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A case study of rainfall-triggered slope instability using projected extremes

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Abstract. In the past years due to climate change the region of South-East Europe is subjected to extreme weather events with intense rainfall fallowed by activation or reactivation of landslides. In this paper a rainfall-triggered landslide is investigated on extreme precipitation estimates. Hence, the behaviour of the slope is controlled by the hydro-mechanical conditions and soil-atmosphere interaction. In this case study a slope stability of a natural landslide is calculated for projected rainfall of 10 mm/h with 24-hour duration. In such scenarios due to the excess pore-water pressure even deep-sited landslides beside local can exhibit global instability. This study aims to quantitatively assess the impact of intense rainfall on the landslides. The extreme precipitation pattern is considered as loading condition in a fully coupled hydromechanical finite element simulation, where the displacements, matric suctions, and suction stresses are calculated. The results indicate that intense rainfall leads to fast pore-water pressure build-up resulting in local strength reduction of the slope. In general, the findings urge to reassess the existing risk maps with more detailed models and higher prognosed precipitation.

Keywords: Landslides; Climate change; Extreme rainfall; Unsaturated soil; Coupled hydro-mechanical analysis

1 INTRODUCTION

The landslides are natural hazards that often pose threats with possible social and economic consequences. In the past years the number of landslides in South-East Europe have significantly increased (Safeland, 2012). Generally, the slope stability is controlled by the hydromechanical conditions and by soil-atmosphere interaction. The climate change is anticipated to increase the frequency, intensity, and duration of climatic extremes in the future (Cheng and AghaKouchak, 2014). Climatic factors such as precipitation, evapotranspiration and runoff water may also have a substantial impact on slope stability through increase of pore-water pressure reduce the soil strength. In most cases the landslide mechanisms are triggered by climatic perturbations with extreme seasonal and long-term rainfall (Robinson et al. 2017). The deep movements may relate to the variations in seepage conditions at depth consequent to the slope–atmosphere interaction. There are cases of increase in the hydraulic heads even by 2 – 3 m measured from 30 m down to 50 m depth in clayey slopes which are connected to the seasonal climatic processes (Cotecchia et al. 2014). Such seasonal cycles in pore-water pressure have been shown to bring about yielding of deep weak clays and consequent seasonal deep movements (Cotecchia et al. 2015). Furthermore, in the slopes with marginal stability, inactive landslides, seasonal cycling of porewater pressure due to climate has been shown to trigger seasonal reactivation of sliding (Cotecchia et al. 2008). The influence of the Continental and Mediterranean climate in Macedonia unequally spreads the precipitations throughout the year with intensity between 500-1500 mm/yr. Usually there are long semi-arid periods (summer – autumn) and short wet periods. The average monthly precipitation is around 150 mm but in the wet seasons the heavy or prolonged rains contribute to excess runoff and extreme raise in GWL.

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In this study a particular case of Ramina landslide was studied through a two-dimensional fully coupled hydro-mechanical finite element calculation. To establish the trigger mechanism, the pore-water pressure, suction stresses and shear strength were closely analysed.

The presented work aims at contributing to determine the rainfall influence on the slope failure while implementing some advanced modelling aspects defining a complex soil-atmosphere interaction.

2 SITE CHARACTERIZATON

The Ramina landslide is a natural landslide located in highly urbanized hilly area of city Veles, Macedonia, on the left bank of the river Vardar (Figure 1). It is a deep-sited landslide which was reactivated several times (1963, 1999). Last time in 2002 it was reactivated with major deformations and severe damage to the existing infrastructure and buildings.

