<u>COMMENTS BY EDITOR</u>

Dear Authors,

based on the Reviewers' comment, I will send out the revised version of your paper for further review. Please address them all.

<u>REPLY TO EDITOR</u>

Dear Editor,

we took into account all issues raised by both the Reviewers. Please find listed below:

- replies to Referee#1;
- replies to Referee#2;
- annotated version of the manuscript, reporting the modifications.

Best regards.

COMMENTS BY REFEREE #1

The paper shows that the eventual presence of a persistent pervious natural soil layer intercepting the drainage trenches in a slope has the beneficial effect of increasing drainage efficiency and reducing time lag. The manuscript is well written with clear figures and tables. The Authors also provide the minimum trench spacing needed to attain the atmospheric pressure at the middle plane, so that a condition of water table can be assumed at the top of the pervious layer. A simplified procedure is developed to analyse this case that provides results in a good agreement with those computed by FE seepage analyses. Then, the design charts available for the design of drainage trenches in homogeneous soils can be still used referring to the equivalent scheme proposed by the Authors.

REPLIES TO REFEREE #1

Dear Referee #1,

many thanks for your comments. We really appreciated your positive assessment.

The goal of the paper is exactly highlighting that the presence of even a small pervious layer could have a very beneficial effect on the performance of a drainage system, thus it should be taken into account in the design.

The replies to the specific suggestions, are reported in the following. All the modifications will be referred to the annotated version of the manuscript. In particular:

- the eliminated parts have been reported as barred ~~words~~;
- the added parts have been reported in yellow.

C1 - In Table 1, first row, last column there are two subcases, but the second seems to be included in the first one in that both refer to b/H0 =0.16 and H/H0 =1, please check.

R1 – You are right. We fixed this mistake in Table 1.

C2 - Page 6, line 111: please cancel "where".

R2 – The word "where" in line 112 of the current annotated manuscript was reported in continuity with the word "where" reported at the beginning of lines 103 and 108. Anyway, it was replaced by "showing" at all the three lines.

C3 - Page 6, line 118: the sentence " Any further increment of the water level would generate an artesian condition" could be eliminated in that introduces an additional comment not needed to understand the concept of reduced seepage domain.

R3 – That sentence was eliminated.

COMMENTS BY REFEREE #2

The manuscript presents an interesting theoretical assessment of the effect of a highly permeable layer in a low permeable soil on drainage efficiency. I understand from the manuscript that the first part shows how t90 decreases with the presence of an permeable layer. The second part describes a simplified approach to calculate drainage efficiency. I recommend major revisions, mainly with regards to the second part, as detailed in the comments below.

REPLIES TO REFEREE #2

Dear Referee #2,

we are grateful for your comments and suggestions that give us the opportunity to improve and clarify some aspects of the paper.

In the following, please find a reply to every point. All the modifications will be referred to the annotated version of the manuscript. In particular:

- the eliminated parts have been reported as barred ~~words~~;
- the added parts have been reported in yellow.

C1 - METHODOLOGY AND DERIVATION OF EQUATIONS

C1.1 - I appreciate the page limit on a technical note, but some of the equations are not clear. - How is the term t90 in equation 3 obtained from either equation 2? Is there a closed form solution or is this obtained through optimisation of the numerical solution?

The value of t_{90} has been obtained by a **numerical integration of** Eq. (1) through the following steps:

- calculation, as a function of time, of the total heads, *h(t,x,y,z)* thus of the pore pressures (t,x,y,z), which turn from the value u_0 to the value u_∞ (Fig. C1a);
- representation of the results in a dimensionless form, through the efficiency E(t,x,y,z) at any point of the domain, and calculation of the average value of the efficiency, $\bar{E}(t,\Gamma)$, along the basal plane of trenches assumed as being the failure surface, Γ;
- determination of the time t_{90}, as the instant at which is $\bar{E}(t,\Gamma)=0{,}90$ (Fig. C1b).

Regarding this point, the manuscript has been integrated at lines 87-88 of the annotated version.

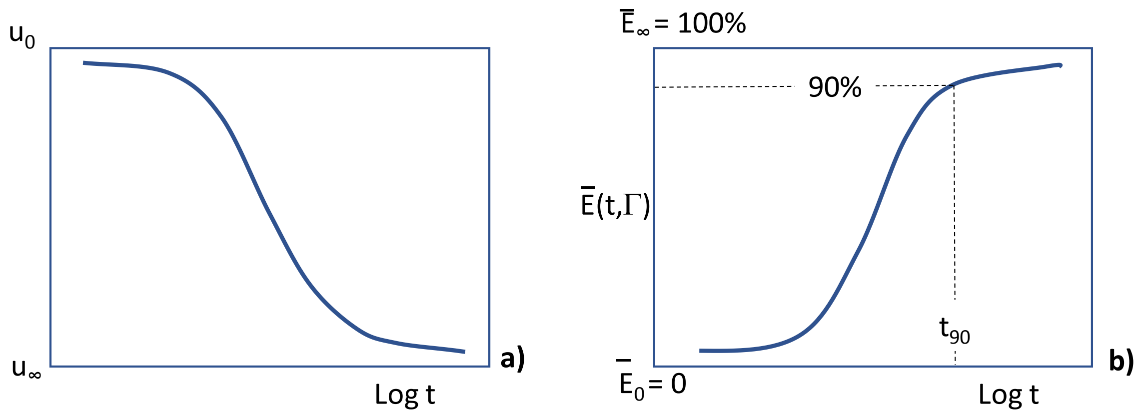

Figure C1. Pore water pressure, u, as a function of the logarithm of time, Logt (a); average efficiency along the failure surface Γ, $\bar{E}$(t,Γ), as a function of the logarithm of time, Logt (b).

