applied sciences

MDPI

Article

Implementation of Climate Change Effects on Slope Stability Analysis

Tamara Bračko, Bojan Žlender * and Primož Jelušič

Faculty of Civil Engineering, Traffic Engineering and Architecture, University of Maribor, Smetanova 17, 2000 Maribor, Slovenia
* Correspondence: bojan.zlender@um.si

Abstract: The objective of this study is to determine the impacts of expected climate change on slope stability. For this purpose, the case study of a slope instability, that was triggered in 2021 was selected. The stability analysis was performed considering the theory of rainfall infiltration and using Geo-Studio's SEEP/W module for the surface infiltration model of the slope. A parametric stability analysis of the slope was conducted to determine the importance of climate change on slope stability. Conditions for changes in volumetric water content, water permeability, porewater pressure, and groundwater flow are important. When soil permeability is low, the factor of safety decreases during rainfall events and on the days following, while when permeability is higher, safety increases after rainfall events. The effect of lower cohesion is nearly linear, with the factor of safety decreasing by 0.1 for every 1 kPa less cohesion. The increase in net infiltration of water may be the most critical factor for slope instability. The results of the analysis indicate that timely reduction of water net infiltration through planting and proper surface water runoff from the upper road and slope would be a relatively simple and inexpensive measure compared to the cost of remediating the landslide, considering expected climate change. Therefore, it is advisable to analyze all slopes with respect to the expected climate change, taking into account the potential impacts of climate change.

Keywords: climate change adaptation; slope stability; rainfall infiltration; water net infiltration; seepage analyses

Citation: Bračko, T.; Žlender, B.; Jelušič, P. Implementation of Climate Change Effects on Slope Stability Analysis. *Appl. Sci.* **2022**, *12*, 8171. https://doi.org/10.3390/app12168171

Academic Editor: Arcady Dyskin

Received: 13 June 2022
Accepted: 26 July 2022
Published: 16 August 2022

1. Introduction

Seepage in slopes is one of the most important factors affecting stability, and many land-slides are caused by seepage. Estimates of pore-water pressures must come from relevant locations in the slope. These pore water pressures are usually estimated from groundwater conditions, which can change rapidly due to intense rainfall affecting water net infiltration and permeability of the soil.

This paper discusses how the stability of slopes can be affected by climate change and how the resilience of slopes can be increased to prevent landslides. Adaptation is the natural or human systems adjustments in response to actual or expected climatic effects, which moderates harm or exploits beneficial opportunities. This paper aims to point out what changes need to be followed up to consider new climate trends in the design of geo-structures. Emphasis is also placed on the question of how to describe these changes in a way that will be useful for planning and designing geo-structures that are in accord-ance with climate change adaptation.

In 2014, Vardon [1] examined the impacts of climate change that will most likely affect geotechnical infrastructures. He referred to the importance of predicted climate changes described as climate change features (temperature, precipitation, wind, sea level rise, storms, river flow, cold) for geotechnical infrastructure.

Determination of the net water flux at the ground surface should be included [2,3]. Davies [4] states that the net water flux quantification at the ground surface depends on the climate, soil, and vegetation data. The climate variables (precipitation, temperature, relative humidity, wind speed, and solar radiation) can be measured at weather stations, while the soil and vegetation properties can be determined either in the laboratory or in the field [1]. Surface runoff is generated if the precipitation rate exceeds the soil's infiltration capacity. Evaporation and transpiration are functions of the other climate variables mentioned above and are responsible for the movement of the water from the soil to the atmosphere [2]. All water balance components must be estimated accurately to estimate the water net infiltration at the ground surface. The computational procedures to determine each water balance component are complex and contain numerous assumptions [4]. Laboratory model tests [5] and finite element software analysis [6] can be used to study the stability and characteristics of water infiltration on the slope in precipitation conditions. Influence of various factors on the soil, such as soil internal friction angle, water volume content, hydraulic conductivity, duration, and intensity of the precipitation is included in analysis [7–10].

The last hundred years have been characterized by a large increase in population and its impact on the urban growth of infrastructure and transport. At the same time, natural and agricultural areas have been shrinking intensively [11,12]. As a result, energy needs, environmental pollution and related climate changes are becoming increasingly pressing issues.

Over the years, international organizations in climate change published numerous publications and documents. The Intergovernmental Panel on Climate Change (IPCC) [13] was jointly established by the World Meteorological Organization and the United Nations Environment Program to provide a credible international statement on the scientific understanding of climate change. Climate change in IPCC usage refers to any change in climate over time, whether due to natural variability or human activity. The European Commission set up the European Climate Change Program (ECCP) in 2000 [14] to help identifying the most environmentally and cost-effective policies and measures that can be taken at the European level to reduce greenhouse gas emissions. The task of the European Environment Agency (EEA) [15] and national environmental agencies is to provide reliable and independent information on the environment.

The IPCC [13] aims to comprehensively and objectively assess the best available information on climate. In its AR6 (2022) report [16], the IPCC notes the following changes: each of the last four decades since 1850 has been successively warmer than any previous decade. Global surface temperature was 0.99 °C higher in the first two decades of the 21st century (2001–2020) than in the 1850–1900 period, and global surface temperature was 1.09 °C higher in 2011–2020 than in 1850–1900, with a larger increase over land (1.59 °C) than over sea (0.88 °C). The estimated increase in global surface temperature since AR5 (IPCC 2014) is primarily due to further warming since 2003–2012 (+0.19 °C). Additionally, methodological advances and new datasets contributed approximately 0.1 °C to the updated estimate of warming in AR6.

Finding the causes of climate change is undoubtedly fundamental from an environmental point of view, as is developing models that focus on forecasting climate change for the future [17]. Unfortunately, climate science is quite uncertain about this. In the past, observations were used to calibrate models and then, extrapolations were made about the future. Nowadays climate change predictions typically use a two-step modeling approach [18]: the General Circulation Model (GCM), including key global physical and chemical processes; and the Regional Climate Model (RCM), which translates the GCM solutions to the local scale. As an example, CORDEX (Coordinated Regional Climate Downscaling Experiment) [19] is a program sponsored by the World Climate Research Program (WRCP) [18]. It was organized to internationally coordinate frameworks that will produce improved regional climate change projections for all land regions, worldwide. The CORDEX results serve as input for the impacts on climate change and adaptation studies.

NASA [20] presented climate models showing that extreme weather events will become more frequent with climate change. For this reason, attention should be focused on the subsequent possible changes in the behaviour and failure of geotechnical infrastructures, which can have significant impact on damages and losses. Nevertheless, not many publications deal with the geotechnical aspect of climate change adaptation. This may be because geotechnical aspects require high-resolution local information on climatic extremes and model results are often only available at a large spatial resolution or do not account for climatic extremes. The measured and projected changes are described for six climate regions in Europe (Northern Europe, Northwestern Europe, Central and Eastern Europe, Mediterranean Europe, coastal and mountainous regions). Tang et al. [21] similarly cited the potential impacts of climate change on slopes for Climate Change Features, but only for four core regions in Europe. The SafeLand project [22] provided the first analysis of natural landslide risk in relation to climate. It used the continuum of soil infiltration, including evapotranspiration, to analyze stability. Vahedifard et al. [23] focused on geo-structures under partially saturated conditions, identifying the change of soil properties as another effect of climate change that may affect geo-structures performance. Pk [24] analyzed the stability of embankments for current and future climate using numerical modeling techniques, and this study shows that the effects of climate change depend significantly on the hydraulic properties of the fill materials. Park et al. [25] analyzed an agricultural embankment's seepage and slope stability, evaluated by considering statistically derived rainfall patterns and hydromechanical soil properties. Finally, Insana et al. [26] investigated how geo-structural concerns are being addressed in national adaptation plans and found out that specific provisions for geo-structural adaptation are generally lacking and mainly come in the form of strategies for specific problems. In this regard, two common strategies are hazard/risk assessment and monitoring, which are mainly implemented in relation to slope stability.

