Climate change effects on slope stability

M. Oggero, A. Insana[1,*] and M. Barla[1]

[1] Department of Structural, Geotechnical and Building Engineering (DISEG), Politecnico di Torino
Corso Duca degli Abruzzi 24, 10129, Torino (Italy)
alessandra.insana@polito.it

Abstract Global warming is taking place and there is no doubt that the stability of natural and artificial slopes is influenced by climate change. In this context, the present study intends to show, as more quantitatively as possible, the effects of climate change on slopes stability. The analysis was developed considering a non-static approach suitable for meteorological phenomena which are expected to change in the next years. In the analysis a statistical method was combined with a mechanical one: the forecasts of the intensity growth of heavy precipitation were used, as well as the physical laws for describing the response of groundwater table to these rainfall events and the resulting slopes stability. A case study located in Monchiero (Cn), Italy, was used as a test for the analysis and the forecasts described above.

Keywords: slope stability, climate change, rainfall thresholds, numerical modelling

1 Introduction

Landslides are natural hazards which take place as a combination of meteorological, geological, morphological, physical and human factors. Extreme climate events such as droughts, heatwaves and heavy precipitations are factors influencing landslides occurrence in Europe (EEA, 2017). The activation/re-activation of shallow and deep-seated landslides are governed by the combination of intense/prolonged rainfalls as well as by the seasonal/annual precipitation trend and snow melting.
In general, climate models show that extreme weather events will become more and more common with climate change (NASA, 2014).
Starting from these considerations essential efforts have been made in recent years by many researchers (Crozier, 2010; Stoffel et al., 2012, 2014; Gariano and Guzzetti, 2016; Gariano et al., 2017; Alvioli et al., 2018; Tang et al., 2017). The European Large Geotechnical Institutes Platform (ELGIP) has recently started a working group to highlight climate change impacts on natural ground and geotechnical constructions. Nevertheless, relevant past trends and robust signals for future projections in landslides occurrence and magnitude have considerable uncertainty, partly due to the lack of enough historical data, and partly due to the complexity of the local physical processes involved (Debele et al., 2019). Moreover, the human-induced drivers and their implications can outweigh the known or forecast changes in landslide activity due to climate change. However, all

the studies agree that the increase or decrease of landslides activity will depend on the type of landslide and the geographical position. Some slope stability models used to forecast the implications of global warming on landslides at different geographical scales ignore that climate data are typically not stationary. Hence, it's recommended to create new slope stability models capable of considering non-stationary climate and landslide records (Gariano and Guzzetti, 2016).
This paper intends to combine a statistical method, based on rainfall thresholds, with a mechanical one, accounting for the infiltration phenomenon and the landslide stability, in order to evaluate climate change effects on landslides with a non-static approach based on physical principles. This method is then used to estimate the rainfall thresholds of an Italian case study placed in Monchiero (Cn), a village in the north-west of Italy.

2 Analysis of climate change effects on slope stability

Although landslide typically is a local event, that depends on slope geometry, geomechanical proprieties, water pressure conditions and other specific situations, there are some general drivers. Indeed, in many cases, landslide is triggered by a specific event such as a heavy rainfall. This extreme weather event can rise groundwater level or increase pore water pressure and change the slope condition from stable to unstable. It's clear that this is only one of the possible instability mechanisms.
This paper analyses the effects produced on slopes stability by increasing heavy precipitation, bearing in mind that this is only one of the several implications of global warming and climate change. The approach is based on the following two steps:

1- The critical water table height (i.e. FS=1) is searched by adopting a numerical model which reproduces the geometry and the stratigraphy of the slope.
2- Based on a hydrogeological model the possible combinations of intensity and duration of a rainy event able to justify the increase of the water table to the critical value attained in step 1 are computed. This allows one to set alarm thresholds.

For the first step, the Finite Element Method (FEM) can be used. In particular, the FEM software RS2 (Rocscience Inc., 2001) and the shear strength reduction method were adopted to determine the safety factor of simple homogeneous slopes with different water-table levels. The mesh and dimension of the model were validated and good agreement was found compared to limit equilibrium methods such as Fellenius (1927), Bishop (1955), Janbu (1967) and Spencer (1967). Due to the complexity of the problem, a simplified homogeneous and isotropic case with constant slope was studied. Under the hypothesis of plain strains, a 2D analysis was carried out. Four geo-materials were analysed: gravel, sand, loam and clay. For average geomechanical and hydrogeological parameters reference was made to Lancellotta (2012), Healy et al. (2002), USDA-SCS (1986). As shown in Fig. 1, the geometrical parameters assumed for the model are: L, horizontal length of the slope, α, slope angle, and H, water-table depth.