C1.2 - Can you elaborate on how you got equation 4? Is this based on the interpretation of the numerical experiment or is this derived from the governing equation? Is it possible to write equation 4 as a set of differential equations?

Eq. (4) has been obtained from the interpretation of the results of the numerical integration of Eq. (1). These have been reported in Fig. 2f of the paper, which shows the dependency of s_d/H_0 on K_d/K and H_1/H_0, having fixed H_d/H_0.

Such an equation may be obtained also in a closed form as an algebraic expression through integration of Eq. (1) by some simplifying hypotheses. Under these hypotheses (described later), it may be demonstrated that the conditions for full layer activation are obtained when the spacing, *s*, between trenches, is equal to the value s_d (or less than it), provided by the following expression:

$$\frac{s_d}{H_0} = 2\frac{H_d}{H_0}\sqrt{\frac{K_d}{K}} \qquad (4a).$$

This may be obtained from Eq. (1) of the paper, written for the layer *d*, assuming $h_t = 0$ (steady state) and $h_{yy}=0$ (the pore pressure distribution along vertical profiles is assumed to be linear). The piezometric surface in the layer *d* is then described by means of the piezometric head, u_d/H_d, at the base of the layer *d*, through the parabolic equation:

$$u_d = ax^2 + bx + c \qquad (5a)$$

in which the abscissa $x=0$ corresponds to the lateral face of the trench (Fig. 1a). The parabolic surface represented by Eq. (5a) separates the upper part of the layer d, where pore pressures are negative, from the lower one, where pore pressures are positive.

The coefficients a, b and c may be obtained based on the following hydraulic boundary conditions:

- for $x = 0 \rightarrow u_d(0) = \alpha\gamma_w H_d$ (i.e. the ordinate of surface (5a) at the trench face is a fraction, α, of the highest value H_d),
- assuming $s'=s-b$, for $x = \frac{s'}{2} \rightarrow u_d\left(\frac{s'}{2}\right) = \gamma_w H_d$ (this is just the condition for full layer activation: the ordinate of surface (5a) is the highest one) and $\frac{\partial u_d}{\partial x} = 0$, for symmetry.

From previous conditions, it follows:

$$x = 0 \rightarrow c = \alpha\gamma_w H_d$$

$$x = \frac{s'}{2} \rightarrow u_d\left(\frac{s'}{2}\right) = a\frac{s'^2}{4} + b\frac{s'}{2} + \alpha\gamma_w H_d = \gamma_w H_d \qquad (6a)$$

$$x = \frac{s'}{2} \rightarrow \left(\frac{\partial u_d}{\partial x}\right)_{x=\frac{s'}{2}} = as' + b = 0 \rightarrow a = -\frac{b}{s'}$$

By entering the values of a and c in Eq. (6a), it may be obtained:

$$u_d\left(\frac{s'}{2}\right) = -\frac{b}{s'}\frac{s'^2}{4} + b\frac{s'}{2} + \alpha\gamma_w H_d = \gamma_w H_d \rightarrow b\frac{s'}{4} = \gamma_w H_d(1-\alpha) \rightarrow b = 4\gamma_w\frac{H_d}{s'}(1-\alpha)$$

It is then easy to calculate the horizontal gradient i_x and the flow rate Q_x, though the trench face in the layer d:

$$(i_x)_{x=0} = \frac{1}{\gamma_w}\left(\frac{\partial u_d}{\partial x}\right)_{x=0} = \frac{1}{\gamma_w}b = 4\frac{H_d}{s'}(1-\alpha);$$

$$Q_x = K_d\alpha H_d(i_x)_{x=0} = 4K_d\frac{H_d^2}{s'}(1-\alpha)\alpha.$$

The highest value of Q_x is obtained for α=1/2:

$$(Q_x)_{max} = Q_x\left(\alpha = \frac{1}{2}\right) = K_d \frac{H_d^2}{s'}.$$

The vertical flow rates, Q_y^s and Q_y^i, through the uppermost and the lowermost boundaries of the layer d , depend on the gradients i_y^s e i_y^i. The numerical analyses discussed above show that i_y^s is around 1 and, on the average, i_y^i is equal to 0.5.

Therefore:

$$Q_y^s = K\frac{s'}{2} i_y^s;\ Q_y^i = K\frac{s'}{2} i_y^i \rightarrow \Delta Q_y = Q_y^s - Q_y^i = K\frac{s'}{2}\left(1 - i_y^i\right).$$

Finally, from the equilibrium condition of the fluid mass, it is:

$$(Q_x)_{max} = \Delta Q_y \rightarrow K_d \frac{H_d^2}{s'} = K\frac{s'}{2}\left(1 - i_y^i\right) \rightarrow \left(\frac{s'}{H_d}\right)^2 = 2\frac{K_d}{K\left(1 - i_y^i\right)} \qquad (7a).$$

Eq. (4a) is obtained from Eq. (7a), assuming s'~s and $i_y^i = 0.50$.

