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Effectiveness of trench and sub-horizontal pipe drains in clayey landslides: the influence of the slip zone permeability

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ABSTRACT: The paper shows numerical results on the effects of two types of drain systems, trenches and sub-horizontal pipes, aimed to the stabilization of two deep clay landslides of the Italian Apennines (Costa della Gaveta and Varco d'Izzo, respectively). The results of three-dimensional numerical analyses carried out with a commercial FEM code show that the hydraulic conductivity of the slip zone is the most influencing parameter of drain systems. Long-term monitoring and experimentation indicate that the hydraulic conductivities of the slip zones of the two landslides are higher than those of their bodies and parent formation. This characteristic causes two effects: on the one hand, the permeable slip zone exerts a generalized drainage action that makes average pore water pressures in the slope decrease; on the other hand, the permeable zone can allow for fast and intense response to rainfall of pore water pressures just along it. Such latter effect causes a rapid response to rain of basal displacement rates. In the case of the CdG landslide, a hypothetical trench drain system can reduce significantly water pressures in the permeable slip zone only if they penetrate it. In the case of the VdI landslide, which is crossed by a tunnel with a system of 15 m long sub-horizontal pipe drains, very close to a slip surface, the numerical results show that the effects of the drains decrease with the slip zone permeability increasing.

KEYWORDS: clay landslide, slip zone, displacements, pore water pressures, hydraulic permeability, drainage.

INTRODUCTION

Deep and very slow landslides in ancient structurally complex clay formations are widespread in the Italian Apennines. For their distribution and extension, they affect many important roads and railways, with high social costs (Di Maio, 2025). The Costa della Gaveta slope, in the upper Basento valley, close to the city of Potenza, is a typical Italian southern Apennine slope subject to such type of landslides. For its representativeness and complexity, it has become an open-air laboratory, by some ten years investigated and monitored by systems of piezometers and tensiometers, inclinometers, GPS stations, total stress cells, distributed fiber-optic strain sensors (Calcaterra et al., 2012; Di Maio et al., 2013a, 2015, 2017; Vassallo et al., 2020; Minardo et al., 2021). Di Maio et al. (2020; 2021) presented data showing that the permeability of the shear zone of the most important landslide of the slope, the homonymous Costa della Gaveta landslide (hereafter named CdG), can be much higher than that of the landslide body itself and of the underlying firm formation. This allowed to explain why pore water pressures in the slip zone vary significantly and rather quickly with rain even at large depths, whereas they vary negligibly elsewhere, even in the shallowest soil under a thin vadose zone. Consequently, the hydraulic peculiarity also explained why the time trend of the basal displacements recorded by the inclinometers is similar to the time trend of cumulated rainfall. In such type of landslides, a trench drain system aimed to reduce the rainfall influence is effective only if the trenches penetrate the slip zone (Vassallo & Di Maio, 2025). The mechanism of movement of the nearby Varco d'Izzo landslide (VdI) is less clear, both because it is more complex than the CdG one, and the available time series of deep displacements and water pressures are not so continuous. Nevertheless, this paper shows that reasonable hypotheses on its kinematics can be formulated on the basis of GPS data and available inclinometer profiles. So, the hydraulic effects of a tunnel crossing the landslide foot and of its sub-horizontal pipe drain system can be analyzed.

1 CASE HYSTORIES

The Costa della Gaveta slope is a typical slope in structurally complex formations of the upper Basento valley (Urciuoli et al., 2016). The formations outcropping along the slope are locally called Varicoloured Clays (Upper Cretaceous – Lower Miocene) and Corleto Perticara (Upper Eocene – Lower Miocene) (Figure 1). The former formation, about 200 m thick, is an alternation of clays, clayey marls and subordinately calcareous marls and limestones. The latter formation, about 100 m thick, is constituted of limestone banks, calcareous marls and clay levels. The hill is affected by fault systems that have strongly influenced its structure and its morphological evolution. The three major landslide systems of the slope, *Varco d'Izzo*, *Costa della Gaveta* and *Mattine*, have in fact developed around the faults. The main landslides of the systems are roto-translational landslides evolved into deep earthflows, which subsequently underwent very slow sliding phases.