In the future we need to operate sustainably, taking into account the parameters of climate change and sustainability means acting now to enable a future in which the environment and living conditions are protected and improved.

This paper presents how slopes can be adapted to the effects of climate change and how the safety of slopes can be improved, using the example of slope instability, which is considered the most critical according to the ELGIP survey [27]. Therefore, the variation of the safety factor of the slope during rainfall was analyzed using the program SEEP/W module of GeoStudio. To identify the most critical factors for instability, a parametric analysis was performed with different climate change effects: Net infiltration of water, degradation of material strength parameters, change in water table and change in porewater pressure.

2. Design of Geo-Structures Considering Climate Change

Climate change will undoubtedly continue, so it makes sense to take it into account when analyzing and planning geo-structures. The scenarios of future climate are called representative concentration pathways (RCPs). There are four pathways, and each includes a range of baseline values and estimated emissions to 2100: an aggressive greenhouse gas mitigation pathway CP2.6, a low scenario RCP4.5, a medium high scenario RCP6.0, and a very high baseline emissions scenario RCP8.5 [13].

It is useful to consider the effects of climate change both when planning new geo-structures and when planning for the use of existing facilities. Table 1 shows the general activities for both cases. If it is a new geo-structure, a climate change analysis should be performed, which is always followed by a new design. However, if it is an existing geo-structure, the measure depends on the foreseeable consequences of predicted climate change on the existing geo-structure and the conditions for safety and usability are still met even when climate change is considered. If soil degradation is observed and safety and serviceability criteria are not met, redesign is required, following the same steps as for a new geo-structure. Climate change analysis is important to avoid the worst-case scenario when damage or failure has already occurred (e.g., a landslide already triggered in the case of a slope).

Table 1. Design step, criteria and measures for new and existing geo-structures.

Geo-Structure	Project Steps	Criterias (with Climate Change Adaptation)	Measures
New geo-structure	Feasibility study	Appropriate criteria (safety, applicability)	New design always
	Outlined design		
	Detailed design		
	Execution		
Existing geo-structure	No project steps	The criteria of safety and applicability are satisfied	No measures
		The criteria of safety and applicability are not satisfied	Re-design
		Reduced qualities of structure or ground	
		Signs of damages and structure failures	Intervention measures

Water Net Infiltration

Water infiltration and evaporation processes at the soil surface are generally controlled by the prevailing climatic conditions and the water content of the soil [24]. Water arrives on the slope surface in the form of precipitation, and some of this water is intercepted and evaporated by leaves, branches, and the forest floor, which is called interception. After the loss of interception, the precipitation water reaches the soil surface. Some of this water flows over the ground as overland runoff when the amount of precipitation exceeds the infiltration rate, and the rest infiltrates into the soil. Overland runoff on a slope depends on several factors, including the angle of the slope, vegetation, and roughness of the sloped surface. The rate of infiltration depends primarily on the hydraulic conductivity of the soil, which is not constant, but changes with soil suction.

The total amount of water infiltrating into the soil has a significant effect on the pore pressure and stability of slopes. However, a significant portion of this water is removed through the soil surface as actual evaporation and through plant roots as transpiration. These two processes by which water moves upward from the soil surface are referred to as actual evapotranspiration. The maximum potential evapotranspiration rate can be calculated using climate parameters such as air temperature, relative humidity, wind speed, and net radiation. The actual evapotranspiration rate can then be estimated using the potential evapotranspiration rate, available soil water near the soil surface, and vegetation characteristics. The amount of water remaining in the soil after the actual evapotranspiration loss is referred to as net infiltration.

The water net infiltration at the ground surface can be positive or negative based on the amount of actual evapotranspiration. Net infiltration is the actual amount of water that changes the storage within the slope and has potential to affect the pore water pressure and stability of the slope. The amount of net infiltration primarily depends upon precipitation, surface runoff and actual evaporation (Figure 1) and can be written as follows [24]:

$$\mathrm{NI} = \mathrm{P} - \mathrm{AE} - \mathrm{AT} - \mathrm{RO} = \mathrm{P} - \mathrm{ET} - \mathrm{RO} \tag{1}$$

where NI is net infiltration (mm/day), P is precipitation (mm/day), AE is actual evaporation (mm/day), AT is actual transpiration (mm/day), ET is evapotranspiration (mm/day) and RO is runoff (mm/day).

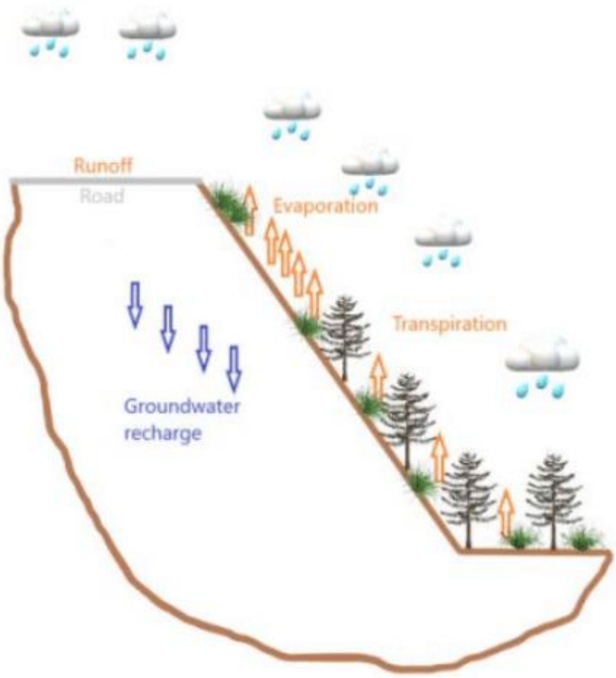

Figure 1. Components of the water balance on the slope.

To estimate NI at the soil surface, each of the components of the water balance must be accurately estimated. The computational procedures for determining each of the components of the water balance are complex and involve numerous assumptions [6]. Without AE, AT and RO, the value of net infiltration (NI) is equal to P. If the sum AE + AT + RO is equal to P or even higher, then NI is zero or negative.

The potential evaporation (PE) is the maximum amount of water that can evaporate from the soil surface when water is abundant. According to Fredlund et al. [2], the availability of thermal energy at the soil surface and the ability of the lower atmosphere to transport water vapor away from the soil surface are the two most important PE factors.

Actual evaporation (AE) is the actual amount of water that can be evaporated from the soil surface. Several methods have been proposed for AE calculations, but they differ mainly in assumptions regarding air and soil temperatures [2]. Net radiation and wind are the two main climate variables controlling PE, while soil suction plays an important role in AE. The AE rate from a saturated soil surface can be assumed equal to the PE. When the soil begins to dry, it tries to hold onto the water more. Actual transpiration is the movement of water within plants and the subsequent loss of water through the stomata. The AE from the soil surface plus the AT from plants form the concept of actual evapotranspiration [2].

One of the more commonly used formulas for calculating ET was developed by the American Society of Civil Engineers (ASCE) [24]. Modeling runoff RO is typical surface water hydrology problem, using selected, of many possible runoff models.