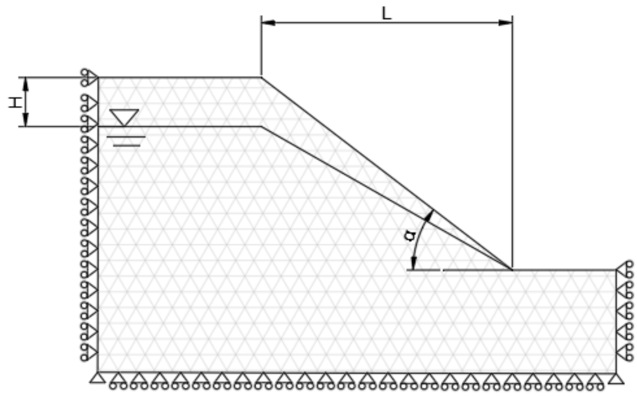

Fig. 1 Schematic view of the model

A simplified linear groundwater trend was assumed, by subdividing it into three main sections, as illustrated in Fig. 1.
For each material an equilibrium limit law between the geometrical parameters and the water-table depth was investigated. Clearly, a local hypothesis on the initial water-table depth was needed.
The second step can be performed by combining the Curve Number (CN) Method (USDA-SCS, 1985) and the Water-Table Fluctuation (WTF) Method (Healy and Cook, 2002). The most important advantages of using CN and WTF methods are the availability of data and their simplicity. Under the hypothesis that the rise in groundwater level in unconfined aquifer is due to recharge water arriving at the water table, the output of this second model are curves that relate groundwater rising (Δh) and the corresponding precipitation required in terms of intensity *i* and duration *d* to produce that rise. The assumption that water reaching the water table is immediately stored is mostly valid over short time periods. This is acceptable when analysing heavy precipitation and slopes with a quick water-table response (shallow water-table). Two principal equations were used:

$$Q = 0 \quad \text{for} \quad P \leq I_A \qquad \text{and} \qquad Q = \frac{(P-I_A)^2}{P-I_A+S} \quad \text{for} \quad P > I_A \tag{1}$$

$$R = S_y \frac{\Delta H}{\Delta t} \tag{2}$$

In Eq. (1) P is the rainfall, Q is the runoff, S is the potential maximum soil moisture retention after runoff begins and I_A is the initial abstraction, while in Eq. (2) H is the water-table depth, R is the recharge, S_y is the specific yield and t is the time.
From a mathematical point of view, the CN Method in Eq. (1) was used to define the infiltration, that is the share of precipitation entering the soil. The parameter that calibrates the model is CN that appears indirectly in the formula, as it is used to estimate the storage. Furthermore, it depends on soil type, land use, treatment and hydrologic condition. The WTF Method was then applied thanks to Eq. (2) to compute the rise of the water table in response to water infiltrated into the ground and arrived at the water table. In this second method, the parameter that calibrates the model is S_y that is the ratio

of the volume of water which, after being saturated, it will yield by gravity to its own volume (Meinzer, 1923).
The combination of these two models allows studying the climate change impacts on landslides. Indeed, the SCIA (national environmental information system for calculating, updating and representing Italian climate data) projections on the maximum daily precipitation in Italy were used as parameters of heavy precipitation intensification (ISPRA, 2017). The forecasts for 2061-2090 were compared with the data referred to 1971-2000. These trends were applied to the output of the second model in order to obtain the records of the water-table variations. Then these results were introduced in the first model to compute the variation of the minimum angle of slopes that can become unstable due to maximum daily precipitation. The results can be observed in Table 1.

