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Capillary Barrier Systems for Prevention of Rainfall-induced Slope Instability

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Abstract

We are currently experiencing more extreme weather conditions as a consequence of the climate emergency. This includes the frequent occurrence of intense and prolonged rainfall events. Such events are the most common cause of slope instability because rainwater infiltration into the soil may cause significant reduction in soil suction, and thus, shear strength. Capillary Barrier Systems (CBSs) are sustainable and economic geo-infrastructures that can be used to prevent or limit rainfall infiltration into the underlying soil, thus preventing slope instability. A conventional CBS consists of a finer soil layer overlying a coarser soil layer and their working principle is based on the contrast between the unsaturated hydraulic properties at the interface of the two layers, where a capillary break limiting the percolation of water is achieved. The application of CBSs for prevention of slope instability was studied by means of advanced 2D thermo-hydraulic FE simulations and limit analyses. The roles of materials and thickness of the CBS, slope height and weather conditions were investigated. The use of finer-grained materials, such as silty sand, for the finer layer of a CBS was proven to be more effective for warm and dry weather with occasional intense rainfall events whereas the use of slightly coarser-grained materials, such as fine sand, are effective under a wider range of climatic conditions. Simulations also demonstrated that intermediate collector drains or multi-layered CBSs can be used to extend the effectiveness of CBSs to greater slope heights. All the CBSs analysed were effective at preventing rainfall-induced slope instability.

Keywords: Slope Stability, Capillary Barrier System, Suction, Unsaturated soils, Soil-atmosphere interaction

1. Introduction

We are currently experiencing more extreme weather conditions as a consequence of the climate emergency. This includes more frequent occurrence of intense and prolonged rainfall events, that are the main cause of landslides and slope instability (Iverson, 2000).

The stability of slopes is often guaranteed by the presence of suction s, defined as the difference between the pore-gas pressure p_g and the pore liquid pressure p_l, i.e. $s = p_g - p_l$, because suction has a beneficial effect on the shear strength of unsaturated soils. However, suction may vanish or greatly decrease after prolonged and heavy rainfall. The stability of slopes is often guaranteed by the effect of suction. In these cases, a heavy rainfall event may cause significant reductions in suction and shear strength in the soil and induce slope instability (Ng and Shi, 1998). The risk of rainfall-induced slope instability can be mitigated by preventing or limiting rainwater infiltration into the soil.

A Capillary Barrier System (CBS), shown schematically in Figure 1, is a geo-structure made of an upper finer layer (FL) overlying a lower coarser layer (CL), placed over the ground with the aim of preventing the percolation of water into the underlying soil (US) (Stormont & Anderson, 1999). A vegetative cover can be placed on top of the barrier to avoid any potential risk of surface erosion. The working principle of a CBS is based on the contrast between the unsaturated hydraulic properties of the FL and CL. The CL is typically at very low degree of saturation and hence the corresponding unsaturated hydraulic conductivity, which decreases by many orders of magnitude with decreasing degree of saturation, is also very low and can be many orders of magnitude lower than that of the FL. Thus, the CL acts as an almost impermeable barrier. This is in contrast to what would happen under fully saturated conditions, when the hydraulic conductivity of the CL would be much higher than that of the FL.

At the top of the slope, infiltrating water starts entering the FL, suction at the interface between FL and CL is relatively high since the water content is low, the CL behaves as an impermeable layer and water is diverted laterally down the slope within the FL due to the effect of gravity (see Figure 1). Moving down the slope, the amount of water flowing laterally within the finer layer increases, the degree of saturation at the base of the

finer layer is greater than that further up the slope, and the suction at the interface is correspondingly lower. If the suction at the interface decreases down to a point where the degree of saturation in the CL increases until continuous water channels are formed within the CL (Scarfone *et al*., 2020a), the CL becomes highly hydraulically conductive, and breakthrough occurs into the CL and eventually into the underlying soil. Beyond this point on the slope, no more water can be diverted laterally, and infiltrating water becomes percolation into the coarser layer (Ross, 1990). In addition to lateral drainage, rainwater can also be removed from the CBS by evapotranspiration.

