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A concept for adapting geotechnical structures considering the influences of climate change

This article addresses potentially unstable slope areas in the context of climate change. A possible approach to mitigating and adapting slopes is presented, considering various solutions primarily based on natural processes. The methodology incorporates planning considerations for the effects of climate change on the geomechanical properties of soils and consequently the response of soils and structures. The effects of selected measures to adapt to climate change are also demonstrated. A concept for adapting potentially unstable geotechnical structures is proposed, considering anticipated climate changes for geomechanical analyses and geotechnical planning, which encompasses the causal chain: climate change signals, effects, impacts (consequences), and measures. The implementation of the concept is illustrated through a typical slope stability analysis. The conclusion of the analysis highlights factors such as water net infiltration into the slope, soil permeability, and groundwater flow within the slope, which are often crucial for slope stability. These factors can also be regulated through nature-based solutions.

Keywords: climate change adaptation, nature-based solutions, slope stability, rainfall infiltration, water net infiltration

1 Introduction

Experiences with landslides show that the most critical slope surfaces are in suburban areas; landslides typically occur in areas sparsely built with structures and within the vicinity of local roads. In Slovenia, it is therefore common practice that for such areas, during the phase of planning and obtaining building permits, a survey is conducted to assess the landslide probability, and the project documentation is supplemented with appropriate geological and geotechnical reports, which serve as the basis for geomechanical analysis and planning.

Geomechanical analyses considering climate change present several challenges that are not adequately addressed by regulations and standards:

- Describing climate characteristics with an evaluation of climate change is difficult; hence, climate characteristics and anticipated climate change in the future are described using so-called climate change signals, determined from climatological forecasts (climate data and climate change prediction models). The challenge lies in the fact that these signals are not precisely determinable, their values have significant deviations depending on the selected climate change scenario, and they are not directly usable as input data in geomechanical analysis.
- The effects of climate change lead to altered geological characteristics of an area and altered geomechanical parameters of soils. The effects of climate change are difficult to precisely determine (geological models, geomechanical tests, and models), even if the signals were accurately determined.
- Climate signals and effects are interdependent. Each individual signal causes one or more effects, but not all simultaneously.
- Signals and effects induce responses (consequences) on the soil and structure, which are difficult to determine due to the simultaneous occurrence of various signals and effects and simultaneous other (non-climatic) influences that are standardly considered in the analysis.
- There are a large number of geotechnical structures, and each type requires specific geomechanical analysis and appropriate geotechnical measures. Standard approaches to analysing individual types of geotechnical structures are known, but they do not provide guidance regarding climate change.
- Defining the causal connection between signals, effects, and responses is challenging; the connection varies for each geotechnical structure.
- There is a wide range of possible geotechnical measures; it is necessary to determine how measures affect climate change signals and effects, and how they affect the safety of geotechnical structures.

A concept for adapting potentially unstable geotechnical structures taking into account the impacts of climate change is presented, which is generally applicable to all typical geotechnical structures. Geotechnical structures here also include embankments and slopes. For this purpose, a causal chain has been developed: climate change signals, effects, responses (consequences), and measures. The implementation of the concept is illustrated using a case study in which meteoric water flows down the slope from the road above. A possible approach to slope adaptation using nature-based solutions (NBS) is proposed. These are solutions inspired and supported by nature. They are cost-effective while simultaneously providing environmental, social, and economic benefits. They bring more diverse nature, natural features, and processes into cities, landscapes, and coastal areas with locally adapted, efficient, and systemic interventions (European Commission, 2023).

The topic presented is part of a research project conducted by the Climate Change Adaptation research group WG-CCA (ELGIP, 2022) within the framework of the European Large Geotechnical Institute Platform (ELGIP, 2022). The WG-CCA study specifically focuses on the European region. The research presented in this article was divided into three main phases. In the first phase, a literature review was conducted. The second phase analysed the causal relationship between climate-change signals and effects, and the potential impacts of climate-change signals and effects on slopes and structures (climate geomechanical design: signals, effects, responses, measures). The third phase provided a concept for geomechanical analysis and planning considering the influences of climate change. Based on this concept, the authors of the article attempted to address all the challenges encountered in analysing existing and new geotechnical structures, considering climate change, and to implement and demonstrate them using a real landslide case study.

1.1 Literature review

International organizations dealing with climate change have previously released numerous publications and documents related to climate change. Many authors discuss the impacts of climate change on the environment. Here, we limit ourselves to the geotechnical aspect of climate change adaptation. Vardon (2015) examined the impacts of climate change likely to affect the environment. He described the following characteristics of climate change: temperature, precipitation, wind, sea level rise, storms, river flow, and frost, which will have an impact on geotechnical structures. Davies (2011) states that the quantification of water net infiltration into the soil depends on climate data, soil, and vegetation.

Climate parameters (precipitation, relative humidity, temperature, wind speed, and solar radiation) can be measured at weather stations, whereas soil and vegetation properties can be determined in the laboratory or in the field (Vardon, 2015). Surface water runoff occurs when the amount of precipitation exceeds the soil infiltration capacity. Computational procedures for determining each water balance are complex and involve numerous assumptions (Davies, 2011). Laboratory tests of models (Chen et al., 2019) and finite element software analysis (Yan & Jiao, 2018) can be used to study slope stability and water infiltration characteristics under rainfall conditions. Geomechanical analysis needs to include the influence of various factors on the soil, such as soil friction angle, water content, hydraulic permeability, and duration and intensity of rainfall (Cho, 2017; Chen et al., 2019; Dyson et al., 2019; Oggero et al., 2021).

