



## Article

# Climate Change Impact on the Stability of Soil Slopes from a Hydrological and Geotechnical Perspective

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**Abstract:** Climate change (CC) is expected to cause significant changes in weather patterns, leading to extreme phenomena. Specifically, the intensity of precipitation extremes is continuously escalating, even in regions with decreasing average precipitation levels. Given that CC leads to long-term shifts in weather patterns and may affect the precipitation characteristics (i.e., frequency, duration, and intensity) directly related to groundwater table fluctuations and soil erosion phenomena, it has the potential to significantly affect soil slope instabilities. In turn, slope stability and the structural integrity of nearby structures and infrastructure will be affected. Accordingly, the present paper focuses on the impact of CC on the geohazard of soil slope instability by considering both hydrological aspects, i.e., the impact on rainfall intensity on the groundwater table and the geotechnical aspects of this complex problem. The findings reveal that the impact of CC on potential slope instabilities can be detrimental or even beneficial, depending on the specific site and water conditions. Therefore, it is essential to do the following: (a) collect all the available data of the area of interest, (b) assess their variations over time, and (c) examine each potentially unstable slope on a case-by-case basis to properly mitigate this geohazard.

**Keywords:** climate change; rainfall intensity; infiltration; groundwater table; soil permeability; slope instability



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## 1. Introduction

The instability of natural or artificial slopes is widely recognized as one of the most unpredictable and destructive geohazards with significant consequences for the environment, the population and the economy [1]. More specifically, slope instabilities have the potential to directly or indirectly affect the integrity of any structure and infrastructure located on or near mountainous or hilly areas. These include buildings, bridges, roads, railways, wind turbines, pipelines, energy transmission and telecommunication cables, dams, tunnels, etc. [2]. Furthermore, slope instabilities can have far-reaching effects on regional and national economies, as well as threaten human lives [3].

According to Varnes [4], slope instabilities are broadly defined as natural geological events that can cause sudden or gradual mass movements on the ground surface. They can be categorized into five main categories: falls, topples, slides, lateral spreads, and flows, based on the type of movement, while these instabilities can be further classified into rock and soil corresponding to the type of material prone to slope instability. Slope instabilities typically occur due to a combination of meteorological, geological, morphological, physical, and human-induced factors. Landslides, in particular, are often triggered by seismic and other dynamic loads (if any), fluctuations in the level of groundwater table, soil erosion, inadequate planning and faulty land use, etc. Turner and Schuster [5] noted that landslides are becoming more common due to continued deforestation, urban growth,

and construction in landslide-prone areas. Furthermore, extreme climate events such as droughts, heatwaves, and heavy precipitation have played a significant role in the occurrence of landslides in Europe [6].

Leroueil [7] highlighted that the global annual cost associated with landslides has surpassed USD 20 billion. The impact on human lives is also significant, with around 110,000 casualties in China alone during the 20th century [8]. A comprehensive investigation conducted by Haque et al. [9] revealed that 1370 deaths and 784 injuries were documented from 476 deadly landslide events in 27 European countries between January 1995 and December 2014. It should be emphasized that increased precipitation levels can also contribute to slope failures. Rainfall-induced landslides, the most prevalent type of landslides, result in approximately 1000 deaths each year according to the EM-DAT Database [10]. According to Zhang and Huang [11], more than 90% of fatal landslides in China are directly related to rainfall events. An examination of over 100 historical landslide incidents in the Alps has revealed that nearly 80% of them were triggered by rainfall events [12]. In addition, the devastating incident that took place in 2014, four miles east of Oso, Washington, DC, USA, resulted in the loss of 43 lives [13]. Furthermore, precipitation can induce landslides in areas previously destabilized by earthquake events, as seen in the landslides following a rainstorm after the Wenchuan (2008) earthquake in China [14].

As it is not always technically and economically feasible to completely avoid potentially unstable slopes, landslides may lead to structural damages or even failures to adjacent or crossing structures and infrastructure due to External Loads (*ELs*), Permanent Ground Displacements (*PGDs*), or a combination of these actions. For example, in the mountainous regions of the Andes, nearly 50% of the critical infrastructure failures were attributed to landslides [15]. Moreover, the European Gas Pipeline Incident Data Group reported in 2015 that 85% of the gas pipeline accidents in Europe from 2004 to 2013 occurred due to landslide-induced tension or buckling, resulting in significant leaks, major environmental impacts and long periods of service disruption [16,17].

On the other hand, it is widely acknowledged that Climate Change (CC) leads to global warming. One of the key issues associated with the complex phenomenon of CC is that higher temperatures are likely to result in large-scale and long-term shifts in weather patterns, leading to more extreme weather events, such as severe storms and heavy rainfall. This is due to the fact that the air capacity to hold moisture is directly influenced by temperature. Numerous studies have highlighted the potential impacts of CC on weather patterns, including research by Fowler and Hennessy [18] and O’Gorman and Schneider [19]. Several researchers have delved into the anticipated effects of CC on hydrological processes [20] and changes in annual precipitation patterns [21].

The intensity of precipitation extremes, such as heavy rainfalls, has escalated over the past 50 years, even in regions experiencing a decrease in average precipitation levels, such as central Europe and the Mediterranean Region. Tang et al. [22] documented a rise in both the intensity and the frequency of precipitation events across the entire European region between 2002 and 2011. Despite previous periods of CC, the Intergovernmental Panel on Climate Change (IPCC) has concluded that the unprecedented impact of humans on Earth climate system in recent decades has led to a climate crisis, creating an urgent and perilous situation on a global scale. According to Masson-Delmotte et al. [23], heavy precipitation events are expected to become more frequent in the near future as a direct consequence of CC. NASA has developed predictive models indicating that extreme weather events will increase in frequency as CC becomes more intense [24].

Given that CC leads to long-term shifts in weather patterns and may affect the precipitation characteristics (i.e., frequency, duration, and intensity) directly related to groundwater table fluctuations and soil erosion phenomena, it has the potential to significantly affect the geohazard of slope instability at different temporal and geographical scales [25]. This, in turn, can have repercussions on the population living in areas prone to landslides, as well as on the structural integrity of structures and infrastructure located on or near mountainous or hilly areas worldwide. These structures and infrastructure are often interconnected

with various social, economic, and environmental factors, further heightening the risks for individuals and households. In parallel, it should be stressed that international organizations and authorities, such as the United Nations (UN) and the European Union (EU), have underlined that the impact of CC on the integrity of any structure and infrastructure is extremely crucial.

In recent years, significant research effort has been focused on investigating the relationship between various aspects of CC and the phenomenon of slope instability (e.g., [26–31]), with a number of studies focusing on temperature-induced slope instability in perma-frost regions due to CC [32,33]. Dehn and Buma [34] and Gariano et al. [35] established regional benchmarks for evaluating the temporary slope stability trends for CC scenarios, local hydrological studies, and geomorphological models. Schmidt and Dikau [36] reported that while generalizations in the impact of CC on slope stability can be made, specific geological and geotechnical conditions govern the stability of any slope.