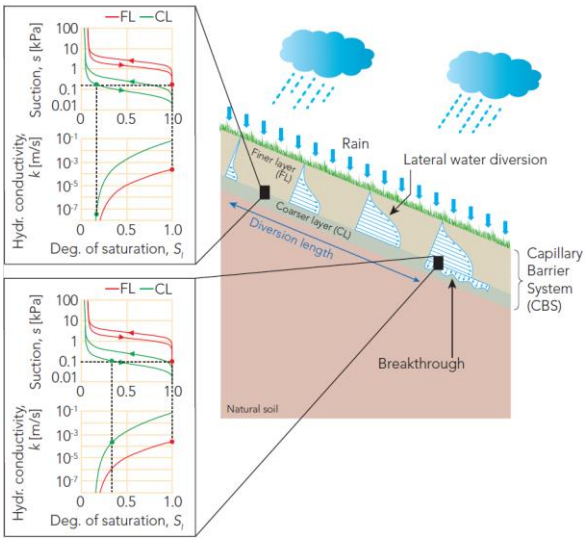

Figure 1: Schematic representation of the working principle of a sloping Capillary Barrier System.

The main advantages of the use of CBSs over traditional concrete-based solutions to ensuring slope stability are lower cost and higher sustainability, thanks to the use of low quality or recycled materials. In addition, the use of CBSs results in solutions of improved aesthetics.

CBSs have been traditionally used as landfill covers (Morris and Stormont, 1998). More recently CBSs have started to be seen as a means to control suction in the ground, with particular application to slope stability (e.g. Rahardjo *et al*, 2011). This paper summarises the outcome of the advanced numerical analyses performed by Scarfone *et al* (2022) investigating the long-term performance of CBSs when used for prevention of rainfall-induced slope instability. These analyses included a comparison between two contrasting European climatic conditions, a dry and warm climate, with occasional intense rainfall events (Cagliari, Italy), and wet and cool climatic conditions (London, UK) characterised by high amount of rainfall and low evaporation. Solutions aimed to extend the effectiveness of CBSs to greater slope heights such as intermediate collector drains or multi-layered CBSs were also analysed.

2. Numerical models

2.1 Numerical procedure

Various numerical analyses were performed in order to analyse the long-term performance of CBSs applied to slopes subject to realistic weather conditions. The modelling procedure was divided into three steps:

1. Advanced FE coupled thermo-hydraulic, multi-phase and multi-physics two-dimensional analyses were performed with the code Code_Bright (Olivella *et al*, 1996). For the mass balance, advective liquid flow and diffusion of water vapour within the gas phase were included. For the energy balance, conductive heat flow and convective heat flow were modelled. At this analysis stage, all materials were assumed rigid, i.e. porosity was modelled to be constant. Climatic conditions representative of Cagliari and London were applied through the advanced modelling of soil-atmosphere interaction. The results of these analyses in terms of temporal and spatial variations of suction s and degree of saturation S_l at the nodes of the FE mesh were exported to a link code.
2. Values of the product of suction and degree of saturation $s \cdot S_l$ were then interpolated to a new grid through a link code developed ad hoc.

3. The new grid values of $s \cdot S_I$ were imported into computational limit analysis (LA) software Limit State:GEO (Limit State, 2019) to perform stability analyses considering the effect of unsaturated conditions on shear strength.

2.2 Geometry

Various two-dimensional geometries were considered in the numerical analyses, as shown in Figure 2 in which the numerical FE meshes are presented. In two models only the underlying soil was considered, with slope heights equal to H_s=6m and H_s=10m, see Figures 2(a) and 2(b) respectively.