3. Example of Landslide

The case under consideration is that of a slope where a landslide was triggered below the local road in the fall of 2021 due to persistent heavy rainfall (Figure 2). Since the landslide had already occurred in Slake (Slovenia) and the causes of the landslide were being researched, the following was chosen for the investigation. Geological and geotechnical investigations were conducted on the slope. It should be noted that geotechnical investigations were also conducted near the site where the landslide occurred and where the soil properties were not affected by the landslide. This included field prospecting, a geodetic survey, soil soundings and sampling, ground water measurement, field testing (SPT), and laboratory testing (classification of soil, determination of unit weight, direct shear test, permeability test, oedometer test). It was determined that the soil cover of the slope consists of layers of sandy clay in a slightly to moderately kneaded state. The base of the marl is at a depth of approximately 6 m. The height of the water table depends on the season and the amount of precipitation.

Figure 2. Studied slope with activated landslide.

The geomechanical properties of the soil layers in the slope were investigated. The geomechanical properties (Table 2) are given based on field and laboratory tests and feedback stability analysis on the slope for the soil cover and bedrock. Based on the values from SPT and literature, the properties of marl were estimated, while the properties of sandy clay were estimated based on laboratory tests, SPT and literature. The soil model considers the peak friction angle and the zero angle of dilatation.

Table 2. Input data for slope soil cover and bedrock assigned to the FEM model.

	Symbol (Unit)	Sandy Clay	Marl
Unit weight	γ (kN/m^3)	18.5	24
Cohesion	c (kPa)	2	200
Friction angle	φ (°)	20	45
Volumetric water content	VWC = V_w/V_s (−)	0.2	
Permeability	$k_y = k_x$ (m/s)	$5{\cdot}10^{-7}$	$5{\cdot}10^{-11}$
Compressibility	m_v (1/kPa)	$5{\cdot}10^{-4}$	$1{\cdot}10^{-8}$

According to the Van-Genuchten and Nielsen method [28], the soil-water characteristic curve of the slope was determined, and then the permeability function curve was obtained. As shown in Figure 3, the hydraulic conductivity decreases with the increase of the matric suction, while the matric suction decreases with the increase of the volumetric water content (VWC). Therefore, the VWC is an important factor affecting the matric suction (Figure 3) and the hydraulic conductivity (Figure 4).

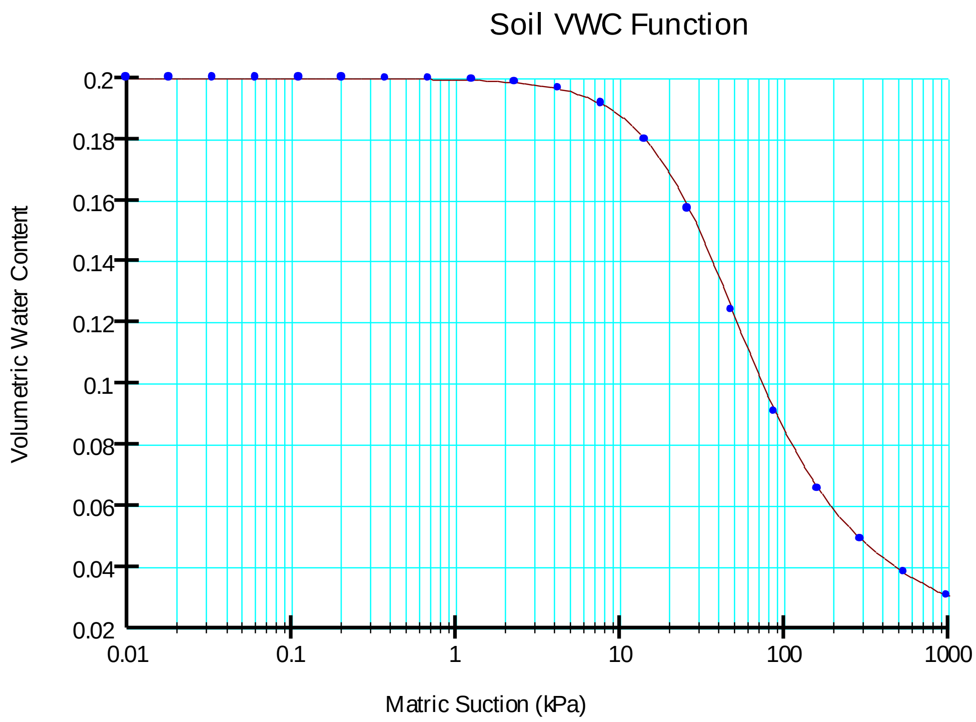

Figure 3. Volumetric water content as a function of matric suction.

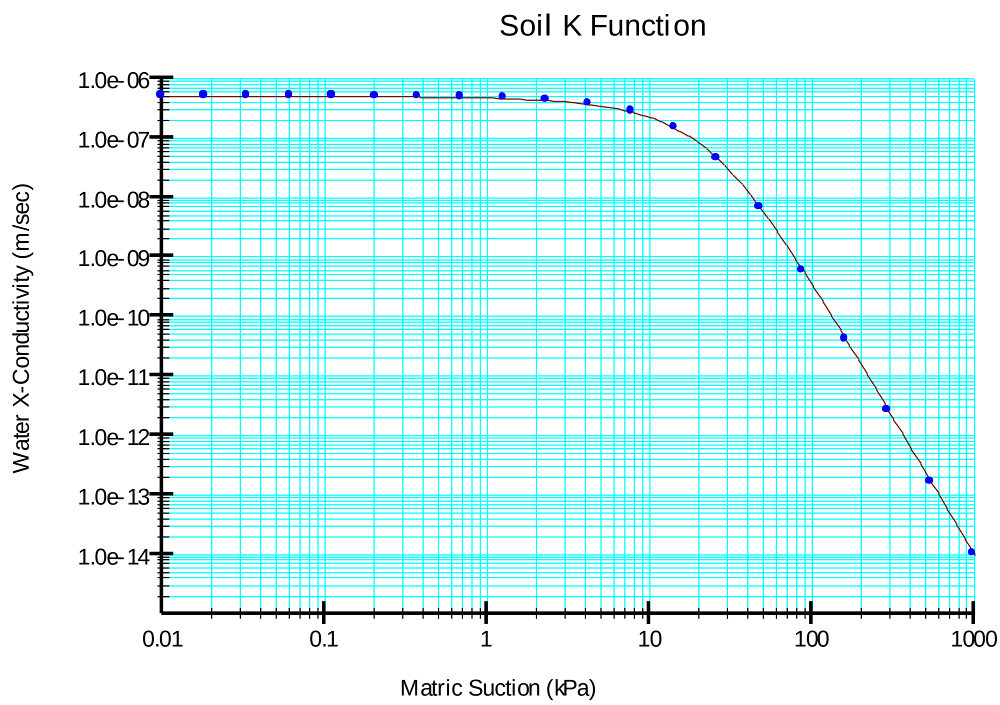

Figure 4. Hydraulic conductivity as a function of matric suction.

3.1. FEM Surface Seepage Model of Slope

The slope safety factor variation during rainfall was assessed by means of FEM numerical modelling. Variation in surface water content and porewater pressure during infiltration process were analyzed by SEEP/W module of GeoStudio. SLOPE/W is a 2D limit equilibrium modeling program for slope stability that provides a wide range of modeling capabilities, including porewater pressure and rapid drawdown. The program supports a comprehensive list of material models. The main advantage of SLOPE/W over other programs is that this program has built-in unsaturated shear strength models that allow modeling of unsaturated soil. However, SLOPE/W does not have the capability to model the progressive failure of a slope due to successive shrink-swell cycles [4]. The SEEP/W is the seepage module of the GeoStudio package and can be used to simulate water flow in saturated or unsaturated soils. Since both the SEEP/W and SLOPE/W are part of the same GeoStudio software package, they allow easy coupling and continuous calculation of the factor of safety for all simulation time steps.