Sidle and Ochiai [37] carried out an evaluation of CC-related variables and processes that can influence the occurrence of landslides. They have found that the rise in average air temperature and alterations in regional annual and seasonal precipitation are key factors in the activation or reactivation of landslides. The effects of CC on vegetation, soil, land use, and land cover were also examined by the authors, highlighting the increased complexity that these factors add to the problem at hand. Crozier [38] conducted a thorough parametric investigation and explored various methods for assessing the impact of CC on landslides. Alvioli et al. [39] emphasized the effect of precipitation characteristics, such as duration and intensity of rainfalls, as an intensifying factor of slope failures.

Collison et al. [40] investigated a particular area in southeast England, where they gathered historic climate data and future estimations. They utilized a digital elevation model to determine the depth of the groundwater table, which was then used as an input for the infinite slope stability model. The authors have reported that an increase in rainfall would balance out evapotranspiration, thereby maintaining a stable number of slope failure events. Dehn et al. [41] examined the ground displacement of an active mudslide in the Dolomites, Italy, considering various scenarios of rainfall decrease. Their findings have indicated that annual displacement rates would decrease, with the most significant reduction occurring in spring. However, they have acknowledged that their results were subjected to uncertainties. Lastly, Insana et al. [42], Park et al. [43] and Vardon [44] examined the impact of CC on the performance of geostructures. Their research aimed to determine how these structures could withstand the challenges posed by CC.

Nonetheless, a review of the existing literature revealed that there is still a lack of understanding of the specific mechanisms through which CC is related to the geohazard of slope instability and the associated risks. Additionally, there are significant uncertainties and gaps in standards and regulations addressing the structural integrity of structures and infrastructure located on or near potentially unstable slopes due to CC. Therefore, it is imperative to conduct a comprehensive assessment of the potential impact of CC on slope stability, as this is a demanding issue of top priority. This assessment serves as the initial and most critical step in mitigating the impact of CC on existing structures and infrastructure. It also plays a vital role in addressing the challenges posed by CC in the design, construction and operation of any safe and resilient new structure and infrastructure in the future.

The present paper aims to: (i) describe the effects of CC on the geohazard of soil slope instability from a general perspective, as intense CC-related rainfalls can occur in many regions with potentially unstable slopes worldwide and (ii) develop a simplified analytical method, through the combination of the widely utilized Soil Conservation Services-Curve Number (SCS-CN) method and the slope stability analysis in terms of Factor of Safety (FS), to evaluate the CC impact on the geohazard of slope instability. The findings of this study indicate that, depending on the specific conditions, CC can have a negative or even a positive impact. Geoscientists and geotechnical engineers can benefit from the proposed methodology, as it can be efficiently implemented in specific case studies, provided that all the required data in the examined area (e.g., topographical, geological, hydrogeological,

geotechnical, seismological, etc.) are collected and their variation over time is assessed, which is beyond the scope of the current paper.

Following the current introduction, the paper is structured as follows: Section 1.1 provides a detailed description of the examined problem. Section 2 outlines the analytical methodologies used to evaluate the impact of CC on slope instability. Section 3 presents the results regarding the direct impact of CC on both infiltration and surface runoff, as well as the indirect impact of CC on the geohazard of slope stability. A comprehensive parametric investigation is conducted, considering various scenarios of rainfall (including typical and CC-induced rainfall), three soil permeability levels, and three distinct soil material cases. Section 4 discusses the results from the parametric investigation, while the paper concludes with insights, limitations, and directions for further research.

### 1.1. Problem Description

To assess the impact of CC on slope instability and its effects on any structure and infrastructure located in mountainous or hilly areas, it is essential to first examine the influence of regional climate conditions on slope stability. The flowchart depicted in Figure 1 graphically illustrates the aim of the current paper, whereas each step is comprehensively described in the sequence.

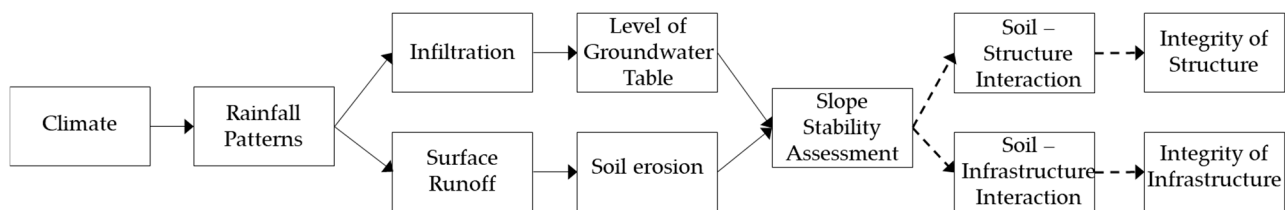


**Figure 1.** Flowchart depicting the indirect relationship between climate and structural integrity of any structure and infrastructure located on soil slopes.

Specifically, the regional climate of a particular area is assumed to have an indirect relationship with both the geohazard of slope instability and the integrity of any structure and infrastructure located on or near potentially unstable mountainous or hilly areas. One of the key factors that is influenced by the regional climate is the precipitation characteristics, including the frequency, duration, and intensity of rainfalls. Precipitation plays a direct role in surface runoff and infiltration of a soil slope. On the one hand, surface runoff can lead to soil erosion phenomena along the slope surface or at the base of the slope toe, potentially altering geometrical characteristics of the slope. Infiltration, on the other hand, dominates the level and the inclination of the groundwater table.

Given (among other parameters) the geometry and the material properties of the slope, as well as the level of the groundwater table, slope stability analyses can be performed and the corresponding Factor of Safety (*FS*) can be derived. Having assessed the *FS*, Soil Structure Interaction and/or Soil Infrastructure Interaction analyses are conducted to realistically assess the structural response of any adjacent structure and infrastructure in terms of stresses and strains, aiming to comply with relevant standards and norms. Nonetheless, it is noted that such analyses are beyond the scope of the present study since the primary research focus is the assessment of slope stability via *FS* calculation.

When the impact of CC is taken into account, various features of the regional climate are expected to be affected for several reasons. One significant factor is the increased atmospheric CO<sub>2</sub> levels, which can lead to substantial changes in rainfall patterns [44,45]. Consequently, the infiltration and surface runoff on a soil slope subjected to precipitation will be directly affected, while the stability of the slope and the integrity of any nearby structure and infrastructure will be indirectly affected.

Figure 2 depicts the water balance on a soil slope during rainfall. A specific water volume reaches the slope surface in the form of precipitation. Part of this volume evaporates from the ground or transpires via plants and trees and re-enters the atmosphere

(evapotranspiration). Nonetheless, the main volume of precipitation is divided into surface runoff ( $V_R$ ) and infiltration ( $V_I$ ). The ratio between  $V_R$  and  $V_I$  depends on the characteristics of precipitation (i.e., frequency, duration and intensity) and the slope's mechanical and physical properties (i.e., slope inclination, soil permeability, hydraulic conductivity, vegetation cover and forestry). Surface runoff is generated if the precipitation rate exceeds the infiltration capacity of the soil [46].

