ANALYSIS OF THE LONG-TERM RESPONSE OF A CLAY SLOPE THROUGH THE HYDRO-MECHANICAL APPROACH

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Abstract

The present paper illustrates the analysis of the long-term stress-strain response of a clay slope affected by a deep weather-induced landslide. The study has been carried out with reference to a prototype slope, the Fontana Monte slope in Volturino (FG), representative of the class of instability mechanisms reactivated at the end of the winter. The impact of the seepage regime, related to the underground water-bearing recharged upslope as an effect of weather conditions, on the evolution of the stress-strain behaviour have been investigated through the hydro-mechanical approach. Both first-time failure and reactivation mechanisms of the landslide have been simulated under steady-state hydraulic conditions, accounting for the partially saturated behaviour of soils above water table. Results showed the impact of the underground hydraulic contact in the reliable formation and progression of the shear strain localization, defining a multiple roto-translation failure mechanism, undergoing an evolution related to the variation of the porewater pressure regime.

1 Introduction

It is well-known that either the onset or the progression of a slope failure might be related to climatic actions, developing through the “slope-vegetation-atmosphere (SLVA) interaction”, which involves the hydraulic boundaries not only at the ground surface, but also along the underground slope boundaries. The variation over the time of the hydraulic boundaries, as a response to the climate, cause the modification of the porewater pressure distribution across the slope, which in turn affects the stability of the slope (Cascini et al. 2010; Tommasi et al. 2013; Vassallo et al. 2015; Cotecchia et al. 2016; Tsiampousi et al. 2017). In the case of slopes made of fine soils bearing rocky aquifers, in which the response to weather of the groundwater in the rocky aquifer combines with the effects of the climatic actions along the slope ground surface, the SLVA interaction should be assessed accounting for also the possible variation with time of the underground hydraulic boundary conditions of the slope.

Under a numerical point of view, the stability of natural slopes affected by SLVA interaction might be investigated through different strategies, accounting for the hydraulic (H), hydro-mechanical (HM), thermo-hydraulic (TH) and thermo-hydro-mechanical (THM) coupling (Elia et al. 2017). The HM approach might entail the comparison of the slope stress-strain conditions for steady-state seepage conditions representative of either the driest period of the year (end of summer) or the wettest one (end of winter).

In the present paper, the HM numerical simulations have been performed to investigate the impact of the hydrogeological setup and its interaction with weather conditions on the evolution of the strain field mobilised in a prototype clay slope, the Fontana Monte slope (Volturino, FG), under steady-state summer-like and winter-like seepage. The Fontana Monte slope has been selected as representative of several clay slopes of the South-Eastern Apennines in Italy, as it is location of a large slow-moving deep-seated landslide, whose current activity has been found to be related to climatic actions, affecting not only the SLVA interaction processes acting through the ground surface, but also the hydrogeological boundary conditions at depth (di Lernia et al. 2022a). The analyses consider the revisited slope hydrogeological and litho-stratigraphical set-up, taking into account the partially saturated behaviour of the soils above the water table (di Lernia et al. 2022b).

2 The prototype slope: the Fontana Monte case study

Several scientific literature has shown significant SLVA interaction effects on the activity of slow-moving deep-seated landslides in the south-eastern Apennines (Italy), for which high piezometric heads down to large depths (e.g. 50 m), together with the low soil strength properties, represent predisposing factors of landsliding, while seasonal piezometric head fluctuations have been recognised to trigger the acceleration of pre-existing landslide bodies (Cotecchia et al. 2010, 2014, 2016; Losacco et al. 2021). A similar scenario applies to the Fontana Monte slope, located in Volturino (FG, Italy) within the same geo-hydro-mechanical (GHM) context of reference, and selected herein as a prototype case study for this class of weather-related instability mechanisms.

The Fontana Monte landslide, affecting the north-western hillslope of Volturino (Fig. 1a) and mainly involving clays belonging to the Toppo Capuana (TPC) formation, is about 1 km long and 300 m wide with the toe at the Giardino stream (Lollino et al. 2010, 2016; di Lernia et al. 2022a). The old town of Volturino lies on the limestone member of the Faeto Flysch (named FAEc herein), which is in contact, to the west, with the outcropping TPC clays and, to the east, with the outcropping clayey member of the Faeto Flysch (named FAEa). Within the longitudinal section 1 (Fig. 1b), crossing the landslide body and extending beyond the Giardino stream along the direction of the watershed, the outcropping TPC formation overlies the FAEc, which, in turn, overlies a sequence of FAEa, Red Flysch (FYR) and Sub-Apennine Blue Clays (ASub) layers.

