable to observe that the existence of a more permeable slip zone must be kept in due consideration in the design of drain systems. For instance, in the case under examination, first calculations show that an effective drain system must intersect the slip band.

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References

Belle, P., Aunay, B., Lachassagne, P., Ladouche, B., Join, J.L. (2018). "*Control of tropical landcover and soil properties on landslides' aquifer recharge, piezometry and dynamics"*. Water 10: 1491.

Bogaard, T.A. and Greco, R. (2016). "*Landslide hydrology: From hydrology to pore pressure*". WIREs Water 3: 439–459.

4. Brunsden, D. (1999). "Some geomorphological considerations for the future development of landslide models". Geomorphology 30(12): 13–24.

Cotecchia, C., Vitone, C., Santaloia, F., Pedone, G., Bottiglieri, O. (2015). "*Slope instability processes in intensely fissured clays: case histories in the Southern Apennines"*. Landslides 12: 877–893.

Di Maio, C., De Rosa, J., Vassallo, R., Coviello, R., Macchia, G. (2020). "*Hydraulic conductivity and pore water pressures in a clayey earthflow: experimental data".* Submitted to Geosciences

De Rosa, J., Pontolillo, D.M., Caputo, V., Di Maio, C., Scaringi, G. (2019). "*Evaluation of hydraulic conductivity in the slip zone of an earthflow in clay shales*". In Proceedings of the XVII European Conference on Soil Mechanics and Geotechnical Engineering ECSMGE, Reykjavik, Iceland. ISSMGE Online Library, 546-552.

Di Maio, C., Vassallo R., Vallario, M., Pascale, S., Sdao, F. (2010). "*Structure and kinematics of a landslide in a complex clayey formation of the Italian Southern Apennines".* Engineering Geology 116: 311-322.

Di Maio, C., Vassallo, R., Vallario, M. (2013). *"Plastic and viscous shear displacements of a deep and very slow landslide in stiff clay formation".* Engineering Geology 162: 53-66.

Di Maio, C., Scaringi, G., Vassallo, R. (2015). *"Residual strength and creep behaviour on the slip surface of specimens of a landslide in marine origin clay shales: influence of pore fluid composition".* Landslides 12(4): 657-667.

Di Maio, C., Vassallo, R., Scaringi, G., De Rosa, J., Pontolillo, D.M., Grimaldi, G.M. (2017). "*Monitoring and analysis of an earthflow in tectonized clay shales and study of a remedial intervention by KCl wells".* Rivista Italiana di Geotecnica 51(3): 48-63.

Guida, G. and Iaccarino, G. (1991). "*Fasi evolutive delle frane tipo colata nell'alta valle del F.Basento (Potenza)*". Proc. Studi Trentini di Scienze Naturali, Acta Geologica LCVIII: 127-152.

Grimaldi, G.M.; Pontolillo, D.M.; De Rosa, J.; Rizzo, E.; Di Maio, C. (2018) Modelling water flow and ion transport in clay soils: the case of KCl wells in the head of an earthflow. In Micro to MACRO Mathematical Modelling in Soil Mechanics, Trends in Mathematics book series, Birkhauser, Basel, Swiss, 159-167.

Hencher, S.R. (2010). *"Preferential flow paths through soil and rock and their association with landslides".* Hydrological Processes 24(12): 1610–1630.

Hvorslev, M.J. (1951). "*Time lag and soil permeability in ground-water observations".* Waterways experimentary station. Corps of Engineers, US Army. Vicksburg, Mississipi. Bulletin 36: 50.

Shao, W., Bogaard, T., Bakker, M., Berti M. (2015). *"The influence of preferential flow on pressure propagation and landslide triggering of the Rocca Pitigliana landslide".* Journal of Hydrology 543(B): 360-372.

Sidle, R.C., Greco, R., Bogaard, T.A. (2019). *"Overview of Landslide Hydrology".* Water 11: 148.

Urciuoli G., Comegna L., Di Maio C., Picarelli L. (2016*)."The Basento Valley: a natural laboratory to understand the mechanics of earthflows".* Rivista Italiana di Geotecnica 50(1): 71-90.

Vassallo, R., Grimaldi, G.M., Di Maio, C. (2015). *"Pore water pressures induced by historical rain series in a clayey landslide: 3D modeling".* Landslides 12: 731-744.

Vassallo, R., Doglioni, A., Grimaldi, G.M., Di Maio, C., Simeoni, V. (2016). *"Relationships between rain and displacements of an active earth flow: a data driven approach by EPRMOGA".* Natural Hazard 81: 1467–1482.

Vitone, C. and Cotecchia, F. (2011). *"The influence of intense fissuring on the mechanical behaviour of clays".* Géotechnique 61(12): 1003–1018.