On the one hand, surface runoff may lead to potential soil erosion phenomena parallel to the slope surface and/or potential flooding phenomena downstream. The latter may cause transversal soil erosion at the slope toe. Soil erosion phenomena can alter the geometrical characteristics of the slope and affect its stability. Infiltration, on the other hand, is related to the level and inclination of the groundwater table, and subsequently to the slope instability. Studies from Greenwood et al. [47] and Reubens et al. [48] have shown that forestry, vegetation, and plant roots provide essential mechanical reinforcement to the soil surface. These elements play a critical role in improving surface permeability and reducing surface runoff, which in turn facilitate infiltration and minimize soil surface erosion phenomena, respectively.

It should be stressed that estimating all the components of water balance accurately constitutes a complex and multidisciplinary process that often requires the adoption of several assumptions and simplifications. Laboratory tests and finite-element analyses can be utilized to examine the stability and characteristics of water infiltration on a slope during precipitation events. Factors such as soil internal friction angle, water volume content, hydraulic conductivity, duration, and intensity of precipitation play a significant role in such analyses [49]. Various modes of slope failure (e.g., scouring erosion collapse, steep slope collapse, wedge-shaped block sliding and caving, etc.) can occur as was shown via in situ model tests and numerical simulations [50], laboratory tests [51], etc.

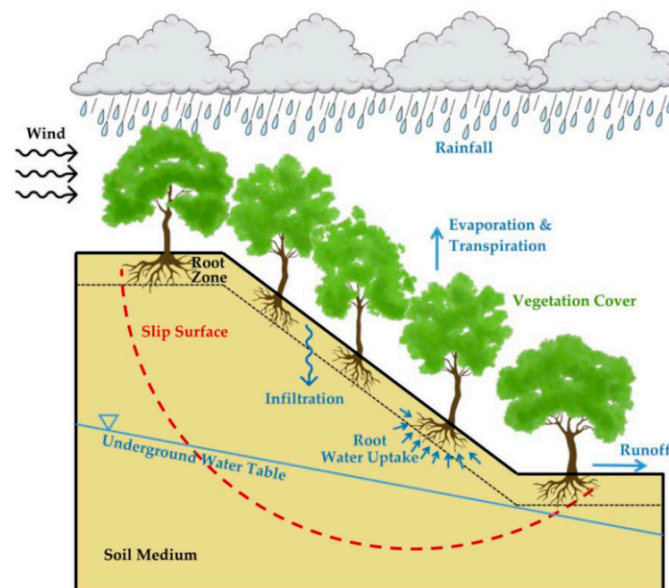


**Figure 2.** Water balance on a soil slope during rainfall (adopted from [52]).

Slope instability is a complicated geohazard that is mainly affected by physical processes (e.g., rainfalls and earthquakes), but can also be influenced by man-made actions (e.g., explosions, traffic vibrations, etc.). As mentioned earlier, slope stability is typically assessed in terms of  $FS$ , which is the ratio of resisting forces to driving forces under static or dynamic conditions. If  $FS$  is less than one, this indicates an unstable slope. Various methods have been developed for calculating the  $FS$  of a soil slope, including the limit equilibrium method and various numerical methodologies [4].

Several key factors affect the resulting  $FS$  in slope stability analysis, such as: (a) the slope angle and geomorphological characteristics of the area under consideration, (b) the

soil mechanical properties, e.g., soil cohesion and angle of internal friction, which determine the shear strength, and (c) the seismic or other dynamic loads that can affect the developed shear stresses. Groundwater flow also plays a crucial role in slope stability. An increase in the level of an inclined groundwater table, often triggered by heavy rainfalls, can decrease the *FS*. Figure 3 illustrates that weathering, heavy rainfall, and erosion at the slope toe can further diminish the *FS* over time [53].

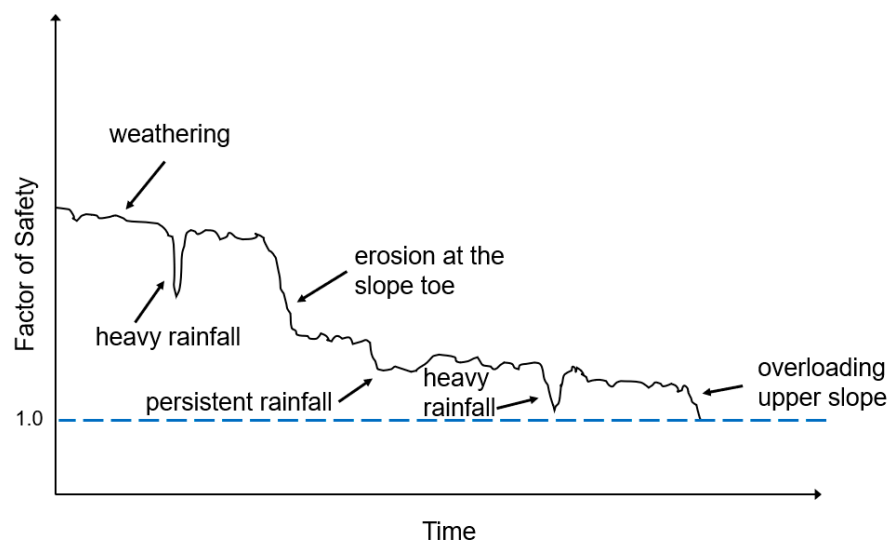
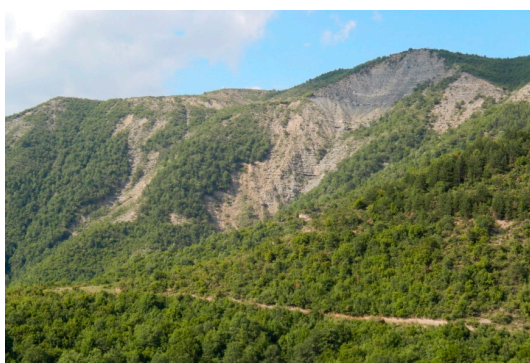


**Figure 3.** Potential changes in factor of safety (modified from [53]). A factor of safety < 1.0 indicates an unstable slope.

Moreover, slope instability can affect the structural integrity of any structure and infrastructure located on or crossing potentially unstable slopes. In the case of  $FS < 1$  (i.e., unstable slope), one of the most crucial consequences of slope failure is the excessive *PGDs* and/or *ELs* that can be generated, which pose a serious threat to structures and infrastructure through Soil Structure Interaction or Soil Infrastructure Interaction [54]. Figure 4a illustrates examples of slope instability phenomena near the routing of the high-pressure gas pipeline TAP (Trans Adriatic Pipeline) in central Albania, while Figure 4b displays soil erosion phenomena along the TAP route near the Greek–Albanian borders.