The sliding surface of the Fontana Monte landslide body (Fig. 1b) has been defined considering the location of the landslide scarp detected during field geomorphological surveys, the location of the Giardino stream, representing the landslide toe the, and the depth of strain localization measured along inclinometric verticals located upslope, i.e. SD1 at 24 m, SD2 at 44 m and S1V at 27 m depths.

The Fontana Monte landslide, recognised to be active since the early nineteenth century, is currently experiencing an evolution of straining along pre-existing shear bands of seasonal nature, as documented by both monitoring data and damages on buildings and roads, mainly evolving during the wet season. Indeed, as for other slopes in the GHM context of reference, the Fontana Monte slope is location of low strength parameter soils and high piezometric heads down to large depth, both representing internal predisposing factor of the deep landslide activity. Besides, the landslide suffers from seasonal reactivations, with the rate of movements increasing in winter and reducing during the dry season (*Fig. 1c*). The piezometric head fluctuations, triggering the accelerations, are related to both the interaction of the slope with the atmosphere and the seasonal groundwater recharge of the deep aquifer, represented by the FAEc layer. Indeed, the direct contact of the low permeability clay and the far more permeable rock represents an important underground boundary condition of the slope affecting the seepage regime in the slope and the landslide mechanism itself (di Lernia et al. 2022b).

The TPC clays is characterised by peak values varying in the range c'_{peak}=15 kPa, φ'_{peak}=16° ÷ c'_{peak}=15 kPa, φ'_{peak}=24° and post-peak value of $\varphi'_{post\text{-}peak}$=18°, suggesting how weak the deep clay is in this slope. The residual strength of the TPC clay, φ'_{res}, measured through a Bromhead ring shear test, is about 8.7°. The fractured heterogeneous topsoil, overlying the TPC stratum along the whole slope for a thickness of 6-7m, exhibits a friction angle of φ'_{peak} =24° (assuming c'=0 kPa). The average strength parameters of FAEc and FAEa, determined through both direct shear and triaxial tests performed on samples collected also in other sites within the same GHM context of reference (Losacco et al. 2021), are equal to c'_{peak}=28 kPa, φ'_{peak}=27° and c'_{peak}=13 kPa, φ'_{peak}=24°, respectively. The field scale saturated permeability of slope soils k_{sat} has been determined through in-situ testing to be equal to $1{\cdot}10^{-9}$ m/s for the TPC soil, $5{\cdot}10^{-6}$ m/s for FAEc soil and $5{\cdot}10^{-8}$m/s for the FAEa.

