Efficacy of drainage trenches to stabilize deep slow landslide in clay slopes

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Efficacy of drainage trenches to stabilise deep slow landslides in clay slopes

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The paper reports the results of a research aiming at the definition of innovative strategies to mitigate the risk generated by deep landsliding due to the slope-atmosphere interaction. The aim stems from the recognition of the connection between the accelerations of deep slow landslides and the seasonal fluctuations of the piezometric heads found to occur down to large depths in slopes, effect of seasonal cumulated rainfall infiltration, as verified in previous research studies for fissured clay slopes of the Italian southern Apennines. Given this slope behavior, the effects as stabilizing measure of systems of drainage trenches, from medium depth to deep, have been verified through the combination of finite element modeling of seepage and limit equilibrium analyses. The model results show that the trench system generates a 'group effect' on the piezometric heads at large depth, due to which the maximum drop in piezometric head occurs along the portion of maximum depth of spoon-shaped slip surfaces underlying the trench system. Hence, the reduction in piezometric head generated by the trench system makes such system an effective mitigation measure for deep landsliding. In the paper, the stabilizing effect of the trench system is also verified through its modeling for a deep landslide case history.

KEYWORDS: landslides; pore pressures; trenches

NOTATION

A	soil activity index
c'_p	peak cohesion of soil
$E(t)$	drainage efficiency at time t
F	slope stability factor
H	trench depth
h_0	piezometric head at time $t = 0$
$h(t)$	piezometric head at time t
k	coefficient of soil permeability
L	total width of the trench system
n	number of trenches
S	spacing between trenches
s	soil suction
v	landslide displacement rate
z	depth of slip surface
θ	soil water content
ϕ'_p	peak friction angle of soil
ϕ'_r	residual friction angle of soil

INTRODUCTION

The mitigation of landslide risk may implement engineering stabilisation measures that need to be designed in light of the failure mechanism generating the risk (Terzaghi, 1950; Cotecchia *et al.*, 2009, 2014c). With regard to slow and deep landslides (deeper than 30 m; Hutchinson, 1977), since the structural stabilisations (e.g. retaining structures, major slope re-profiling, deep wells etc.) may be highly expensive and, in some cases, also not effective in the long term (e.g. piled diaphragms in rear scarp areas intended to delay failure retrogression), it is rational to investigate alternative stabilisation strategies. These should be addressed to either increase the available shear strengths or mitigate the external triggering causes. On the basis of studies that have shown deep and slow landslides to be connected to the slope–atmosphere interaction even in clay slopes (Cotecchia *et al.*, 2014b, 2014c), this paper proposes the mitigation of the activity of deep landslides by means of medium depth drainage trenches.

The above-mentioned studies have been carried out in a pilot region, the Daunia–Lucanian Apennines (Southern Italy, Fig. 1; Cotecchia *et al.*, 2009, 2010), where deep landsliding is widespread across slopes formed of clayey flysch, the clay matrix of which is fissured and characterised by very low shear strength properties. The stabilisation strategies proposed in the paper have been identified through a study of the causes triggering landslides all over the pilot region; hence, in the following, the main results of this study are briefly recalled first.

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HYDROMECHANICAL FACTORS TRIGERRING LANDSLIDES IN THE DAUNIA–LUCANIAN APENNINES

Flysch, which are widespread in the study region, is generally formed of alternating layers of fissured clays and fractured rocks. The clays, which include a clay fraction ranging between 50 and 70%, are of high plasticity [plasticity index (PI) $30\% < \text{PI} < 80\%$], medium-to-high activity ($0{\cdot}5 < A < 1$) and are found to be characterised by medium-to-high overconsolidation ratios. Due to fissuring, their peak strength parameters are significantly low, ranging between $c'_p = 0$, $\phi'_p = 15°$ and $c'_p = 20$ kPa, $\phi'_p = 20°$ (Vitone & Cotecchia, 2011; Vitone *et al.*, 2013; Cotecchia *et al.*, 2014a).

The results of the studies of landslides across the region have shown the recurrence of slow to very slow ($v < 5 \times 10^{-5}$ mm/s; Cruden & Varnes, 1996) sliding mechanisms, deeper than 35 m, which are the result of evolution of old landslides, with operational strengths, ϕ', between peak and residual stages, $\phi'_p < \phi' < \phi'_r$ (Cotecchia *et al.*, 2010). Furthermore, both ground surveying and inclinometer monitoring have given evidence to the recurrence of movement accelerations from the end of winter to mid-spring.