The geometry of the model is shown in Figure 5. The dimensions of the model are 45 m × 20 m, with two soil layers defined, the upper layer being sandy clay and the lower layer being marl. The mesh of the model contains elements of 1 m × 1 m. The model boundaries are also defined.

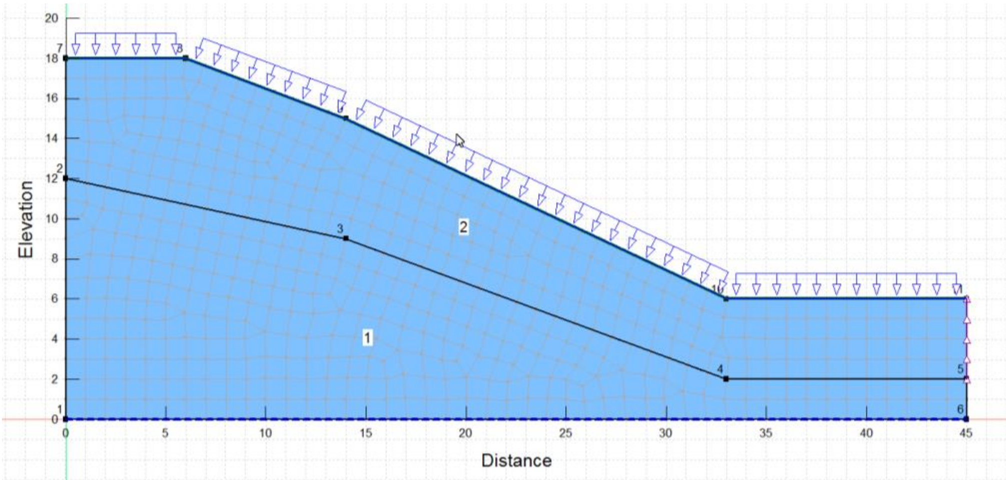

Figure 5. Geometry and mesh of the numerical model of the slope.

The upper surface was defined as rainfall infiltration boundary. All rainwater was infiltrated at the beginning of rainfall. The bottom of the model was nearly impermeable, while the right side of the model allowed the water to drain. Figure 5 shows the mesh of the model of the slope with the water loading and boundary conditions defined to simulate the flow of water in the soil down the slope. The infiltration depth is defined by layers geometry, because of the impermeable rocky base. The rainfall intensity defined as Climate change in this paper is set to 139 mm/day [29]. Simultaneously, the simulation lasted for 3 days from the start of rainfall. The blue dashed line indicates the groundwater level. Water drainage is possible on the right side.

The analysis includes three phases: the first phase, the second phase in which the rain is applied for three days, and the third phase in which the rain stops.

3.2. Analyses and Results

Based on the geological-geotechnical survey and estimated, extreme rainfall of 139 mm/day [29], the stability analysis was performed. The failure of slope occurred after three days of rainfall, therefore the three days average water net infiltration at the ground surface was evaluated as 27.8 mm/day, or $3.22 \cdot 10^{-7}$ $m^3/m^2/s$.

The FEM analysis, using the SEEP/W with coupling and continuous calculation of the factor of safety for all simulation time steps shows a decrease in the factor of safety from F = 1.158 at the beginning of the extreme rainfall (Figure 6) to less than 1 after the third day of rain (Figure 8).

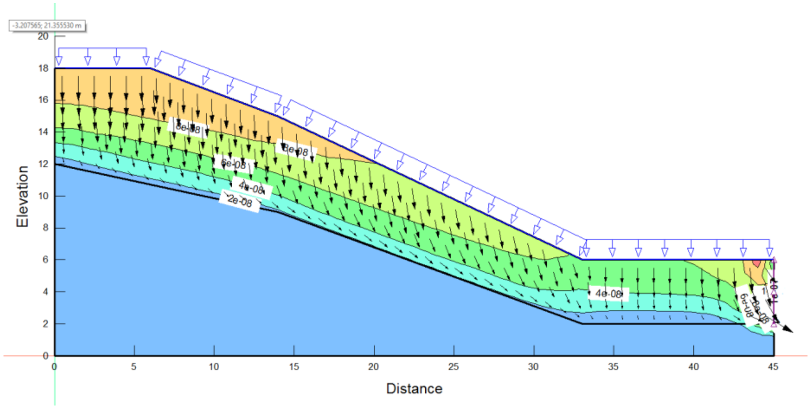

Figure 6. Computed water flow within the slope after 3 days of rainfall (in $m^3/m^2/s$).

The factor of safety changes constantly after the onset of rainfall, depending on the characteristics of the slope and soil parameters. Figure 6 shows the water flow through the slope 3 days after the beginning of the rainfall.

Similarly, the porewater pressure changed with time after the onset of rainfall, during water flow, depending on the characteristics of the slope model and soil parameters. Figure 7 shows the porewater pressure, 3 days after the beginning of the rainfall.

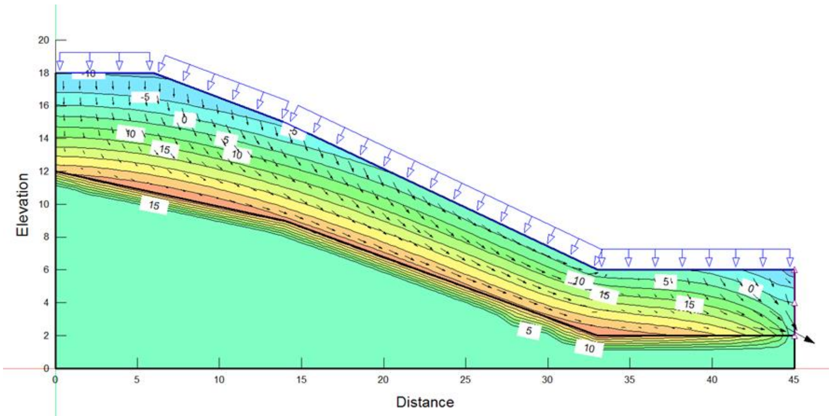

Figure 7. Computed porewater pressure within the slope after 3 days of rainfall (in kPa).

At the beginning of the rainfall when net infiltration of water has no effect on stability the factor of safety depends on soil shear characteristics and slope geometry and stratigraphy (Figure 8).

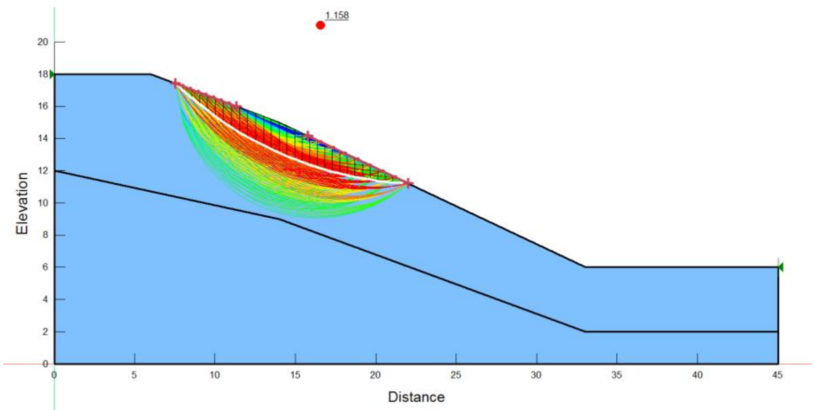

Figure 8. Slope with critical failure line and safety factor at the beginning of rainfall.

