# On the combined use of hydrated lime and guar gum for rainfall-induced shallow landslide risk mitigation

*Giuseppe* Pedone[1,*], *Agostino Walter* Bruno[2], *Marianna* Pirone[3], *Talenta* Pitso[2], and *Domenico* Gallipoli[2]

[1]University of Trento, Department of Civil, Environmental and Mechanical Engineering, Via Mesiano 77, Trento, Italy
[2]University of Genova, Department of Civil, Chemical and Environmental Engineering, Via Montallegro 1, Genoa, Italy
[3]University of Naples Federico II, Department of Civil, Building and Environmental Engineering, Via Claudio 21, Naples, Italy

**Abstract.** Recent studies have shown that biopolymers, like guar gum, can be employed as sustainable soil stabilisers, offering promising alternatives to traditional energy-intensive binders, like lime. While their field application is still limited, biopolymers could also be introduced at shallow depths through soil mixing for mitigating superficial landslide risks. This paper explores the application of biopolymers for the stabilisation of the pyroclastic slopes located in south-western Italy, typically affected by rainfall-induced shallow landsliding. The proposed treatment combines guar gum (GG) and hydrated lime (HL), whose potential effects are evaluated, at the slope scale, through finite element seepage models and limit equilibrium stability analyses, considering realistic interactions between the top unsaturated soil layer and the atmosphere. Treatments include two stabiliser combinations (i.e. 2%HL-1%GG and 1%HL-2%GG, with percentages by dry soil mass) to assess the impact of partially replacing HL with GG. The water retention curve, the saturated permeability and the shear strength of both untreated and treated soils are evaluated based on evaporation, oedometer and direct shear laboratory tests. Although the paper focuses on an idealised slope, the results highlight the potential of combining hydrated lime and guar gum for the sustainable mitigation of rainfall-induced shallow landslide risk.

## 1 Introduction

The research community has shown growing interest in the use of more sustainable soil stabilisers, which could replace traditional energy-intensive soil treatments based on cement or lime [1]. To this aim, several researchers have recently shown that biopolymers, like guar gum or xanthan gum, can enhance the mechanical properties [2] and modify the hydraulic characteristics [3] of soils.

Biopolymers could also be deployed in combination with traditional binders, as shown by Pitso et al. [4], who employed a blend of hydrated lime (HL) and guar gum (GG). Pitso et al. [4] tested two different treatment blends, i.e. 2%HL-1%GG and 1%HL-2%GG, with percentages by dry soil mass. The effects of these two treatments were explored by performing retention, oedometer and direct shear tests on both treated and untreated soil samples.

The experimental campaign by Pitso et al. [4] was carried out on a pyroclastic soil from the Lattari Mountains (Campania region, south-western Italy), an area often affected by rainfall-induced shallow slope instabilities. These superficial pyroclastic cohesionless soils usually exist in unsaturated conditions [5], with suction and root reinforcement allowing the slopes to remain stable throughout the year. Intense long-lasting rainfall events, if insisting on areas predisposed to failure [5], could reduce suction and trigger shallow landslides. A similar rainfall-induced landslide risk is also observed in other areas around the globe [6]. In these scenarios, soil treatment could increase the stability of slopes, even just by slightly increasing the effective cohesion.

Field applications of biopolymer treatments are very limited, but it is likely that biopolymers, like other binders, are more easily applicable at shallow depths, for instance through soil mixing techniques. Such an application could be of interest for areas, like the Lattari Mountains in south-western Italy, in which the mechanical enhancement of the outcropping unsaturated soil layers could sustainably contribute to the mitigation of shallow landslide risk.

When testing both the 2%HL-1%GG and the 1%HL-2%GG treatments, Pitso et al. [4] observed a general increase in shear strength mainly due to an increase in effective cohesion, c’, from 0 up to around 8-9 kPa, according to the Mohr-Coulomb failure criterion. This relatively small cohesion increase was associated to a mild reduction in effective angle of shearing resistance, φ’, from 36° down to 34° (being c’=0 kPa and φ’=36° the strength parameters of the untreated material, i.e. 0%HL-0%GG). Pitso et al. [4] also investigated the impact of the two treatments on changes of saturated hydraulic conductivity, $K_{sat}$. These changes appeared to be negligible for the 1%HL-2%GG treatment and close to half an order of magnitude for the 2%HL-1%GG treatment.