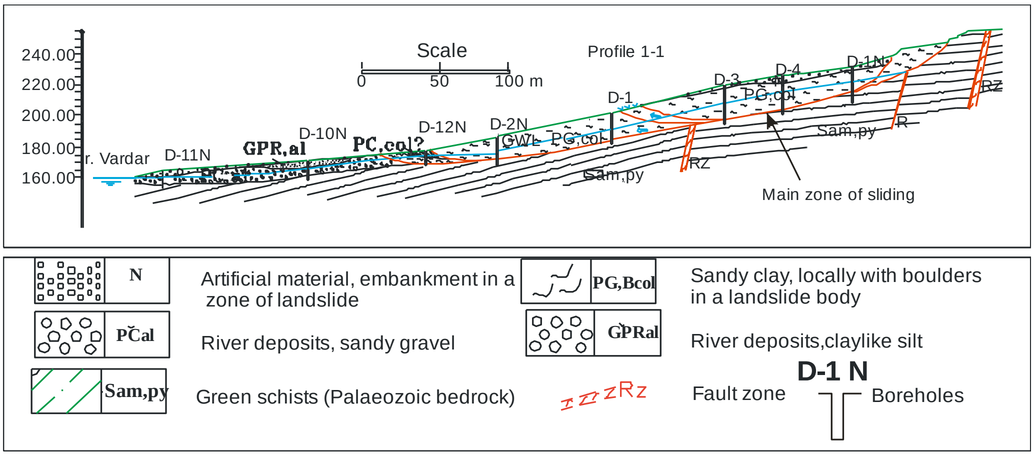


Figure 1. Typical geological profile of the Ramina landslide

The site is located on the transition of relatively steep mountain slopes to a river valley with slope elevation of around 1000 m above sea level. Actually, the position is such that it is attacked by a surface and ground water from wider catchment area. The average slope angle is around 15º and maximal 22º. The landslide is about 500 m long with average width of about 100 m and height of 95 m (figure 1). An important element of the ground characterization is that approximately in the middle of the slope there is a natural buttress almost splitting the slope profile in two.

The geotechnical investigations indicate a sliding surface on the contact between weathered bedrock (Palaeozoic amphibolitic schists, highly foliated and faulted) and low plasticity claylike soil. The hydrogeological conditions indicate that the zones with increased water contents relate to the sliding zone. Also, a sub-artesian effect was present in almost all boreholes. In the upper part of the landslide the GWL was detected at around 8 m while in the lower part it was higher around 2 m bellow the terrain.

According to the site investigations and inclinometer measurements it was concluded that the sliding mechanism is complex comprised of two parts, the upper with a length of 350 m, width 110 m, height 60 m; and lower with length of 200 m, width 90 m, height 35 m. The sliding mass is estimated to reach depth of 18 m to 24 m. The total area of the landslide is estimated to be 37,600 m^2 with around 475,200 m^3 of sliding mass, ranking as one of the largest in the Balkans, and possibly in South East Europe (Josifovski et al. 2016).

3 NUMERICAL SIMULATION AND MODEL PARAMETERS

To analyse the soil-atmospheric interaction of saturated or partially saturated slope it is necessary to take into account both deformation and groundwater flow. For time dependent behaviour, this leads to fully coupled hydro-mechanical approach where mixed equations of displacement and pore pressure have to be solved simultaneously (Ellia et. al. 2017).

In the present study the slope stability is simulated through a two-dimensional finite element model of Ramina landslide using the Plaxis software (Galavi, 2010). The advanced approaches employed in this study require implementation of hydraulic models such as the van Genuchten with laboratory measured Soil Water Retention Curve (SWRC) to evaluate the effects of rainfall water infiltration on the slope stability (Hughes et al. 2015). The shear strength of the unsaturated soil is examined based on effective stress concept considering suction. In terms of the stability check, the phi-c reduction technique was used to determine the factor of safety.

For mechanical definition of the soil a fairly simple, small strain Mohr-Coulomb (MC) model. A special emphasis was put on the definition of mechanical and hydraulic parameters critical for more realistic simulation. The geomechanical profile of the slope is modelled as homogeneous isotropic sandy clay layer over the schist bedrock. The soil parameters are given in Table 1.