As part of the SafeLand project (2012), the risk of landslides was analysed in connection with climate. It used a continuum of soil infiltration, including evapotranspiration, for stability analysis. Vahedifard et al. (2018) focused on geotechnical structures under partially saturated conditions, with changes in soil properties defined as the cause of climate change impacts. Pk (2017) analysed the stability of embankments for current and future climates using numerical modelling and showed that the effects of climate change are strongly dependent on the hydraulic properties of embankment materials. Infiltration and evaporation processes on the soil surface generally depend on prevailing climatic conditions and soil water content. The total amount of water infiltrating the soil significantly affects pore pressure and slope stability. During rainfall, water infiltrates into the slope and gradually forms a transient saturated zone. Suction gradually decreases, reducing the shear strength of the soil on the slope and increasing the risk of slope instability (Andreea, 2016; Wang et al., 2018; Zhou et al., 2019). Park et al. (2019) analysed embankments and slope stability, considering statistical rainfall patterns and soil hydromechanical properties. Insana et al. (2021) explored how issues with geotechnical structures under the influence of climate change are addressed in national adaptation plans. They found that specific provisions for adapting geotechnical structures to climate change are generally lacking and are mainly provided in the form of strategies for addressing specific problems.

According to climate change predictions from the Slovenian Environment Agency in the Climate Change Report 2021 (Agencija Republike Slovenije za okolje, 2021), changes in air temperature and precipitation are forecasted, with the magnitude of changes depending on the amount of greenhouse gases. In various climate scenarios, the air temperature is expected to increase compared to the period from 1981 to 2012 by 1.3 °C to 4.1 °C (Bertalanič et al., 2018). Bertalanič et al. (2018) predict that by mid-century we can expect an increase in the number of extreme weather events: severe heatwaves in the summer, increased temperature and precipitation variability in the summer, more intense rainfall events, a strengthened hydrological cycle, more frequent floods, a significant increase in the frequency of summer droughts, and a probable increase in the number of days conducive to the formation of summer storms.

Adapting cities to extreme events or enhancing their resilience to these events is a complex process that requires the involvement and collaboration of all stakeholders shaping and managing urban space (Klemen, 2020). Radinja et al. (2021) highlight the issue of urban water management, which can only be successful through interdisciplinary cooperation involving experts from all fields (water engineers, spatial planners, urban planners, architects and landscape architects, builders, geographers, sociologists, etc.). They propose measures involving so-called blue-green infrastructure (BGI). BGI comprises natural and semi-natural decentralized systems designed to manage stormwater in urban areas while simultaneously providing a wide range of ecosystem services. Except for a few cities in other countries where strategies for its systematic introduction have already been adopted, the implementation of BGI is limited to isolated cases. Krajnc (2019) notes that the effects of climate change and the current state in urban settlements create conditions where urban infrastructure is increasingly unable to cope during critical moments (e.g., extreme rainfall and heatwaves). Kristl et al. (2020) address the main challenges related to climate change resilience from the perspective of the building sector, such as climate change adaptation schemes, energy efficiency, and measures to mitigate these changes. Challenges are evaluated based on the latest developments in the field, research interests, and regulatory issues, with the literature review assessing progress and identifying research gaps. The literature shows that resilience to climate change mostly relates to larger systems, but at the level of building structures this area is still evolving.

Raymond et al. (2017) and Cohen-Shacham et al. (2016) present solutions that address numerous social challenges simultaneously. These solutions are nature-based and include enhancing human wellbeing, urban regeneration, improving coastal resilience, integrated flood management and ecosystem restoration, promoting sustainable use of materials and energy, enhancing ecosystem insurance value, and increasing carbon sequestration. A list of possible measures, well known in geotechnical engineering, has been presented in the LaRimiT database (Uzielli et al., 2017; Capobianco et al., 2022). Initially including conventional solutions based on traditional methods, the LaRiMiT database has been expanded to include NBS for erosion control and shallow landslide mitigation using vegetation and natural materials. NBS and conventional solutions can also be combined into hybrid solutions.

2 Research structure and methodology

Climate characteristics such as wind, humidity, cloudiness, fog, atmospheric pressure, and so on, and their changes significantly affect soils and structures (embankments, foundations, retaining structures, etc.). However, describing the characteristics of climate change does not make geotechnical analysis possible; therefore, they need to be expressed in a more usable form. All signals of climate change, the effects of climate change, and the impacts of climate change were collectively proposed and presented by the ELGIP Climate Change Adaptation working group (WG-CCA), which began its work in April 2018. The WG-CCA produced a description of climate change characteristics with signals and effects of climate change and presented them in an article (Insana et al., 2021).

The characteristics of climate change describe climate change, but this is too general to address geotechnical problems. The most important signals of climate change for soils are increased precipitation, decreased precipitation or prolonged drought periods, elevated air temperature and warm periods in winter, an increased number of heavy rain and drought cycles, an increased number of freeze-thaw cycles, increased frequency and intensity of cyclones and storms, sea level rise, and increased wind speed (Insana et al., 2021).

Signals of climate change have various effects on soils, bedrock, groundwater, surface water, and vegetation, affecting the behaviour of soils and structures. These impacts, referred to here as the effects of climate change, are determined by geological and geotechnical experts based on climatological data. The most characteristic effects of climate change from a geotechnical perspective include reduced soil bearing capacity, increased weathering, increased water erosion, increased surface runoff, increased or decreased level and flow of surface water and groundwater, increased wind erosion, altered geotechnical properties of frozen soils, increased surface runoff due to snowmelt, altered properties of clayey soils during shrinkage and swelling, increased water and wind erosion, frequent and higher sea level rise due to storm surges, increased loading due to strong winds and waves, coastal erosion, and increased dynamic loading (Insana et al., 2021).

2.1 Slope responses to climate change

Signals and effects of climate change induce responses in slopes and consequent outcomes, which, in the case of slopes, manifest as instability and, in extreme cases, slope failure. According to European standard EN 1997: Geotechnical design (Eurocode 7, 2005), the response is calculated as a result of increased loading and changes (deterioration) in the properties of the material forming the slope (Eurocode 7, 2005). The manifestations of slope instability are diverse (Table 1) and depend on the geometry and layering of the slope, the material of the unstable mass, and climate signals and effects.

Table 1: Forms of slope instability.