Different models in which a CBS covers the slope surface were analysed, shown in Figures 2(c–g). In all these models, the underlying slope was identical either to the model shown in Figure 2(a) or to that shown in Figure 2(b). Figure 2(c–g) only shows a zoomed view of the central part of the model, where the slope is covered by a CBS. In the model shown in Figure 2(c), the 6 m-high slope was covered by a sloping CBS of a total thickness of t_{CBS}=60 cm, measured perpendicular to the slope. In the models shown in Figures 2(d,e), the 10 m-high slope was covered by sloping CBSs of a total thickness of t_{CBS}=60 cm and t_{CBS}=100 cm, respectively. The CL of the CBSs was 20 cm thick in all models, whereas the finer layer was either 40 cm thick (for t_{CBS}=60 cm) or 80 cm thick (for t_{CBS}=100 cm). The application of a non-conventional CBS, such as a multi-layered Capillary Barrier (MCB), was also analysed when applied to the 10-m-high slope (see Figure 2(f)). The MCB was made of two coarser layers and two finer layers. The FLs were 27.5 cm thick, the intermediate CL was 5 cm thick, and the bottom CL was 20 cm thick, for a total thickness of t_{CBS}=60 cm. The presence of a drain was modelled at the toe of all the slopes covered by a CBS (Figures 2(c–g)) in order to collect the water potentially diverted laterally down the slope by the CBSs. In the model shown in Figure 2(g), in addition to the bottom drain, the presence of an intermediate drain located at the mid-height of the slope was modelled to assess the effect of the presence of multiple drains on the hydraulic response of the slope and its stability. A conventional CBS with a thickness of t_{CBS}=60 cm applied to a 10-m-high slope was considered for this model. In all cases the slope angle was 35°. The geometries of the LA models coincided with those of the FE models.

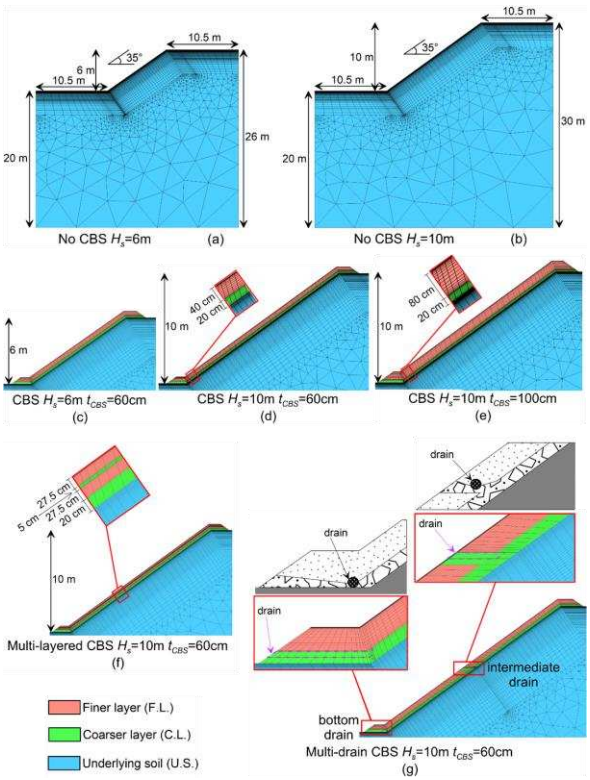

Figure 2: Geometry and mesh of the models analysed.

2.3 Materials

Four materials were considered in these analyses. The material properties adopted for the US and for the CL of the CBS were, respectively, representative of a silt and a gravelly sand. Two types of material were considered for the FL, with properties representative of a fine sand or a silty sand. From the comparison of the results obtained considering these two materials, it was possible to assess the role of the material properties of the FL

on the response of the system. The soil water retention curve (SWRC), relating degree of saturation S_l and suction s, and the soil hydraulic conductivity curve (SHCC), relating the unsaturated hydraulic conductivity k_l and suction s, of the materials are shown in Figure 3. These properties were modelled using advanced constitutive models for the SHCC (Scarfone *et al*, 2020a) and for the SWRC (Scarfone *et al*, 2020b). The former improved the van Genuchten-Mualem (Van Genuchten, 1980) models at very low degree of saturation to include consideration of the contribution of adsorbed liquid films to hydraulic conductivity. The latter included hydraulic hysteresis in the SWRC using a bounding surface approach. Further details regarding the laws and parameters used to model the materials in the FE analyses are described by Scarfone *et al* (2022).

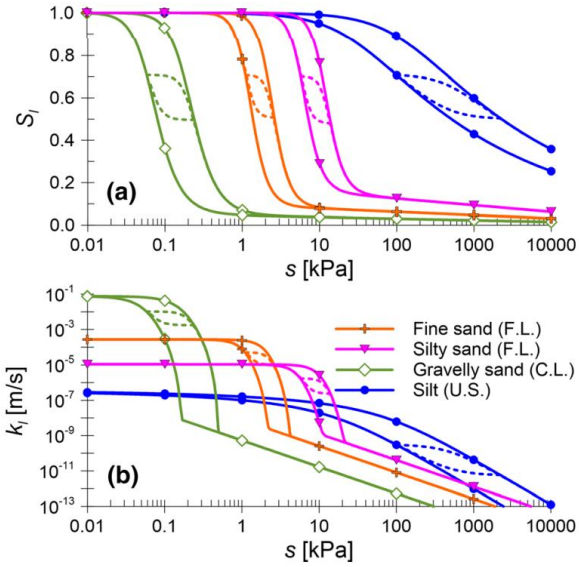

Figure 3: Hydraulic properties of the materials: (a) SWRC and (b) SHCC.