Net infiltration of surface water starts at the beginning of the rainfall and due to water flow through the slope the porewater pressure changes. Therefore, the factor of safety decreases during the rainfall and thereafter, depending on slope soil characteristics. Figure 9 shows the slope with critical failure line and safety factor after 3 days of rainfall.

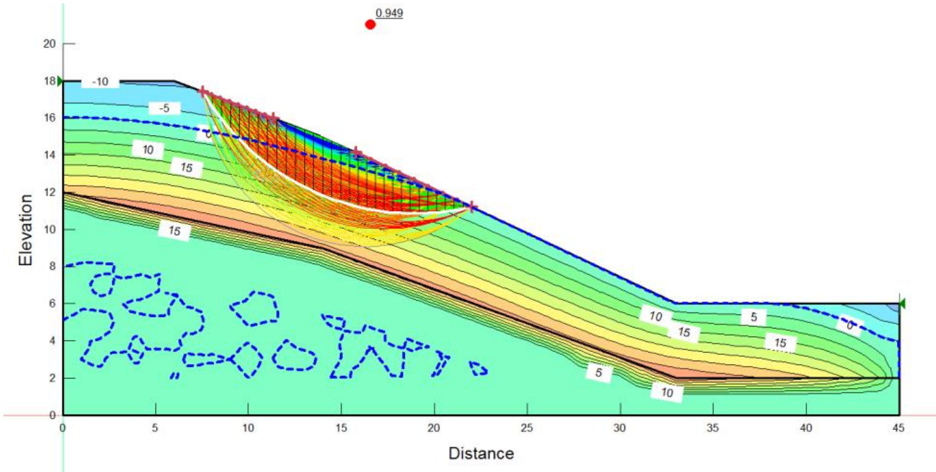

Figure 9. Slope with porewater pressure, critical failure line and safety factor after 3 days of rainfall.

On the slope under consideration, the landslide has already been triggered. However, if intervention reconstruction measures are taken to reduce the net infiltration of water (from $3.22 \cdot 10^{-7}$ $m^3/m^2/s$ to $8.05 \cdot 10^{-8}$ $m^3/m^2/s$), the slope will remain stable. The analysis shows that in the case before the activation of the landslide, only an already increased surface runoff on the road surface would be sufficient and the safety factor would remain above the value of 1. This can be achieved by ditches and drainage system which lead the surface water away from soil body. Figure 10 shows the slope critical failure line and the safety factor after 3 days of rainfall, for increased surface runoff and thus decreased net infiltration.

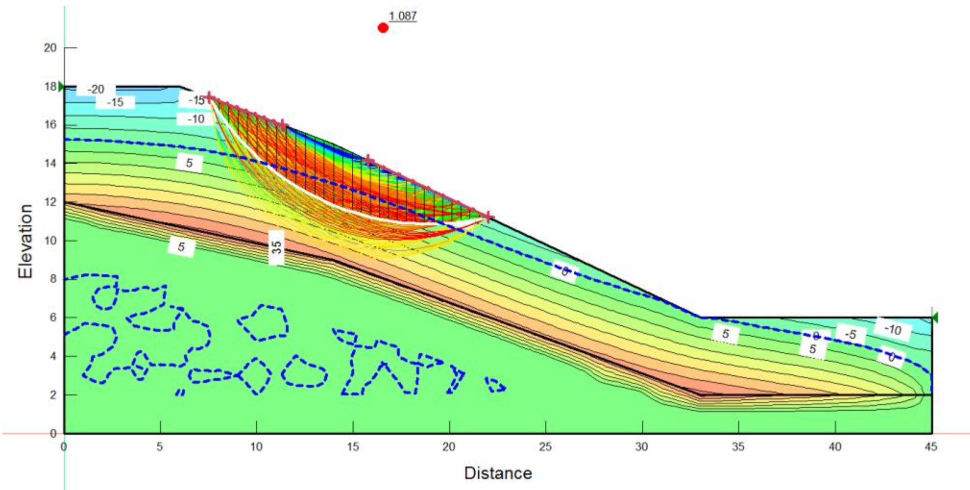

Figure 10. Slope with critical failure line and safety factor after 3 days of rainfall, at decreased water net infiltration due to increased runoff.

4. Study of the Effect of Climate Change on Slope Stability

Remedial works must be carried out for landslides and remaining stable slope. It should be noted that such a measure must be carried out to ensure that the slope next to the landslide will be stable in the future in the face of climate change.

The analysis considers climate change impact on slope instability due to: increased precipitation, increased air temperature, and increased wind speed.

It was found that the increased precipitation is most important for slope stability, while increased air temperature and increased wind speed are less important, as assessed by ELGIP [27], however, it should be emphasized that net water infiltration is the result of all three combined. Consequently, main climate change impacts on slope instability are degradation of material strength parameters, increased surface runoff, increased surface and ground water level and flow, and the change in porewater pressure.

Projected climate change by 2050 and correspondingly increased precipitation were considered. For the landslide site, information from the Precipitation Changes report [29] was used to calculate changes in precipitation levels by 2050 due to increases in precipitation and temperature, using a selected ensemble of regional climate models. The most significant changes are expected in the winter months when precipitation in the lowlands is projected to fall as rain rather than snow. Thus, snow cover will be less frequent than it is today, so more problems associated with large amounts of rain (e.g., landslides) can be expected [29].

The estimate of current extreme rainfall (return period of 100 years) and rainfall in 2050 for the selected landslide site using the climate change scenario RCP4.5 is shown in Table 3.

Table 3. Estimate of current and in 2050 precipitation level.

Rainfall Time	Precipitation Level Today	Precipitation Level 2050 (RCP4.5) (Min-Max)	
(min)	(mm)	(mm)	(mm)
5	19	20	24
10	33	35	41
15	41	43	51
20	46	48	57
30	54	56	67
120	77	81	95
180	84	88	104
1440	139	138	149

4.1. Sensitivity Analysis

Because there is some uncertainty in determining soil properties and water net infiltration, the effects of key input parameters on slope stability were examined by means of sensitivity analyses using 27 combinations as follows:

1. Three different values of rainfall intensity: current extreme (P = 139 mm/day) and future extreme obtained by increasing the current one by 5% and 15%. Consequently, there are three different values of water net infiltration $1.61 \cdot 10^{-7}$ m^3/m^2/s, $4.02 \cdot 10^{-7}$ m^3/m^2/s and $7.24 \cdot 10^{-7}$ m^3/m^2/s;
2. Three different values of soil cohesion, c: 1 kPa, 3 kPa and 5 kPa;
3. Three different values of soil permeability, k: $1 \cdot 10^{-7}$ m/s, $5 \cdot 10^{-7}$ m/s and $1 \cdot 10^{-6}$ m/s.

The water table and the change in porewater pressure (climate change effect A5) were calculated as a function of the input parameters. The time spans from zero to 3 days of rainfall and then another 4 days after rainfall.

The change in the safety factor by days for the current extreme net infiltration is shown in Table 4. The results show that the slope is unstable for the actual extreme rain-fall at given water net infiltration, soil strength and physical properties. However, with climate change, extreme rainfall is likely to be higher in the future.

Table 4. Input data for sensitivity study of slope stability and safety factor both at the beginning of rainfall (SF_0) and during the rainfall or after (SF_{cr}).

