Analysis of a potentially unstable slope in the context of climate change

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ABSTRACT: The article presents the problem of a potentially unstable slopes in the context of climate change. Essentially, the aim is to show the possibilities of using climate data and forecasts of expected climatic changes in the design of geotechnical installations. The direct description of climate change used in climatology is too general and useless for geotechnical analyses. Therefore, climate change signals, effects and impacts are introduced for geotechnical processing, which can be evaluated based on climate data. The research results show that simple, nature-based solutions can successfully ensure long-term stability, even in the face of expected climate change. The costs of such measures, such as timely weeding and planting of trees and shrubs as well as proper surface water drainage, are generally quite low compared to the follow-up costs of landslide remediation.

1 INTRUDUCTION

Many authors in their works discuss the impacts of climate change on the environment; here we confine ourselves solely to the geotechnical aspect of climate change adaptation. Vardon examined the impacts of climate change likely to affect the environment (Vardon, 2015). Davies (2011) states that the quantification of net water infiltration into the soil depends on climate, soil, and vegetation data. Computational procedures for determining each water balance are complex and involve numerous assumptions (Davies, 2011). Laboratory model tests (Chen et al., 2019) and finite element software analysis (Yan and Jiao, 2018) can be used to study stability and water infiltration characteristics on slopes under rainfall conditions. Geomechanical analysis needs to include the influence of various factors on soils, such as: soil friction angle, water content, hydraulic permeability, duration, and intensity of rainfall (Oggero et al., 2021). 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) analyzed the stability of embankments using numerical modeling and showed that the effects of climate change strongly depend on the hydraulic properties of embankment materials. Insana et al. (2021) investigated 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 specific problems.

This article presents the concept of adapting potentially unstable geotechnical structures, considering the impacts of climate change, which is general and can be applied to all typical geotechnical structures. Geotechnical structures here also include embankments and slopes. The implementation of the concept is illustrated by the example of a slope where rainwater freely flows. A possible approach to regulation and management is proposed, based on nature-based solutions (NBS). These solutions are inspired and supported by nature. They are cost-effective while providing environmental, social, and economic benefits. They bring more diverse nature, natural features, and processes into cities, landscapes, and seascapes with locally adapted, efficient, and systemic interventions.

2 IMPACTS AND EFFECTS OF CLIMATE CHANGE

The characteristics of climate change can be described through the so-called signals of climate change (Insana et al., 2021). These describe climate change, but they are too general to adequately address geotechnical problems.

The most important climate change signals are Increased precipitation, Decreased precipitation/extended drought periods, Increased air temperature and periods of warm weather in winter, Increased frequency of heavy rain and drought cycles, Increased frequency of freeze-thaw cycles, Increased frequency and intensity of cyclones and storms, Rising sea levels, and Increased wind speed.

The most characteristic effects of climate change from a geotechnical point of view are Deterioration of soil strength, Increased weathering, Increased water erosion, Increased surface water runoff, Increased level and flow of surface and groundwater level, Decreased level and flow of surface and groundwater, Increased wind erosion, Changed geotechnical properties of perennially frozen soil, Increased surface runoff due to snowmelt, Increased shrink-swell behaviors of clay soils, Increased water and wind erosion, Frequent and higher sea level rise due to storm surges, Increased load due to strong winds and waves, Landward encroachment of the sea and Increased dynamic loading.

3 RESPONSES OF SLOPES TO CLIMATE CHANGE

The impacts and effects of climate change lead to reactions in slopes which, in the case of slopes, manifest themselves as instability and, in extreme cases, as slope failure. According to the European standard EN 1997: Geotechnical Design, the reaction is calculated as the result of an increased load and a change (deterioration) in the properties of the material forming the slope (EN 1997-1, 2005). The manifestations of slope instability vary and depend on the geometry and stratification of the slope, the material of the unstable mass, and the climatic signals and effects.