The landslides' bodies are constituted by fine clayey matrices incorporating rock elements of various sizes. The clay fraction c.f. varies between 25% and 75%. The liquid limit w_L varies between 50% and 100%; the plastic limit w_P varies slightly around an average value of 25%. The average water content w is about 15% in the firm formation, around 25% in the landslide bodies. The lab residual friction angle varies in a large range, the average mobilized value, determined by 3D LEM back analyses for CdG, is $\varphi'_m \cong 13°$ (Di Maio et al., 2021).

The displacements of the landslides are being monitored

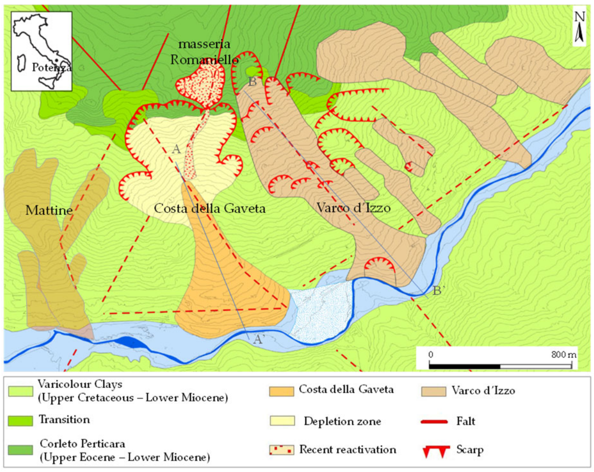


Figure 1. Geological map of the Costa della Gaveta slope with the homonymous landslide system, the Mattine and the Varco d'Izzo systems (Di Maio, 2025).

by inclinometers and GPS antennas since 2005. DInSAR series are also analyzed and compared to the other types of data. Figures 2 and 3 show some inclinometer profiles relative to CdG and VdI, respectively, highlighting that the prevalent type of movement is sliding localized in a narrow band in both landslides. Internal deformations also occur, but basal displacements largely prevail (Di Maio et al., 2013a-b). So, the superficial displacements are very close to the deep ones. The main landslide bodies, with lengths of more than 1000 m and average widths of 200 m - 300 m reach depths of about 40 m (Figure 4). The VdI system is characterized by two main slip surfaces, at about 20 m and 40 m respectively. In the monitoring period, the basal displacements occurred at constant yearly rate, with average values between a few cm/y and a few mm/y. Such spatial variation has been interpreted in the CdG landslide as the effect of the variations in the area of the cross-sections, according to a mechanism of movement at constant soil discharge (Di Maio et al., 2010). In the VdI landslide system, the kinematics is more complex but its main landslide also moves along the slip surfaces with constant yearly rates. Substantial constancy over time is also exhibited by the superficial yearly rates of both CdG and VdI landslides, evaluated by inclinometers, GPS stations and DInSAR data (Vassallo et al., 2021).

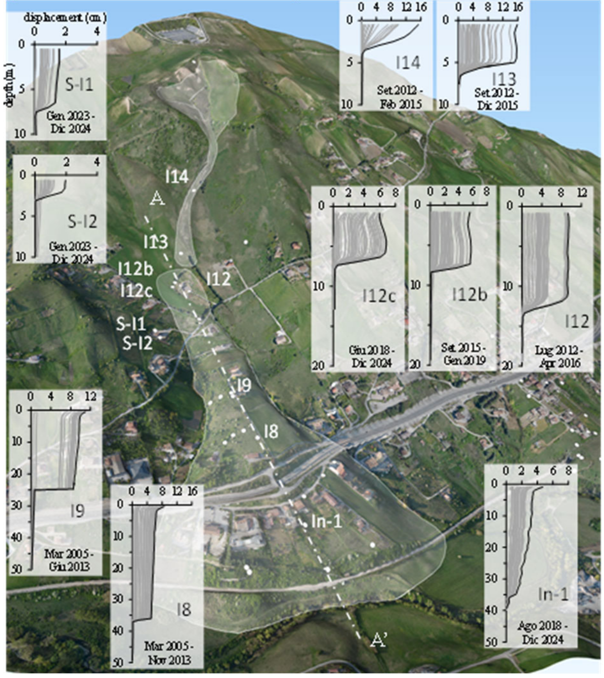


Figure 2. Inclinometer location and profiles indicating the type of landslide movements in the Costa della Gaveta (CdG) system (Di Maio, 2025). The units of measure are all the same as in SI-1.