Table 1 Results obtained by combining the mechanical and hydrological models

Slope material	Gravel	Sand	Loam	Clay
Variation of the minimum angle of slopes that can became unstable due to maximum daily precipitation	-0.2°	-0.1°	-0.2°	-0.2°

Climate change, considered in this case as an increase of the maximum daily precipitation, will decrease the minimum slope angle of the landslides subject to instability. This can also be seen as an increase of the number of the slopes that can became unstable due to the daily maximum precipitation (Fig. 2). The variations obtained are relatively little. However, it should be reminded that the climate change effect analysed is not the only one that would occur and that the timeframe considered for the projection is quite short.

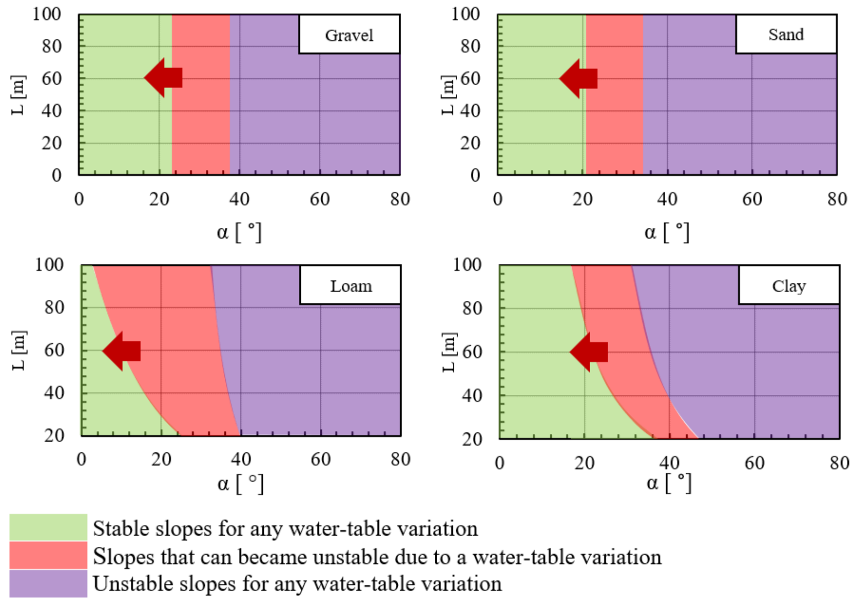

Fig. 2 Slopes stability conditions for the different soils analyzed. The red arrow indicates the direction of the variations induced by climate change

3 Case study: Monchiero

The case study in the village of Monchiero (Cn) was used as a test-bench for the analysis described in the previous chapter. The analysed area is located in the Langhe, an area of southern Piedmont where many flooding and mainly planar landslides events occurred, causing damage to properties and loss of lives. As described in Bottino et al. (2011), usually, the moving mass splits up into a series of prisms, sliding along bedding planes dipping at 6° to 12°, almost parallel to the dip of the layers. Water flow has always been observed along these discontinuities. Larger blocks exhibited displacements of more than 30 m, with vertical cracks in the top and middle part of the landslides and compression of the toe, when this part was subjected to boundary constraints.
Typically, the triggering cause of landslides in Langhe is related to rain intensity and local hydrogeological conditions (Aiassa et al., 1996; Bottino et al., 2000). Moreover, the events analysed show a quick water-table response that allows focusing on a brief timeframe. It's clear that the groundwater shows a cyclic pattern following the seasons, but the main movement events happened in late spring when the water table is nearly constant until heavy precipitation occurs. Therefore, reference was made to this level of about -1.8 m.
The site is monitored with six manual inclinometers, an automatic one, a rain gauge and an automatic piezometer. The combination of this monitoring system enabled studying both the correlation between rain and water-table fluctuation and the interaction between water-table fluctuation and slope movements. In light of the inclinometers data, it was possible to observe that four main movements had occurred: 1.5 mm in March 2011, 1.0 mm in May 2013, 1.0 mm in March 2014, 3.0 mm in February/March 2015. Heavy precipitations and melting snow characterised these periods. For each of the above-mentioned movements it was possible to observe that when the water-table rises up to a certain level (-0.5 m) the displacement starts. Therefore, the heavy rainfall events that made the groundwater critical increase were looked for and are summarized in Table 2.