Table 1. Soil material parameters for MC model

Parameter / Soil material	Sandy-Clay
Unit weight γ (kN/m^3)	20.14
Eff. friction angle ϕ' (^{0})	23
Eff. Cohesion c' (kPa)	12
Eff. Poisson's ratio ν' (/)	0.32
Elastic modulus E' (kPa)	10000

For hydraulic definition a van Genuchten model was used with parameters detrminted according the SWRC (Figure 2) obtained through laboratory tests and UNSODA curve fitting.

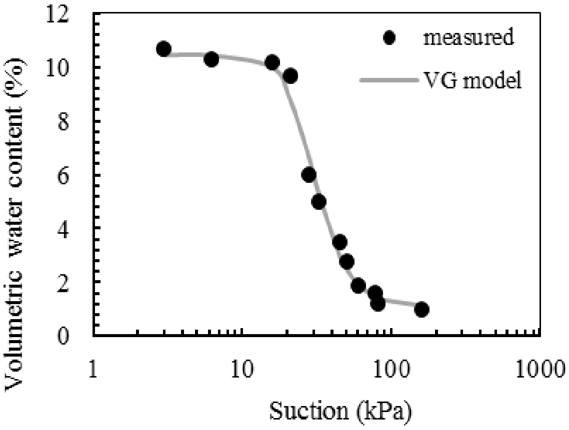


Figure 2. SWRC of Sandy-Clay from the Ramina landslide profile

The van Genuchten parameters (van Genuchten 1980) are given in Table 2.

Table 2. Hydraulic data of the van Genuchten model

Soil	k_{sat} (m/s)	θ_s (%)	θr (%)	(1/kPa)	n (-)
Sandy-Clay	1E-6	38.70	10.45	0.35	4.17

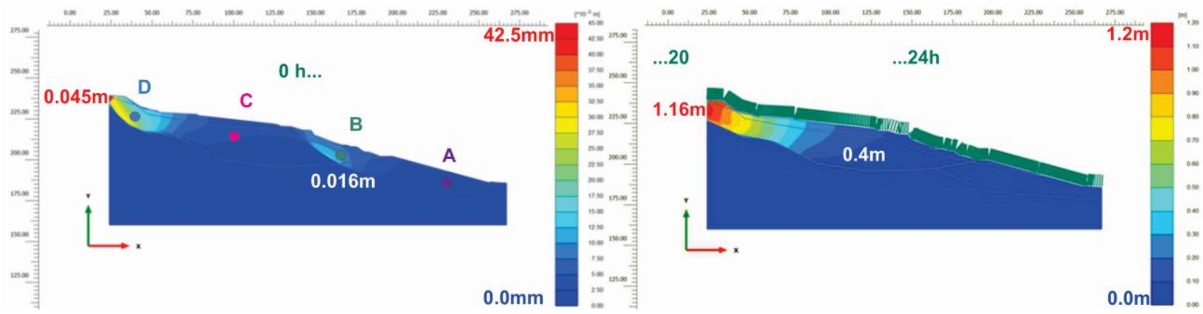
The projected extreme of 50-year rainfall was assumed with intensity of 10 mm/h. In addition, a to ground water infiltration of 1 m^3/h was prescribed at the top of the slope. The free surface an infiltration boundary with 10 mm/h and additional a runoff water from 0.5 mm/h due to the terrain condition without vegetation cover is assumed. The left (lower) boundary is open outflow because the slope ends with open recipient, namely the river Vardar. The right (upper) boundary is inflow with constant infiltration of $1m^3/h$ is prescribed.

The Dirichlet condition restrains in vertical direction the right and left model boundary and totally fixes the bottom. On the interface between the schist bedrock and sandy-clay layer interface elements are employed to check the stresses and deformations.

4 RESULTS AND DISCUSSION

The simulation was able realistically to describe the whole sliding process in time interval of 24-hours. The calculation produced good agreement in comparison to the measured values on site.

The slope displacements are of key importance when the sliding mechanism is determined, thus in Figure 3 the model predictions are presented.