Rigid-perfectly plastic behaviour was assumed for all materials in the LA, with Mohr-Coulomb yield criterion and associative plastic flow. The material parameter values adopted for these analyses, i.e. unit weight γ, friction angle ϕ' and effective cohesion c' are shown in Table 1.

Table 1: Parameters used in the Limit Analyses

Material	γ (kN/m3)	ϕ' (°)	c' (kPa)
Fine sand	17	40	0.1
Silty sand	19	35	0.1
Gravelly sand	16	40	0.1
Silt	19	20	0.1

It should be noticed that the friction angles of FL and CL, representative of a fine sand and a gravelly sand properly compacted, are much higher than that of the US, representative of a silt which itself does not provide sufficient strength for the stability of the slope, except with the assistance of suction. Small values of c' were introduced to avoid numerical instabilities. Unsaturated conditions were included in the yield criterion using the Bishop (1959) stress with χ=S_l. The resulting shear strength τ on a failure surface can be expressed as:

$$t = c' + \left[s - p_g + s \cdot S_l\right] \cdot \tan\phi' \qquad (1)$$

where σ is the normal total stress acting perpendicular to the same failure surface.

2.4 Atmospheric boundary conditions

The response of the models in the long-term was analysed when subjected to the application of realistic atmospheric conditions. Soil–atmosphere interaction was modelled by means of the application of an "atmospheric" boundary condition at the top of the FE models. This included the advanced modelling of rain, runoff and evaporation for the mass transfer; and solar radiation, sensible heat flux (advection) and latent heat flux (convection) for the energy transfer.

Two different climatic conditions were considered for this study: Cagliari (Italy), representative of a dry and warm European climatic area but subjected to sporadic intense rainfall events, and London (UK), representative of a wet and cool European climatic area. Climatic data for the years 1981-2010 were obtained from the

meteorological office of the Italian air force (Servizio metereologico Aeronautica Militare) for the weather in Cagliari, and from the meteorological office of the UK Government (Met Office) for the weather in London. The average yearly rainfall height for this period was 373 mm for Cagliari and 733 mm for London. The most critical rainfall event in Cagliari consisted of a daily rainfall of 73.8 mm on 7th of March 1985, whereas the most critical rainfall event in London consisted of a daily rainfall of 63.4 mm on 1st of January 1998, after a particularly wet period. The wettest 10-year period was simulated for both Cagliari (1984-1993) and London (1993-2002) after setting up realistic initial condition in the numerical models.

Further information about the modelling of the boundary conditions, initial conditions and atmospheric parameters adopted in the analyses are provided by Scarfone *et al* (2022).

3. Results of the analyses

Fourteen different simulations (see Table 2) were performed combining different weather conditions, materials and thicknesses of the finer layer and slope heights. In addition, the effects of the use of multiple drains across the slope and the use of multi-layered CBSs were investigated.

Table 2: Summary of the analyses.

Weather	H_s (m)	CBS type	Material FL	t_{CBS} (cm)	Drain
Cagliari	10	No CBS	-	-	-
Cagliari	10	Single	Fine sand	60	Single
Cagliari	10	Single	Fine sand	100	Single
Cagliari	10	Single	Silty sand	60	Single
Cagliari	10	Single	Silty sand	100	Single
London	10	No CBS	-	-	-
London	10	Single	Fine sand	60	Single
London	10	Single	Fine sand	100	Single
London	10	Single	Silty sand	60	Single
London	10	Single	Silty sand	100	Single
Cagliari	6	No CBS	-	-	-
Cagliari	6	Single	Fine sand	60	Single
Cagliari	10	Single	Fine sand	60	Multi
Cagliari	10	Layered	Fine sand	60	Single

3.1 Effect of slope height

The effect of slope height is illustrated by comparing the results obtained for slope heights of H_s=6 m and H_s=10 m for the weather conditions of Cagliari. For each case, the bare slope and the slope covered by a CBS were analysed. The form of the CBS selected for this illustration is a single CBS with the FL made of fine sand and with t_{CBS} = 60 cm.