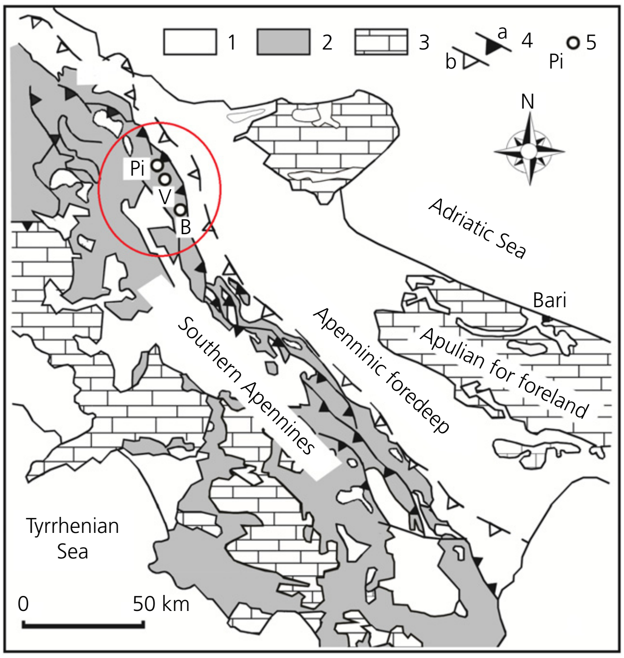


Fig. 1. Schematic geological map of the Southern Apennines (after Scrocca *et al.* (2005), modified) and location of the study region (included in the ellipse). 1 – marine and continental deposits, wedge basin deposits, 2 – Apenninic units, 3 – carbonate platform units, 4 – main thrust (a) and buried overthrusting (b), 5 – location of the pluviometric stations (data in Fig. 2): B – Bovino, Pi – Pietramontecorvino, V – Volturino

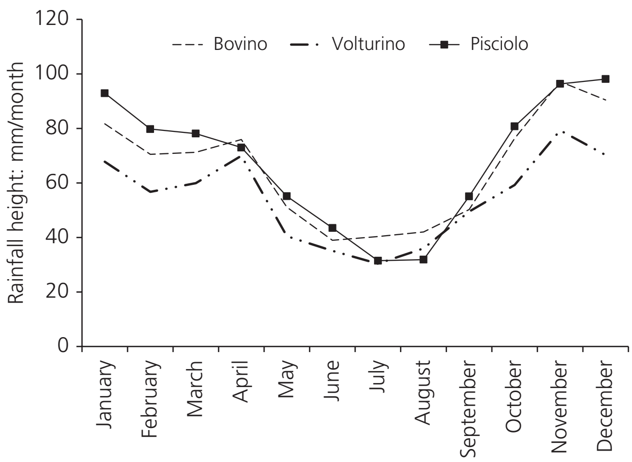


Fig. 2. Average monthly rainfalls measured at three different stations of the study region

The piezometric regime of the slope has been found to be generally consistent with a groundwater table at shallow depth and high piezometric heads down to large depths. Therefore, it represents a landslide predisposing factor (Cotecchia *et al.*, 2014b), in addition to clay fissuring.

Figure 2 reports the average monthly rainfalls, from 1972 to 2003, at three representative sites in the region; the data show that the climate is generally dry in summers and wettest from mid-winter to mid-spring. As example of the piezometric heads monitored at several sites in the region, Fig. 3, from Cotecchia *et al.* (2014b), reports the piezometric level excursions (P7 electric piezometers in the figure) against time, as monitored in the Pisciolo slope, along with the 180 days cumulated rainfalls at the site and the rates of movement for a deep landslide body measured through both GPS (sensor S2) and inclinometer (I12) monitoring. The data in the figure indicate that both piezometric heads and landslide displacement rates follow a seasonal trend, in accordance with the 180 days cumulated rainfall trend, with all the maximum values occurring between the end of winter and mid-spring. Hence, the hydraulics of the slope represents a predisposing factor of landslide reactivation and the slope–atmosphere interaction represents a triggering cause of the displacement acceleration (Cotecchia *et al.*, 2009, 2010).