Type of instability	Rotational/translational landslide
	Rockfall
	Toppling
	Lateral spread
	Flow
Material	Soil
	Debris
	Rock
Depth	Surface (≤ 0.5 m)
	Shallow (0.5–3 m)
	Medium depth (3–8 m)
	Deep (8–15 m)
	Very deep (≥ 15 m)
Velocity	Extremely fast (≥ 3 m/s)
	Very fast (~ 30 cm/min)
	Fast (~ 1 m/day)
	Moderate (~ 1 m/month)
	Slow (~ 1 m/year)
	Very slow (≤ 30 cm/year)

Source: adapted from Varnes (1978).

2.2 Measures

Climate change can be represented using various scenarios of greenhouse gas concentrations (Representative Concentration Pathways, RCP). There are four pathways of greenhouse gas concentrations, each encompassing a range of baseline values and estimated emissions until 2100: the mitigation scenario RCP2.6; two intermediate scenarios, RCP4.5 and RCP6.0; and the high-emission scenario RCP8.5 (Intergovernmental Panel on Climate Change, 2022). It is advisable to consider the effects of climate change both in the planning of new structures and in the analysis of existing conditions. Table 2 provides general guidelines for both scenarios. When planning a new geotechnical structure, an analysis is always carried out first,

Table 2: Planning steps, criteria, and measures for new and existing geotechnical structures.

Object	Project steps	Criteria (climate adaptation)	Actions
New geotechnical structure	Feasibility study	Criteria are considered for safety and usability, taking into account climate change.	New design
	Preliminary design		
	Detailed design		
	Implementation		
Existing geotechnical structure	Suitability assessment	Criteria for safety and usability, considering climate change, are met.	No actions required
		Criteria for safety and usability, considering climate change, are not met.	Redesign
		Deteriorated mechanical characteristics of slope layers	
		Signs of slope damage and collapse	Intervention measures

Source: adapted from Bračko et al. (2022).

taking into account climate change for the future, followed by planning based on the results. However, when examining an existing geotechnical structure, the action depends on the assumed consequences of climate change. If the analysis shows a deterioration of the soil properties that leads to a lower safety factor and non-compliance with the safety criteria, similar steps as for a new structure are required. Intervention measures are carried out when damage to the structures or slope failure has already occurred.

Approaches to mitigate the consequences of climate change include construction measures; for each geotechnical structure and the expected impact of climate change, an appropriate measure from the list of possible measures is followed (see SafeLand, 2012). Here, we only address measures that are applicable to slopes and are simultaneously NBS. Table 3 shows that some measures fully meet the criteria for NBS. However, for some measures, a combination of NBS and conventional solutions with the incorporation of artificial materials is required.

To classify a measure as an NBS, the following criteria had to be met: 1) natural processes are used for the measure, 2) the measure provides or enhances social benefits, 3) the measure provides or enhances economic benefits, 4) the measure provides or enhances environmental benefits, and 5) the measure is beneficial for biodiversity.

In analyses of adaptation to climate change, a challenge arises regarding how to utilize existing computational models for geomechanical slope analyses and how to incorporate input data that accurately describe expected climate changes. Therefore, this article delineates an approach for adapting potentially unstable geotechnical structures to expected climate changes (see Figure 1), using climate parameters such as precipitation, temperature, wind, and sea level as indicators of climate variability. Climate changes induce effects on soils and structures. Each signal triggers one or more effects of climate change. Signals and effects of climate change are the cause of consequences of climate change, which are reflected as altered physical properties of soils and additional influences (i.e., loads). Based on the predicted response of soils and structures to expected climate changes, the necessary geotechnical measures for ensuring safety and stability of soils are then determined.

For the geotechnical structure under consideration, it is important to first define which signals of climate change are most significant and what effects of climate change they cause, as well as what potential consequences might arise due to the given signals and effects. For each specific case, there are multiple signals and resultant effects, and so it is crucial to understand the correlations between individual parameters of climate change. Therefore, within the WG-CCA, a study (an online survey) was conducted involving geotechnical experts from European countries to provide an assessment of the impact of signals of climate change, effects on areas and structures, and the most problematic consequences for urban areas and structures. The survey results indicate that, in most countries, the most problematic signals of climate change are increased or decreased precipitation, increased cycles of rain/drought, and increased cycles of freezing/thawing (ELGIP, 2022).

A methodology has been formulated to recognize climate signals, assess the impacts of climate change, and provide guidance for incorporating climate variability into geotechnical analysis and design. This methodology follows a procedural sequence commonly used by geotechnical engineers for evaluating existing geotechnical structures and designing new ones.

Table 3: Measures for ensuring slope stability.

	Action description	Natural measures	Stone, wood	Artificial and recycled materials
Surface protection	Hydroseeding, turfing, and trees/bushes	✓		
	Geosynthetic reinforcement			✓
	Drainage blanket		✓	✓
	Beach replenishment, rip rap		✓	
	Dentition	✓		✓
Slope geometry modification	Removal of (potentially) unstable slope mass	✓		
	Removal of loose (potentially) unstable blocks	✓		
	Removal of material from driving areas	✓		
	Substitution of material with lightweight fill			✓
	Addition of material to maintain stability		✓	
Modifying surface water regime, surface drainage	Surface drainage work	✓	✓	
	Local regrading to facilitate runoff	✓		
	Sealing tension cracks	✓		
	Insulation barriers, geo-membranes			✓
	Vegetation, hydrological effect	✓		
	Hydraulic control work	✓		
	Diversion channels	✓		
Modifying groundwater regime	Shallow trenches filled with free-draining material		✓	
	Deep trenches filled with free-draining material		✓	
	Sub-horizontal drains	✓		
	Wells	✓		
	Drainage tunnels, adits, galleries	✓		
Modifying the mechanical characteristics of unstable mass	Vegetation	✓		
	Substitution		✓	
	Compaction from surface	✓		
	Deep compaction	✓		
	Mechanical deep mixing with lime and/or cement			✓
	Low-pressure grouting with cement/chemical binder			✓
	Jet grouting			✓
Transfer of loads to more competent strata	Counterfort drains			✓
	Piles		✓	✓
	Diaphragm walls			✓
	Caissons, mechanical effects			✓
	Soil nailing			✓
	Dowels and harnessing			✓
	Rock bolting			✓
	Strand anchors			✓
Retaining structures	Reinforced soil			✓
	Gabion walls		✓	✓
	Crib walls		✓	
	Drystack masonry walls		✓	
	Mass concrete or masonry walls		✓	✓
	Reinforced concrete stem walls			✓

Source: adapted from Capobianco et al. (2022).