---

[*] Corresponding author: giuseppe.pedone@unitn.it

© The Authors, published by EDP Sciences. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

Based on the laboratory test data in Pitso et al. [4], this paper investigates the impact of HL and GG treatments on the stability of the pyroclastic covers of the Lattari Mountains, which are particularly prone to rainfall-induced landslides. The combined use of HL and GG was tested, at the slope scale, by first considering the impact in terms of soil hydraulic properties. To this aim, 2D finite element (FE) seepage analyses were conducted, simulating realistic slope-atmosphere interactions. The results of these seepage simulations were then input into limit equilibrium slope stability analyses, accounting for the mechanical improvement due to soil stabilisation. The two treatments of this study correspond to those tested by Pitso et al. [4], i.e. 2%HL-1%GG and 1%HL-2%GG. A third scenario was also simulated to model untreated conditions, referred to as 0%HL-0%GG and used as a reference.

## 2 Seepage analyses

A slope representative of the conditions encountered on the Lattari Mountains was analysed. The slope reproduces a 30 m long pyroclastic cover sitting on a carbonatic or dolomitic bedrock with an inclination of 34° to simulate a potentially unstable scenario. As shown in Figure 1, the pyroclastic cover is divided in a 1.2 m thick top silty sand unit (referred to as unit A1 [5]) and a 0.8 m thick bottom sandy silt unit (referred to as unit C1 [5]).

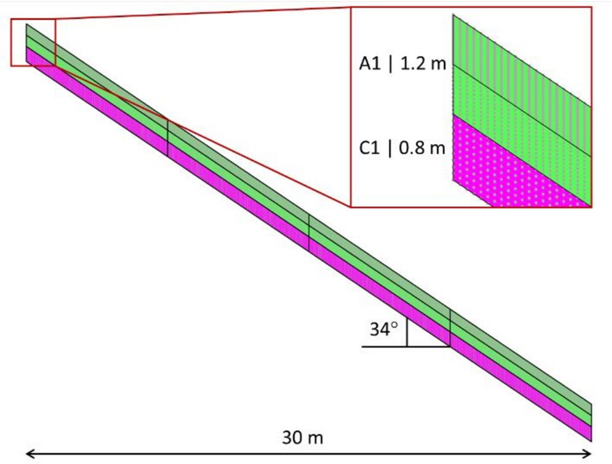

**Fig. 1.** Slope geometry, stratigraphy and mesh generated for the FE seepage analyses.

The 2D seepage analyses were conducted with the finite element (FE) code Seep/w of the Seequent GeoStudio suite. Four-noded quadrilateral elements were employed to discretise the domain (Figure 1), the size of the elements being 0.02 m at the surface and gradually increasing with depth. The hydraulic properties from Pitso et al. [4] were assigned to unit A1, while unit C1 was modelled using the properties reported in [5] and [7]. The retentive behaviour of both soil units was simulated using the van Genuchten model [8] which relates volumetric water content, $\theta_w$, to suction, $s$, as:

$$\theta_w = (\theta_{w,max} - \theta_{w,res})/(1+(\alpha \cdot s)^n)^m + \theta_{w,res} \qquad (1)$$

where $\theta_{w,max}$ and $\theta_{w,res}$ are the maximum and residual volumetric water content, respectively, while $\alpha$, $n$ and $m$ are model parameters, with $m = 1 - (1/n)$. Table 1 summarises the van Genuchten parameters of both soil units, together with the corresponding saturated hydraulic conductivities. The van Genuchten model [8] was also used to estimate the hydraulic conductivity function, based on the parameters in Table 1.

**Table 1.** Hydraulic soil properties of the FE seepage analyses.

| | $\theta_{w,max}$ (-) | $\theta_{w,res}$ (-) | $\alpha$ (1/kPa) | $n$ (-) | $K_{sat}$ (m/s) |
|---|---|---|---|---|---|
| Unit A1 *0%HL-0%GG* | 0.488 | 0.12 | 0.372 | 1.40 | 6.8E-7 |
| Unit A1 *2%HL-1%GG* | 0.491 | 0.12 | 0.092 | 1.57 | 2.5E-6 |
| Unit A1 *1%HL-2%GG* | 0.485 | 0.12 | 0.234 | 1.45 | 6.9E-7 |
| Unit C1 | 0.66 | 0.257 | 0.12 | 1.78 | 4.4E-7 |