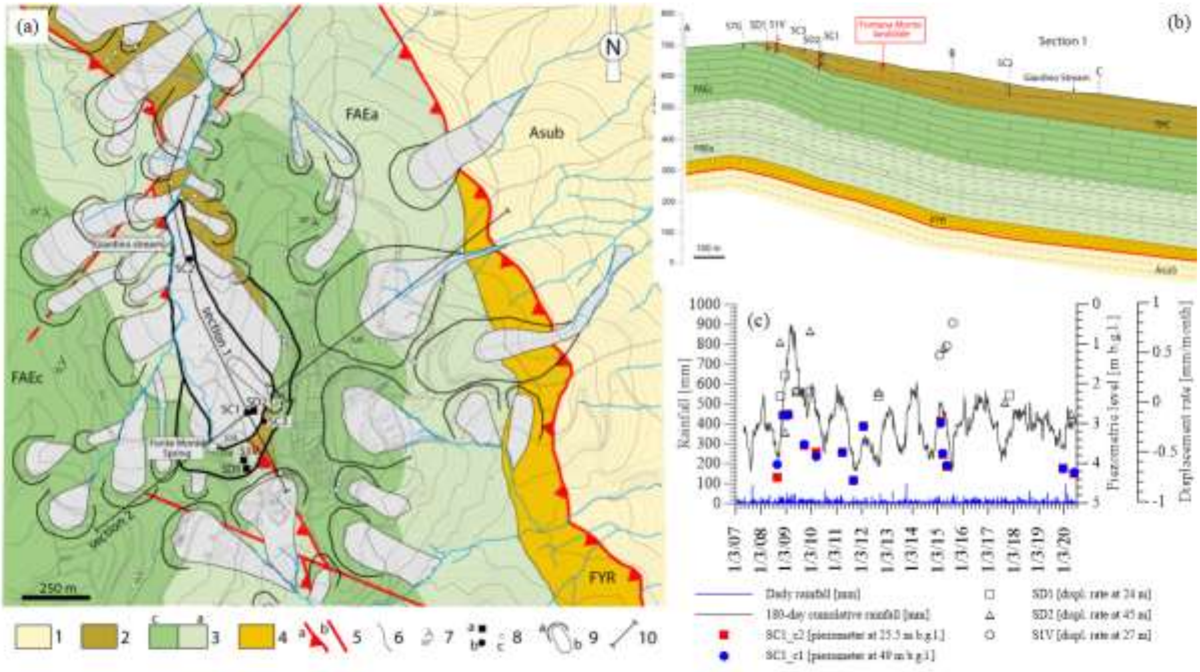

Fig. 1 Geological and geomorphological map (a) and longitudinal section 1 (b); recorded rainfalls and in-situ monitoring data (c). Legend: 1. Asub; 2. TPC; 3. Limestone member (FAEc) (c) and clayey member (FAEa) (a) of Faeto Flysch; 4. FYR; 5. Overthrust (a) and fault (b); 6. stratigraphic contact; 7. Bedding (dip in degree); 8. boreholes hosting inclinometer (a) or piezometer (b) drilled during the 2008-2012 campaigns; (c) previous field investigations; 9. Landslide (a-crown, b-body); 10. cross section trace

3 Hydro-mechanical modelling

The hydro-mechanical equilibrium of the slope has been investigated through the FE code PLAXIS 2D (Brinkgreve et al. 2019). The HM simulations have been carried out assuming, at first, the soils to be undisturbed in the whole slope, to evaluate the effect of the piezometric regime on the generation of a first-time failure mechanism; secondly, pre-existing shear bands have been implemented in the FE models, in order to assess the progression of the strain field along a pre-imposed weakened band.

The FE slope model have been discretised using 14300 15-node triangular elements, with a coarseness distribution variable with depth, in order to have coarser distribution at the bottom and gradually finer one approaching to both the topsoil layer close to the ground surface, where water table fluctuations occur, and within the shear band (*Fig. 2*). In order to minimise the effects of the vertical lateral boundaries, the FE mesh has been extended horizontally for 200 m both upslope and downslope.

Based on the hydrogeological surveys of the area and the in-situ piezometric levels (di Lernia et al. 2022a), the upstream hydraulic boundary conditions have been set to be hydrostatic with constant water table (w.t.) 4 m below ground level (b.g.l.), during summer, and 1 m b.g.l. when reproducing the winter season condition. Zero porewater pressures are imposed to the nodes in proximity of the Giardino stream, while a hydrostatic groundwater head with the w.t. coincident with the ground surface has been imposed to the downslope vertical boundary. The bottom boundary has been considered impermeable according to the low permeability of the deep layers, whereas free drainage has been allowed along the whole ground surface.

The partially saturated behaviour of the soils has been described by WRCs, implemented through the Van Genuchten model (van Genuchten 1980), whose fitting parameters have been calibrated based on the literature WRCs (Bottiglieri et al. 2012; Cafaro and Cotecchia 2015; Tagarelli and Cotecchia 2020), selected to be representative of the retentive properties of the Fontana Monte slope soils (di Lernia et al. 2022a).

When the process of reactivation along the pre-existing slip surface is simulated, a shear band of weakened soil has been activated in the FE model. The morphology and the mechanical properties of the pre-existing shear band, characterised by a maximum depth of 44 m along vertical SD2 and 5 m of thickness, have been determined based on both the inclinometric monitoring data and the results of the LE back-analyses. The effective friction angle of the shear band is equal to φ'=20°, which is representative of an intermediate strength between peak and post-peak for the TPC clay, while c′=1 kPa to avoid numerical convergence issues at the contact between the intact and the pre-sheared material. (di Lernia et al. 2022b). A summary of the hydro-mechanical parameters adopted in the HM FE analyses for each slope soil is reported in *Table 1*.

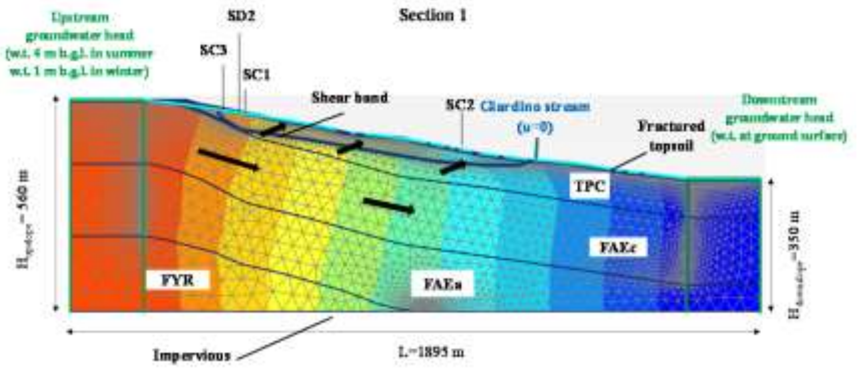

Fig. 2 FE slope model with the implemented boundary conditions; representation of the equipotential lines obtained at the end of the steady-state simulation under summer condition