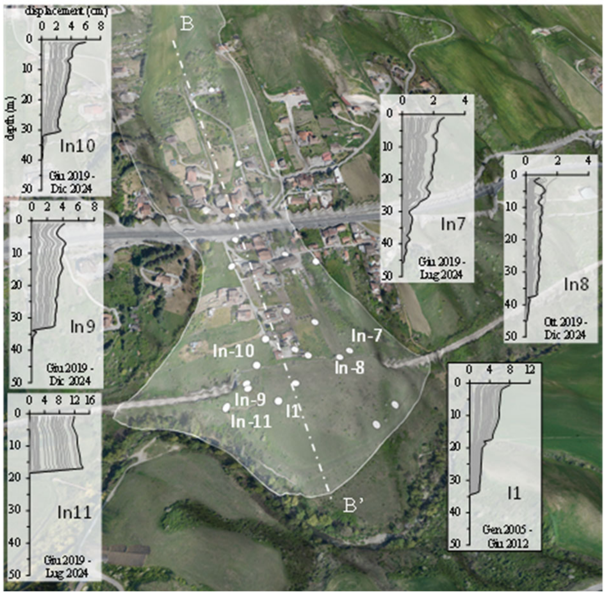


Figure 3. Inclinometer profiles representative of the type of landslide movements in the Varco d'Izzo (VdI) system (Di Maio, 2025). The units of measure are all the same as in In10.

To constant yearly displacement rates, there corresponds significant rain-dependent seasonal variability. The time trend of cumulated rainfall is compared in Figure 5 to the time trend of basal displacements recorded in three inclinometers of the CdG landslide. The displacement rates in I9 and I12 obtained by dividing, respectively, the former by 2 and the latter by 4.3 are very close to each other and to those recorded in I8. This is one of the occurrences that allowed the kinematic interpretation of the landslide movement at constant soil discharge. Furthermore, the three displacement curves exhibit a time trend similar to that of cumulative daily rainfall. The analysis of the correlation between displacements and rainfall over long periods performed with the EPRMOGA technique (Evolutionary Polynomial Regression Multi Objective Genetic Algorithm) allowed to evaluate quantitatively the strong influence on the displacement rates of contemporary rainfall (Vassallo et al., 2016).

The Varco d'Izzo landslide is more complex than the CdG one, and its inclinometer data series are less continuous. Notwithstanding this, the comparison of the GPS series of the two landslides allows reasonable hypotheses on the VdI response to rainfall.

Figure 6a shows the basal displacements obtained by inclinometers and the GPS superficial displacements measured in the CdG landslide. Moreover, it can be observed that the GPS F5 data series is consistent and synchronous with the basal displacement series determined by inclinometers. The difference is that when the inclinometer displacement rate decreases, the GPS displacement rates become negative. This

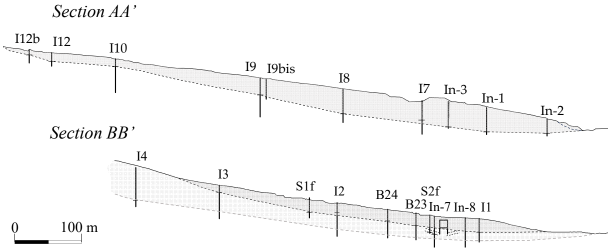


Figure 4. Longitudinal sections of the CdG and VdI landslides with indication of some inclinometers.

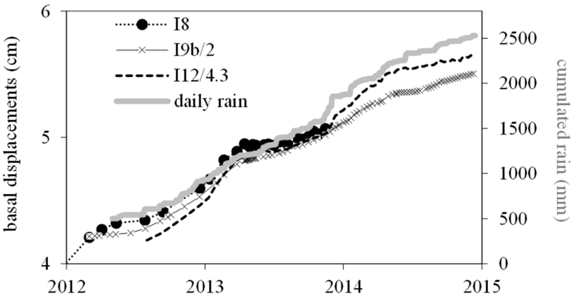


Figure 5. Basal inclinometer displacements at Costa della Gaveta and cumulated daily rainfall.

effect has been explained by Calcaterra et al. (2015) as due to swelling and shrinkage of the shallower soil layers.