According to Table 1, three different scenarios were simulated: (1) untreated, i.e. 0%HL-0%GG, (2) A1 unit treated with 2%HL-1%GG, (3) A1 unit treated with 1%HL-2%GG. These treatments were tested by simulating realistic slope-atmosphere interactions. To this aim, an initial pore pressure distribution was first defined by running a steady-state analysis with imposed suctions at the top and bottom model boundaries equal to 25 and 50 kPa, respectively (values typically observed at the end of summer). On the lateral boundaries, a zero unit flux was imposed in combination with a zero pore water pressure cut-off.

The initial steady-state analysis was followed by the simulation of transient seepage, with a time step of 0.2 days, in which time-dependent top and bottom boundary conditions were applied. The suction variation reported in Pirone et al. [5] was imposed at the bottom boundary, corresponding to suction values ranging from 50 kPa at the end of summer to 10 kPa at the end of winter. The top boundary condition corresponded to a unit flux equal to the difference between the gross daily rainfall and the evaporation (thereafter referred to as net rainfall).

The gross daily rainfall was measured, over the period from 01/09/2020 to 31/12/2023, at the San Mauro weather station in the proximity of the Lattari Mountains. Evaporation was estimated, on a monthly basis, according to the FAO Penman-Monteith method [9] using the temperatures recorded at the same weather station. Other missing climatic data (e.g. relative humidity and radiation) were estimated based on temperature measurements and recommendations included in the FAO Penman-Monteith method [9]. In particular, the single crop coefficient approach reported in [9] was adopted, based on the crop coefficients, $K_c$, shown in [5]. Bare soil conditions were considered for simplicity, hence neglecting plant transpiration and only accounting for evaporation. The latter was simulated by adopting the minimum $K_c$ value in [5] throughout the entire analysis.