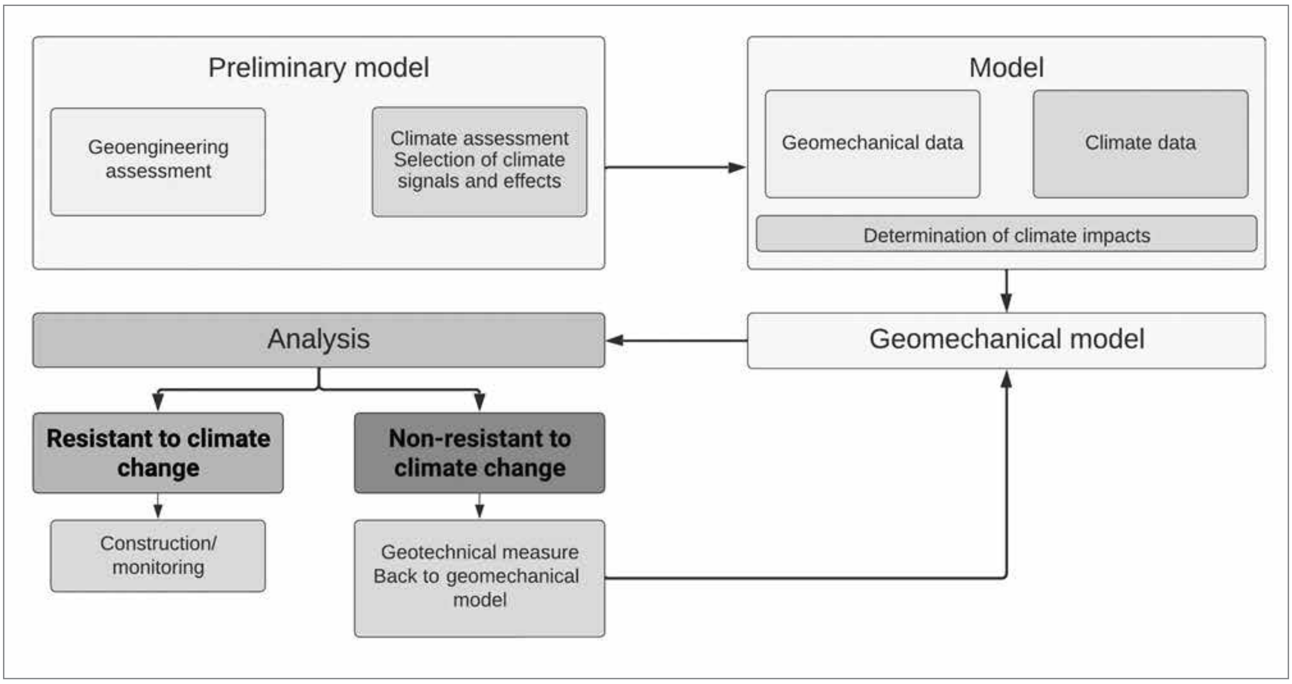

Figure 1: Conducting geomechanical analysis and designing geostructures taking into account climate change impacts (illustration: authors).

The individual steps of this sequence are shown in Figure 1. In addition, compliance with the project specifications defined in Eurocode 7 (2005) is essential.

In the initial phase, comprehensive analyses are carried out by experts in geotechnical engineering, geology, seismology, and climatology. These analyses aim to develop a model for a subsequent geomechanical analysis. If the geomechanical analysis shows that the structure can withstand the effects of climate change, the construction process or monitoring is continued. However, if the structure is found to be at risk from climate change, geotechnical measures are taken and the analysis process is repeated.

In the case of existing geotechnical structures, compliance can be achieved by modifying the geotechnical structure, if feasible, with technical maintenance interventions. A list of possible structural mitigation measures, well known in geotechnical engineering, is presented in Table 3. The suggested procedure for geomechanical analysis and design can be applied to all typical geotechnical structures, including slopes and embankments, because it does not change established fundamental principles and analytical approaches of geotechnical design but adds aspects related to climate.

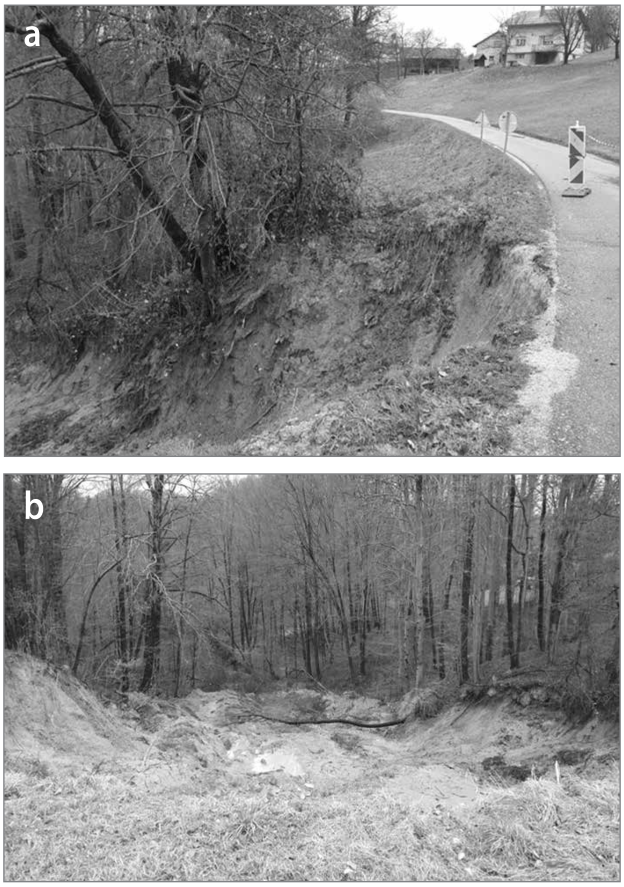

Figure 2: a) typical slope failure resulting from water infiltration into the slope and simultaneous runoff of stormwater from the road, and b) the body of the landslide with earth ridges at the base of the slope (photo: Bojan Žlender).