Combination	c (kPa)	NI ($m^3/m^2/s$)	k (m/s)	SF_0 (−)	SF_{cr} (−)
1	1	$1.61{\cdot}10^{-6}$	$1.00{\cdot}10^{-7}$	1.022	0.987
2	1	$1.61{\cdot}10^{-6}$	$5.00{\cdot}10^{-7}$	1.022	0.848
3	1	$1.61{\cdot}10^{-6}$	$1.00{\cdot}10^{-6}$	1.022	0.878
4	1	$4.02{\cdot}10^{-7}$	$1.00{\cdot}10^{-7}$	1.022	0.987
5	1	$4.02{\cdot}10^{-7}$	$5.00{\cdot}10^{-7}$	1.022	0.666
6	1	$4.02{\cdot}10^{-7}$	$1.00{\cdot}10^{-6}$	1.022	0.613
7	1	$7.24{\cdot}10^{-7}$	$1.00{\cdot}10^{-7}$	1.022	0.987
8	1	$7.24{\cdot}10^{-7}$	$5.00{\cdot}10^{-7}$	1.022	0.666
9	1	$7.24{\cdot}10^{-7}$	$1.00{\cdot}10^{-6}$	1.022	0.596
10	3	$1.61{\cdot}10^{-6}$	$1.00{\cdot}10^{-7}$	1.281	1.157
11	3	$1.61{\cdot}10^{-6}$	$5.00{\cdot}10^{-7}$	1.281	1.034
12	3	$1.61{\cdot}10^{-6}$	$1.00{\cdot}10^{-6}$	1,281	1.052
13	3	$4.02{\cdot}10^{-7}$	$1.00{\cdot}10^{-7}$	1.281	1.157
14	3	$4.02{\cdot}10^{-7}$	$5.00{\cdot}10^{-7}$	1.281	0.875
15	3	$4.02{\cdot}10^{-7}$	$1.00{\cdot}10^{-6}$	1.281	0.819
16	3	$7.24{\cdot}10^{-7}$	$1.00{\cdot}10^{-7}$	1.281	1.157
17	3	$7.24{\cdot}10^{-7}$	$5.00{\cdot}10^{-7}$	1.281	0.874
18	3	$7.24{\cdot}10^{-7}$	$1.00{\cdot}10^{-6}$	1.281	0.798
19	5	$1.61{\cdot}10^{-6}$	$1.00{\cdot}10^{-7}$	1.452	1.327
20	5	$1.61{\cdot}10^{-6}$	$5.00{\cdot}10^{-7}$	1.452	1.205
21	5	$1.61{\cdot}10^{-6}$	$1.00{\cdot}10^{-6}$	1.452	1.223
22	5	$4.02{\cdot}10^{-7}$	$1.00{\cdot}10^{-7}$	1.452	1.327
23	5	$4.02{\cdot}10^{-7}$	$5.00{\cdot}10^{-7}$	1.452	1.043
24	5	$4.02{\cdot}10^{-7}$	$1.00{\cdot}10^{-6}$	1.452	0.988
25	5	$7.24{\cdot}10^{-7}$	$1.00{\cdot}10^{-7}$	1.452	1.327
26	5	$7.24{\cdot}10^{-7}$	$5.00{\cdot}10^{-7}$	1.452	1.043
27	5	$7.24{\cdot}10^{-7}$	$1.00{\cdot}10^{-6}$	1.452	0.966

Table 4 shows the 27 combinations of input data with different net infiltration of water, cohesion and permeability. The factor of safety at the beginning of rainfall SF_0 (−), when it has no effect on stability, and the critical factor of safety SF_{cr} (−), during the rainfall or after, are also shown as the result of the analyses. The time, in days, when factor of safety arises to minimum value is different and depends mostly on soil permeability.

Table 5 shows the changes in the factor of safety with time from the beginning of rainfall, when net infiltration of water has no effect on stability, and thereafter for 27 combinations of input data with different water net infiltration, cohesion, and permeability.

Table 5. The progress of safety factor from beginning of the rainfall for 27 combinations of Input data.

			k (m/s)		
			$1{\cdot}10^{-7}$	$5{\cdot}10^{-7}$	$1{\cdot}10^{-6}$
Day	**c (kPa)**	**NI ($m^3/m^2/s$)**		**SF (−)**	
0	5	$1.61{\cdot}10^{-7}$	1.452	1.452	1.452
1			1.429	1.394	1.380
3			1.339	1.205	1.223
4			1.337	1.209	1.234
6			1.331	1.221	1.261
7			1.327	1.227	1.272

Table 5. *Cont.*

			k (m/s)		
			$1·10^{−7}$	**$5·10^{−7}$**	**$1·10^{−6}$**
Day	**c (kPa)**	**NI ($m^3/m^2/s$)**		**SF (−)**	
0	3	$1.61·10^{−7}$	1.281	1.281	1.281
1			1.259	1.224	1.209
3			1.168	1.034	1.052
4			1.167	1.038	1.063
6			1.160	1.05	1.090
7			1.157	1.056	1.101
0	1	$1.61·10^{−7}$	1.022	1.022	1.022
1			1.008	1.022	1.022
3			0.934	0.848	0.878
4			0.995	0.868	0.893
6			0.990	0.880	0.920
7			0.987	0.886	0.931
0	5	$4.02·10^{−7}$	1.452	1.452	1.452
1			1.429	1.27	1.255
3			1.339	1.043	0.988
4			1.337	1.069	1.030
6			1.331	1.088	1.085
7			1.327	1.095	1.107
0	3	$4.02·10^{−7}$	1.281	1.281	1.281
1			1.259	1.1	1.085
3			1.168	0.875	0.819
4			1.167	0.9	0.859
6			1.160	0.918	0.912
7			1.157	0.924	0.934
0	1	$4.02·10^{−7}$	1.022	1.022	1.022
1			1.008	0.87	0.900
3			0.934	0.666	0.613
4			0.995	0.727	0.670
6			0.990	0.74	0.717
7			0.987	0.743	0.736
0	5	$7.24·10^{−7}$	1.452	1.452	1.452
1			1.429	1.268	1.151
3			1.339	1.043	0.966
4			1.337	1.068	1.009
6			1.331	1.087	1.070
7			1.327	1.094	1.093
0	3	$7.24·10^{−7}$	1.281	1.281	1.281
1			1.259	1.097	0.982
3			1.168	0.874	0.798
4			1.167	0.899	0.838
6			1.160	0.917	0.896
7			1.157	0.923	0.918

Table 5. *Cont.*

			k (m/s)		
			$1{\cdot}10^{-7}$	$5{\cdot}10^{-7}$	$1{\cdot}10^{-6}$
Day	**c (kPa)**	**NI ($m^3/m^2/s$)**		**SF (−)**	
0	1	$7.24{\cdot}10^{-7}$	1.022	1.022	1.022
1			1.008	0.869	0.763
3			0.934	0.666	0.596
4			0.995	0.726	0.651
6			0.990	0.739	0.700
7			0.987	0.742	0.720

4.2. Discussion of Sensitivity Analysis

The increased precipitation, increased air temperature and increased wind speed causes the degradation of material strength parameters, increases water net infiltration, and in-creases surface and ground water level and flow, including porewater pressure. The re-sults of the analyses show a large influence of climate change.

Figures 11–13 show the typical trend of the factor of safety at the beginning of the rainfall SF_0 (−), when this has no effect on stability, and the time evolution of the factor of safety SF (−), during the rainfall and afterwards.