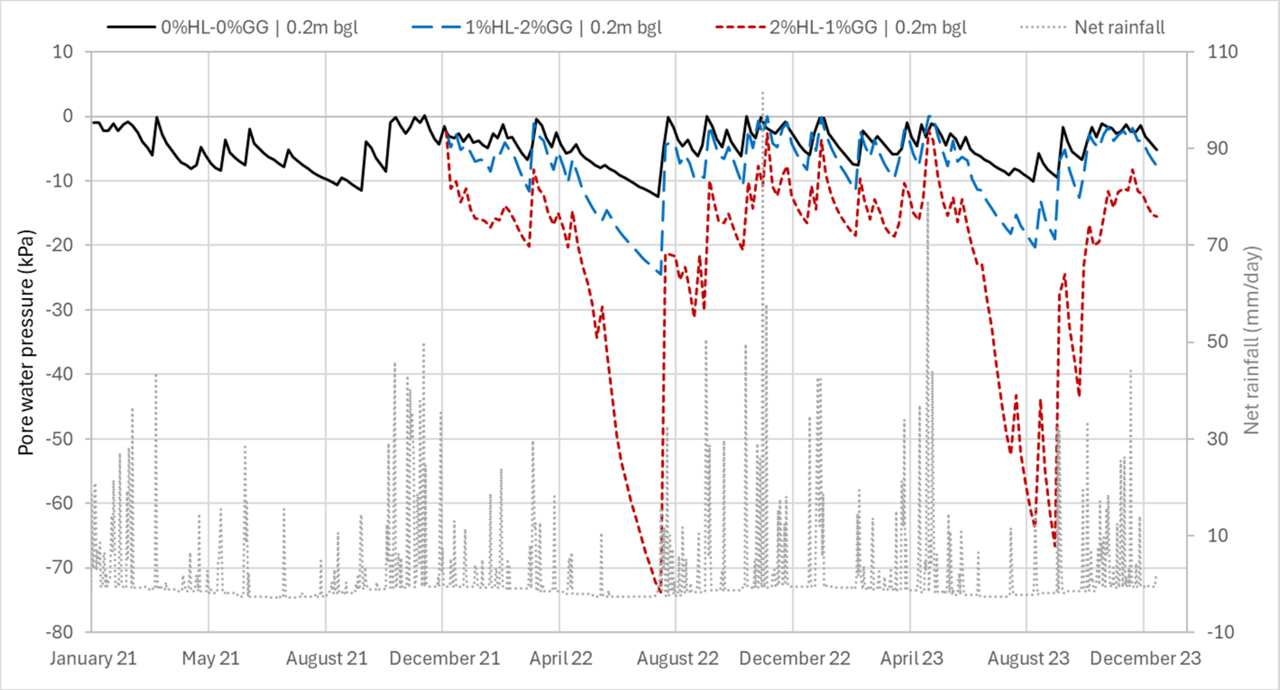

**Fig. 2.** Temporal evolution of the pore water pressure at the slope centre (0.2 m b.g.l.) and net rainfall.

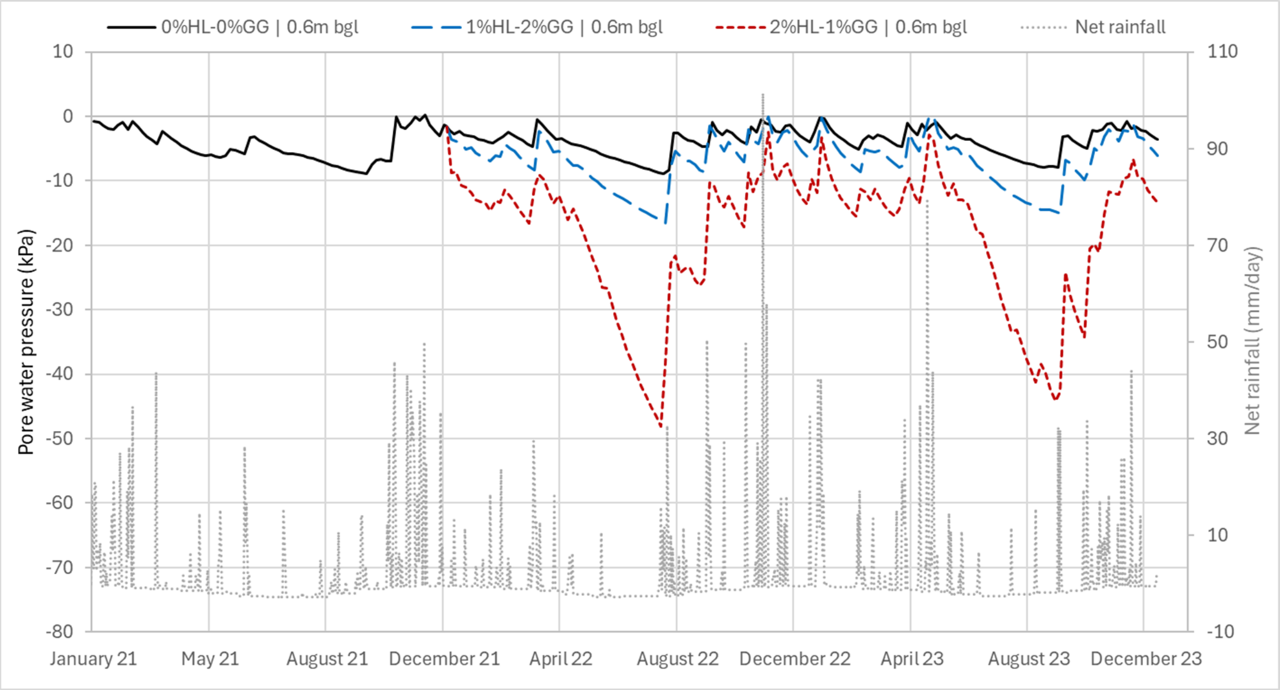

**Fig. 3.** Temporal evolution of the pore water pressure at the slope centre (0.6 m b.g.l.) and net rainfall.

Water stress conditions were simulated by assuming an outflow reduction function linearly decreasing from 1 to 0 in the range 100-300 kPa. A zero pore water pressure cut-off was also adopted at the top boundary, to avoid water ponding and simulate superficial run-off.

The results of the FE seepage analyses are reported in Figures 2 and 3 in terms of pore water pressures at the slope centre, at depths of 0.2 m and 0.6 m below ground level (b.g.l.), respectively. The analyses were conducted from September 2020, but only results from January 2021 are shown, because the first four months were used to overwrite the effects of the initial pore water pressure distribution within the slope. Figures 2 and 3 also indicate that the slope treatment was ideally implemented at the end of December 2021, as discussed later.