The slope internal factor allowing for sufficiently high rates of infiltration down to large depths is the 'mass permeability' of flysch formations, which results from the permeability of the fissured clay matrix, and is found to be about $k_{clay\ field} = 1 \times 10^{-9}$ m/s through field tests (Pedone, 2014; Cotecchia *et al.*, 2014b), and that of the fractured rocks, floating within the clay matrix, and of the coarse soil inter-beddings.

Finite-element analyses of the yearly transient seepage taking place in prototype slopes of the region have been carried out by Pedone (2014) implementing the net daily rainfalls at the ground surface (Allen *et al.*, 1998; Cotecchia *et al.*, 2014b). These have confirmed that a combination of climate and the hydraulic properties of the slope soils allows for seasonal fluctuations of the piezometric heads down to large depths, which bring about variations in the slope stability factor from 20 to 8% for slip surfaces of maximum depth from 20 to 40 m, respectively. Such diagnosis of the landslide mechanisms recurrent in the region has brought about the proposal of using drainage interventions as a remedial measure for medium to deep sliding, the efficacy of which is discussed in the following.

DRAINAGE TRENCHES: EFFECTS ON DEEP SLIDING SURFACES

The proposed intervention is represented by a system of drainage trenches, parallel to the longitudinal section of the landslide body, of depth ranging from 12 to 16 m, the cross-section of which is schematically shown in Fig. 4 (see the geometrical parameters of the system).

The dependence of the hydraulic efficiency of the drainage system (Hutchinson, 2004) on the flow component normal to the cross-section in Fig. 4 has been considered to be negligible, according to the evidence provided by Stanic (1984) and Hutchinson (2004). Hence, the efficiency of the drainage trenches has been calculated using the code SEEP/W (GeoStudio, 2004) through a two-dimensional (2D) finite-element analysis of the transient seepage in the transverse section of the system, shown in Fig. 4. This figure also shows the cross-section of a deep spoon-shaped slip surface of a landslide body to be stabilised by means of the drainage trenches.

The trenches have been simulated as rectangular clusters of 1 m width (Fig. 4), filled with a coarse-grained soil, while the rest of the section has been set as formed of uniform clay. The lateral boundaries of the mesh have been set at a distance of 126 m from the centreline, hence at a distance from the side of the most lateral trench ranging from 87 to 113 m (depending on the number of trenches). Along these boundaries the pore pressures have been fixed and assigned equal to those applying to the initial condition. The depth of the lower boundary of the mesh, which has been prescribed as impermeable, has been set equal to 70 m from the ground level (g.l.).

The soil above the water table has been assumed to be partially saturated, according to its water retention curve (WRC) $\theta(s)$ (θ for volumetric water content and s for suction), and to have a permeability function, $k(s)$, modelled according to the equations proposed by Mualem (1976)