Figure 6b compares the GPS data of F5 in CdG landslide to F1 and F2 (multiplied by 0.9 and 1.1, respectively) in VdI landslide, showing the synchrony of the data in the monitoring period. Since, as said above, in both landslides the surface displacements are largely influenced by the basal ones, the synchrony can reasonably be hypothesized to hold also in the basal displacements of the two landslides. The VdI basal displacements can thus be considered synchronous with rainfall. This is not so obvious in deep clay landslides.

Di Maio et al. (2020; 2021; 2025), for the CdG landslide, on the basis of a number of *in situ* permeability tests and long-term piezometric monitoring, explained the synchrony among basal displacements and cumulated rainfall with the high values of hydraulic permeability of the slip zone - much higher than those of the landslide and firm formation - and the connection of the zone with the atmosphere. The experimental results shown in this section suggest that similar hydraulic characteristics can also be hypothesized for the VdI landslide.

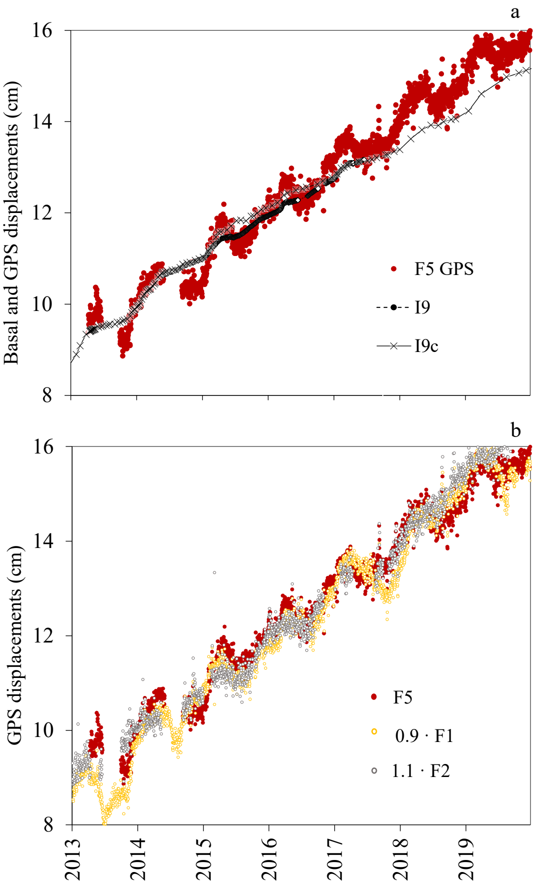


Figure 6. Comparison of: the inclinometer basal displacements and superficial GPS (F5) displacements of Costa della Gaveta landslide (a); the GPS displacements F1 - F2 of Varco d'Izzo and F5 of Costa della Gaveta (b).

2 3D MODELING OF A DEEP DRAINAGE EFFECTS

Subsurface drainage is one of the most widely used remedial measures for slow landslides in saturated fine-grained soils, when pore water pressures play an important role on stability. This is the case of the considered two landslides, for which it seems thus interesting to explore the influence of the peculiar hydraulic characteristics on the effects of drainage systems. Section 2.1 presents numerical results showing the influence of the slip zone permeability on the effectiveness of a trench drain system designed for the CdG landslide. Section 2.2 shows the effects of a sub-horizontal pipe drain system for the VdI landslide, the foot of which is crossed by a tunnel with such a type of drainage system. In both cases, the influence of the slip band permeability is investigated.

2.1 *Trench drains*

Trench drains are considered the most suitable solution for landslides on gentle slopes, with slip surfaces sub-parallel to the ground, as in the case of CdG landslide body. For simplicity, hereafter, the term "trench" is used irrespective of the excavation depth and of the intersection with the slip surface. It is understood that deep trench drains that intercept the slip surface and provide additional frictional resistance coincide with counterfort drains. The technology to excavate the trenches depends on the excavation depth. Shallow trenches up to a depth of approximately 5 m can be dug by an excavator. Deep trenches reaching the maximum depth of 25–30 m are excavated by means of grab shells. Some technologies adopted for constructing deep trenches are described by Urciuoli and Pirone (2013).

Many theoretical solutions are available for a simplified ideal scheme of parallel trenches in an infinite slope (among others: Hutchinson, 1977; Burghignoli & Desideri, 1987; Bromhead, 1984; Di Maio & Viggiani, 1987; Desideri et al., 1997; Pun & Urciuoli, 2008). Cotecchia et al. (2016; 2019; 2020) and Elia et al. (2017) analyzed the influence of the geometry of the landslide cross-section, of the partial saturation of the soil, of the slope-vegetation-atmosphere interaction. Tagarelli & Cootecchia (2022) performed fully coupled 2D numerical hydromechanical analyses using different constitutive laws. Urciuoli et al. (2020) evaluated the influence of permeable soil layers not connected to the atmosphere.