(a)



(b)

**Figure 4.** (a) Slope instability phenomena and (b) soil erosion phenomena close to the routing of TAP (photos taken by P.N. Psarropoulos).

In general, CC has a significant impact on the regional climate and particularly on weather patterns, leading to changes in precipitation characteristics and ultimately affecting the aforementioned water balance. Two key concerns are the higher temperatures and

greater wind speeds, which result in increased rates of evaporation. This, in turn, leads to more frequent and intense storms and heavy rainfall events [23].

The high volume of rainfall alters soil hydraulic conductivity and moisture levels, affecting water infiltration and consequently lowering the groundwater table. Furthermore, high temperatures pose a direct threat to vegetation and forestry, which, in turn, affect root water uptake. CC-induced rainfall can also contribute to increased surface runoff (i.e., intensified soil erosion phenomena). Hence, since slope instabilities and landslides are expected to occur more or less frequently in certain regions due to CC [55], it is crucial to realistically quantify the effects of CC on average annual precipitation in order to assess slope stability more realistically. To address this complex issue, efficient hydrological models combined with slope stability analysis methods have been developed to calculate the FS of a slope under such conditions [56].

## 2. Materials and Methods

### 2.1. The SCS-CN Method for Hydrologic Modelling

To realistically and reliably assess the direct consequences of the anticipated CC on the geohazard of slope instability, the present paper utilizes a simplified analytical method, which is a combination of the widely utilized Soil Conservation Services-Curve Number (SCS-CN) method and the slope stability analysis in terms of FS. The SCS-CN method is a fundamental rainfall-runoff model designed to calculate abstractions from storm rainfall events. Over the past decades, the SCS-CN method has been widely used in relevant studies [57–62]. Researchers worldwide have developed several models based on modifications of the SCS-CN method, such as the Mishra–Singh (MS) model [63], the Michel model [64], and the Sahu model [65]. These models have expanded the capabilities of the original SCS-CN method and have contributed to advancements in hydrologic modeling and relevant analyses.

The SCS-CN method has established an empirical relationship between rainfall, denoted as  $P$ , and surface runoff (or rainfall-excess), by utilizing the curve number [66]. Although the SCS-CN method was originally developed for analyzing single storm events, it can also be adapted to calculate average annual runoff values. Assuming that the approximate amount of direct surface runoff from rainfall,  $P_e$ , in a specific area will always be less than or equal to the total rainfall,  $P$ , once runoff begins, the amount of water retained in the watershed (cumulative infiltration), denoted as  $F_a$ , will be less than or equal to a maximum retention capacity,  $S$ . There exists a certain amount of rainfall, i.e., initial abstraction before ponding, denoted as  $I_a$ , for which no runoff will occur. Therefore, the potential runoff can be calculated as the difference:  $P - I_a$ . The fundamental principle of the SCS-CN method can be expressed as follows:

$$\frac{F_a}{S} = \frac{P_e}{P - I_a} \quad (1)$$

From the continuity principle:

$$P = P_e + I_a + F_a \quad (2)$$

Combining Equations (1) and (2), the general equation for the SCS-CN method is derived:

$$P_e = \frac{(P - I_a)^2}{P - I_a + S} \quad (3)$$

Equation (3) is an empirical formula based on trends observed in collected data from various sites. After further empirical evaluations, the initial abstraction,  $I_a$ , could be defined as a percentage of  $S$  (i.e.,  $r \cdot S$ , where  $r$  is a user-defined ratio, typically ranging between 0.05 and 0.2). With this assumption, and setting  $r = 0.2$ , Equation (3) can be written in a more simplified form:

$$P_e = \frac{(P - 0.2S)^2}{P + 0.8S} \quad (4)$$

The so-called curve number,  $CN$ , is based on the soil type of the examined area, land use, hydrologic conditions and is used to make interpolating, averaging, and weighting operations in a linear manner. In addition,  $CN$  is a dimensionless number ranging from 0 to 100 and is expressed with respect to  $S$  as follows:

$$S = \frac{1000}{CN} - 10 \quad (5)$$

Evidently, high  $CN$  values (e.g., 98 for pavement) correspond to increased runoff, while the opposite occurs for low  $CN$  values that refer to soils with increased ability to retain rainfall. The initial categorization of  $CN$  is representative of slopes with low inclination ( $<5\%$ ) which is typical for U.S. land cover conditions. Subsequent studies introduced modifications in  $CN$  calculations to include the impact of slope inclination, soil moisture, etc., which are influenced by the local data of the examined region [67–70].

## 2.2. FS Calculation for Planar Translational Slide

Slope stability analyses of the current study are based on the typical scenario of a planar translational slide of infinite length, where the upper soil layer moves along a planar surface parallel to the ground surface. This movement is represented in a simplified manner by a rigid block of height  $z$  sliding on an inclined planar surface at an angle,  $\theta$ , as illustrated in Figure 5. Two different cases were considered:

- static conditions without groundwater table (i.e., for dry conditions), and
- static conditions with inclined groundwater table.

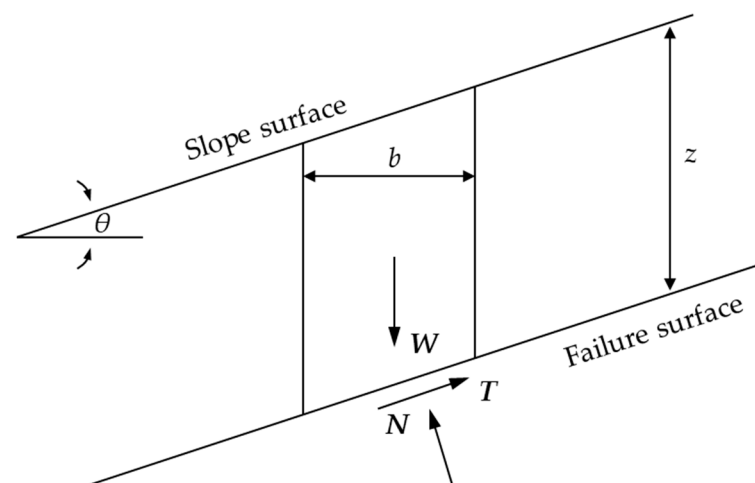


**Figure 5.** Sketch of a planar translational slide under dry conditions.

### 2.2.1. Static Conditions Without Groundwater Table

According to Barnes [71]  $FS$  under dry static conditions, can be expressed as:

$$FS = \frac{c}{z \cdot \gamma \cdot \sin \theta \cdot \cos \theta} + \frac{\tan \varphi}{\tan \theta} \quad (6)$$

where  $\gamma$ ,  $c$  and  $\varphi$  denote the unit weight, cohesion and internal friction angle of the examined soil material, respectively. Therefore, it becomes evident that:

- in the case of dry sand, where  $c$  is equal to 0 kPa and  $\varphi \neq 0^\circ$ :

$$FS = \frac{\tan \varphi}{\tan \theta} \quad (7)$$

- in the case of a clay under undrained conditions ( $\varphi = 0^\circ$ ):

$$FS = \frac{c_u}{z \cdot \gamma \cdot \sin \theta \cdot \cos \theta} \quad (8)$$

where  $c_u$  is the undrained shear strength of the clay.