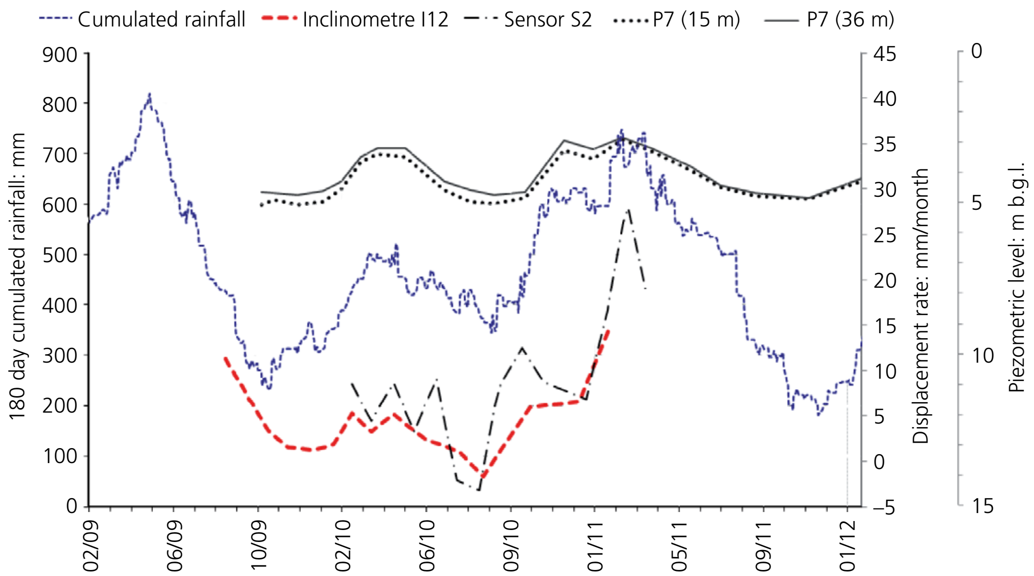


Fig. 3. Rate of movements measured with GPS sensor S2 and inclinometer I12 (at 19 m depth); piezometric levels logged by means of the P7 electric pore pressure cells (at 15 and 36 m from g.l.) and 180 days cumulated rainfalls at Pisciolo site (Cotecchia *et al.*, 2014a)

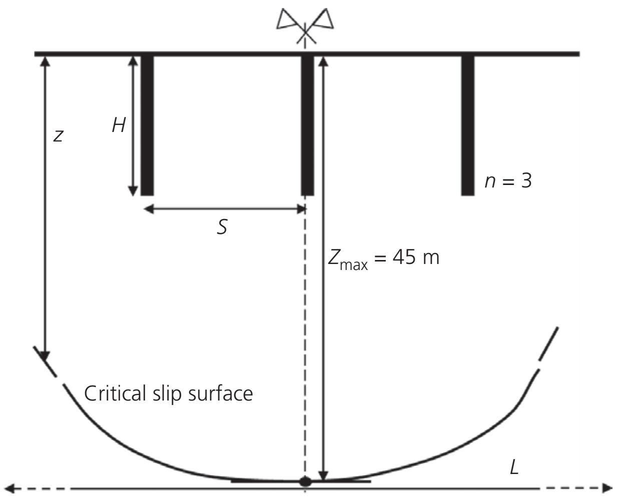


Fig. 4. Schematic cross-section of the drainage system and of the slip surface. *S* – spacing between trenches; *H* – depth of trenches; *z* – depth of slip surface; *L* – total width of the trench system

and Van Genuchten (1980). The retention data of both clay and the trench filling soil, which have been regressed according to the Van Genuchten (1980) model and thereafter implemented in the analyses, are shown in Fig. 5. In particular, the WRC used for the clay is representative of unfissured high retention overconsolidated clays (Cafaro & Cotecchia, 2001; Cotecchia *et al.*, 2006), whereas the WRC of the soil in the trenches is representative of gravel. In the figure, they are compared with the WRC measured for silty sand (Bottiglieri *et al.*, 2012). For the permeability of saturated clay, a value representative of the 'mass clay permeability', which is equal to $k_{sat} = 1 \times 10^{-9}$ m/s, has been adopted. Both high retention capacity and the very low permeability of the clay implemented in the model are to be considered conservative in the assessment of the efficiency of the drainage system (Cotecchia *et al.*, 2014b).

Initial hydrostatic conditions with water table at 3 m depth below g.l., representative of winter conditions, have been set in the analyses. At the ground surface, it has been assigned, during each month, a constant vertical flow rate consistent with the average monthly rainfall measured in the period 1972–2009 for the month of interest (Fig. 2). Both evapotranspiration and surface run-off have been disregarded (D'Acunto & Urcioli, 2006), making the model overestimate water infiltration in the slope, according to a conservative approach. A detail of the mesh used in the calculation is shown in Fig. 6, for a given set of geometrical parameters.

In the analyses, after setting the initial conditions, the trench clusters have been activated by assigning $\theta(s)$ and $k(s)$ functions to the filling material and prescribing zero pore water pressure to the nodes at the trench bottom; thereafter, the flow rate at the ground surface has been imposed. The efficiency of the drainage system with time

$$E(t) = \frac{1 - h(t)}{h_0} \tag{1}$$

has been computed along several horizontal planes, where $h(t)$ stands for the piezometric head at time t and h_0 refers to the initial piezometric head at the same point.