Figure 4 shows the time histories of suction *s* in the underlying soil at the toe of the slopes. In the absence of a CBS, suction *s* and the degree of saturation S_l (not shown here) fluctuated depending on the weather conditions, attaining full saturation and very low values of suction during extreme rainfall events. In the presence of a CBS on the 6-m-high slope (Figure 4(a)), the magnitude of these fluctuations was controlled and relatively high values of suction and low values of degree of saturation were always maintained, even during rainfall, because water breakthrough did not occur. The CBS applied to the 10-m-high slope was able to prevent rainwater infiltration into the underlying soil for most of the time. However, water breakthrough occurred at the toe of the slope on two occasions, as shown by the low values of suction attained by the dashed curves in Figure 4(b).

In the two cases, the diversion length was the same. However, unlike the 6-m high slope, in the 10-m-high slope the horizontal distance between the top of the slope and the bottom drain is greater than the diversion length of the CBS. This demonstrates that, if the main working mechanism of a CBS is lateral water diversion down the slope, the CBS will be effective for relatively small slopes but may not be fully effective in preventing water breakthrough in tall slopes.

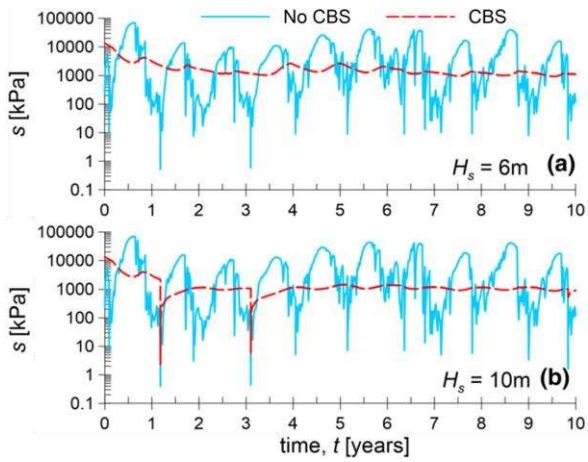

Figure 4: Suction in the underlying soil at the toe of the slope for different slope heights H_s.

3.2 Effect of thickness and materials of the CBS and weather conditions

Different models were analysed considering different thicknesses of the CBS (t_{CBS}=60 cm and t_{CBS}=100 cm), different materials of the finer layer of the CBS (fine sand and silty sand) and different weather conditions (Cagliari and London). The corresponding bare slopes were also analysed. For all these models, the slope height was H_s=10 m and only a single drain at the toe was modelled.

Figure 5 shows the time histories of suction obtained in the underlying soil at the toe of the slopes for the different models.

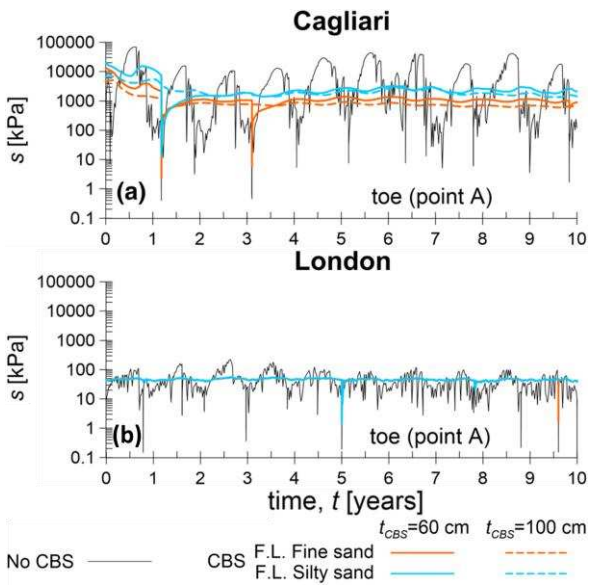

Figure 5: Suction in the underlying soil at the toe of the slope for different models.

