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Weathering impact on the long-term stability of weak rocks

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Abstract

Weathering processes and prolonged atmospheric exposure significantly impact the mechanical properties of weak metamorphic rocks, notably compromising their structural integrity and increasing the risk of slope failure. This comprehensive study examines the impact of weathering on schists and phyllites along the A2 motorway in Macedonia. Methodologically, the research integrates detailed field surveys and slope stability assessments to quantify changes in key geotechnical parameters, including uniaxial compressive strength, the geological strength index, and the material constant, as functions of exposure duration.

The results demonstrate significant deterioration in strength characteristics attributable to progressive mineral decomposition, fissuring, and disintegration driven by climatic factors. Empirical data indicate that slopes subjected to prolonged weathering exhibit a higher incidence of shallow landslides and surface instabilities, which strongly correlate with reductions in strength parameters. Graphical models illustrate the temporal progression of strength degradation, providing valuable insights for predictive stability assessments.

The findings underscore the need to incorporate weathering effects into geotechnical design, especially for infrastructure projects with long service lives on weak rock foundations. An empirical relationship between exposure time and strength degradation is proposed. Recommendations include continuous monitoring and the integration of degradation factors into slope stability analyses to effectively mitigate geohazard risks.

Keywords

Long-term Stability, Slope Stability, Strength Degradation, Weak Rocks, Weathering.

1 Introduction

The stability of slopes in rock masses, especially in low-quality rock masses, is directly related to weathering, which has a negative impact through reduction in shear strength, acceleration of decomposition (especially in surface zones), and the creation of tension cracks. The intensity of rock weathering and its geochemical alteration influence shallow landslide occurrence in weak metamorphic rocks, establishing a link between weathering degree and slope failure susceptibility (Silwal et al. 2024). Weathering has been demonstrated to weaken rock mass structure and decrease slope safety factors in long-term stability analyses. Although weathering effects play a crucial role in determining slope stability, few researchers have investigated the effects of weathering, and the traditional analysis methods either overlook these factors or oversimplify them (Liu et al. 2024). Therefore, the alteration, i.e., the decomposition of the rock masses over time, as a result of the negative atmospheric influence, in the surface zones of the slopes, in the zone of the joint walls, but also generally at the level of the massif, should be taken into account, especially in weak rock masses, which are susceptible to these unfavourable processes.

There have been a number of studies related to weathering and slope stability. Berisavljevic et al. 2018 investigate the weathering-induced failures of the heterogeneous fissile rock mass consisting of sandstone and shale and propose a model aimed at addressing the delayed failure of cuts. Recent research has specifically addressed the degradation of schist rock masses due to climatic weathering cycles. Experimental evidence shows that dry–wet and freeze–thaw cycles significantly reduce the mechanical strength and alter the microstructure of schists, leading to increased porosity and reduced bearing capacity, which directly impacts the long-term stability of rock slopes under environmental loading (Jin et al. 2025). Similarly, investigations into combined weathering cycles demonstrate that these processes accelerate deterioration and strength losses in schist, emphasising the need to incorporate weathering effects into predictive slope stability models (Gao et al. 2025). Zhang et al. 2025 emphasise that weathering coupled with rainfall infiltration in weak interlayer rock slopes alters failure mechanisms and expands instability zones, highlighting the need for comprehensive stability assessment and mitigation planning.

Based on the above considerations, several excavated slopes are selected to evaluate the long-term stability through stability analyses. The findings indicate that slopes subjected to prolonged weathering show higher incidences of shallow landslides and surface instabilities, which correlate strongly with reductions in UCS and GSI values. Graphical models were developed to illustrate the temporal trends of strength degradation, providing valuable insights for predictive assessments.

The study underscores the importance of incorporating weathering effects into geotechnical design, especially for long-term infrastructure projects situated on weak rock masses. Recommendations emphasise the necessity for ongoing monitoring, proactive stabilisation measures, and the integration of degradation factors into slope stability analyses to mitigate potential geohazards effectively.

2 General characteristics of the analysed slopes

The study area encompasses a part of the A2 highway, specifically the Kicevo–Ohrid section (Fig. 1), currently under construction. The geological composition predominantly includes low-metamorphic Palaeozoic rocks, with phyllite as the dominant lithology, along with graphitic schists and quartz-sericite schists.