Taking as a reference the untreated scenario 0%HL-0%GG, the results in Figures 2 and 3 (continuous lines) clearly show that pore water pressures vary seasonally in response to the net rainfall on the slope. The highest suctions are observed at the end of the driest periods, while wetter periods are associated with pore water pressures close to zero, both at 0.2 m and

0.6 m b.g.l. It is worth highlighting that the suction variations measured on site [5] are generally more pronounced than those shown in Figures 2 and 3. This difference is likely due to the lower air-entry values measured in laboratory tests on untreated reconstituted soil samples by Pitso et al. [4] compared to the higher values measured on site, for instance, by Pirone et al. [5]. In this respect, it is also worth noting that the water retention data reported in [4] refers to an evaporation test, in which only drying is allowed to take place. On the other hand, the water retention curve adopted in the analyses presented in [5] is based on field data, the latter following cycles of wetting and drying.

As shown in Table 1, the 1%HL-2%GG treatment results in a slightly higher air-entry value compared to the untreated scenario, allowing for the soil to experience higher suctions at a given volumetric water content. Higher suctions are therefore attained at the end of the driest periods of the year in the 1%HL-2%GG analysis (long dashed lines in Figures 2 and 3) compared to the 0%HL-0%GG analysis (continuous lines).

The 2%HL-1%GG treatment is associated with an even higher air-entry value (Table 1), giving rise to significantly larger suctions in the summer periods (short dashed lines in Figures 2 and 3). While this treatment allows the slope to retain some degree of suction even during the wettest periods, the 1%HL-2%GG treatment experiences a complete loss of suction during certain times of the year. These differences can also be partly attributed to the differences in hydraulic conductivity, even though the oedometer test data [4] indicates that hydraulic conductivity remains within a similar order of magnitude (Table 1).

## 3 Slope stability analyses

The pore water pressure distributions from the FE seepage models were input into the corresponding limit equilibrium analyses of a 1.2 m deep landslide body entirely located within the A1 soil unit (Figure 4). The selected slip surface, similar to those investigated in [5], was fixed for all the analyses, to assess the impact of soil treatment on a given landslide body.

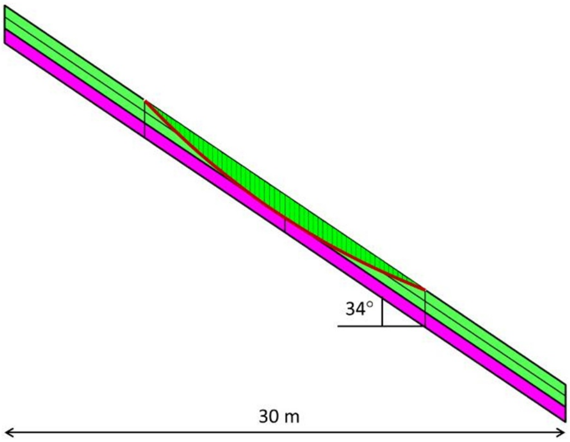

**Fig. 4.** Geometry of the landslide body.

Stability analyses were performed according to the Morgenstern and Price [10] method, as implemented in the software Slope/w (GeoStudio). The physical and mechanical properties of the A1 soil unit correspond to those measured by Pitso et al. [4] through direct shear tests on both untreated and treated samples, as summarised in Table 2. The C1 soil properties are not reported, as they did not play any role, given that the selected slip surface only intersects unit A1 (Figure 4).

**Table 2.** Physical and mechanical soil properties of the slope stability limit equilibrium analyses.

| | $\gamma_{max}$ (kN/m$^3$) | $c'$ (kPa) | $\varphi'$ (°) |
|---|---|---|---|
| Unit A1<br>*0%HL-0%GG* | 15.14 | 0.0 | 36.0 |
| Unit A1<br>*2%HL-1%GG* | 15.03 | 8.9 | 34.0 |
| Unit A1<br>*1%HL-2%GG* | 15.09 | 7.9 | 34.0 |

It is worth highlighting that the unit weights in Table 2 correspond to the maximum unit weights at zero suction, i.e. when the maximum volumetric water content is attained. Slope/w allows to update the unit weight during the analyses based on the actual soil volumetric water content. The code also accounts for the increase in shear strength due to suction according to the failure criterion proposed by Vanapalli et al. [11].