4 CONCEPT OF MEASURES

Climate change can be illustrated using different scenarios of greenhouse gas concentrations (Representative Concentration Pathways - RCP). There are four greenhouse gas concentration pathways, each comprising a range of baseline values and estimated emissions up to the year 2100: the mitigation scenario RCP 2.6, two intermediate scenarios RCP 4.5 and RCP 6.0, and the high emissions scenario RCP 8. It makes sense to consider the effects of climate change both when planning new structures and when analyzing existing ones. Table 1 provides general guidelines for both cases. When planning a new structure, an analysis should always be carried out first, taking climate change into account for the future, and a design should be drawn up on this basis. When investigating an existing geotechnical structure, however, the measure depends on the assumed consequences of climate change. If the analysis shows that the soil properties will deteriorate, resulting in a lower safety factor and that the safety criteria for the structure on the slope will not be met, measures must be taken for a new structure. In the event of damage to the structure or slope failure, intervention measures are implemented.

Table 1: Design steps, 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

5 EXAMPLE OF IMPLEMENTING CLIMATE CHANGE ADAPTATION CONCEPT

There are distinct types of slope instability phenomena that vary according to the geometry and layering of the slope, the material of the unstable mass, and the influence of climate signals and effects. For each type of slope, a specific geomechanical analysis is carried out and appropriate geotechnical measures are selected. To demonstrate the application of the concept, an example of a slope above a road where rainwater flows freely was chosen. The example shows the occurrence of freezing and thawing weather as well as extreme amounts of snow and precipitation leading to mudflow. A measure was chosen for the remediation in which semi-natural solutions were used.

Mudflow on the road, Javorje, Carinthia (see Figure 1 and Figure 2)
On the steep hill, grassy above and wooded at the bottom, 70 cm of snow fell during a heavy snowfall in winter. This was followed by 3 days of heavy thaw and very intense rainfall, which later turned back into snowfall. This triggered a mudflow that destroyed tall trees. The mud with the fallen trees quickly flowed onto the road below, where it blocked the culvert and spilled the material over the road and 80 m along the road.

Figure 1: Location of mudflow.

Figure 2: Direction of movement the mudflow.

Geology: the hill is formed by a phyllidiid schist with limestone inlays shown in Figure 3 and. The soil cover consists of layers of clay and sandy silt. On the steeper slope, the soil cover is quite thin; in the upper part, where the slope of the terrain is less steep, it is several meters thick. The ground cover is locally very moist and carries a lot of water.

Figure 3: Geology of the hill.

The landslide is considered as over 500 m long mudflow, starting at the upper edge of the forested steep slope, and ending with a landslide in the valley, on the lower regional road. The following facts were established.

- In the area where the slope becomes steep and forested, the branches of the watercourses merge into a torrent that runs along a very steep slope for about 500 m crosses the regional road with a culvert in the lower valley and flows into the Javorski potok.
- Earth from debris was mixed with water from the slope flows.
- The gorge of the Hudournica stream has damaged banks; traces of the flood flow and local landslides as well as the erosion of soil and fallen trees are visible.
- The mud flowed with the fallen trees to the lower regional road, where it blocked the culvert and the material spilled over the road and along the road for a length of 80 meters as shown on Figure 4 and Figure 5.
- The mudflow destroyed the road fences and the consequences for the culvert will be visible after the area has been cleaned.

Figure 4: Movement of mudflow over the road.

Figure 5: Consequences of mudflow.

In accordance with the specific circumstances of the case, the following Climate Change Signals, Effects, and Impacts, and design consideration have been identified:

Climate Change Signals: these include increased precipitation, increased air temperatures, especially in winter, and a greater frequency of freeze-thaw cycles.
Climate Change Effects: these include deterioration in material strength due to increased saturation and physical weathering, deterioration due to saturation and physical weathering caused by snowmelt, and deterioration due to increased freeze-thaw cycles and physical weathering.
Climate Change Impact: destabilization of slopes, leading to mudslides.