3 Results and discussion: a case study applying the concept of adaptation of potentially unstable geotechnical structures to expected climate change

Table 1 illustrates the occurrence forms (i.e., types) of slope instability, which vary based on slope geometry, stratification, material of the unstable mass, and the influence of climate signals and effects. Specific geomechanical analyses are conducted for each type of slope, and appropriate geotechnical measures are selected. As an example of the application of the concept, a case study of a slope beneath a road with free-flowing stormwater runoff was chosen. The example demonstrates the stability analysis of the slope, focusing on the probability of landslide occurrence. The impact of climate change is considered, and a measure involving the use of NBS is implemented.

3.1 Preliminary model

The purpose of the analysis is to understand the causes of potential slope instability and to plan and verify the effectiveness of mitigation measures to ensure climate resilience of the slope and the road, and the safety of residential structures nearby. In accordance with the Eurocode standard, the design life is fifty years (Eurocode, 2004).

The landslide probability map shows that the location under consideration is in an area with a high probability of landslides, and the erosion warning map indicates that it is in an area requiring demanding protective measures. Key signals of climate change include increased precipitation, elevated air temperature, and increased wind speed. A preliminary assessment of the geological conditions of the area under consideration is provided by the geological map of the area. The Oligocene layers of the slope consist of grey schistose clay and slate, clayey shale, and slaty shale. The Holocene layers are alluvial deposits composed of fine-grained pebbles, sand, silt, and clay. The results of soil classification were obtained following the standard ISO TS 17892-4:2016 (2016). The groundwater level and flow rate, which depend on the season and rainfall amount, were estimated. Seismic data consider the recommendations of the standard EN 1998-1:2005 (Eurocode 8, 2005), which accounts for a seismic return period of 475 years. The area under consideration falls into the seventh degree on the EMS (European Macroseismic Scale). According to the project's ground acceleration map, the design ground acceleration for the area under consideration is 0.2 *g* (Eurocode 8, 2005).

3.2 Model

The research has shown that the soils at the site consist of layers of sandy clay, with a light to medium compact consistency, extending to a depth of three metres. Deeper layers consist of clay of medium to heavy consistency, transitioning to a semi-hard state, and extending to a depth of six metres. Below lies shale bedrock. Climate-related effects associated with climate signals include deteriorating material strength due to increased water saturation, increased permeability, intensified physical weathering, and elevated groundwater levels and flow, including pore water pressure. A geotechnical survey of the site was conducted, which included topographic surveying, soil probing and sampling, groundwater level measurements, field standard penetration testing (SPT), and laboratory tests (soil classification, density determination, direct shear test, permeability test, oedometer test). The properties of shale and sandy clay were determined. The soil model considers the maximum friction angle and zero dilation angle. The soil-water characteristic curve on the slope and the permeability function curve were determined using the Van-Genuchten and Nielsen method (1985).

Projected climate change effects until 2050 and accordingly increased rainfall amounts were considered for inclusion in the model. An assessment was made of current extreme rainfall (with a return period of 100 years) and rainfall in 2050 for the selected landslide site based on the RCP4.5 climate change scenario. The current extreme rainfall amount was defined as P = 139 mm/day. The future extreme is achieved by increasing the current rainfall amount by 7.2% (P = 149 mm/day). Computational procedures for determining water infiltration into the soil are complex and involve numerous assumptions (Yan & Jiao, 2018). The analysis uses an equation developed by the American Society of Civil Engineers (ASCE; Pk, 2017).

3.3 Geomechanical model

The geomechanical model is obtained in this phase by incorporating the results of climate modelling into the geotechnical model and input data analysis, expressing the increase in rainfall with water net infiltration, evaluated based on extreme rainfall. Two models, FEM (Finite element method) and LEM (Limit equilibrium method), were created, with a mesh size of 1 × 1 m. Boundary conditions were also determined: the upper limit is set as the rainwater infiltration boundary, the bottom of the model is impermeable, and the right boundary allows water drainage. The depth of infiltration is determined by the geometry of the layers and hydraulic conductivities due to the impermeable bedrock.

Table 4: Input data for the numerical model.

	Unit	Sandy clay	Shale
Bulk density	γ (kN/m^3)	18.5	24
Cohesion	c (kPa)	2	200
Shear angle	φ (°)	20	45
Volumetric water content	VWC = V_w/V_s (–)	0.2	/
Permeability	$k_y = k_x$ (m/s)	5×10^{-7}	5×10^{-11}
Compressibility	m_v (1/kPa)	5×10^{-4}	1×10^{-8}

Source: Bračko et al. (2022).