Figure 6 shows the results of the analyses in terms of pressure head along a horizontal plane at 45 m depth below g.l. (passing through point A in Fig. 4), after 5 years since the activation of drainage – that is, when the pressure heads calculated at the nodes along the plane are found to approach a steady-state condition. In the figure, the pressure head after 5 years is also compared with the initial uniform pressure head at the same depth. The results refer to a trench depth, H, of 12 m, with spacing between the trench axes, S, variable between 13 and 22 m and the number of trenches, n, ranging between 3 and 7. Therefore, the results in the figure refer to different values of the ratio S/H, usually considered as a parameter mainly in control of system performance (Hutchinson, 1977; Desideri & Rampello, 2009).

The first new finding is the 'necklace shape' of the piezometric head distribution along the deep horizontal plane, according to which the highest pore pressure depression occurs below the centre of the system, that is where the deeper portion of the spoon-shaped slip surface occurs (Fig. 4). The results also show how the reduction in piezometric head at depth is controlled not only by the S/H ratio, but also by the number of trenches, n, and, hence, the total width of the trench system, $L = n \times S$. As such, a 'group

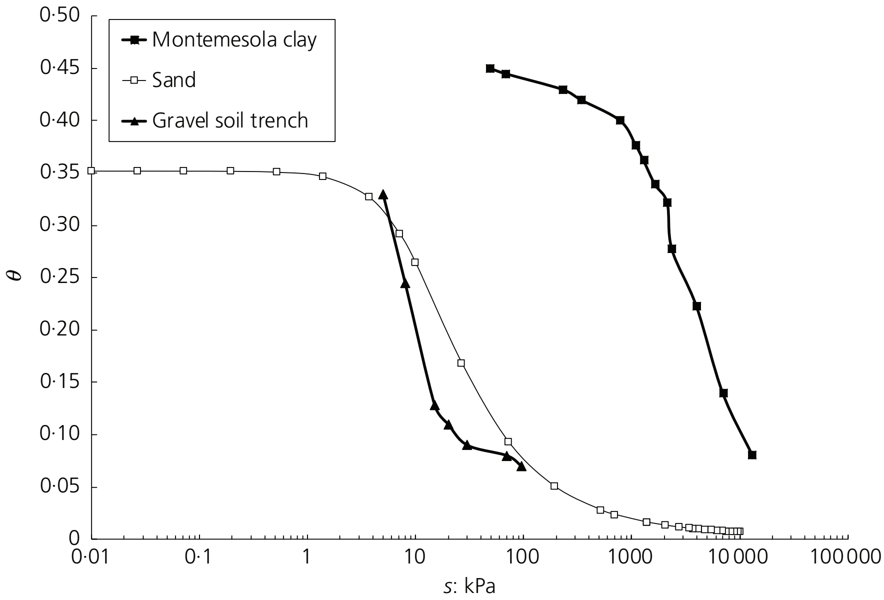


Fig. 5. Retention curves of the Montemesola clay and of the trench filling material (Cafaro & Cotecchia, 2001)