Accounting for the type of paper at hand (Technical Note), the Authors did not consider suitable to report such a detailed series of expressions, which lead to Eq. (7a) that is valid only in the case h_{yy}=0 into the permeable layer and for reasonable but arbitrary values of the gradient i_y^i. Moreover, Eq. (4a) does not highlight the dependency of s_d/H_0 on H_1/H_0, which has been evidenced by the results of the numerical analyses.

Please find some changes in the text at lines 124-125 of the annotated manuscript.

C1.3 - How do you calculate pore pressures in equations 5-8? From line 145 it appears these are not based on the FEM calculation. Is there a closed-form solution?

Pore pressure (and efficiency) in Eq. 5-8 (indicated with *) have been obtained from well known dimensionless solutions present in the literature for the design of draining trenches in homogeneous soils referring to a simplified geometric scheme, which accounts for the presence of the permeable layer. Some changes in the text may be found at lines 138-140 and at line 150 of the annotated manuscript.

C2 - DISCUSSION OF LIMITATIONS OF SIMPLIFIED APPROACH

The simplified approach is only valid if the drainage layer is fully activated. Can you add a discussion on how to determine if this condition is satisfied?

The Reviewer is right: the simplified approach may be used only when the drainage layer is fully active. To check this condition, Fig. 2f of the paper may be used. Being known the depth of permeable layer (H_1) and its hydraulic conductivity (K_d), the spacing between trenches should be lower than the one provided by the curves in Fig. 2f, this in order to activate the drainage layer all over its length.

However, the Author added in the text some considerations about the use of the simplified approach, suggesting, in particular, to adopt the "observational method" by installing some piezometers in the permeable layer or close to it. These aspects are illustrated at lines 170-176 of the annotated version of the manuscript.

C3 - DISCUSSION ON REAL-WORLD APPLICABILITY AND FIELD TESTING

I would recommend a section discussing how this theoretical finding could be corroborated in a field experiment (especially the concept of fully activated drainage layer).

We added some considerations at lines 170-176 of the annotated version.

C4 – CHANGE TITLE

I suggest to make the title more specific, for instance 'The effect of a permeable layer in a low permeable soil on soil stabilisation by drainage trenches'

Following your suggestion, we decided to modify the title in "The beneficial role of a natural permeable layer on slope stabilization by drainage trenches".

C5 – PERVIOUS

Change 'pervious' to the more commonly used word 'permeable'

The word "pervious" was replaced by "permeable" in the modified version of the manuscript.

Technical note: The beneficial role of stratigraphy a natural permeable layer on slope stabilization by drainage trenches

Gianfranco Urciuoli[1], Luca Comegna[2], Marianna Pirone[1], Luciano Picarelli[2]

[1]Dipartimento di Ingegneria Civile, Edile e Ambientale, Università di Napoli "Federico II", Napoli, 80125, Italy
[2]Dipartimento di Ingegneria, Università della Campania "Luigi Vanvitelli", Aversa, 81031, Italy

Correspondence to: Luca Comegna (luca.comegna@unicampania.it)

Abstract. Slope stabilization through drainage trenches is a classic approach in geotechnical engineering. Considering the low hydraulic conductivity of the soils in which this measure is usually adopted, a major constraint to the use of trenches is the time required to obtain a significant pore pressure decrease, here called "time lag". In fact, especially when the slope safety factor is small, the use of drainage trenches may be a chancy approach due to the probability that slope deformations will damage the system well before it will become fully operative.

However, this paper shows that the presence of persistent pervious permeable natural soil layers in the slope can provide a significant benefit by increasing drainage efficiency and reducing time lag. As a matter of fact, any pervious permeable layer that is intercepted by trenches may operate as part of the global hydraulic system, reducing the drainage paths.

A simplified approach to design a drainage system accounting for the presence of a persistent pervious permeable layer is proposed. This approach, which can exploit solutions available in literature for parallel drainage trenches, has been validated by numerical analyses.

1 Introduction

The stabilization of deep landslides in clay is one of the greatest challenges to engineers due to the high cost and the unreliability of many structural solutions. Often, the only available approach is by deep drainage, which can lead to some shear strength increase through a generalized pore pressure decrease. Available solutions (Hutchinson, 1977; Bromhead, 1984; Stanic, 1985; Desideri et al., 1997; Pun and Urciuoli, 2008; Urciuoli and Pirone, 2013) concern the case of deep parallel trenches (and of deeper drainage panels as well), which is dealt with also in this paper, and the case of tubular drains in a homogeneous soil.