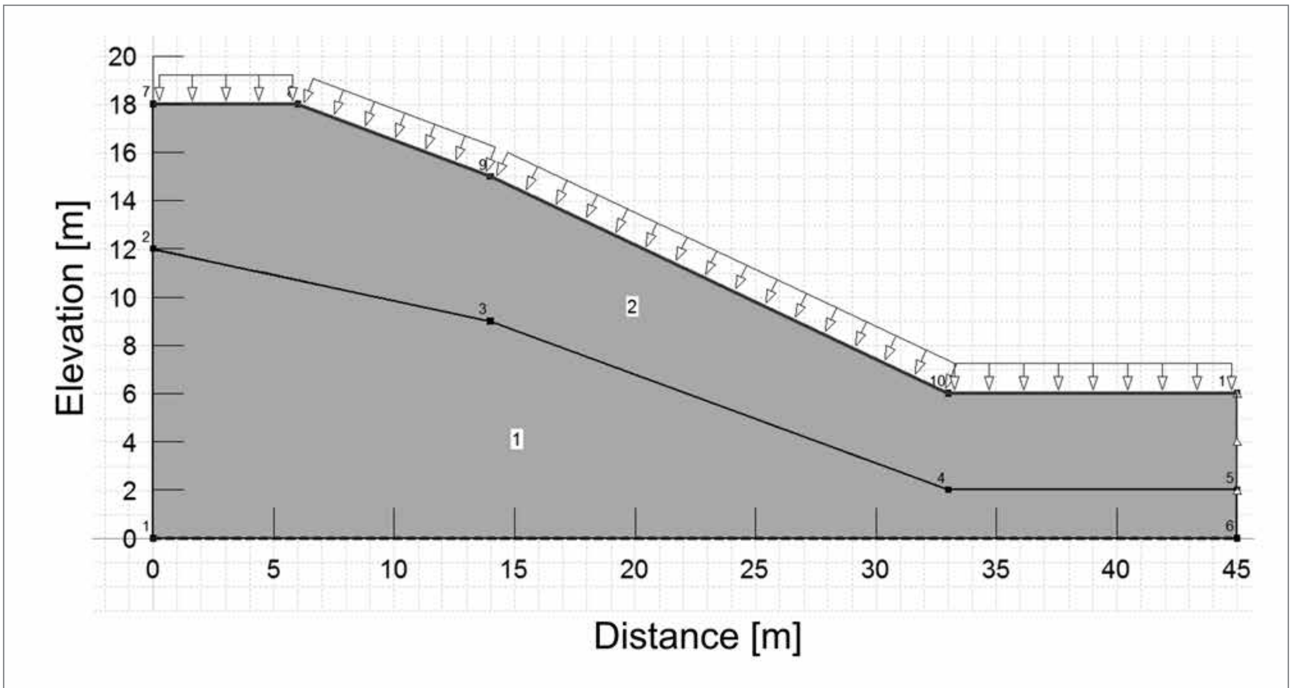

Figure 3: Geometry and mesh of the numerical slope model (source: Bračko et al., 2022).

The model geometry is shown in Figure 3. The model dimensions are 45 × 20 m, with two defined soil layers: the upper layer is sandy clay, and the lower layer is shale. Climate change projections until 2050 and accordingly increased rainfall amounts were considered. Data from the precipitation change report were used for the landslide location. Calculations were made for changes in precipitation levels until 2050, assuming increased rainfall and temperature for the selected landslide site using the RCP4.5 climate change scenario. The rainfall intensity is defined as a climate change, and currently, considering a hundred-year return period, it is 139 mm/day, with a 5% increase in extreme rainfall due to climate change. Table 4 shows the input data for the numerical model analysed. Default values were selected for shale because it is intact rock, and its shear strength properties are not relevant for slope analysis.

The slope stability is assessed using the slope safety factor before and during rainfall through FEM numerical modelling. Changes in surface water content and pore pressure during the infiltration process were analysed using the SEEP/W module of GeoStudio. SLOPE/W is a 2D program for slope stability modelling that provides a wide range of capabilities. The program has an extensive list of materials. The main advantage is the ability to model partially saturated soils. SEEP/W is a module of the GeoStudio permeation package and can be used to simulate water flow in saturated or unsaturated soils. Because both SEEP/W and SLOPE/W are part of the same GeoStudio software package, they allow easy integration and calculation of the safety factor of the slope for all time steps of the simulation.

3.4 Analysis

Based on the results of the analysis, it is possible to assess the slope's climate adaptability. The analysis demonstrates that the slope is non-resistant to the predicted climate changes and