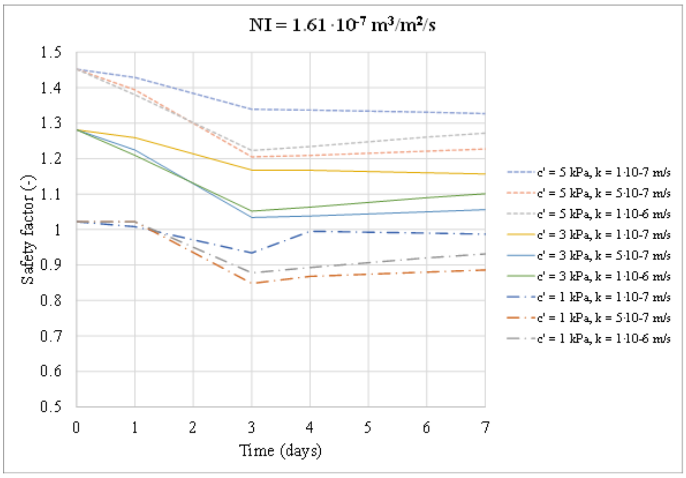

Figure 11. Time progress of factor of safety for NI = $1.61{\cdot}10^{-7}$ $m^3/m^2/s$.

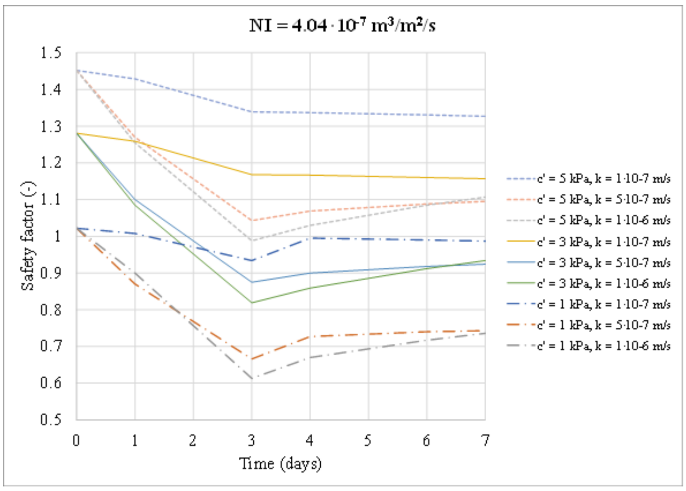

Figure 12. Time progress of factor of safety for NI = $4.04{\cdot}10^{-7}$ $m^3/m^2/s$.

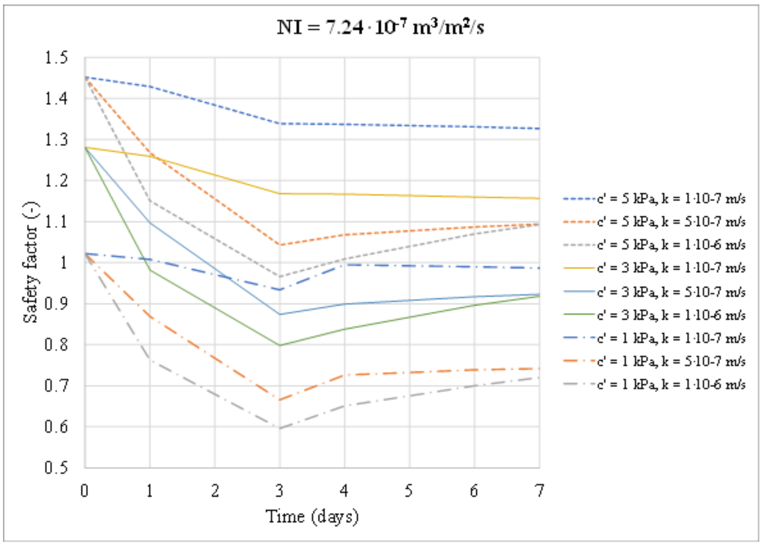

Figure 13. Time progress of factor of safety for NI = 7.24·10^{-7} $m^3/m^2/s$.

The climate change scenarios are the basis for estimating current extreme precipitation (100-year return period) and future extreme precipitation. Precipitation results in net infiltration of water, depending on conditions of evaporation, transpiration, and surface water runoff. In conjunction with climate change, the increase in net infiltration of water may be the most critical parameter.

The results show a large impact of cohesion. The factor of safety decreases almost linearly by 0.1 for each 1 kPa less cohesion.

When soil permeability is low (k = 1·10^{-7} m/s), the factor of safety decreases during rainfall and days thereafter, whereas when permeability is higher (k $\geq$ 5·10^{-7} m/s), safety decreases during rainfall and increases thereafter (Figure 13).

Figure 14 shows that the factor of safety decreases with increasing water net infiltration under permeable conditions. However, at low permeability (k = 1·10^{-7} m/s), the factor of safety does not decrease when the value of water infiltration is higher.

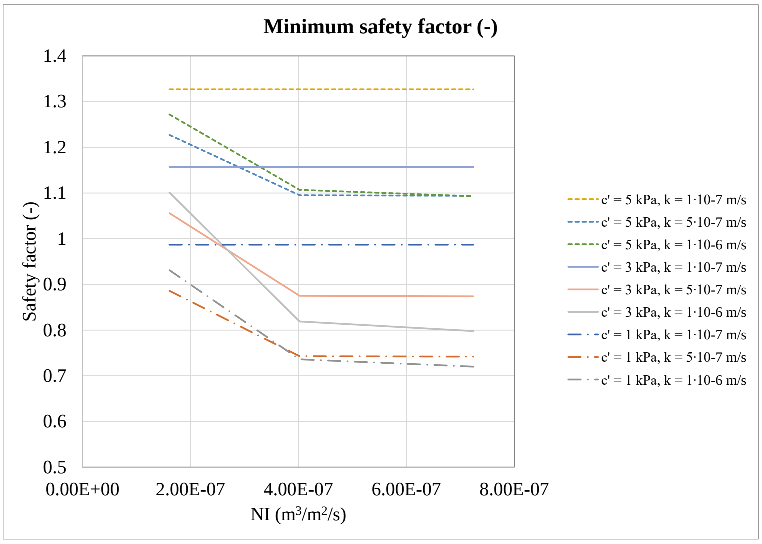

Figure 14. Factor of safety vs. water net infiltration for different permeability.

The analysis shows that in the case before landslide activation, the reduction of water net infiltration by half due to increased surface runoff on the road surface would be sufficient and the safety factor of the slope would remain above the value of 1, even when climate change is considered.

5. Conclusions

The article presents part of the research work on the importance of geotechnical analysis of climate change adaptation related to slope stability. The objective of this study is to de-termine the effects of expected climate change on geotechnical structures and slopes and their causal relationships. In this article it was chosen to address slope instability, which is the main problem and could be due to increasing precipitation. Therefore, a parametric study of the effects of climate change on slope stability is presented. Moreover, previous studies have shown that slope stability is the most important climate change impact [2].

The aim is to propose guidelines to consider the importance of climate change for planned new structures and for existing geo-structure sand slopes.

The case study presented the landslide located in Slovenia, triggered in 2021. The stability analysis was performed considering the theory of rainfall infiltration. It has been shown that the stability of the slope was already low without extreme precipitation, but the slope was stable. In the case of extreme precipitation, taking into account the current extreme precipitation, the slope becomes unstable on the third day of extreme precipitation, which corresponds to the described situation and also more to the predicted precipitation in 2050. The net infiltration of water, was identified as the most critical factor for stability. The analysis clearly shows that timely reduction of net water infiltration through planting and proper surface water runoff from the upper road and slope would be a fairly simple and cost-effective measure compared to the cost of landslide remediation. The analyses also show that measures to reduce net infiltration of water would ensure long-term stability, even considering expected climate change.

The importance of climate change to slope stability is determined through a sensitivity stability analysis of the slope. Climate change as expected future extreme rainfall events are important because they affect the net infiltration of water into the slope. Conditions of water permeability and groundwater flow in the slope are important. Conditions of water permeability and groundwater flow are important. When soil permeability is low, the fac-tor of safety for rain events on subsequent days decreases. When permeability is higher, safety decreases more rapidly.