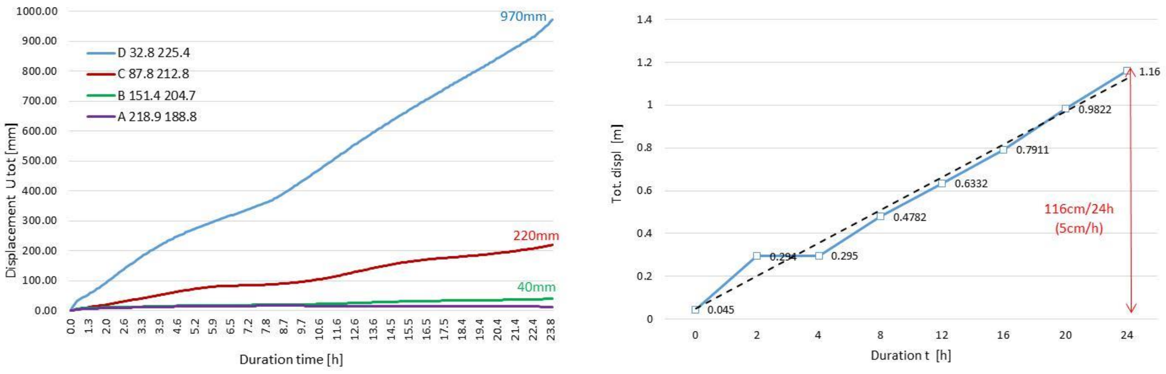


(a) (b)

Figure 3. Total landslide displacement at (a) t_0=0h and (b) t=24h

Figure 4(a) presents the displacements field at initial time t_0= 0 s where the max. displacement is 4.5 cm at the top and 1.6 cm around the middle of the slope. A development of two sliding masses is evident due to the strong presence of the buttress. The initial factor of safety is 1,53. Comparably, Figure 4(b) presents the displacements after 24 h of constant precipitation and infiltration. The max. displacement is 1.16 m at the top are while in the middle a 0.4 cm are registered. After 24h both sliding masses (upper and lower) are connected and the sliding surface forms along the 300 m of contact with the schist bedrock.

To have better picture of time dependent effects such as strain accumulation the displacement of four different points (A, B, C and D) are given as time dependent curves, see Figure 4(a).

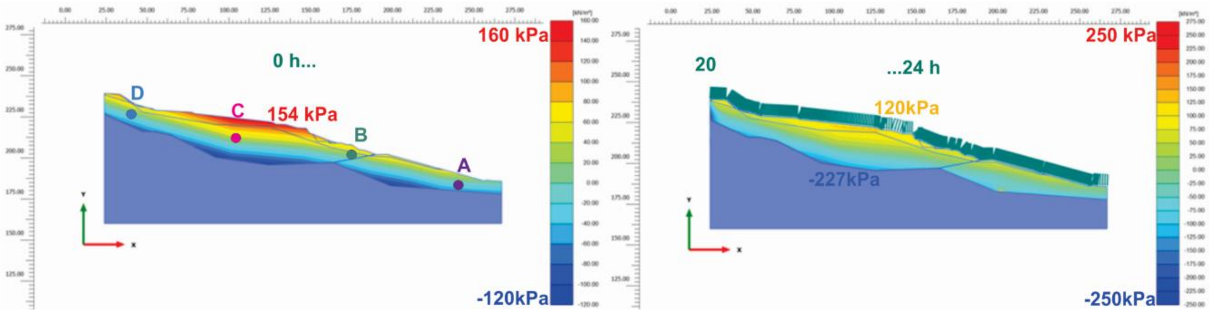


(a) (b)

Figure 4. Time dependent displacements at (a) selected points and (b) max. value

The position of points is given in figure 4, hence point (D) near the top is displaced by 970 mm, in contrast to the point (C) positioned near the middle of the landslide is displaced by 220 mm. The difference grater then four times clearly describing a mechanism where most of the energy is spent for the deformation in the upper part. Moreover, in Figure 4(b) the maximal total displacement is given with the time. It is quite interesting that the displacement is linearly increased with average rate of 5 cm/h, hence there are no stabilization or accumulation effects only continuous deformations or mass movement during 24-h rainfall. Thus, Ramina landslide can be classified as fast moving.