### 2.2.2. Static Conditions with Inclined Groundwater Table

Figure 6 displays an infinite planar translational slide of a slope with inclined groundwater table (GWT). Assuming that the unit weights of the soil above and below the groundwater table are equal to  $\gamma$ , the weight  $W'$  of the submerged segment is expressed as follows:

$$W' = \gamma' \cdot a \cdot z \quad (9)$$

where  $\gamma'$  is the effective unit weight that is easily derived by subtracting the unit weight of water  $\gamma_w$  from  $\gamma$ .

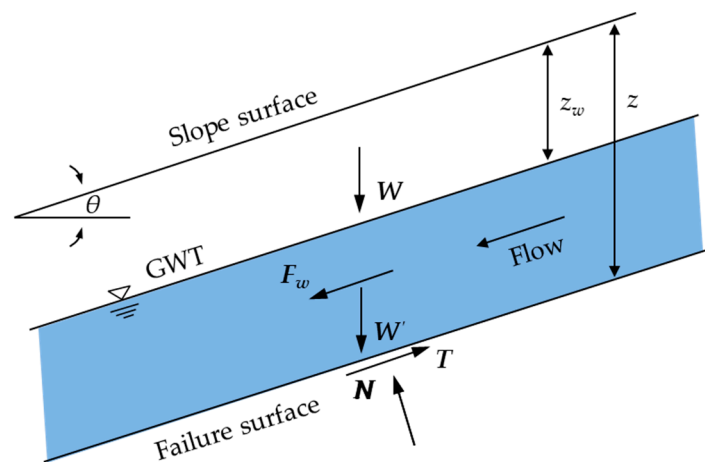


**Figure 6.** Sketch of a planar translational slide with inclined groundwater table.

$FS'$  under static conditions considering the inclined groundwater table is given by:

$$FS' = \frac{\frac{c}{\cos^2 \theta} + (z \cdot \gamma' + z_w \cdot \gamma_w) \cdot \tan \varphi}{z \cdot \gamma \cdot \tan \theta} \quad (10)$$

- In the general case of fully saturated soil material, where  $z_w = 0$  m,  $c \neq 0$  kPa and  $\varphi \neq 0^\circ$ :

$$FS' = \frac{\frac{c}{\cos^2 \theta} + z \cdot \gamma' \cdot \tan \varphi}{z \cdot \gamma \cdot \tan \theta} \quad (11)$$

Therefore:

- in the case of a fully saturated sand, where  $z_w = 0$  m,  $c = 0$  kPa and  $\varphi \neq 0^\circ$ :

$$FS' = \left( \frac{\gamma'}{\gamma} \right) \frac{\tan \varphi}{\tan \theta} \quad (12)$$

The fact that soil materials typically have unit weight ranging from 14 kN/m<sup>3</sup> to 23 kN/m<sup>3</sup> highlights the importance of the groundwater table when assessing slope stability. Equation (12) demonstrates the impact of the level of groundwater table on slope stability, particularly when dealing with fully saturated sandy slopes ( $z_w = 0$  m,  $c = 0$  kPa and  $\varphi \neq 0^\circ$ ). In such cases,  $FS'$  is significantly lower compared to dry conditions (Equation (7)). The ratio of  $FS'$  under saturated conditions to  $FS$  under dry conditions can range from 0.3 to 0.6, depending on the specific unit weight of the soil material.

- for fully saturated clay material and undrained conditions ( $\varphi = 0^\circ$ ):

$$FS' = \frac{c_u}{z \cdot \gamma \cdot \sin\theta \cdot \cos\theta} \quad (13)$$

Note that Equation (13) is identical to Equation (8), i.e.,  $FS' = FS$ , as it is not affected by the presence of groundwater table.

### 3. Results

#### 3.1. Impact of CC on Rainfall and Groundwater Table

Initially, valuable insights are provided regarding the impact of varying rainfall intensities and soil permeability levels on the accumulation of rainwater. For this purpose, two scenarios with varying rainfall intensities were considered. The first scenario, which was adopted from a relevant hydrology textbook [66], represents a typical rainfall event lasting seven hours and resulting in a total of 136.1 mm of rainwater. The second scenario, referred to as the CC scenario, has hypothetically the same duration and total amount of rainwater as the first scenario, but it is characterized by a higher rainfall intensity. Table 1 lists the cumulative rainfall, while Figure 7 illustrates the time histories of the cumulative and absolute rainfall for both scenarios. Additionally, three different soil permeability levels were considered: high with  $CN = 40$ , medium with  $CN = 60$ , and low with  $CN = 80$ . Figure 8a–c display the results of infiltration (GW) and surface runoff (*Runoff*) for the two aforementioned rainfall scenarios and the three soil permeability levels.

**Table 1.** Cumulative rainfall of the two examined scenarios.

| Typical Scenario |                            | Climate Change Scenario |                            |
|------------------|----------------------------|-------------------------|----------------------------|
| Time (h)         | Cumulative Rainfall P (mm) | Time (h)                | Cumulative Rainfall P (mm) |
| 0                | 0.0                        | 0                       | 0.0                        |
| 1                | 5.1                        | 1                       | 5.1                        |
| 2                | 22.9                       | 2                       | 25.4                       |
| 3                | 32.3                       | 3                       | 114.3                      |
| 4                | 58.7                       | 4                       | 124.5                      |
| 5                | 118.1                      | 5                       | 127.0                      |
| 6                | 134.4                      | 6                       | 129.6                      |
| 7                | 136.1                      | 7                       | 136.1                      |