Considering the fine-grained nature of the soil, a major constraint to slope stabilization by draining trenches is the long time required to obtain a significant pore pressure decrease (time lag). Especially when the slope is characterised by a small safety factor or is subjected to slow movements (Urciuoli, 1998), the use of draining trenches is in fact problematic due to the probability that slope deformations will damage the system well before it will become fully operative thus vanishing its potential effectiveness. However, as higher is the depth of trenches (or of drainage panels) as higher the probability that these intercept even thin soil layers of higher hydraulic conductivity at an intermediate depth between the ground surface and the slip surface. This would be a lucky chance since the incorporation of such layers in the drainage system may play a highly beneficial role on both the time to attain the final steady-state condition, and the system efficiency.

The scope of this paper is just examining the influence on the drainage system, of a pre-existing ~~pervious~~ permeable soil layer parallel to the ground surface.

2 The basic model

The solutions presented below are based on the following assumptions:

- the groundwater flow is two-dimensional;
- each soil layer is homogeneous, isotropic and is characterized by a linear elastic constitutive law;
- total stresses are constant during the consolidation process (this allows to uncouple the analysis of the hydraulic and of the mechanical soil response).

The governing equation of the problem (i.e. soil consolidation induced by the draining elements) is the following:

$$h_t - c_v^{2D}\left(h_{xx} + h_{yy}\right) = 0 \ , \qquad (1)$$

where $h = \zeta + \frac{u}{\gamma_w}$ and $c_v^{2D} = \frac{KE}{2(1+\nu)(1-2\nu)\gamma_w}$.

The technical literature reports solutions concerning the case of parallel draining trenches and of tubular drains in homogeneous soils, which are generally presented in the form of dimensionless design charts, providing the average efficiency, $\bar{E}(t,\Gamma)$, along the slip surface Γ:

$$\bar{E}(t,\Gamma) = \frac{u(0,\Gamma) - \bar{u}(t,\Gamma)}{u(0,\Gamma)}. \qquad (2)$$

In Eq. (2), $u(0,\Gamma)$ is the initial pore pressure on the slip surface, Γ, and $\bar{u}(t,\Gamma)$ is the average pore pressure at time t modified by the draining elements; $u(0,\Gamma)$ is generally assumed to be hydrostatic. During the consolidation phase, pore pressures decrease towards the minimum steady-state value $\bar{u}(\infty,\Gamma)$, which is attained at time $t \to \infty$ when the efficiency $\bar{E}(\infty,\Gamma)$ reaches the highest value.

The available solutions for parallel trenches, featured by a thickness H_0 and a width b, consider the soil volume between the two axes of symmetry, which respectively coincide with the middle of a trench and the centreline between two adjacent trenches (Fig. 1a). This volume is delimited by the ground surface and by an ~~impervious~~ impermeable bottom surface located at the distance H from the ground surface. The ground and bottom surfaces are both horizontal: the slope angle is indeed assumed to play a negligible role on the hydraulic process (Aloi et al., 2019). The slip surface Γ is a horizontal plane as well, located at depth D. In this paper it is assumed to be coincident with the base of trenches (D=H_0).

A key hypothesis, which strongly affects the solution, is the presence of a permanent film of water at the ground surface (Burghignoli and Desideri, 1987; D'Acunto and Urciuoli, 2006; D'Acunto et al., 2007; D'Acunto and Urciuoli, 2010). However, due to local formation of water ponding and saturation of vertical cracks in the ground, often this is not far from the truth, at least during the wet season. Based on this assumption, the pore pressure decrease is uniquely due to rotation of the flow lines towards the drainage trenches. Pore pressures in the zone between parallel trenches are then at any time less than hydrostatic (Fig. 1b). In contrast, beyond the bottom of trenches, the upward direction of the flow lines leads to a pore pressure distribution higher than hydrostatic. It is just for this reason that the drains should always reach a depth close to the slip surface.