The influence on the effects of trench drains of a slip zone connected to the atmosphere and more permeable than the surrounding soil has been analysed by Vassallo & Di Maio (2025). The authors, using the finite element software SEEP3D, evaluated the effects of a system of trench drains installed in a clay landslide characterized by very low values of hydraulic conductivities ($\leq 10^{-9}$ m/s) within its body and by higher values in the slip zone, in the sliding direction. The used 3D model is a simple reference case, easily reproducible (Figure 7). The slip surface transversal section is an arc of a circle with a depth of 25 m from the ground. The subsoil consists of three different regions: landslide body, 2-m-thick sliding zone and stable formation; the hydraulic and mechanical properties are those evaluated for CdG landslide and reported in Figure 7. 3D analyses were performed applying on the ground the historical rainfall series recorded at Costa della Gaveta. Rainfall was applied as an infiltration q_{rain}. A weekly temporal resolution was adopted for both the rainfall series, Δt_{rain}, and the calculation step, Δt_{calc}. On the upper and lower boundaries, constant values of the hydraulic total head were assumed, corresponding to u = 0 and u = -30 kPa at ground level, respectively. The lateral and basal planes were considered impervious, i.e., the zero-flux condition was applied. The steady state initial condition necessary to conduct the transient calculation under the historical rainfall series was evaluated considering an infiltration at the ground $q = 9 \cdot 10^{-10}$ m/s. After several attempts, such value was found to provide a water pressure distribution close to the average distribution relative to historical transient of about 20 years. The analyses were performed for four cases: a) without permeable slip zone and without drains, b) without permeable slip zone and with drains, c) with permeable slip zone and without drains, d) with permeable slip zone and drains. Figure 8 shows, for a trench depth of 12 m, the results in the central cross section of the landslide at the time t* which is the most penalizing for the slope stability (October 2017). The figure reports pore water pressures along the slip zone and shows that in the case of $k_{sz}=k_l$ (absence of permeable slip zone, cases a and b), the drain effects on the slip surface are important even if the trenches do not reach the surface. On the contrary, in the presence of permeable band (case c and d), the effects of the trenches are much lower. The results clearly suggest that a drain system designed without considering the hydraulic peculiarities of the slip zone risks to be ineffective. The influence of the drain depth on pore water pressures in the slip zone was also analysed. Figure 9 shows the results in terms of water pressures in the lowest point P of the considered median transversal section at the time t*, and also in terms of average water pressure on the slip surface in the same section. The results refer to $k_{sz} = 10^{-6}$ m/s and u=0 on the ground surface. It can be observed that pore water pressures decrease slightly with the trench depth until about 20 m whereas they undergo dramatic reductions for depths between 20 m and 21 m, i.e., when the lateral trenches penetrate the slip zone. Further deepening of the internal trenches causes further pressure decrease. Similar effects are obtained for different boundary conditions at the ground surface. It is worth noting that with $k_{sz} = 10^{-9}$ m/s, the trend of pore water pressures against depth would have been very different and almost linear (Vassallo & Di Maio, 2025).