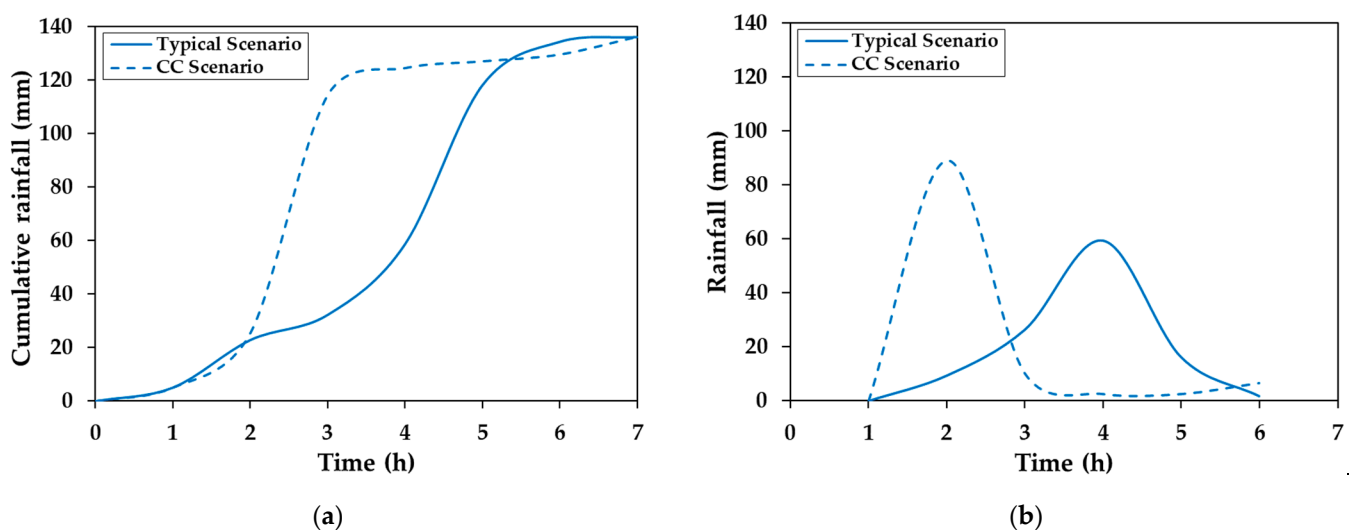


**Figure 7.** Time histories of: (a) the cumulative rainfall and (b) the absolute rainfall of the two examined rainfall scenarios.

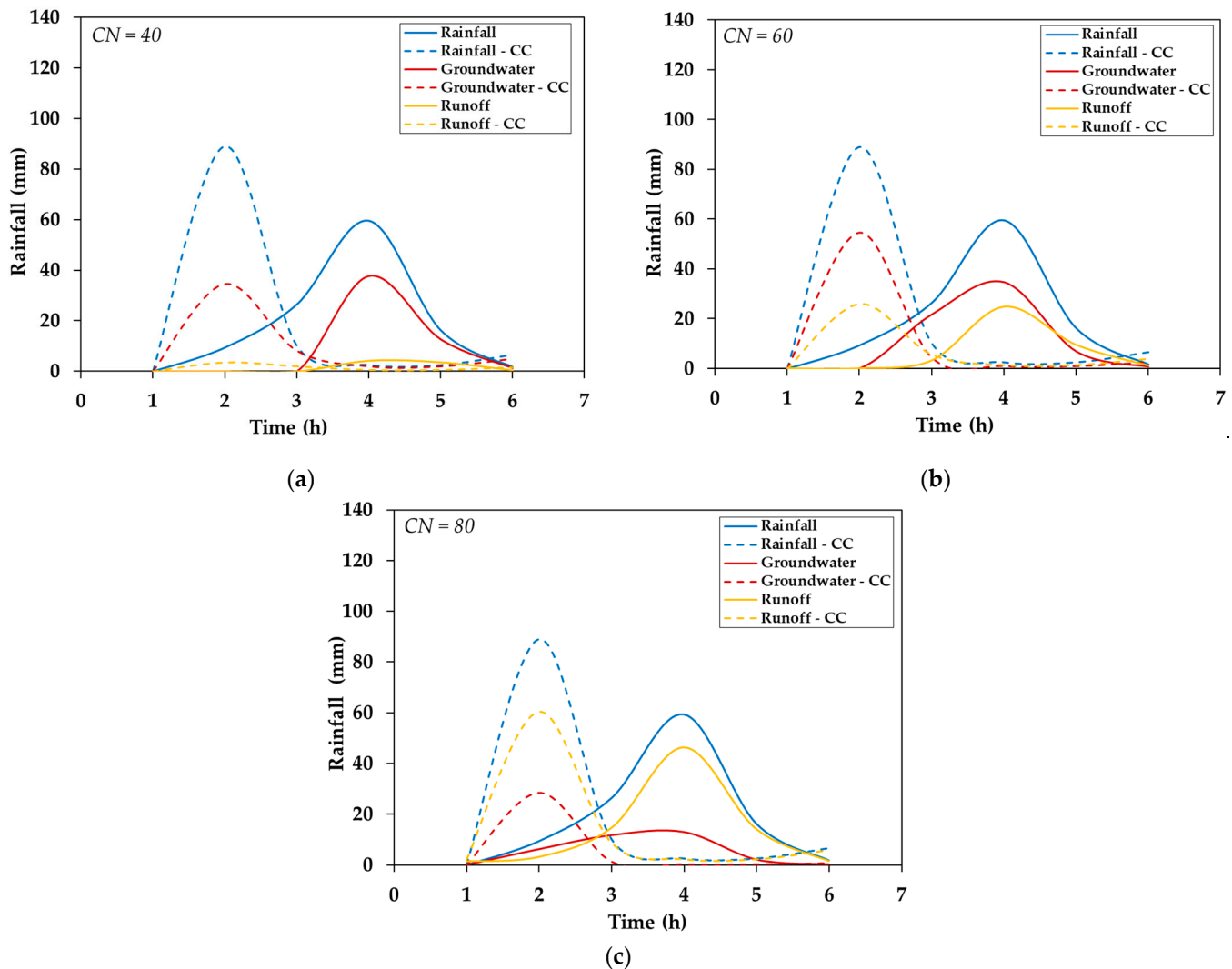


**Figure 8.** Time histories of infiltration and runoff for the three examined soil permeability levels: (a) high, (b) medium, and (c) low.

### 3.2. Impact of Rainfall Scenario on Slope Stability

Figure 8a–c illustrate the impact of CC on both infiltration and surface runoff, which can directly determine the level of the groundwater table and the changes in slope inclination due to soil erosion, respectively. Hence, a thorough parametric investigation was carried out to demonstrate how various factors, including the level of groundwater table (related to the phenomenon of infiltration) and slope inclination (related to the phenomenon of soil erosion) affect the *FS* of a translational slide under static conditions. To demonstrate the effectiveness of the proposed methodology, the main soil types (i.e., clay under drained/undrained conditions and sand) for various slope conditions were analyzed. Accordingly, three different scenarios were examined based on the type of soil slope material:

- clay under drained conditions with  $\phi = 30^\circ$  and  $c = 20$  kPa,
- sand with  $\phi = 30^\circ$ , and
- clay under undrained conditions with  $c_u = 20$  kPa.

Two values of  $z$  were examined:  $z = 5$  m and  $z = 15$  m, whereas, in all cases, the unit weight,  $\gamma$ , was set equal to  $17$  kN/m<sup>3</sup>. Figure 9a–c depict the resulting *FS* in terms of the slope inclination angle and height for the three soil types.