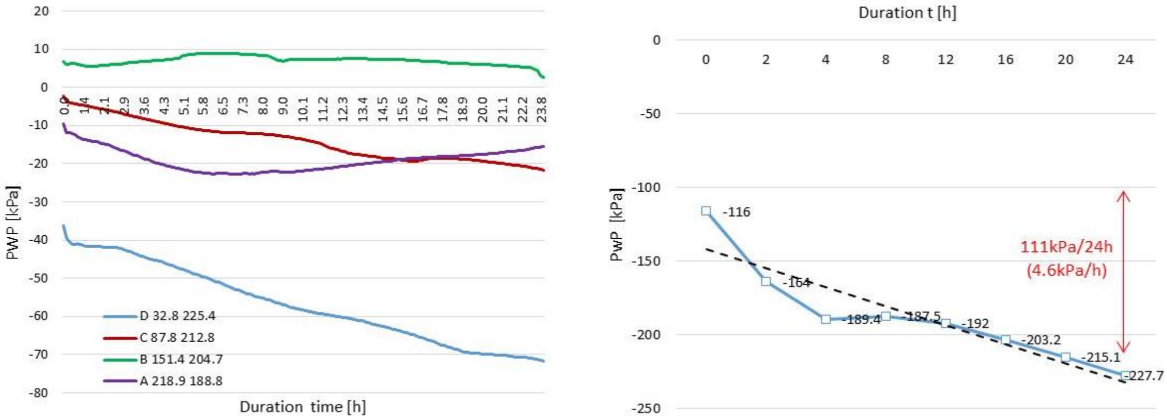
A key destabilizing factor is the excess pore-water pressure (PWP) with negative value acting bellow the saturation level. His positive contra-par is the suction (S) which by acting above the saturation level stabilizes the slope. The surface rainfall infiltration reduces the suction and at the same time raises the GWL. The initial pore-water pressure and pore-water pressure after 24h is presented in Figure 5 (a) and (b), respectively.



(a) (b)

Figure 5. PWP graph at (a) t=0h and (b) t=24h

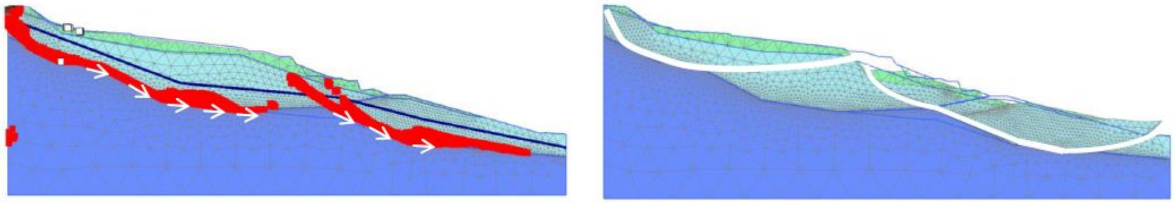
As expected the suction forces at the top soil layer are reducing with time from 154 kPa to 120 kPa after 24h. In contrast, the pore-water pressure at the contact with the schist bedrock increases almost by double from -116 kPa to -227 kPa after 24h. The negative pore pressure development at different points (A, C and D) and suction stress at point (B) are presented in Figure 6(a).



(a) (b)