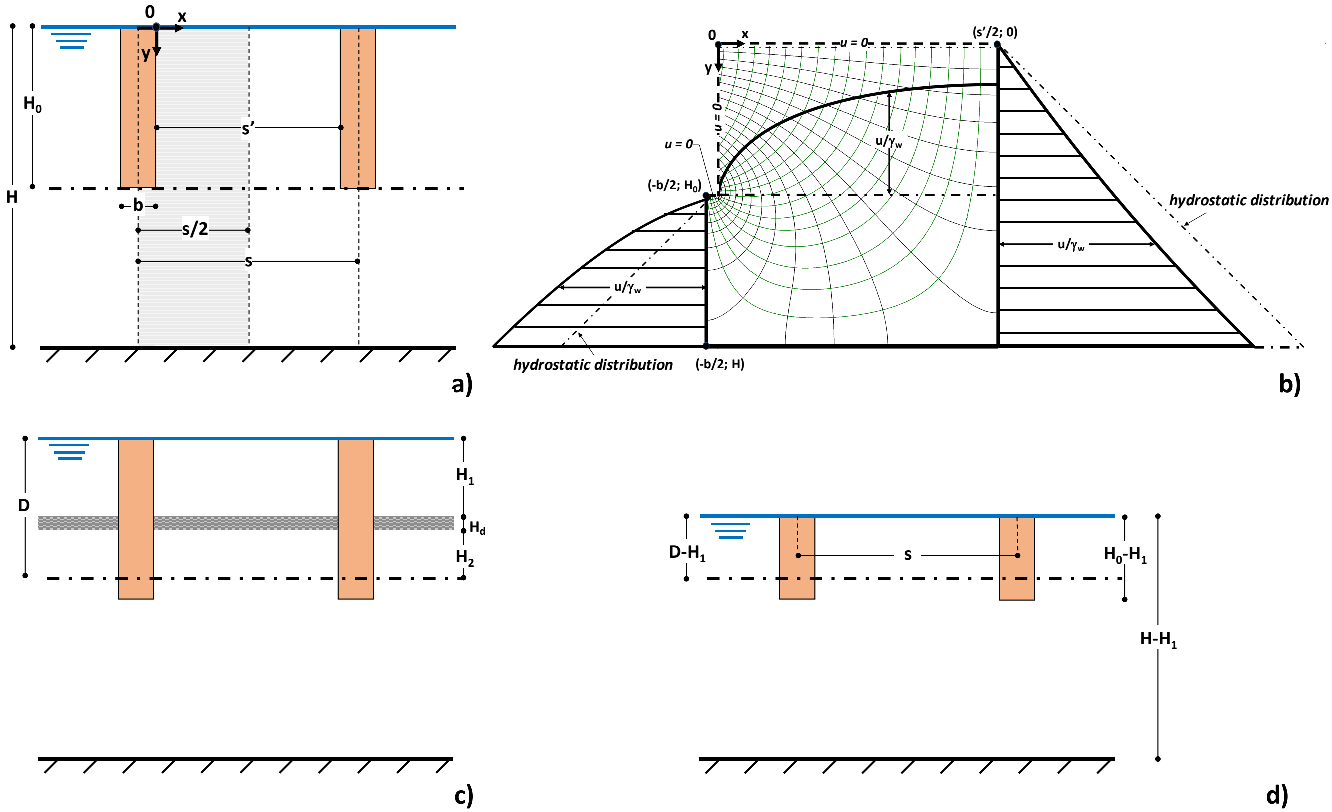

Figure 1: (a) Schematic representation of the case at hand. (b) Flow lines and equipotential lines in homogeneous soil; piezometric heads along the vertical axes at the middle of the trench, at the centreline between two adjacent trenches and on the horizontal plane at depth of trench bottom. (c) Scheme with an intermediate ~~pervious~~ permeable layer; (d) equivalent scheme with a water film at the depth of the uppermost boundary of layer *d* .

3 Influence of a ~~pervious~~ permeable layer located at an intermediate depth between ground and slip surface

3.1 Time of consolidation

As outlined above, the presence of one or more persistent ~~pervious~~ permeable layers in the soil body to be stabilized (a not unlikely situation in deep clay deposits to be stabilised with draining panels) may play a highly beneficial role on time lag and effectiveness of the drainage system.

The influence of a layer parallel to the ground surface, here indicated as the “draining layer *d*”, featured by a thickness H_d as in Fig. 1c, has been investigated by FEM analyses using the code SEEP® (GEO-SLOPE Int. Ltd., 2012). The cases examined in this paper are indicated in Tab. 1; the results of the analyses have been elaborated in a dimensionless form.

Table 1: Examined cases studied with FEM.

Numerical analyses by SEEP/W		Soil properties					Geometry			
		K (m/s)	K_d/K -	θ -	E (kPa)	ν -	H_0 (m)	s/H_0 -	b/H_0 -	H/H_0 -
Homogenous soil model H_d=0		10^{-7}, 10^{-9}	-	0.5	15000	0.3	10, 20,30	1,2,3 4,5,6	0.16 0.16	1,1.5, 2.5
Stratified soil model H_d= 0.025 H_0	H_1=0.25H_0	10^{-7}, 10^{-9}	10,100, 1000,10000	0.5	15000	0.3	10,20,30	1,2,3 4,5,6	0.16	1
	H_1=0.50H_0	10^{-7}, 10^{-9}	10,100, 1000,10000	0.5	15000	0.3	10,20,30	1,2,3 4,5,6	0.16	1,1.5, 2.5
	H_1=0.75H_0	10^{-7}, 10^{-9}	10,100, 1000,10000	0.5	15000	0.3	10,20,30	1,2,3 4,5,6	0.16	1

The data show that the presence of the ~~pervious~~ permeable layer allows to significantly shorten the time lag, here represented by the time factor, T_{90}, corresponding to an efficiency $\bar{E}(t_{90},\Gamma)$ = 90%:

$$T_{90} = \frac{c_v^{2D} t_{90}}{H_0^2}. \tag{3}$$

The value of t_{90} in Eq. (3) has been obtained by a numerical integration of Eq. (1), being the time at which $\bar{E}$(t,Γ) = 0.90 (see Eq. (2)).

Figures 2a and 2b, which report some results concerning the horizontal plane located at depth D = H_0, suggest quite a rapid attainment of $\bar{E}$ = 90%, which is a crucial issue of the design. For significant values of trench spacing in the practice (i.e.

s/H_0<3), the following considerations may be drawn: i) for H_1/H_0 = 0.75 and K_d/K = 100 (Fig. 2a), the dimensionless time T_{90} ranges between one half and one third of the value that would be obtained in the absence of the draining layer; ii) for K_d/K= 1000 (Fig. 2b), T_{90} significantly decreases with depth of the layer d (for H_1/H_0= 0.75, it drops to about 20% of the value obtainable in homogenous soils).