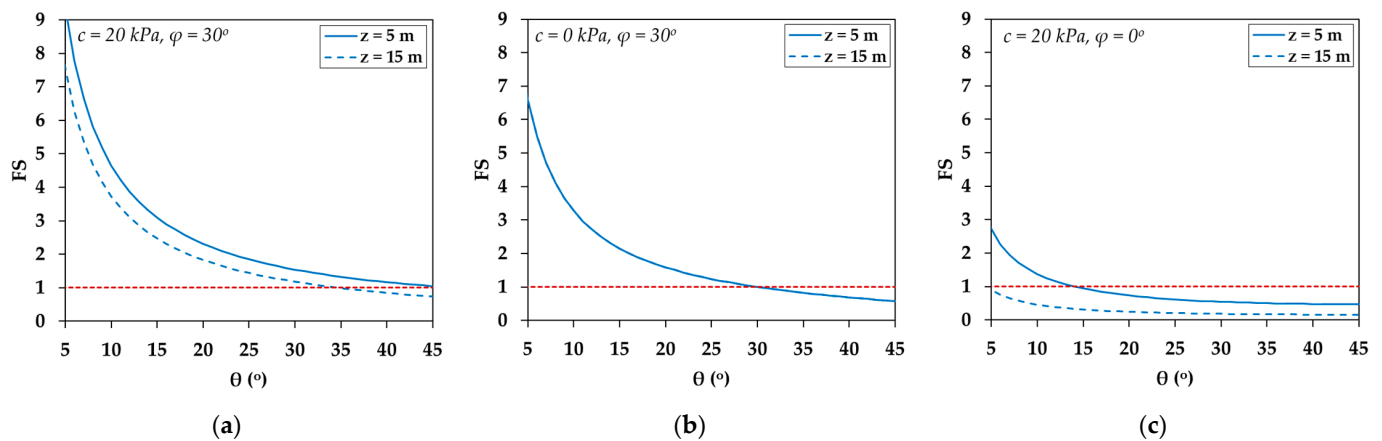


**Figure 9.** Variation of  $FS$  with respect to slope inclination,  $\theta$ , without groundwater table for the three examined soil types, as compared to the critical  $FS = 1$ : (a)  $c = 20 \text{ kPa}$ ,  $\varphi = 30^\circ$ , (b)  $c = 0 \text{ kPa}$ ,  $\varphi = 30^\circ$  and (c)  $c = 20 \text{ kPa}$ ,  $\varphi = 0^\circ$ .

The three soil types were analyzed in an additional parametric study taking into account the level of groundwater table as follows:

- inclined groundwater table up to the middle of the sliding soil layer (i.e.,  $z_w = z/2$ ), and
- inclined groundwater table up to the surface of the soil layer (i.e.,  $z_w = 0 \text{ m}$ ).

Figure 10a–c display the results for the first case, where  $z_w = z/2$ , while Figure 10d–f illustrate for the second case, in which  $z_w = 0 \text{ m}$ .

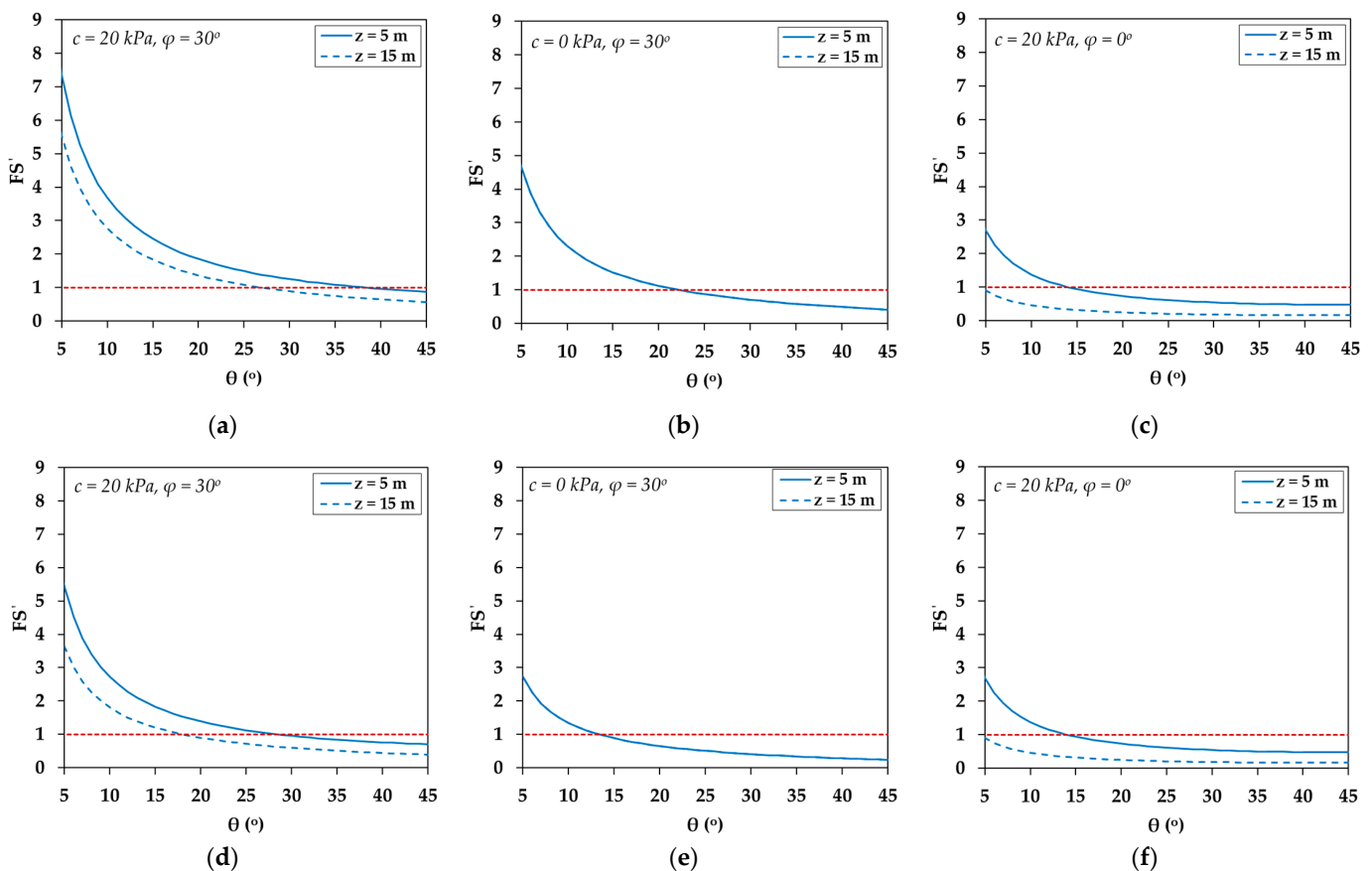


**Figure 10.** Variation of  $FS'$  with respect to slope inclination,  $\theta$ , with inclined groundwater table for the three examined soil types. Cases (a–c) refer to  $z_w = z/2$ , while cases (d–f) to  $z_w = 0$ . A direct comparison with the critical  $FS = 1$  can be performed for all cases.