Figure 6. Time dependent PWP at (a) points A, B, C, D and (b) max. value

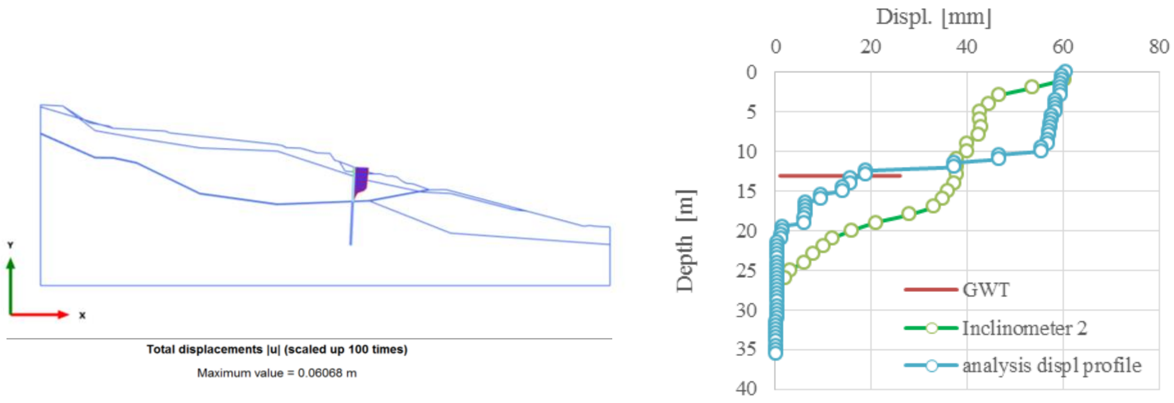
The suction in point (C) is almost constant with value bellow 10 kPa. In point (D) at the top of the slope the PWP increases with the time is from -40 kPa to -73 kPa, while the PWP increase is smaller in the other three points. In general, when looking at the maximal PWP values there is a gradual increase with the time, see figure 6(b). Similarly, to the one of the displacements the max. registered PWP difference is -111 kPa in 24h or -4.6 kPa/h. The strain shear increments are largest in the plastic zones where the sliding occurs, see figure 7(a). The results show how the plastic zone start to develop in the upper part on the contact with the schist bedrock, later to spread down toward the middle of the slope. Most important is the fact that due to the rainfall there is significant raise of GWL for 3-4 m. In time the PWP equals the shear resistance of the material, thus triggering the sliding of the soil mass Figure 7(b). After destabilization the new equilibrium is established with safety factor of 1.03.



(a) (b)

Figure 7. Sliding mechanism described through (a) plastic zones and (b) deformation after 24h

Additionally, the displacements profile in the middle of the slope (Figure 8a) is analysed and compared to those measured by the inclinometers, see Figure 8a.



(a) (b)

Figure 8. Slope displacement (a) profile and (b) comparison graph

On the top of the slope there is almost a perfect agreement in the displacements (60 cm), but when comparing them in the depth there is not so good overlapping, see Figure 9(b). In the case of the inclinometer the displacements show more gradual decline with depth, in contrast to the calculated results. At the depth between 10 to 13 m there is sharp decrease of displacement, which could be connected to the GWT positioned at 13m of depth. According to the inclinometer the zero displacement or the sliding surface is at 26 m while in the calculated model it is positioned at 22 m. Furthermore, the analysis an overall slope stability gives the factor of safety with time, see Figure 9.

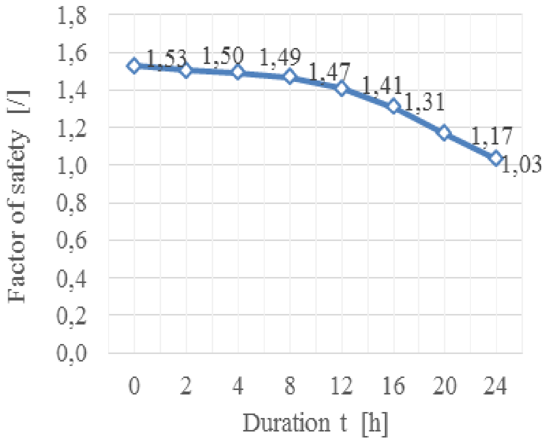
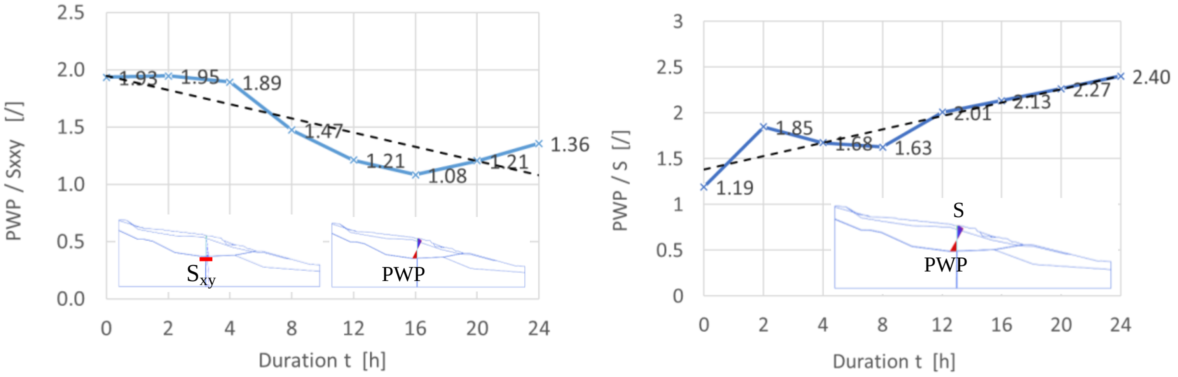