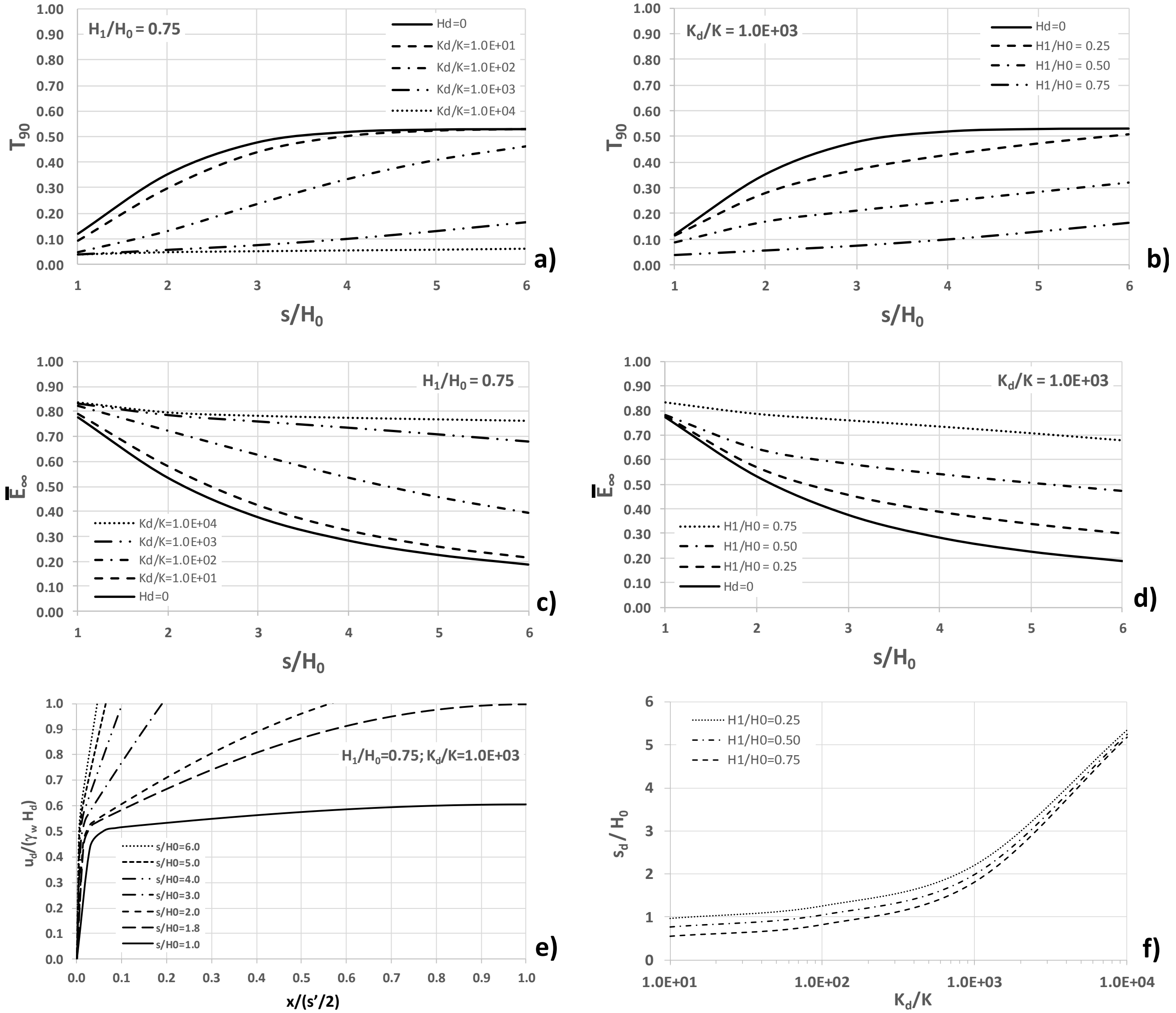

Figure 2: Results of the FEM analyses (assuming $H = H_0$). Dimensionless time, T_{90}, as a function of trench spacing and of (a) K_d/K ratio for H_1/H_0 = 0.75 and (b) H_1/H_0 ratio for K_d/K =1000. Average steady-state efficiency as a function of trench spacing and (c) K_d/K ratio for H_1/H_0 = 0.75; (d) H_1/H_0 ratio for K_d/K =1000. (e) Dimensionless pore pressure over the lowermost boundary of layer d, $u_d/(\gamma_w H_d)$, as a function of x/(s'/2) and s/H_0, for K_d/K = 1000 and H_1/H_0 =0.75. (f) Values of s_d/H_0 as a function of K_d/K and H_1/H_0.