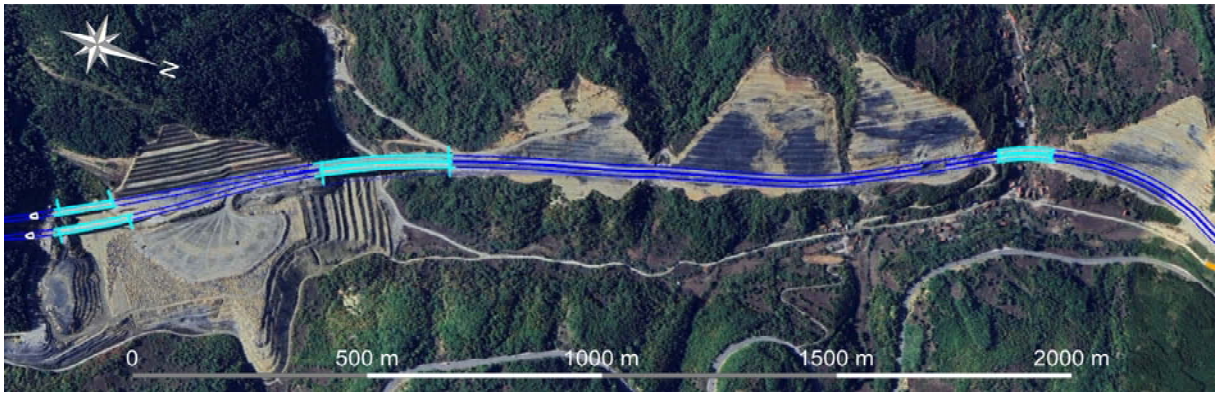


Fig. 1 Aerial view of a part of the A2 highway route, Section Kichevo–Ohrid.

The terrain is characterized by mountainous topography, which has historically experienced instability during construction phases. The rock masses are tectonically disturbed and susceptible to local instability, especially during prolonged or intense rainfall. During excavation, these rock masses are relatively solid, but after a certain time of exposure to atmospheric influence, they significantly lose their properties and soften, especially in the surface zones. Therefore, the assessment of slope stability must incorporate the progressive effects of weathering, especially in weak rock masses, to ensure long-term safety and performance. Given these site conditions, the methodology used to assess the slope stability is briefly explained.

3 Methodology

In this research, several cut slopes were selected (Fig. 2) which, after several months, processes of local instability started to appear with signs of intensification over time.



Fig. 2 Illustration of the selected slopes, demonstrating shallow failures primarily in surface zones attributable to weathering.

For each slope shown in Fig. 2asafety factor (Fs = 1,31–1,53) was calculated in the design phase, but after a certain period, instabilities and landslide processes were observed. Subsequent observations revealed progressive instability, attributed to reductions in shear strength and deformability due to atmospheric exposure.

The material properties adopted in the initial design stage correspond to moderately weathered rock-mass conditions identified during excavation. Laboratory testing and field rock mass classification were performed during the construction stage, before the development of significant atmospheric weathering effects on exposed slope surfaces. The rock masses were modelled using the generalized Hoek-Brown failure criterion. The Geological Strength Index (GSI) classification incorporated discontinuity conditions, blockiness, and surface conditions observed at the time of excavation. However, it did not explicitly account for long-term degradation caused by progressive weathering processes. Similarly, the laboratory uniaxial compressive strength (UCS) values were obtained from samples representing the intact-rock condition at the time of sampling, without accelerated-weathering treatment or durability testing. Therefore, the subsequent parameter reductions applied in the long-term stability analyses were intended to simulate the progressive deterioration of the exposed rock mass due to weathering effects occurring after excavation and prolonged atmospheric exposure. Namely, the UCS, GSI, and the material constant (m_i) are reduced to obtain the labile limit equilibrium at failure, i.e., Fs = 1,0. For simplification purposes and due to the limited availability of long-term degradation data, UCS, GSI, and m_i were reduced using the same proportional reduction factor to simulate progressive weathering-induced deterioration. This approach was adopted to evaluate the overall sensitivity of slope stability to weathering-induced degradation rather than to reproduce the exact deterioration mechanism of each parameter. The analysis incorporated the time elapsed since excavation, with the main parameters summarized inTable 1.

Table 1. Main characteristics of the analysed slopes and computed safety factors.

Slope ID	UCS [MPa]	GSI	m_i	Exposure to weathering	Sliding depth	Fs	Reduction to Fs = 1,0 [%]
a	5	17	5	12 months	2,5 m	1,34	17,9
b	10	23	6	22 months	3,0 m	1,43	21,8
c	4	17	5	14 months	3,0 m	1,31	17,5
d	12	27	6	17 months	5,5 m	1,46	20,1
e	15	30	7	8 months	2,5 m	1,34	14,7
f	10	25	6	11 months	3,5 m	1,31	17,1
g	8	23	6	5 months	4,5 m	1,33	15,2
h	3,5	15	5	26 months	2,0 m	1,53	23,2

The results indicate that in susceptible rock masses, strength parameters decrease progressively with increased exposure duration, leading to a corresponding decline in safety factors. Slopes with longer exposure times, such as slopes “b” and “h,” exhibited higher initial safety factors but also experienced greater percentage reductions, highlighting the significant weakening due to weathering.

These results indicate significant weakening of the slopes over time due to weathering. This is consistent with studies showing that weathering processes reduce rock strength and lower slope stability. These findings underscore the necessity of considering time-dependent strength degradation in long-term slope stability assessments, especially in weak, weathering-prone rocks.

4 Results

The graphical display of the dependence between the value of the safety factor and the exposure time of the slopes to atmospheric influences is shown in Fig. 3, and the dependence between the percentage reduction of the UCS, GSI, and m_i, concerning the exposure time, is shown in Fig. 4.Fig. 3 depicts the relationship between safety factor and exposure time, illustrating a clear downward trend as exposure increases. Fig. 4 presents the percentage reduction of key parameters (UCS, GSI, mi) as functions of exposure duration, highlighting the progressive weakening of rock masses due to weathering. The trend lines suggest that the strength degradation can be approximated by empirical equations, facilitating predictive modeling of long-term stability. It should be emphasized that the adopted reduction factors represent post-excavation degradation effects and are therefore additional to the initial geotechnical characterization performed during the design stage.