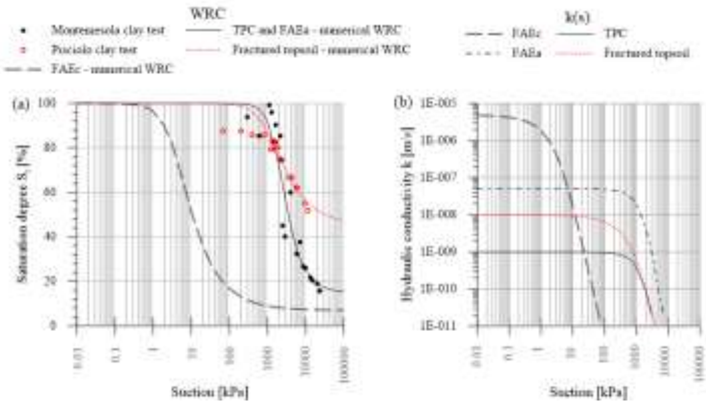

Fig. 3 (a) Soil water retention curves (Sr-s) and (b) hydraulic conductivity function adopted in the FE simulations compared to the laboratory test data available in the literature for similar soils

Table 1 Mechanical parameters of the soils involved in the landslide process and adopted in the HM analyses

	γ (kN/m^3)	c′ (kPa)	φ'(°)	E′ (MPa)	ν	k_{sat} (m/s)	S_{sat} (-)	S_{res} (-)	g_a (1/m)	g_n (-)	g_l (-)
Fractured topsoil	18.8	0	24	70	0.25	1E-08	1	0.45	0.0095	1.7	0.5
Intact TPC	18.8	13	20	70	0.25	1E-09	1	0.15	0.005	2.334	0.5
Shear Band	18.8	1	20	70	0.25	1E-09	1	0.15	0.005	2.334	0.5
FAEc	19	28	27	100	0.25	5E-06	1	0.0699	2.625	1.69	0.5
FAEa	19	13	24	100	0.25	5E-08	1	0.15	0.005	2.334	0.5
FYR	16.2	17.5	22.5	100	0.25	1E-10	1	-	-	-	-

4 Stress-strain evolution of the slope in the long term

The steady-state seepage analysis (groundwater head contours in *Fig. 2*) shows the effect of the underground aquifer, located within the FAEc layer, on the hydraulic fluxes, tending to move from the bottom toward the ground surface in the TPC stratum, while they are directed downslope in the FAEc layer itself (black arrows in *Fig. 2*). Thus, the underground aquifer in the more permeable FAEc layer represents a source of hydraulic feeding for the TPC layer and is responsible for the high piezometric heads even at large depth.

To the aim of evaluating the impact of the presence of the underground aquifer and its interaction with weather on the generation of a first-time failure mechanism, all the soils in the FE model are assumed to be intact. Thus, after the simulation of the slope formation process by excavation (for the generation of the initial stress-strain condition), the strain field mobilised in the slope at the end of the summer (*Fig. 4a*) has been investigated and its evolution due to porewater pressure variation at the end of winter season has been observed (*Fig. 4b*). The shear strain distribution, γ_s, at the end of summer highlights the tendency of the shear strains to localise at large depth, starting from the toe of the slope (*Fig. 4a*). Strains accumulates along three zones complying with the depth of the landslide body: the first one starts from the Giardino stream and deepens toward the stratigraphic contact between the TPC and FAEc layers; the second one is shallower and develops in the area immediately above the Giardino stream; the third zone is located in the middle part of the slope and is characterised by a retrogressive movement. A retrogressive roto-translational failure mechanism is generated, as highlighted by plastic points distributions, which cannot progress further at depth because of the presence of the FAEc layer. The variation from summer to winter porewater pressure regime enhances the propagation of shear strain localisation further upslope, while the slope remains stable (*Fig. 4b*).