3.2 Steady state condition

The presence of a ~~pervious~~ permeable layer allows to obtain higher values of $\bar{E}(\infty,\Gamma)$, and sooner than in homogeneous soils. Some significant data are provided:

i) in Fig. 2c, ~~where~~ showing the steady-state efficiency for H_1/H_0= 0.75 ~~is~~ reported as a function of the ratio K_d/K and of trench spacing; as shown, as higher is the hydraulic conductivity of the draining layer as higher the efficiency (as an example, for K_d/K=1000 and s/H_0 = 3 it practically doubles); a major effect of layer *d* is in fact diversion of a significant part of water coming from the ground surface towards the trench thus strongly reducing water flow towards the slip surface;

ii) in Fig. 2d, ~~where~~ showing the efficiency for K_d/K=1000 ~~is~~ reported as a function of depth of layer *d* and trench spacing; the figure shows that it increases as the dimensionless distance, H_1/H_0, increases; the effect of layer *d* is a strong pore pressure reduction at depth H_1; as a consequence, pore pressure decrease, due to the action of layer *d*, increases with its depth;

iii) in Fig. 2e, ~~where~~, showing the non-dimensional pore pressure distribution, u_d, along the lower boundary of the draining layer *d* is plotted as a function of trench spacing for H_1/H_0= 0.75 and K_d/K=1000; near the trench boundary, the pressure head is less than H_d, hence, a free water surface forms in the layer *d* (here water can move towards the trench only below this surface where pore pressures are positive).

3.2.1A simplified approach to predict the steady-state condition

In the following, a simplified model for the optimization of the design is briefly described. A very efficient working condition is achieved if, at the centreline between two adjacent trenches, the atmospheric pressure is attained at the uppermost point of layer *d*. ~~Any further increment of the water level would generate an artesian condition. This is what is here called "full draining layer activation".~~

The first step in the design of the drainage system is just creating the conditions for full layer activation. This is obtained when the spacing, *s*, of trenches is equal to the value s_d, according to the following expression:

$$\frac{s_d}{H_0} = f\left(\frac{H_d}{H_0},\frac{H_1}{H_0},\frac{K_d}{K}\right). \qquad (4)$$

The values of s_d/H_0 in Eq. (4) have been obtained from the results of the numerical integration of Eq. (1). These have been reported in Figure 2f, which shows the dependency of s_d/H_0 on K_d/K and H_1/H_0, having fixed H_d/H_0. ~~Numerical values of s_d/H_0 are reported in Fig. 2f~~.

In case of full activation of layer *d*, the response of the entire draining system may be analysed by a simplified approach. Since the fluid pressure at the uppermost boundary of the layer *d* is equal to the atmospheric pressure (or to a small suction especially near the trench boundary), a water film may be fictitiously assumed at the same depth (Fig. 1d). This obviously leads to a generalized pore pressure decrease in the lowermost soil. In the following, any parameter referred to this fictitious condition will be indicated with the apex*.

Table 2: Comparison among steady-state efficiency values computed by Eq. (8), $\overline{E}(\infty)$, and FEM analyses, $\overline{E}(\infty)_{\mathrm{FEM}}$.($\Delta = \left|\frac{\overline{E}(\infty)_{FEM}-\overline{E}(\infty)}{\overline{E}(\infty)_{FEM}}\right|$%). Only results obtained for fully drained activation are reported ($s \leq s_d$).

H_1/H_0=0.50	$\overline{E}(\infty)$	$\overline{E}(\infty)_{\mathrm{FEM}}$							
		K_d/K=10	Δ %	K_d/K=100	Δ %	K_d/K=1000	Δ %	K_d/K=10000	Δ %
s/H_0=1	0.766			0.780	1.73	0.783	2.10	0.783	2.10
s/H_0=1.5	0.697					0.697	0.00	0.699	0.28
s/H_0=2	0.642					0.646	0.54	0.651	1.30
s/H_0=3	0.594	Draining layer not fully activated						0.601	1.08
s/H_0=4	0.570							0.576	0.95
s/H_0=5	0.556							0.559	0.53
s/H_0=6	0.546								

H_1/H_0=0.75	$\overline{E}(\infty)$	$\overline{E}(\infty)_{\mathrm{FEM}}$							
		K_d/K =10	Δ %	K_d/K =100	Δ %	K_d/K =1000	Δ %	K_d/K =10000	Δ %
s/H_0=1	0.821					0.833	1.41	0.834	1.50
s/H_0=1.5	0.797					0.803	0.71	0.807	1.20
s/H_0=2	0.785							0.795	1.22
s/H_0=3	0.773	Draining layer not fully activated						0.782	1.11
s/H_0=4	0.767							0.774	0.83
s/H_0=5	0.764							0.768	0.52
s/H_0=6	0.761								

The values of $\bar{u}^*(\infty,\Gamma)$ and $\bar{E}^*(\infty,\Gamma)$ may be ~~calculated from the scheme of Fig. 1d~~ obtained from the well known dimensionless solutions for the case of parallel trenches in homogeneous soil, as a function of spacing~~ from ~~(see to the simplified scheme in Fig. 1d)~~,~~ ~~as a function of spacing~~. ~~through the solutions for parallel trenches in homogeneous soil~~. The steady-state efficiency is

$$E^*(\infty,\Gamma) = \frac{u^*(0,\Gamma)-\bar{u}^*(\infty,\Gamma)}{u^*(0,\Gamma)}\,, \qquad (5)$$

thus

$$\bar{u}^*(\infty,\Gamma) = u^*(0,\Gamma)\big(1 - E^*(\infty,\Gamma)\big) = \gamma_w(D - H_1)\big(1 - E^*(\infty,\Gamma)\big). \tag{6}$$