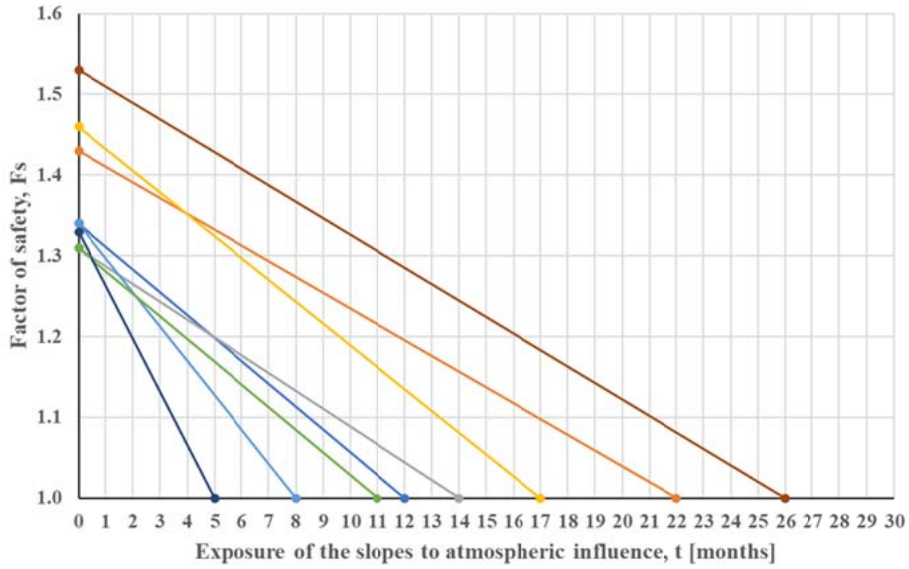


Fig. 3 Graphical dependence between the safety factor and the exposure time of the analysed cuts.

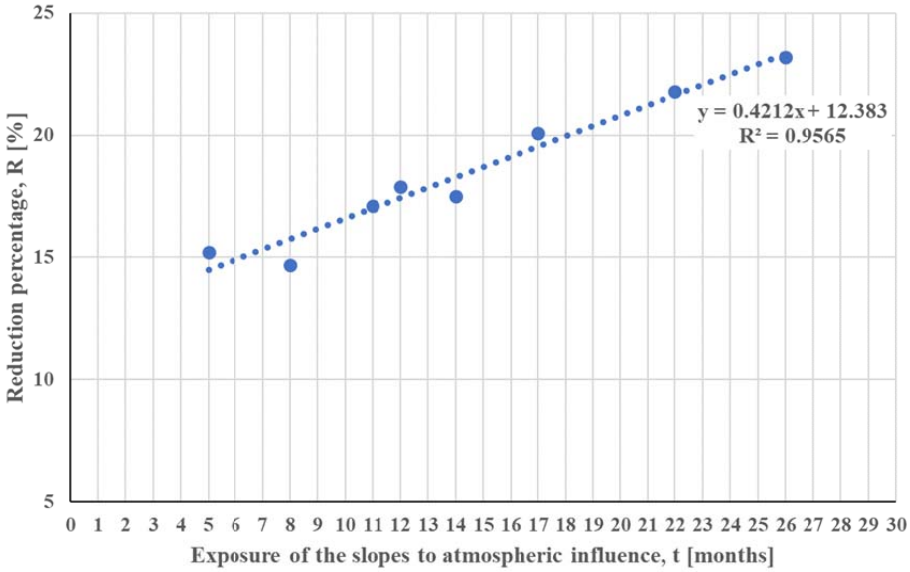


Fig. 4 Graphical dependence between the exposure time and the reduction percentage of the parameters (UCS, GSI, and m_i).

Based on these empirical trends, an equation (see Eq. 1) is obtained by linear regression of the empirical data shown in Fig. 4 to estimate the reduction factor (R) as a function of exposure time in months (t), providing a practical tool for long-term stability assessments and design considerations.

$$R = 0.4t + 12.4 \quad (1)$$

5 Conclusions

Prolonged weathering significantly diminishes the shear strength of weak rock slopes, accelerating surface degradation and increasing the likelihood of shallow failures. The rate of strength reduction correlates strongly with exposure duration, emphasizing the importance of long-term monitoring and adaptive design strategies. Analyses indicate that safety factors decrease over time under constant geometrical conditions, necessitating the incorporation of time-dependent weakening models into slope stability evaluations. The use of conservative strength parameters or empirical reduction equations is recommended to ensure long-term safety. The findings advocate for the revision of geotechnical design standards to explicitly account for aging and weathering effects. Future research should focus on advanced monitoring techniques and the development of predictive weathering models to improve the reliability of long-term slope stability assessments in weak rock environments.

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