The effect of reduced cohesion is nearly linear, with the factor of safety decreasing by almost 0.1 for every 1 kPa less cohesion.

Precipitation causes water net infiltration, depending on conditions of evaporation, transpiration, and surface water runoff. In conjunction with climate change, the increase in net infiltration of water may be the most critical factor in slope instability.

The results of the analysis indicate that adaptation measures have to be implemented for the presented example of geological and geotechnical conditions of the slope. These can often be achieved quite simply with the planting of trees and shrubs and with well-regulated surface water runoff, which is usually a low cost compared to the cost of landslide removal. Therefore, it makes sense that in the future all slopes should be analysed according to the expected climate change, taking into account climate change, similarly to the procedure shown in this article.

The parametric study presented shows that the water infiltration has a great influence on slope stability. Therefore, further research is needed to accurately determine the water in-filtration by incorporating land-climate interactions such as air temperature, relative hu-midity, wind speed, solar radiation, snowmelt, and vegetation. Further research is also proposed to evaluate the effects of increasing soil water content on reducing soil cohesion.

Author Contributions: Conceptualization, T.B., P.J., B.Ž.; methodology, T.B., P.J., B.Ž.; formal analysis, P.J., T.B., B.Ž.; writing—original draft preparation, T.B., P.J., B.Ž. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Slovenian Research Agency (grant number P2-0268) and the GEOLAB project (grant number 101006512).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available upon request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Vardon, P.J. Climatic influence on geotechnical infrastructure: A review. *Environ. Geotech.* **2015**, *2*, 166–174. [CrossRef]
2. Fredlund, D.G.; Rahardjo, H.; Fredlund, M.D. *Unsaturated Soil Mechanics in Engineering Practice*; Wiley Online Books; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2012; ISBN 9781118280492.
3. Yuan, B.; Xu, K.; Wang, Y.; Chen, R.; Luo, Q. Investigation of Deflection of a Laterally Loaded Pile and Soil Deformation Using the PIV Technique. *Int. J. Geomech.* **2017**, *17*, 4016138. [CrossRef]
4. Davies, O. *Numerical Analysis of the Effects of Climate Change on Slope Stability*; Newcastle University: Newcastle, UK, 2011.
5. Chen, R.; Liu, J.; Ng, C.W.W.; Chen, Z.K. Influence of Slope Angle on Water Flow in a Three-Layer Capillary Barrier Soil Cover under Heavy Rainfall. *Soil Sci. Soc. Am. J.* **2019**, *83*, 1637–1647. [CrossRef]
6. Yan, C.; Jiao, Y.-Y. A 2D fully coupled hydro-mechanical finite-discrete element model with real pore seepage for simulating the deformation and fracture of porous medium driven by fluid. *Comput. Struct.* **2018**, *196*, 311–326. [CrossRef]
7. Chen, R.; Huang, J.W.; Chen, Z.K.; Xu, Y.; Liu, J.; Ge, Y.H. Effect of root density of wheat and okra on hydraulic properties of an unsaturated compacted loam. *Eur. J. Soil Sci.* **2019**, *70*, 493–506. [CrossRef]
8. Cho, S.E. Prediction of shallow landslide by surficial stability analysis considering rainfall infiltration. *Eng. Geol.* **2017**, *231*, 126–138. [CrossRef]
9. Dyson, A.P.; Tolooiyan, A. Prediction and classification for finite element slope stability analysis by random field comparison. *Comput. Geotech.* **2019**, *109*, 117–129. [CrossRef]
10. Oggero, M.; Insana, A.; Barla, M. *Climate Change Effects on Slope Stability BT—Challenges and Innovations in Geomechanics*; Barla, M., Di Donna, A., Sterpi, D., Eds.; Springer International Publishing: Cham, Switzerland, 2021; pp. 473–481.
11. International Plant Protection Convention. Available online: https://www.ippc.int/en/ (accessed on 12 June 2022).
12. Iglesias, A.; Garrote, L. Adaptation strategies for agricultural water management under climate change in Europe. *Agric. Water Manag.* **2015**, *155*, 113–124. [CrossRef]
13. The Intergovernmental Panel on Climate Change. Available online: https://www.ipcc.ch/ (accessed on 12 June 2022).
14. European Climate Change Programme. Available online: https://ec.europa.eu/clima/eu-action/european-climate-change-programme_en (accessed on 12 June 2022).
15. European Environment Agency. Available online: https://www.eea.europa.eu/ (accessed on 12 June 2022).
16. WCRP—World Climate Research Programme. Available online: https://www.wcrp-climate.org/ (accessed on 12 June 2022).
17. European Environment Information and Observation Network. Available online: https://www.eionet.europa.eu (accessed on 12 June 2022).
18. Füssel, H.-M.; Jol, A.; Kurnik, B.; Hemming, D. *Climate Change, Impacts and Vulnerability in Europe 2012: An Indicator-Based Report*; World Meteorological Organization (WMO): Geneva, Switzerland, 2012; ISBN 9789292133467.
19. CORDEX—Coordinated Regional Climate Downscaling Programm. Available online: https://cordex.org/ (accessed on 12 June 2022).
20. Risks, M.C. *NASA 2014 Climate Risk Management Plan: Table of Contents*; NASA: Washington, DC, USA, 2017.
21. Tang, A.M.; Hughes, P.N.; Dijkstra, T.A.; Askarinejad, A.; Brenčič, M.; Cui, Y.J.; Diez, J.J.; Firgi, T.; Gajewska, B.; Gentile, F.; et al. Atmosphere–vegetation–soil interactions in a climate change context; impact of changing conditions on engineered transport infrastructure slopes in Europe. *Q. J. Eng. Geol. Hydrogeol.* **2018**, *51*, 156–168. [CrossRef]
22. SafeLand: Living with Landslide Risk in Europe; Assessment, Effects of Global Change, and Risk Management Strategies. Available online: http://www.safeland-fp7.eu/ (accessed on 12 June 2022).
23. Vahedifard, F.; Williams, J.M.; AghaKouchak, A. Geotechnical Engineering in the Face of Climate Change: Role of Multi-Physics Processes in Partially Saturated Soils. In Proceedings of the IFCEE 2018, Orlando, FL, USA, 5–10 March 2018; American Society of Civil Engineers: Reston, VA, USA, 2018; pp. 353–364.
24. Pk, S. *Effects of Climate Change on Soil Embankments*; YorkSpace: Denver, CO, USA, 2017.
25. Park, J.; Vilayvong, K.; Son, Y.; Fujisawa, K.; Murakami, A. Slope stability evaluation of an agricultural embankment by statistically derived rainfall patterns. *Paddy Water Environ.* **2019**, *17*, 303–313. [CrossRef]
26. Insana, A.; Beroya-Eitner, M.A.; Barla, M.; Zachert, H.; Žlender, B.; van Marle, M.; Kalsnes, B.; Bračko, T.; Pereira, C.; Prodan, I.; et al. Climate change adaptation of geo-structures in europe: Emerging issues and future steps. *Geosciences* **2021**, *11*, 488. [CrossRef]
27. ELGIP The European Large Geotehnical Institut Platform. Available online: https://elgip.org/working-groups/climate-change-adaptation/ (accessed on 12 June 2022).
28. Van Genuchten, M.T.; Nielsen, D.R. Describing and predicting the hydraulic properties of unsaturated soils. *Ann. Geophys.* **1985**, *3*, 615–627. [CrossRef]
29. Medved, A. Evaluation of Changes in Precipitation in the Surroundings of the Settlement Virštanj. 2021.