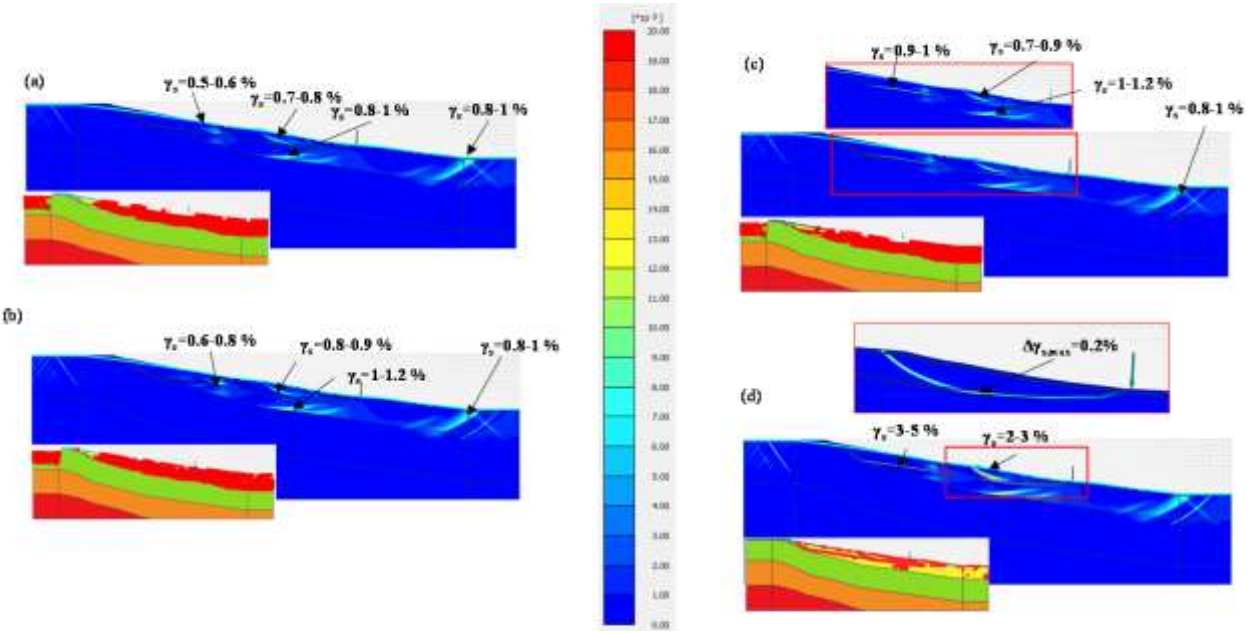

Fig. 4 Contours of shear strains γs due to first-failure mechanism (a) during summer and (b)during winter; contours of shear strains γs due to reactivation mechanism (c) during summer and (d)during winter;

With the aim of assessing the evolution of the strain field along a weakened band, a pre-existing shear band has been implemented in the FE models. After the simulation of the slope formation process by excavation, the evolution of the strain field in the slope has been investigated at the end of both the dry and the wet season. Under the summer-like piezometric regime, the slope is found to be stable (*Fig. 4c*). Plastic deformations concentrate in the central and lower portion of the shear band, propagating upslope in a retrogressive mechanism; moreover, shear strain localizes also downslope in the undisturbed soil layer in proximity of the stream. When the winter seepage regime is considered, the change in effective stress induces a progression of the strain localization zone, propagating toward and inside the lower part of the shear band (*Fig. 4d*). Therefore, a fully developed landslide mechanism, bounded by a continuous localization zone, can be observed just above the Giardino stream, leading to the slope failure (i.e. no convergence of the numerical analysis). The distribution of the plastic points indicates that full yielding of the downslope portion is reached, while a propagation of yielding develops upslope in the shear band.

5 Conclusions

The coupled two-dimensional HM simulations allowed to recognise the effect of the underground aquifer on the stress-strain evolution across the slope in the long-term conditions. In the simulation of first-time failure process, deep shear strains are localised downslope complying with a deep-seated mechanism. The FAEc layer contributes to prevent the progression of the shear strain localisation further at depth, allowing for a retrogressive propagation of plastic strains in the intact TPC soil, resulting in a roto-translational landslide mechanism involving the whole slope.
When the process of reactivation along a pre-imposed weakened band is simulated, the shear strains localise in different portions of pre-existing shear bands, as well as in the lower part of the slope above the Giardino stream flowing at its toe. Multiple strain localization areas develop also in the intact soil layer outside the pre-existing shear band, forming a retrogressive roto-translational mechanism.
Additionally, simulations proved the tendency of the landslide mechanism to be reactivated by seasonal variations in porewater pressures, controlled by the weather conditions.

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