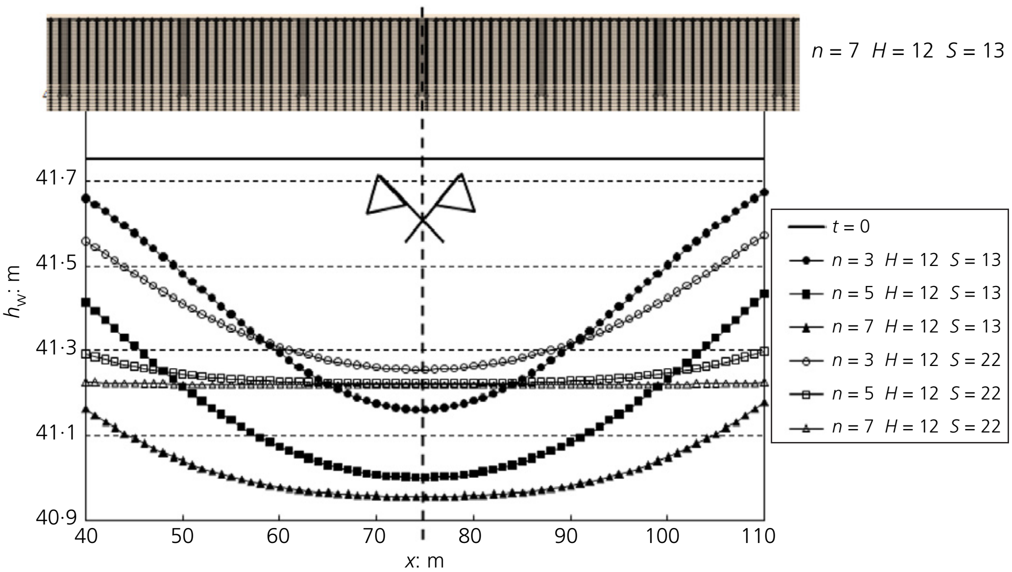
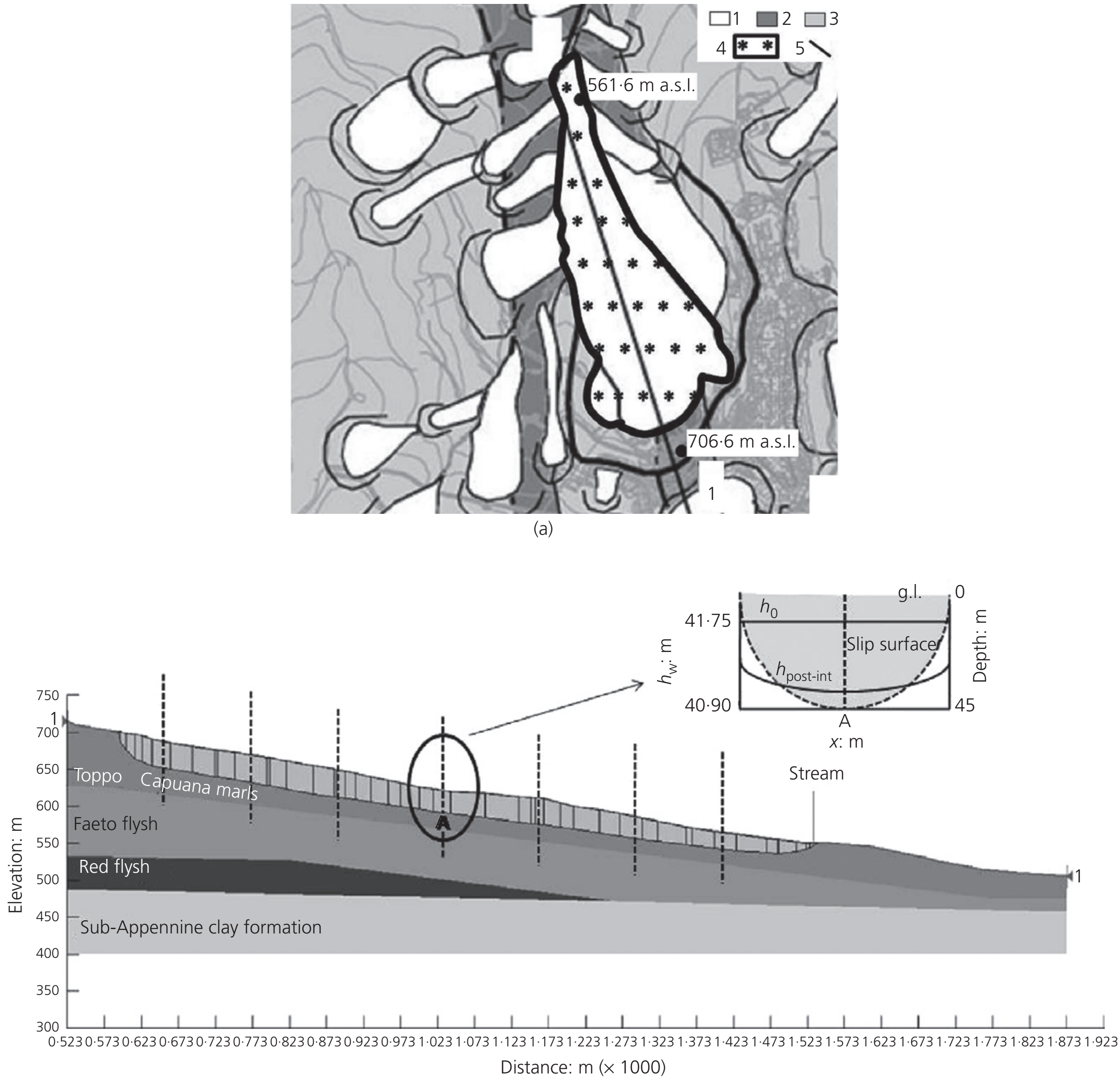