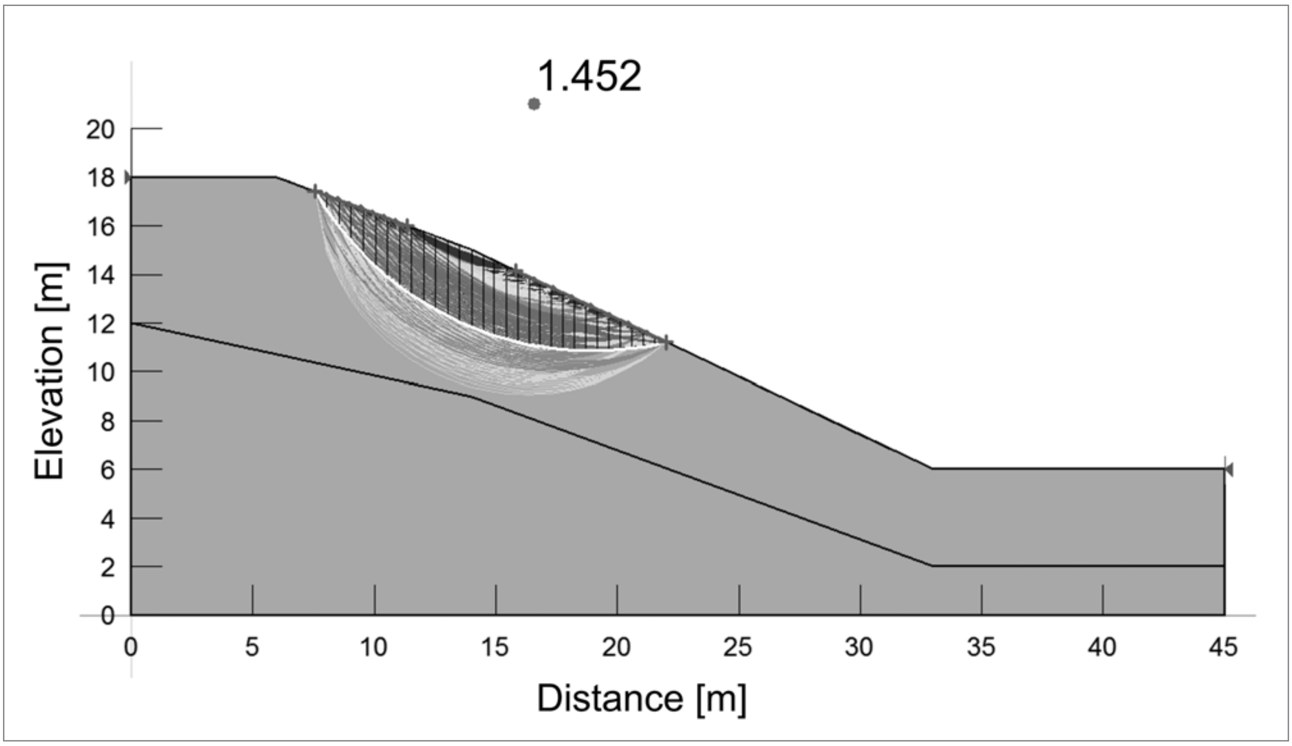

Figure 4: Critical failure and safety factor without the influence of water infiltration (no rainfall; illustration: authors).

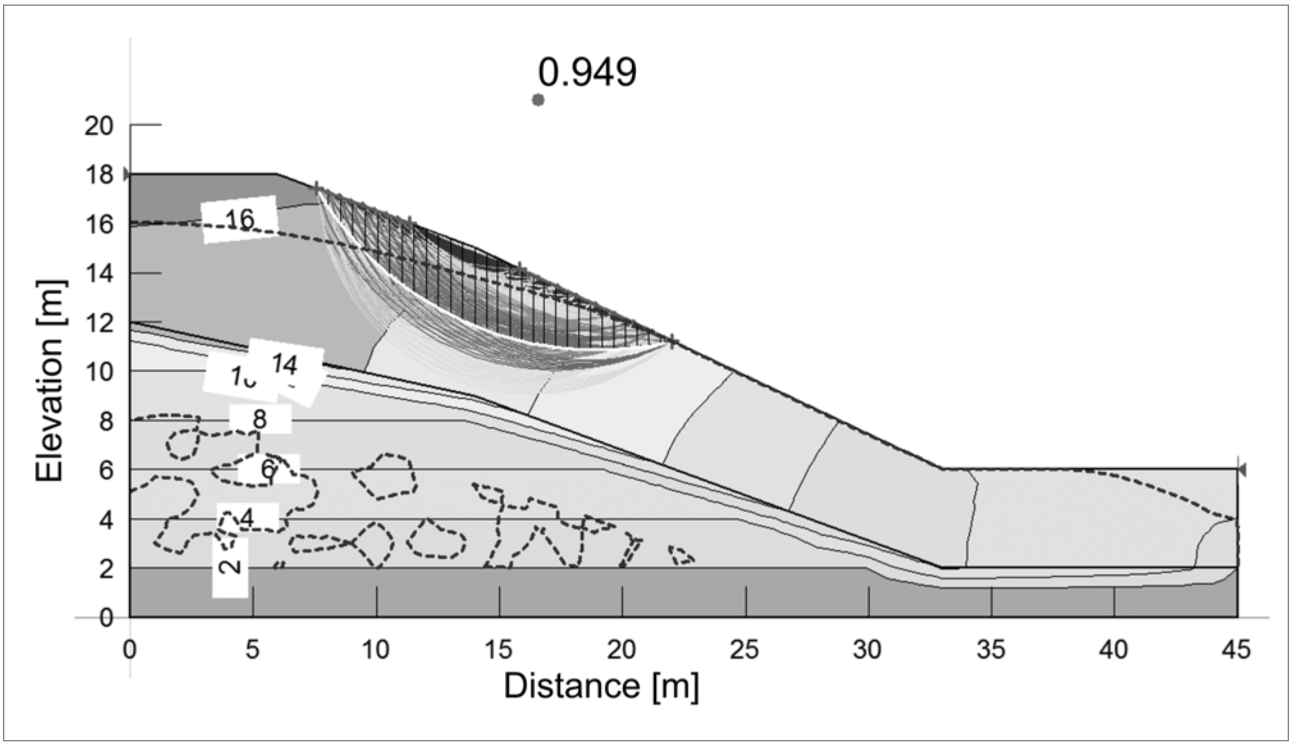

Figure 5: Critical failure and safety factor (three days of rainfall, NI = 30 l/m^2/day; illustration: authors).

requires adaptive measures. The analysis comprises three phases: the first phase represents the initial state, the second phase involves intense rainfall lasting for three days, and the third phase occurs when the rainfall ceases.

The analysis considers the impact of climate change on slope instability due to increased rainfall, elevated air temperature, and increased wind speed. It was found that increased precipitation has the most significant impact on slope stability, whereas elevated air temperature and increased wind speed are