Note that for the London weather (Figure 5(b)), the results with the 4 different versions of CBS are indistinguishable from each other apart from during a few extreme rainfall events. When a CBS is used, in Cagliari or London, the fluctuations of *s* due to rain and evaporation have a lower amplitude than in the absence of a CBS. At the toe of the slope, in Cagliari (Figure 5(a)) only the CBS having the F.L. made of silty sand and a thickness of t_{CBS}=100 cm was able to prevent suction drops (i.e. breakthrough) at all times whereas in London (Figure 5(b)) both CBSs having a thickness of t_{CBS}=100 cm were able to prevent suction drops at all times. The use of a thicker F.L. improves the effectiveness of the CBS at preventing or limiting water breakthrough into the underlying soil in the lower part of the slope, hence preventing the underlying soil from attaining very low values of suction in this region.

The silty sand is more effective than the fine sand as a material for the FL in Cagliari. By contrast, the use of fine sand is equally or more effective than the use of silty sand as a material for the FL in London. The reason for this difference is that the key response of the CBSs having the FL made of fine sand is to divert rainwater laterally

down the slope to the drain located at the toe while the key response of the CBSs having the FL made of silty sand is to store water in the FL and subsequently remove it by evaporation, as occurs for horizontal CBSs.

For the finer layer made of fine sand, using a higher thickness does not lead to a significantly improved performance of the CBS because the upper part of the F.L. remains at low values of degree of saturation and contributes little to the lateral water diversion capacity of the CBS. By contrast, increasing the thickness of the F.L. when this is made of silty sand leads to a significant improvement of the performance of the CBS because the upper part of the F.L. significantly contributes to the water storage capacity.

A high water storage capacity is generally useful in climates in which the water storage capacity of the CBS is easily recharged so that it is fully available for the subsequent rainfall event, i.e. warm and dry climatic conditions, with occasional intense rainfall (e.g. Cagliari). In cool and persistently wet climates (e.g. London), in which the water storage capacity is often fully or partially occupied, a high lateral water diversion capacity is expected to be more useful as a means of dealing with periods of maximum rainfall intensity.

3.3 Effect of multiple drains and multi-layer CBS

CBSs working mainly by diverting water laterally down the slope may not be effective at preventing water breakthrough into the underlying soil when applied to tall slopes. Possible solutions to this limitation are the use of multiple drains placed in the CBS at intermediate heights and/or the use of multi-layered CBSs. Figure 6 shows the degree of saturation contours obtained at the most critical rainfall event for these two solutions compared to a standard single CBS with a single drain at the toe.

It can be seen that, while breakthrough was predicted at the toe of the slope with the conventional solution shown in Figure 6(a), both the alternative solutions proposed to extend the application of CBSs to taller slopes (Figures 6(b) and 6(c)) were effective at preventing water breakthrough into the underlying soil.

In the case of the multi-drain model, all the water diverted by the CBS in the upper part of the slope was collected by the intermediate drain. Below this, the FL was again at low degree of saturation, suggesting that the lateral water diversion capacity was fully restored below the intermediate drain.

In the multi-layered CBS, the capillary barrier effect is replicated at multiple interfaces between a FL and the underlying CL. In this way, the lateral water diversion ability is replicated within almost the whole thickness of the CBS, whereas for a single CBS made of a relatively coarse FL this would be limited to a sub-layer at the bottom of the FL.

3.4 Assessment of the slope stability

Figure 7 shows the minimum factors of safety obtained for all the models analysed. It can be seen that all the models with no CBS had a minimum FoS lower than 1. Shallow failure mechanisms passing through superficial fully saturated areas caused by rainfall were predicted for these models. All the models with a CBS led to a minimum FoS higher than 1, meaning that all the CBSs analysed were effective in guaranteeing the stability of the slopes in the long-term, even under extreme rainfall conditions. For all these models, the minimum FoS values were related to the stability of the CBSs rather than the underlying slope.

It must be noted that the small amount of water breakthrough into the underlying soil that occurred in some models did not affect significantly the stability of the slope because the critical failure surface did not pass through the area affected by water breakthrough. In other words, some small amount of water breakthrough into the underlying soil can be accepted without compromising the stability of the slope.