#### 4. Discussion

The results from Figure 8a–c clearly demonstrate that changing a single rainfall characteristic as a result of CC, particularly the intensity, can have a substantial impact on both infiltration and surface runoff depending on soil permeability. However, a decrease in CN (i.e., an increase in permeability) leads to reduced runoff in both scenarios. It is important to note that these effects may be either beneficial or detrimental for slope stability as will be shown in the sequence, where the influence of the resulting groundwater table on  $FS$  values of the examined slopes is highlighted. Certainly, there are several uncertainties involved, especially related to potential CC-induced rainfall scenario(s) that cannot be fully covered with the employed SCS-CN method, which is based on certain assumptions and simplifications. To overcome these limitations, a full dataset, preferably including in situ measurements, is required to realistically assess all hydrogeological parameters involved.

It is noted that infiltration, which is affected by rainfall characteristics, dominates the level and the inclination of the groundwater table, which in turn also influences the flow of the underground water within the slope. In addition, surface runoff can lead to surface soil erosion along the slope or at the slope toe, potentially altering the geometrical characteristics of the slope. These complex phenomena, especially in CC-induced (i.e., intense) rainfall conditions, may affect slope stability. This impact cannot be known a priori and it should be examined on a case-by-case basis.

Figure 9a reveals that  $FS$  is high for small values of slope inclination (i.e.,  $\theta < 10^\circ$ ), while it gradually decreases as the inclination increases. It is worth noticing that the height,  $z$ , has a minor impact on  $FS$ . In contrast, Figure 9b shows that cohesionless soil material exhibits a different behavior compared to the other soil types, as  $FS$  values remained unaffected by the changes in  $z$ . Additionally, as was expected,  $FS$  reaches 1 (the critical  $FS$ ) when the slope inclination is equal to the angle of internal friction (i.e.,  $\varphi = \theta$ ).

Figure 9c clearly illustrates that for clay (with  $\varphi = 0^\circ$ )  $FS$  is affected by both the slope inclination and height. The resulting  $FS$  is notably lower compared to the corresponding values in Figure 9a,b, particularly for  $z = 15$  m, even at a lower slope inclination. It is apparent that the mechanical properties of soil and/or the slope inclination may have a negative impact on  $FS$ , as a decrease in shear strength parameters (i.e., cohesion,  $c$ , and the internal friction angle,  $\varphi$ ) or an increase in slope inclination lead to lower  $FS$  values.

It is evident that an increase in slope inclination results in a significant decrease in  $FS'$ . Additionally, an unfavorable impact of the increase in slope height on  $FS'$  was observed. When comparing Figure 10a,b ( $z_w = z/2$ ) with Figure 10d,e ( $z_w = 0$  m), it can be clearly observed that—as was expected—an increase in the level of groundwater table may have a negative effect on  $FS'$ .

It is important to note that for clayey materials under drained conditions and for sandy soil materials,  $FS'$  equal to 1 occurs when  $\theta$  is much lower than  $\varphi$ , compared to dry conditions. However, it is worth emphasizing that increasing the level of groundwater table has not affected the stability of a clayey slope under undrained conditions. In general, the  $FS$  of a soil slope was significantly affected by the mechanical properties of the soil and the slope inclination, regardless of the presence of groundwater table.

Decreasing the cohesion and/or the angle of internal friction or increasing the slope inclination can result in lower values of  $FS'$ . Furthermore, when comparing a clayey soil material under drained conditions with and without the presence of groundwater table, it is evident that the presence of water has significantly reduced  $FS'$ . A similar trend can be observed for cohesionless soil materials, with the exception that the height,  $z$ , of the sliding mass has not affected the resulting  $FS$ . Nevertheless, decreasing the level of groundwater table (as a potential impact of the anticipated decreased infiltration due to CC) has led to increased values of  $FS'$ .

It must also be stressed that soil slope stability (not only for natural slopes but also for artificial ones in various types of geostructures) must follow a multi-hazard perspective, i.e., taking into account the seismic hazard as well, rather than just considering static conditions and flooding hazard. Gravitational forces constitute a determining factor in slope failure,

and their combination with seismic and/or intense rainfall activity can be catastrophic in areas where these phenomena coexist. This is not an extreme scenario, as it was observed in many catastrophic landslide incidents worldwide, whenever severe earthquakes occur after intense rainfall (e.g., [14]).

## 5. Conclusions

The current study initially describes the effects of CC on the geohazard of slope instability from a general perspective, which constitutes the initial and most critical step in mitigating the impact of CC on existing structures and infrastructure located on or near potentially unstable slopes due to CC. Subsequently, based on existing and widely used methodologies, a simplified analytical method is developed to evaluate the CC impact on the geohazard of slope instability. Its effectiveness and applicability are presented through its implementation on various general scenarios of rainfall (including typical and CC-induced rainfall), three different soil permeability levels, and three distinct soil material cases.

The present investigation has revealed that in the field of geotechnical engineering, the impact of CC cannot be known a priori. In particular, in relation to slope instabilities, CC can be detrimental or even beneficial in certain cases, depending on the circumstances and the prevailing local site conditions. CC undoubtedly results in more intense, but shorter in duration and less frequent, rainfall events. This increased precipitation leads to higher runoff, causing floods downstream and transversal erosion at the slope toe, ultimately decreasing slope stability and posing a threat to nearby structures and infrastructure. Additionally, the increased runoff can induce erosion phenomena along the slope surface, which may either increase or decrease the slope inclination, depending on the circumstances. On the other hand, CC may also result in a lower level of groundwater table due to decreased infiltration, consequently being beneficial for slope stability and becoming less threatening to the safe performance and integrity of any structure and infrastructure.

This preliminary study focuses mainly on potential groundwater table alterations, which can be affected by rainfall intensity, as presented in the two scenarios examined. It has also highlighted how this phenomenon affects slope stability in terms of *FS* values. This impact is more pronounced in the case of sandy material, while a clayey slope under undrained conditions is not affected by water table fluctuations. Based on the promising findings and considering all simplifications adopted herein, future extensions could consider the application of the proposed methodology in specific case studies, including also the structural response of structures and infrastructure, taking into account the results from relevant Soil Structure Interaction and Soil Infrastructure Interaction analyses.

It should be stressed that it is imperative for geoscientists and geotechnical engineers to gather all necessary input data, including hydrological, topographical, geological, hydro-geological, geotechnical, and seismological information. Processing all data and assessing their potential variations over time on a case-by-case basis is essential to reliably evaluate the impact of CC on potentially unstable hilly or mountainous areas. Furthermore, potential mitigation strategies certainly require a thorough examination of each case, where CC-adaptive measures could be examined, depending on the severity of the problem. This is a very important issue from a practical point of view, but it is beyond the scope of this study.

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