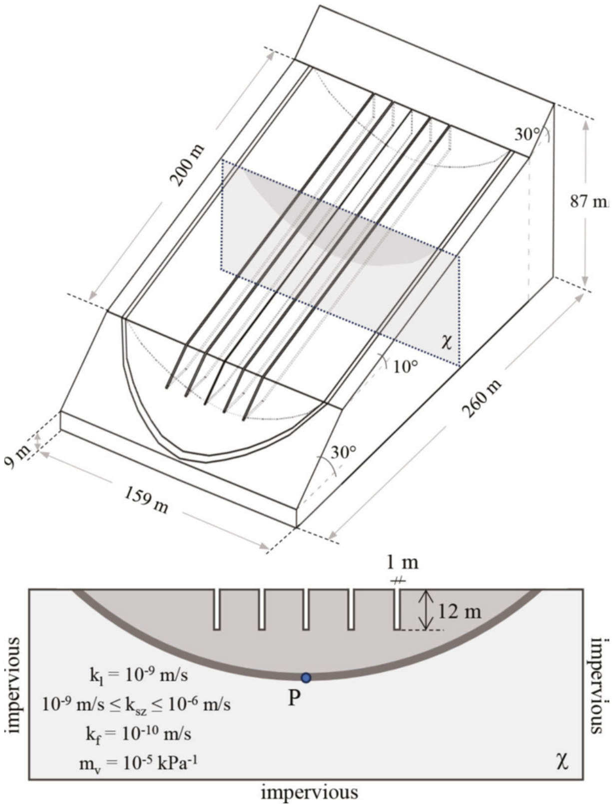
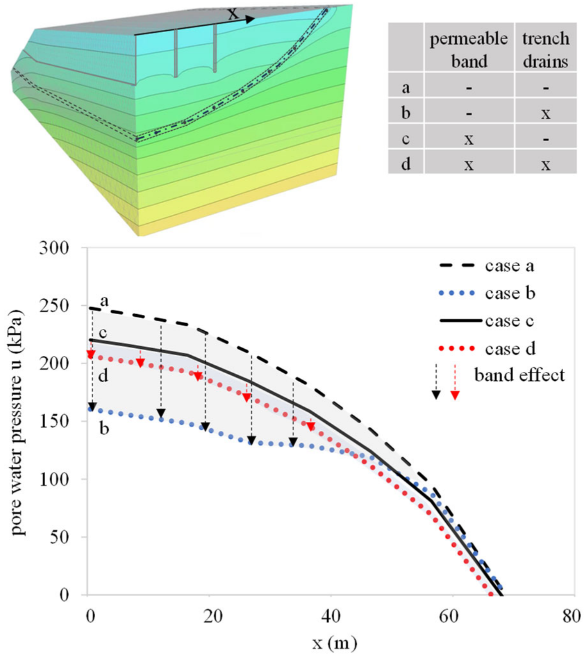


Figure 7. 3D model and transversal section of a landslide with trench drains (Vassallo & Di Maio, 2025).



	permeable band	trench drains
a	-	-
b	-	x
c	x	-
d	x	x

Figure 8. Pore water pressures on the slip surface in section χ at t = t*, and for a trench depth of 12 m (redrawn from Vassallo & Di Maio, 2025).

2.2 *Sub-horizontal pipe drains installed from a tunnel*

The accumulation of the Varco d'Izzo landslide is crossed by a tunnel of the national railway. The tunnel, 200 m long, first constructed in 1870, having been damaged by the landslide movements, was rebuilt in 1992. A reinforced concrete box structure 7.5 m × 7.5 m, 1 m thick, was constructed between two pile walls with pile diameter of 1 m and depth of 20-21 m. Longitudinally, the tunnel is constituted by eight sectors linked by joints (Ostuni et al, 2025). From the base of the tunnel, both upslope and downslope, sub-horizontal drain pipes approximately 15 m long were installed. In order to analyze the effects on pore water pressures of the tunnel structure, horizontal pipe drain length and slip surface permeability, a 3D model was constructed by the software SEEP3D.

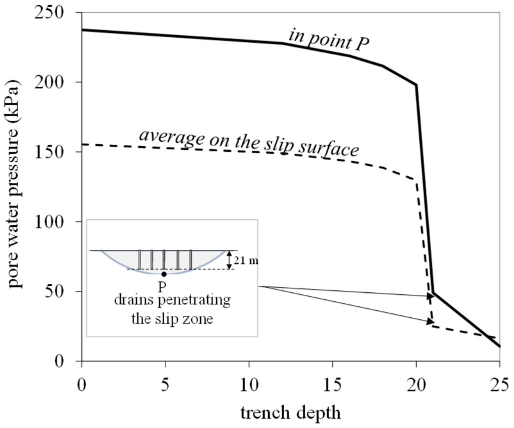


Figure 9. Effects of drain depth on pore water pressures in P and average pressures on the slip surface, under the hypothesis of u=0 on the ground surface and permeable slip band with $k_{sz}=10^{-7}$ m/s.