It is worth to notice that

$$\bar{u}(\infty,\Gamma) = \bar{u}^*(\infty,\Gamma) \tag{7}$$

and

$$\bar{E}(\infty,\Gamma) = \frac{u(0,\Gamma) - \bar{u}^*(\infty,\Gamma)}{u(0,\Gamma)}. \tag{8}$$

The values ~~calculated with~~ obtained from Eq. (8), through the value of $\bar{u}^*(\infty,\Gamma)$ provided by mentioned solutions, have been compared to those obtained by FEM (Tab. 2). The good agreement allows validating the proposed method. It is worth to mention that the solid lines in Figs. 2c and 2d for H_d=0 are just those that are reported in the design charts.

4 Conclusions and final considerations

The scope of this paper is to demonstrate that the presence of soil layers of higher permeability, a not unlikely condition in some deep landslides in clay, may be exploited to improve the efficiency of systems of drainage trenches for slope stabilization. Once established the depth of trenches, which should reach the slip surface, the selection of a proper spacing may create a hydraulic system in which such layers can work as additional drains. The problem has been examined for the case that a unique ~~pervious~~ permeable layer is present at an elevation higher than the bottom of trenches.

The results of numerical analyses show that it significantly speeds up the consolidation process triggered by drainages, leading also to a higher steady efficiency of the system. However, as mentioned in the Introduction, in many practical cases the critical aspect of the design concerns the time requested to achieve an adequate effective stress and safety factor increase. In these cases, trench spacing should be established looking essentially at the T_{90} value.

If pore pressures in the draining layer do not exceed the atmospheric pressure, a hydraulic disconnection forms between the two parts of the landslide body respectively located above and below the layer. In such a way, the water film which is normally assumed at the ground surface ideally moves to the depth of the draining layer. This simple consideration allows to employ the design charts available for the design of drainage trenches in homogeneous soils in the equivalent scheme characterised by groundwater level located at the depth of the draining layer, in order to calculate the final system efficiency.

It is worth to mention that the hydraulic continuity of layer *d* is a fundamental condition for the design. Considering the variability and the unpredictability of many natural situations, proper investigations ~~including the observational method~~ to check the validity of such an assumption~~,~~ are then warmly recommended. In particular, the adoption of such a stabilization measure should be always managed through the “observational method”, i.e. by monitoring the system response in order to i) check the validity of the design and ii) to adopt proper modifications to it due to unexpected or neglected factors. The installation of piezometers is an obvious measure to check in real-time the efficiency of the drainage system (especially during the critical rainy season). The piezometers should be installed both in proximity of the slip surface (near and far from the trenches) and, if possible depending on thickness, in the permeable layer. This will allow to verify the full activation of the permeable layer.

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List of symbols

b	width of the trench
c_v^{2D}	2D coefficient of consolidation
d	draining layer
D	depth of the slip surface
E	Young modulus of the soil
$\bar{E}(t, \Gamma)$	average efficiency of the draining trenches at time t along the sliding surface Γ
$\bar{E}(\infty, \Gamma)$	average steady-state efficiency of the draining trenches along the sliding surface Γ
$\bar{E}^*(\infty, \Gamma)$	average steady-state efficiency of the draining trenches along the sliding surface Γ according to the simplified approach (full activation of layer d)
γ_w	unit weight of water
Γ	slip surface
h	total head
h_t	first derivative of total head h with respect to time t
h_{xx}	second derivative of total head h with respect to abscissa x
h_{yy}	second derivative of total head h with respect to ordinate y
H	depth of the ~~impervious~~ permeable bottom surface
H_0	depth of the base of trench
H_1	depth of the draining layer d
H_d	thickness of the draining layer d
K	coefficient of hydraulic conductivity
K_d	coefficient of hydraulic conductivity of the draining layer d
θ	soil moisture
s	spacing between trenches

s_d	spacing between trenches creating the conditions for full activation of the draining layer *d*
s'	distance between the boundaries of the trenches
ν	Poisson ratio of the soil
t	time
t_{90}	dimensional time corresponding to $\bar{\bar{E}}$(t, Γ) = 90%
T_{90}	dimensionless time factor for $\bar{\bar{E}}$(t, Γ) = 90%
u	pore pressure
u_d	pore pressure at the base of the draining layer *d*
$u(0,\Gamma)$	initial pore pressure (time *t*=0) on the slip surface Γ
$u^*(0,\Gamma)$	initial pore pressure (time *t*=0) on the slip surface Γ according to the simplified approach (full activation of the draining layer *d*)
$\bar{u}(t,\Gamma)$	average pore pressure at time *t* on the slip surface Γ, modified by drainage trenches
$\bar{u}(\infty,\Gamma)$	average steady-state pore pressure on the slip surface Γ, modified by drainage trenches
$\bar{u}^*(\infty,\Gamma)$	average steady-state pore pressure on the slip surface Γ, modified by drainage trenches according to the simplified approach (full activation of the draining layer *d*)
ζ	elevation head