Figure 5 shows the factor of safety calculated by the limit equilibrium analyses at different times. The untreated slope (continuous line in Figure 5) appears generally stable, even though the factor of safety approaches 1 at the end of 2021, showing that prolonged wet periods can potentially trigger slope instabilities.

Following soil stabilisation at the end of December 2021, there is a significant increase in the factor of safety for both treated scenarios (dashed lines in Figure 5). While both treatments induce similar increases in effective cohesion (Table 2), the 2%HL-1%GG treatment results in a larger improvement of slope stability compared to the 1%HL-2%GG treatment. This notable difference is attributed to the different unsaturated hydraulic responses, driven by the differing water retention and permeability properties in Table 1, as discussed in the previous section.

Overall, the results demonstrate the positive impact of soil treatment on the stability of the topsoil layer, which is particularly susceptible to rainfall-induced landslides. In this respect, the influence of the adopted treatment on the water retentive behaviour appears to play a crucial role, hence prompting the need for in-depth unsaturated characterisations of treated soils when new binders, like guar gum, are considered.

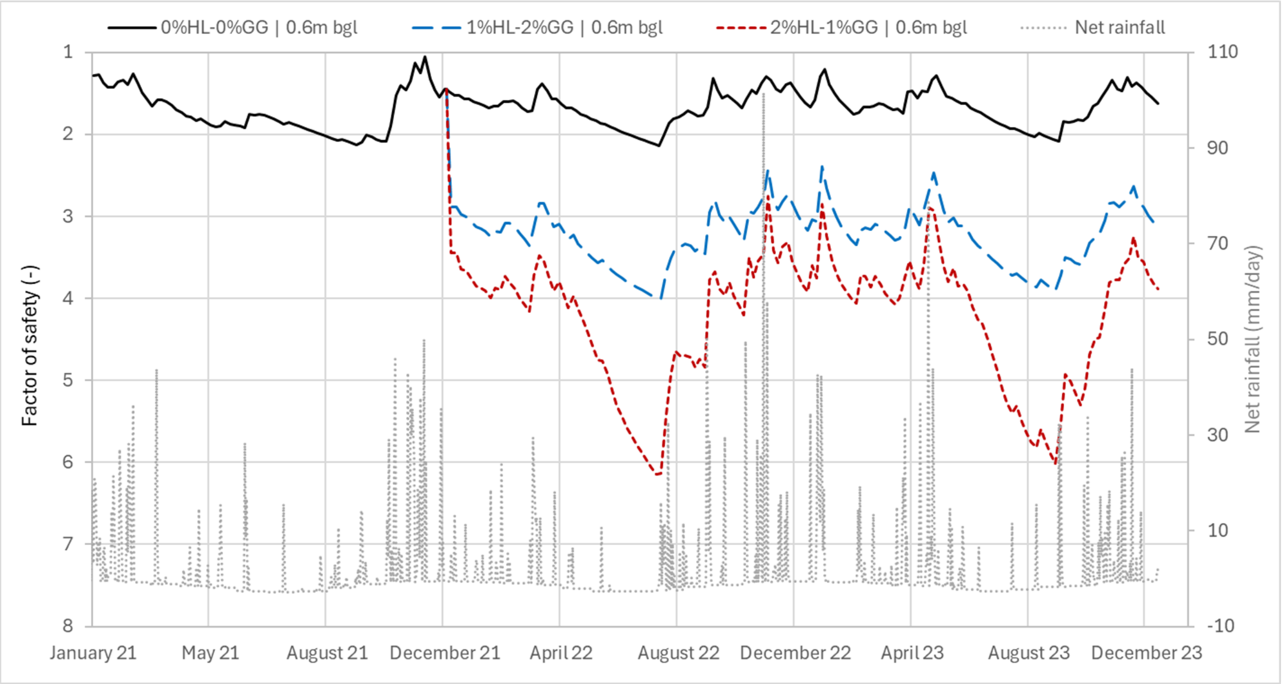

**Fig. 5.** Temporal evolution of the factor of safety and net rainfall.

## 4 Conclusions

Field treatment of soils can be adopted as an effective risk mitigation measure against rainfall-induced shallow landsliding. Traditionally, these treatments involve the deep mixing of energy-intensive binders, like cement or lime. In recent years, however, more sustainable binders, like biopolymers, have been explored for soil stabilisation, even though field applications of these alternatives are seldom discussed in the literature.