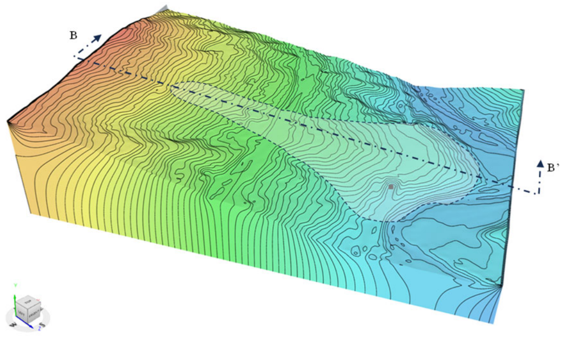


Figure 10. Seep 3D model of the Varco d'Izzo landslide.

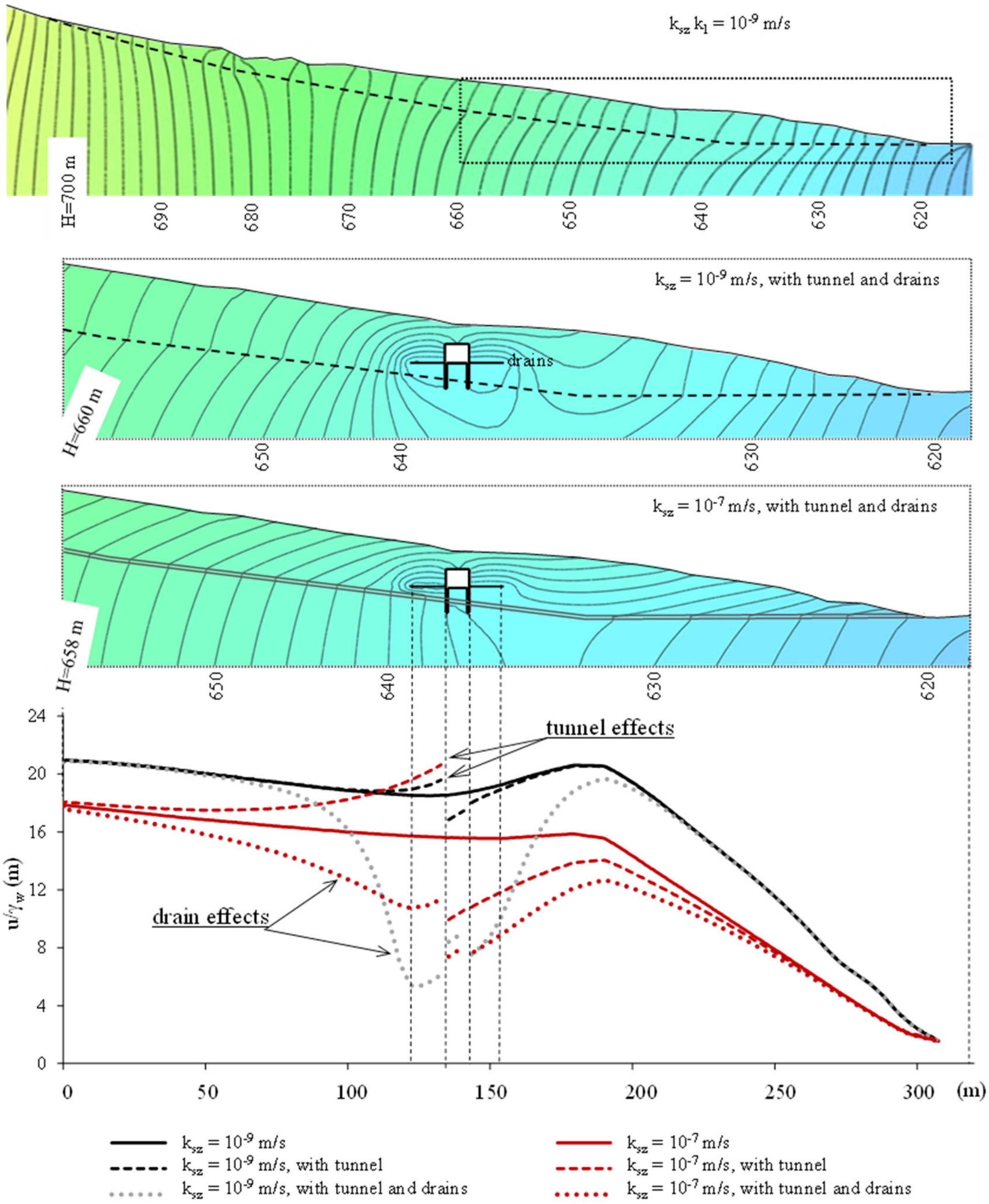


Figure 11. Hydraulic total head contours obtained in the absence of the tunnel and drains, and for a slip zone with the same hydraulic conductivity as the landslide body (a); zoom of the section in the case of the presence of tunnel, pile walls (21 m deep) and drains (15 m long) (b); slip band more permeable than the landslide (c); pressure head along the slip surface with and without tunnel, drains, permeable slip band (d).