Figure 9. Factor of safety (FoS)

Up till the 8 hours duration the safety factor is relatively stable with negligible decrease after which comes a period of strongly pronounce decrease of the factor. Hence, after 24-hour of intense rainfall the landslide is back in labile equilibrium (FoS=1.03) with potential to be re-activated after any other similar event.

To understand the influence of the rainfall infiltration the strength variables near the slip surface are closely examined in Figure 10.



(a) (b)

Figure 10. Ratio between (a) Shear / PWP and (b) PWP / Suction

In Figure 10(a) the shear strength degradation is evaluated through the Sxy/PWP ratio between the shear strength and pore-water pressure at the contact with the bedrock. The decreasing trend (dashed line) is clear with some fluctuations. Similar, in figure 10(b) the ratio between the pore-water pressure and suction with the time is presented, hence under water infiltration the PWP is increasingwhile the suction is reducing with time. Both together define the degradation trend (dashed line) and eminent instability with deformations as those depicted in Figure 11.

(a) (b)

Figure 11. Photo of the (a) top zone of main scarp and (b) buttress zone of the landslide

The Figure 10(a) confirms the findings of the analysis that the largest displacement will occur in the top where the main scrap is formed and most deformations are to be in the middle where the buttress breaks the sliding mass in two.

5 CONCLUSION

The consequences of climate change on landslide rate, size and frequency are difficult to predict because they depend on a range of variables. The precipitation is among the most important factors especially severe seasonal storm with intense rainfall. In addition, the indirect impact of climate change on landslide is exerted through changes of vegetation cover, quality and density, runoff, overland flow and oversaturation would increase raising the rate of erosion and frequency of landslides (Josifovski et al. 2017). Rainfall is often the main factor for landsliding. The modelling has shown that suction responses to rainfall vary on a number of different timescales. On shorter timescales (ranging from minutes to hours and days) heavy rainfall which was of primary interest in this study produced very interesting results. The rainfall infiltration effects in the literature (Casini 2015) are usually critical for shallow landslides, but here it proven that also the deep sited landslides with high GWL could be destabilized.

The combination of rainfall infiltration and GW inflow to the slope is the main reason for destabilization in Macedonia around 60% of all the total number. Therefore, the need to asses that impact of climate change and revaluate current landslide risk maps especially near infrastructure and urban areas is necessary (Ellia et al. 2017).

The presented coupled hydro-mechanical analysis underlines the importance to check on intensive rainfall (10 -20 mm/h) longer duration, because as shown they could have a significant influence on stability, thus should be considered in future with given probability of occurrence. In the analysis it has been evaluated the influence in the sense of infiltration and duration of rainfall on the slopes. It was proven that relatively short but gust rainfall could have a significant influence on the overall (global) stability. According to the statistics this type of rainfall are to be expected more frequently in future (Chang and AghaKouchak 2014). This requires existing risk maps to be revaluated thoroughly, based on advanced calculations that include the new data about the rainfall intensity and partial soil saturation.

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