4. Conclusions

On the basis of advanced numerical analyses, it has been demonstrated that CBSs are resilient geostructures that can be used to mitigate the effects of adverse climatic conditions on slope stability. It was found that all the CBSs were in general effective at preventing or limiting the percolation of water into the underlying soil, to maintain high values of suction in the underlying soil and to maintain the stability of the slope even during intense rainfall events, for the different weather conditions analysed. It was shown that a small amount of water breakthrough into the underlying soil can be tolerated without affecting the slope stability, as long as this breakthrough affects only a small area of underlying soil and the potential failure mechanisms do not involve this area. The use of finer-grained materials, such as silty sand, for the finer layer of a CBS was proven to be

more effective for warm and dry weather with occasional intense rainfall events whereas the use of slightly coarser-grained materials, such as fine sand, are effective under a wider range of climatic conditions.

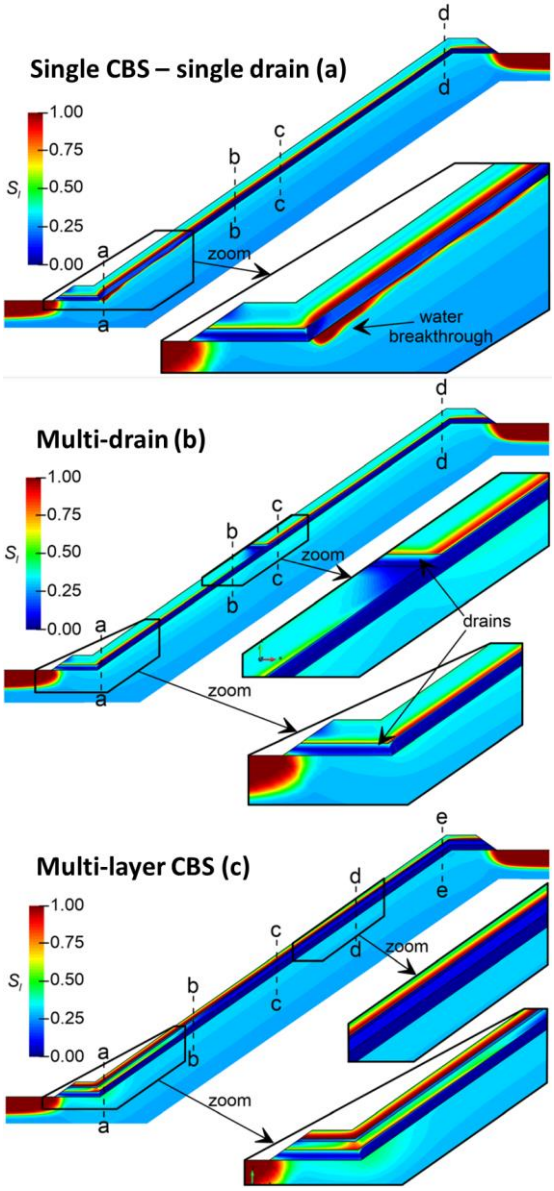

Figure 6: Degree of saturation contours at the most critical rainfall event in Cagliari for the models with (a) a single drain and single CBS, (b) multiple drains and (c) multi-layer CBS.

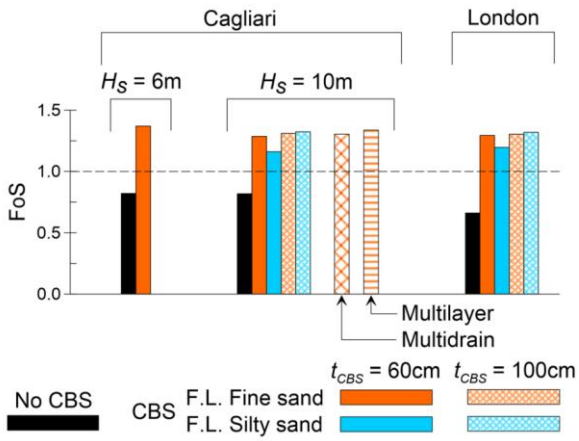

Figure 7: Minimum factors of safety obtained for the models analysed.

The effectiveness of CBSs at preventing water breakthrough decreases with increasing slope height, in particular for CBSs whose main working principle is lateral water diversion. However, simulations also demonstrated that intermediate collector drains or multi-layered CBSs can be used to extend the effectiveness of CBSs to greater slope heights.

Acknowledgements

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