Design consideration: To address these challenges, a hydrological analysis was carried out to assess the implementation of retention facilities in the streambed and the hydrotechnical requirements for the culvert. A project was then developed for the construction of a retention barrier, a mesh barrier and a culvert under the road (see Figure 6, Figure 7, Table 2). In addition, Nature-

Based Solutions (NBS) were selected, including live gully breaks, stone cladding, stone barrier, and live gully breaks, to further mitigate the risks.

Table 2: Design parameters

Layer	Volumetric weight γ [kN/m^3]	Elastic modulus E [MPa]	Poisson ratio ν [-]	Shear angle φ [°]	Cohesion c [kPa]
Mudflow			Useless		
Soil layers of low consistency	19.0	1.5	0.35	15.0	0.0
Soil layers of medium to stiff consistency.	19.0	5.0	0.35	25.0	10.0
Weathered rock	24.0	50.0	0.25	30.0	50.0

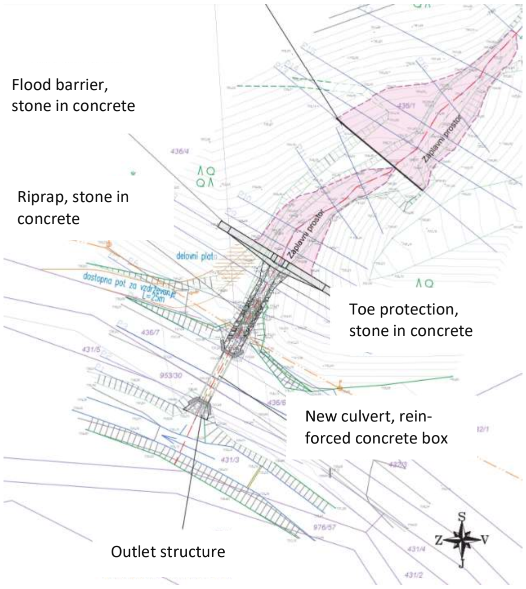

Figure 6: Plan view of the construction. (based on design project)

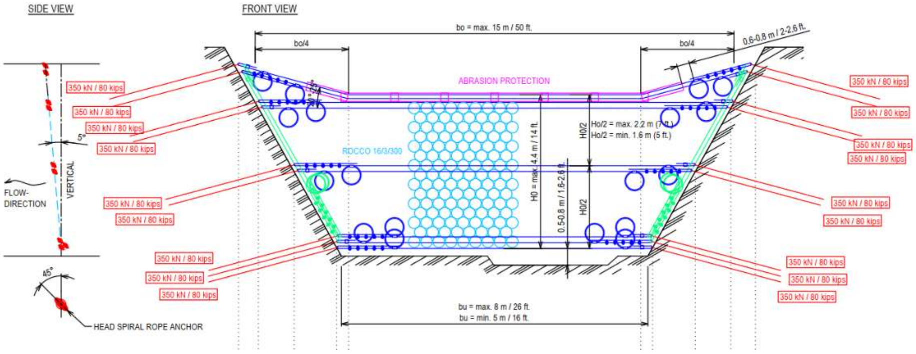

Figure 7: Cross-section of the construction through the mesh barrier. (based on design project)

6 CONCLUSION

The study emphasizes the urgent need to address the geotechnical implications of climate change, particularly regarding erosion and slope instability. While these challenges are recognized in the existing literature, a gap in comprehensive adaptation strategies in national plans is evident. To address this gap, the article argues for an approach to adapting geotechnical structures, including embankments and slopes, through the integration of nature-based solutions (NBS). These nature-inspired solutions offer cost-effective and versatile benefits and are in line with the principles of environmental, social, and economic sustainability. By considering various signals and impacts of climate change, such as increased precipitation and temperature fluctuations, the study emphasizes the importance of proactive planning and design measures. Using a detailed example of mudflow mitigation on a road embankment, the article shows the practical implementation of adaptation measures and illustrates the effectiveness of NBS solutions in overcoming specific challenges caused by climate change. Overall, the results emphasize the urgency of integrating climate change adaptation into geotechnical practice to increase the resilience of infrastructure and mitigate the risks posed by environmental change.

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