Table 2 Monchiero heavy rainfall events leading to a critical groundwater rise

Rainfall event		Duration [h]	Intensity [mm/h]
March	2011	96	1.42
May	2013	24	3.05
March	2014	72	0.89
March	2015	72	1.66

The simplified method proposed with this research was applied to create an alert threshold, not only statistically based but also with a physical background. Firstly, the critical water-table variation was here computed statistically from the historical events (ΔH=1.3 m), without applying a FEM landslide stability for simplicity. Then, the threshold was created using the second step of the approach described in chapter 2. Based on local characteristics, a value of 78 for the Curve Number and, due to stratigraphy, a value of 0.035 for the specific yield were chosen (USDA-SCS, 1985; Healy and Cook, 2002).
The computed threshold curve and the data in Table 2 are reported in Figure 3.

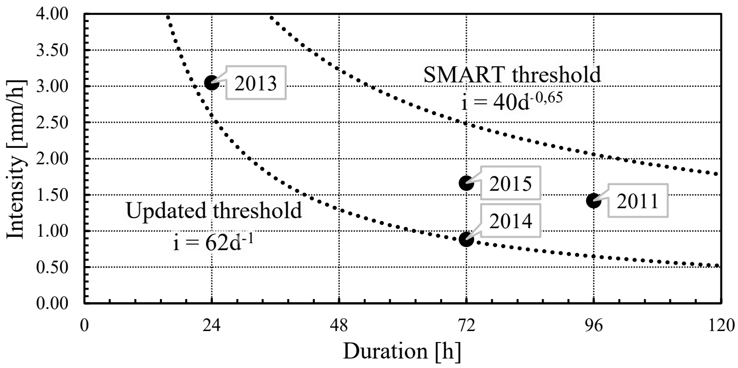

Fig. 3 Computed and existing rainfall threshold for Monchiero case study

The computed alert threshold was compared with the rainfall events analyzed. It is possible to observe that all the points, that represent critical past rainfall events, are over the curve. Moreover, the new threshold was also compared with the one suggested by the Environmental Protection Agency of Piemonte (ARPA Piemonte) in the framework of the SMART (Shallow landslides Movements Announced through Rainfall Thresholds) project. The validation of the SMART thresholds was performed on the 1990–2002 rainfall and shallow landslides data sets. The project usually recorded shallow landslides only if they produced damages to anthropic structures, in order to reduce the number of false alarms (Tiranti et al., 2010). As can be inferred from Fig. 3, many of the events analyzed fall below the SMART threshold.

Finally, it was observed that the precipitations that caused instabilities usually match with the maximum annual daily rainfall. Therefore, the SCIA forecast on the maximum annual daily precipitation has been used to estimate climate change effects. Indeed, it has been computed that the threshold would be reached if the intensity of the maximum local daily rainfall rose by 27%. This would result in one instability event every year probable. In order to compare this value, SCIA expects an increase of 10% for this parameter in the Italian region for 2061-2090, considering the RCP8.5 scenario.

6 Conclusions

This paper discussed the influence of climate change on slopes stability with the objective to try to quantify this phenomenon. Firstly, a simple geomechanical model was created to derive an equilibrium limit law between the geometrical parameters and the water-table depth. Then, the CN and WTF methods were combined to define the infiltration law.

The results of the analyses carried out show a general decrease, about -0.2°, of the minimum angle of slopes that can become unstable due to maximum daily precipitation. In particular, sandy slopes display better behaviour because of the higher value of specific yield. The little variation can be explained considering that the effect of climate change considered here will not be the only one. Indeed, progressive desertification, heatwaves

and other extreme weather events related to them can affect the geomechanical characteristics by decreasing the soil materials strength. However, it should not be overlooked that there can also be benefits, such as the average decrease of the water table due to the increase in the average global temperature and the most frequent heatwaves.
Moreover, other aspects can explain these results like the relatively brief timeframe that represents the assumption underlying the WTF method. Using a more sophisticated infiltration model would be fundamental to obtain more valuable results, in order to be able to account for a higher number of parameters.
The application of the developed method to a case study led to the creation of an alert threshold not only based on historical events but also with a physical background. It was observed that if there was an increase of 27% of the daily maximum precipitation intensity, the threshold would be reached. This means that an event every year would be probable and not four in ten years as in the analysed period. To give a comparison term, according to the 2061-2090 SCIA forecasts an increase of 10% of the daily maximum precipitation intensity will occur.

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