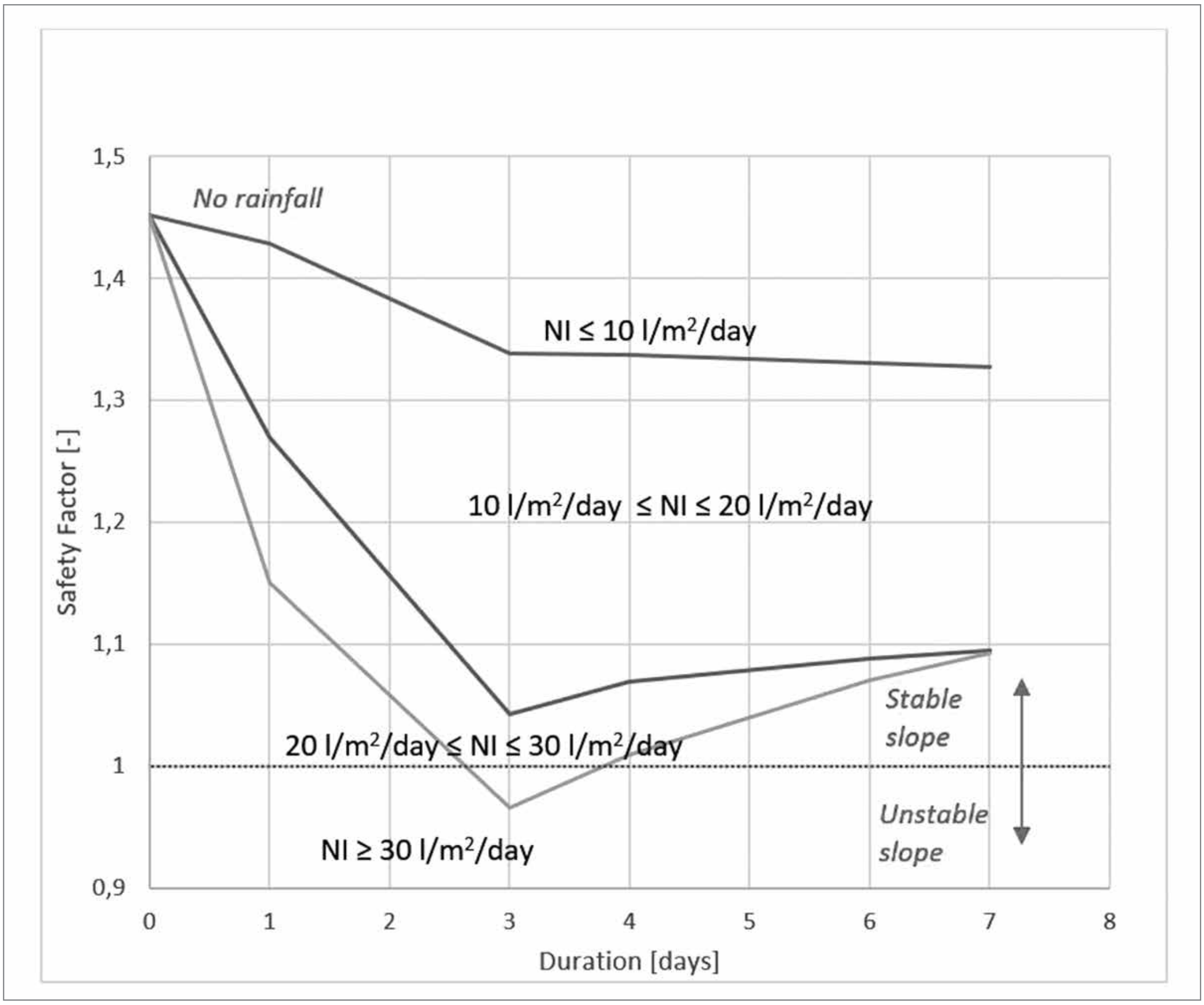

Figure 6: Influence of water infiltration into the slope on the temporal evolution of the safety factor for stability, with simultaneous reduction in soil shear strength (illustration: authors).

considered less important (ELGIP, 2022). However, it should be emphasized that net water infiltration is the result of all three interacting climate signals. Consequently, the main influences of climate change on slope instability are the deterioration of material strength parameters, increased surface water runoff, elevated groundwater levels and flow, and changes in pore water pressure.

The analysis shows that the safety factor for slope stability in the absence of rainfall ensures stability (Figure 4). As the duration of rainfall increases, the safety factor decreases, depending on the amount of rainfall and thus water infiltration into the slope. With increased water infiltration into the slope, pore water pressure increases, leading to increased soil permeability within the slope. The safety factor decreases with increasing water infiltration into the slope, accompanied by increased permeability. In this regard, research on soil permeability within the slope is crucial because it is difficult to accurately determine for natural conditions and significantly affects the results. Interestingly, slope stability decreases very slowly when soil permeability within the slope is sufficiently low ($k \leq 10^{-7}$ m/s), which is favourable for maintaining slope stability. However, as permeability increases, the safety factor for slope stability decreases more rapidly, but up to a certain limit. For the data analysed, this limit is three days, even if rainfall continues (Figure 5). For the data analysed, the threshold at which the slope would still remain stable is slightly above the limit of NI = 20 l/m^2/day, assuming that both soil permeability and shear strength do not unfavourably change simultaneously within the slope (Figure 6).

A further issue is that increased water infiltration into the slope also increases the soil moisture content and pore water pressure, consequently leading to a decrease in shear strength.

Therefore, the safety factor decreases even further. The relationship between the safety factor and the shear strength of the slope soil is nearly linear. The results of the analysis are elaborated further in the article by Bračko et al. (2022), indicating a significant impact of climate change on slope stability. To ensure adequate slope stability, measures need to be implemented that also consider expected climate changes. If the stability conditions are not met, the analysis process reverts to Step 2 (Concept analysis). Remedial measures are then implemented in accordance with the NBS conditions; that is, counterfort drains, drainage, road runoff management, and vegetation planting. After the implementation of measures, it would be beneficial to monitor road displacements and water drainage at the inspection manhole and outlet of drainage pipes.

4 Conclusion

Climate change will pose a significant challenge in the future. It is crucial to first define the causal relationship between climate signals (climate characteristics) and their effects (geological and geomechanical description), as well as to delineate the consequences (response of geotechnical structures). However, geomechanical analyses aimed at studying the effects of climate change encounter a series of unresolved issues concerning regulations and standards. Therefore, this article presents a concept for climate-adapted geomechanical analysis and planning.

For easier comprehension, the concept is illustrated using a slope stability example, along with the analysis results from the SEEP/W module of GeoStudio software. The conclusion of the analysis emphasizes that ensuring slope stability often relies significantly on factors such as net infiltration of water into the slope, soil permeability, and groundwater flow within the slope. The analysis concept presented could serve as a foundation for developing geomechanical analyses that effectively detect the consequences of climate change in a timely manner. Therefore, it is essential to conduct thorough slope monitoring and gather relevant data for future analyses and examination of the impact of climate change on slopes.

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