Pitso et al. [4] combined hydrated lime (HL) and guar gum (GG) to investigate the synergistic effects of these binders in two differing proportions, i.e. 1%HL-2%GG and 2%HL-1%GG, with percentages by dry soil mass. This paper presents a numerical study of the impact of both these treatments on slope stability at the field scale. In particular, the study performs seepage and slope stability analyses of the pyroclastic covers located on the Lattari Mountains in south-western Italy. The interaction between the slope and the atmosphere was simulated, allowing to compare untreated and treated scenarios.

The results indicate that both treatments enhance the water retentive behaviour of the pyroclastic silty sand tested by Pitso et al. [4], while only mildly affecting hydraulic conductivity. The enhanced water retention due to soil treatment allows the slope to maintain higher suctions throughout the year, leading to an increased slope stability during the wettest periods. Slope stability is also significantly improved by the relatively small increase in shear strength resulting from the 1%HL-2%GG and 2%HL-1%GG treatments. This increase in shear strength is primarily due to an augmentation of effective cohesion, by approximately 8-9 kPa, despite a slight reduction in the effective angle of shearing resistance.

The results of this study are promising, as they suggest that sustainable soil treatments could be effectively applied to mitigate the risk of rainfall-induced shallow landslides. However, the present analyses refer to an idealised slope, assuming that the treatment extends throughout the entire topsoil layer and remains stable over time. Soil treatment may also depend on factors such as soil type and climatic conditions. Therefore, in-situ investigations are needed to test the proposed stabilisation alternatives and evaluate their durability. Specifically, field studies on biopolymer treatments should be conducted under different ground conditions and climatic scenarios before considering the replacement of traditional binders with biopolymers in geotechnical practice.

First and third authors gratefully acknowledge the contribution from the European Union Next-Generation EU (National Recovery and Resilience Plan - NRRP, Mission 4, Component 2 – Investment 1.1 – PRIN PROJECT ‘Integrated appPROach for MItigation of flowSlidE risk: full-scale test and advanced numerical modelling’ PROMISE – CUP E53D23003430006 and E53D23003450006). The contribution from the European Union Next-Generation EU (National Recovery and Resilience Plan – NRRP, Mission 4, Component 2, Investment 1.3 – D.D. 1243 2/8/2022, PE0000005) through funding of the last author in the framework of the RETURN Extended Partnership is gratefully acknowledged.

## References

[1]. G. Guidobaldi, C. Cambi, M. Cecconi, D. Deneele, M. Paris, G. Russo, E. Vitale, Eng. Geol. **221**, 193-201 (2017)

[2]. A.F. Cabalar, H. Canakci, Ground Improv. **164**, 57-64 (2011)

[3]. A. Bouazza, W.P. Gates, P.G. Ranjith, Géotechnique **59**, 71-72 (2009)

[4]. T. Pitso, A.W. Bruno, G. Pedone, M. Pirone, D. Gallipoli, *5th European Conference on Unsaturated Soils – EUNSAT 2025* (Lisbon, Portugal, 2025)

[5]. M. Pirone, R. Di Maio, G. Forte, C. De Paola, E. Di Marino, R. Salone, A. Santo, G. Urciuoli, Eng. Geol. **315**, 107045 (2023)

[6]. T. Tsuchida, A.M.R.G. Athapaththu, T. Hanaoka, M. Kawaguchi, Soils and Found. **55**, 1305-1317 (2015)

[7]. S. Guglielmi, M. Pirone, A.S. Dias, F. Cotecchia, G. Urciuoli, J. Geotech. Geoenviron. Eng. **149**, 05023005 (2023)

[8]. M. Th. van Genuchten, Soil Sci. Soc. Am. J. **44**, 892-898 (1980)

[9]. R.G. Allen, L.S. Pereira, D. Raes, M. Smith, *Crop evapo-transpiration (guidelines for computing crop water requirements) – FAO Irrigation and Drainage Paper 56* (1998)

[10]. N.R. Morgenstern, V.E. Price, Géotechnique **15**, 79-93 (1965)

[11]. S.K. Vanapalli, D.G. Fredlund, D.E. Pufahl, A.W. Clifton, Can. Geotech. J. **33**, 379-392 (1996)