Fig. 6. Details of the finite-element mesh adopted for the seepage analysis and curves of pressure head calculated for different trench systems at depth $z = 45$ m from g.l., after 5 years of transient seepage

effect' of the trenches on the piezometric regime at depth emerges from the modelling, which had not been mentioned in the literature before. This is probably because previous studies had considered drainage trenches mainly as a measure to mitigate pore water pressures at shallow depths. The 'necklace shape' of the piezometric depression at large depths, instead, shows that the analysis must account for the whole geometry of the trench–landslide system. So, for example, the reduction of the head depression with increasing distance from the plane of symmetry of the trench system is counterbalanced by the reduction in depth of the slip surface, which becomes shallower and intercepts depths where the drainage efficiency is larger. Hence, on the whole, the modelling reveals that the piezometric distribution determined by a drainage trench system may be beneficial for the stabilisation of deep landslides.

To calculate stabilisation effects of a trench system of the type in Fig. 4, it has been assumed to be installed within a prototype deep sliding body, located at Volturino (Fig. 1; Lollino *et al.*, 2014), the map and longitudinal section of which are shown in Fig. 7. The maximum depth of the slip surface is about 45–50 m; the morphology and style of activity of the landslide have been reported by Lollino *et al.* (2010, 2014). The increase in stability factor of the landslide after the installation of trenches has been investigated so far by means of 2D limit equilibrium (LE) analyses (Morgenstern & Price, 1965; GeoStudio, 2014), with reference to the central longitudinal section 1-1 in Fig. 7(a). The decrease in pore water pressure generated by the drainage system has been deduced through 2D numerical seepage analyses, carried out using the model discussed above for several transverse sections of the slope, as shown with dotted vertical lines in Fig. 7(b). In particular, the change in piezometric head calculated at point A of Fig. 4 in each transverse section [see in Fig. 7(b): $h_{\text{post-int.}}$] has been imposed in the LE analyses to derive the stability factor, *F*, of the landslide body and,



(b)

Fig. 7. (a) Geomorphological map of the Volturino unstable slope (modified from Lollino *et al.*, 2010): 1 – sub-Appenine clays, 2 – Toppo Capuana marls, 3 – red flysch, 4 – landslide of reference in the paper, 5 – trace of the section considered in the LE analyses; (b) longitudinal section of the landslide body subjected to LE analysis with the prototype scheme of the transverse section of reference in the seepage analyses

hence, its variation with respect to the pre-intervention conditions. The increase in stability factor, ΔF, has resulted to comply with the values reported in the following for two example geometries of the drainage system

$n = 5$, $H = 16$ m, $S = 12$ m: $\Delta F = 8{\cdot}40\%$
$n = 7$, $H = 16$ m, $S = 12$ m: $\Delta F = 10\%$

These results indicate that although the change in piezometric head calculated at 45 m depth is limited to values between 0·5 and 0·8 m, it is sufficient to increase the overall stability of the landslide body to a value compatible with significant risk mitigation.

Given the three-dimensional (3D) features of the trench–landslide system, the 2D analyses described above should be considered as conservative and the overall increase in stability factor is expected to be higher when deduced from 3D seepage analyses combined with 3D LE analyses. These 3D analyses that are aimed at exploring the 3D effects of the drainage system are currently underway.

CONCLUSIONS

The present work suggests that drainage trenches may be a remedial measure also for deep slope instabilities, when these are related to slope–atmosphere interaction. The results of the analyses provide evidence of the patterns of reduction in pore water pressures in slopes, down to large depths, even in low permeability soils. The effectiveness of the intervention is guaranteed by the trenches' 'group effect', which allows for a reduction of the piezometric head at depth that is maximum, where the depth of the slip surface is maximum. The drainage intervention being proposed overcomes some drawbacks of other stabilisation measures generally used with deep slip surfaces, such as the crushing of subhorizontal drainage pipes while slope deformations progress due to consolidation, and the high costs of deep draining shafts. Both the flexibility of the drainage trenches and their expected limited costs make them worth being considered as an innovative mitigation strategy for deep landslides.

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