Figure 10 shows the considered domain with an example of hydraulic total head contours for one of the considered cases, i.e., without drains. The results relative to the longitudinal section BB' are shown in Figure 11 under various conditions. Figure 11a shows the total head contours obtained in the absence of tunnel and drains, and for a slip zone with the same hydraulic conductivity as the landslide body (k_{sz}=k_l=10^{-9} m/s). Figure 11b shows a zoom of the rectangle indicated in Figure 11a, but in the presence of tunnel, pile walls and drains. Figure 11c considers the presence of a slip band more permeable than the landslide. Significant changes in the total head contours can be clearly appreciated. Figure 11d shows two sets of curves of pressure head along the slip surface in the considered section: one relative to a slip band with the same permeability as the landslide body, k_{sz}=k_l=10^{-9} m/s (black curves), and the other relative to a more permeable slip band, with k_{sz} = 10^{-7} m/s (red curves). Each set considers three cases: 1) the slope without anthropic works, 2) the slope with the tunnel and its pile walls, 3) addition of pipe drains. The results show a significant influence of the slip band permeability. In particular, when k_{sz}=k_l=10^{-9} m/s, the impermeable tunnel and pile walls cause only a small increase in pore water pressures upslope of the structure and close to it, and a small decrease downslope. On the contrary, when k_{sz}=10^{-7} m/s, the same structure causes large variations for large distances, both upslope and downslope of the structure, and the slip surface itself causes a generalized drainage. The drain effects are much influenced by their length. This is shown by Figure 12 for length of the upslope drains varying between 0 and 40 m, in the case in which the downslope drains are 15 m long. For lengths between 25 m and 27 m, the upslope drains intercept the permeable slip band. Their effects increase further if the drains penetrate the parent formation. However, the intersection of the pipes with the zone of localized shear strains should be avoided.

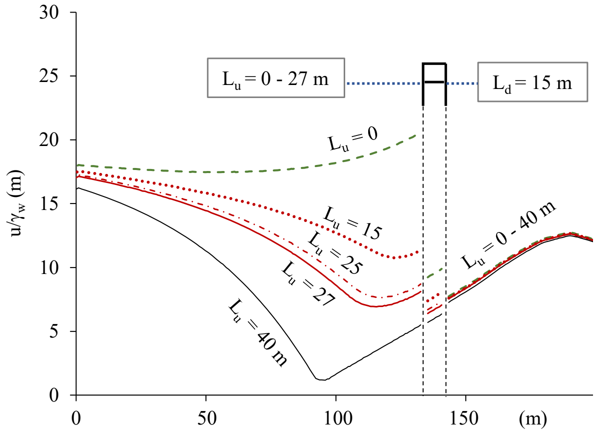


Figure 12. Pressure head along the permeable slip surface ($k_{sz}=10^{-7}$ m/s) for various lengths L_u of the sub-horizontal upslope pipe drains and for a length L_d = 15 m of the downslope drains.

3 CONCLUSIONS

This paper presents experimental and numerical results relative to the influence of the slip band permeability on the effectiveness of two types of drains. First it shows that in slow moving, deep, clayey landslides, the hydraulic conductivity of the slip zone ($\leq 10^{-5}$ m/s) can be much higher than in the landslide body and in the firm formation which, in turn are very low ($\leq 10^{-9}$ m/s). If the slip zone is connected to the atmosphere, such characteristics imply that pore water pressures and basal displacements rapidly respond to rain. Under these conditions, the design of drain systems aimed to risk reduction needs to take into account the peculiar permeability distribution. This latter makes trench drains effective if the trenches reach the slip band. The slip zone more permeable than the landslide also reduces the effects of sub-horizontal pipe drains compared to the case of equal permeabilities. Their effects increase with their length but, obviously, after the intersection with the slip surface the drains would shortly go out use.

4 ACKNOWLEDGEMENTS

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