DOI: https://doi.org/10.68732/ab28790c7bc72c44

ISBN: 978-9989-2053-7-8

Failure Mechanism of Symbiotic Slope of Carbonaceous Phyllite and Graphite Schist

Guanya Xiang[1], Ning Nan[2], Chuanke Xu[1], Junyong Liu[2], Weiwei Su[2] & Bo Wang[2]

1. Sinohydro Bureau Co., Ltd. International Engineering Corporation, Chengdu, China;
2.China Communications First Highway Survey and Design Institute Co., Ltd.; National Key Laboratory of Green and Long-lasting Road Engineering in Extreme Environments, Xi'an, China;
983314524@qq.com

Abstract

Along the Kičevo-Ohrid Highway in North Macedonia, completely to strongly weathered carbonaceous phyllite and strongly weathered graphitic schist are widely distributed. Under the disturbances of rainfall and engineering excavation, slope failures occur frequently, severely restricting the construction and operation safety of the project.

Taking a typical landslide along this highway as the research object, this study systematically investigates the failure mechanism of the symbiotic slope of carbonaceous phyllite and graphitic schist by means of engineering geological survey, borehole exploration, deep displacement monitoring, and laboratory and field tests.

The results show that the landslide exhibits a typical complex structure of "interbedded soft and hard layers with soil-rock coexistence". The completely to strongly weathered carbonaceous phyllite is soil-like and highly water-sensitive, while the graphitic schist has smooth foliation surfaces with extremely low friction angles. The landslide develops shallow and deep shear zones. The shallow shear zone is located at the lithological boundary between phyllite and graphitic schist. The deep deformation zone is located within the fractured zone of the graphitic schist, exhibiting evidence of distributed shear and bending deformation, and plays a dominant role in controlling the overall stability of the landslide. The failure mechanism is characterized as a progressive composite failure mode of "shallow sliding zone traction and deep sliding zone control", with rainfall infiltration and engineering excavation unloading being the main inducing factors.

Keywords

Carbonaceous Phyllite, Graphite Schist, Composite Shear Zone, Progressive Failure, Landslide Mechanism.

1 Introduction

With the deepening of the "Belt and Road" initiative, China and Central and Eastern European countries have increasingly close cooperation in transportation infrastructure. The construction of the Kičevo-Ohrid highway in North Macedonia is of great strategic significance for improving the pan-European transportation network (Stanev S et al. 2025). However, this highway, which runs through a complex geological environment, encountered severe slope geological disasters caused by carbonaceous metamorphic rocks during its construction. Among them, the symbiotic slope landslides composed of fully to strongly weathered carbonaceous phyllite and strongly weathered graphite schist are the most representative, becoming the core geological problem restricting the progress of the project and the safety of operation.

The main body of the landslide in the study area is composed of two types of rocks: carbonaceous phyllite is mostly in a state of complete to strong weathering, the original rock structure is basically destroyed, and it has become soil-like in macroscopic terms, showing extremely strong water sensitivity and disintegration (Deng Tao 2022; Liang Zongji 2023; Liu Li 2021); graphite schist is rich in scaly graphite, with smooth foliation surfaces and extremely low friction angles (Brideau M et al. 2009), and has relatively strong resistance to weathering. It still retains the original rock foliation characteristics and constitutes the potential sliding control surface of the slope. The two are interlayered or transitional in space, forming a unique complex slope of "interspersed soft and hard, with soil and rock coexisting". During the infiltration of rainfall, the weathered layer of the overlying phyllite is saturated and softened, and its strength is reduced (Dong Jiao 2013; Cai Guojun M et al. 2021). The infiltrated water accumulates on the top surface of the graphite schist and softens its foliation surface, triggering a composite failure mode of "overlying soil displacement + underlying rock layer creep along the bedding plane" (Zheng Bin 2015). Field investigations show that this type of landslide often exhibits progressive failure characteristics. In the early stage, the slope top is mainly cracked and the slope foot is bulged. In the later stage, it slides rapidly under the stimulation of rainfall, combining the arc sliding characteristics of soil slopes and the bedding sliding characteristics of rock slopes. Traditional stability analysis methods based on a single failure mode are difficult to accurately evaluate (Ni Wenjuan 2017; Janevski B et al.2021).

In view of this, this paper takes this type of slope along the Kičevo-Ohrid highway as the research object systematically analyzes their material composition and physical and mechanical properties, deeply reveals the landslide evolution mechanism under the control of weathering differences, in order to provide theoretical basis and engineering reference for the prevention and control of similar geological disasters in the Balkans.

2 Overview of the study area and slope survey

The Kičevo-Ohrid Highway, located in western North Macedonia, is an important component of the Pan-European Corridor 8, with a total length of 56.6 kilometers. The region has a Mediterranean continental climate, with annual precipitation of 700-1000 mm, concentrated in winter and spring. The terrain is part of the southern extension of the Dinara Mountains, characterized by alternating mountain ranges and valleys with significant topographic relief. The exposed strata along the route are primarily Paleozoic-Mesozoic regional metamorphic rocks, mainly carbonaceous phyllite and graphite schist, which are spatially interbedded or transitional, forming a binary structure of "soil-rock coexistence." The region is experiencing active neotectonic activity and strong seismic activity; a magnitude 6.5 earthquake has occurred in nearby areas, and the basic seismic intensity is VII. Groundwater is mainly composed of bedrock fissure water and weathered pore water, replenished by atmospheric precipitation. It tends to accumulate on the top surface of the graphite schist, forming weak zones and being a significant contributing factor to slope instability. To further reveal the disaster-causing pattern and evolution law of this type of landslide, a typical unstable slope section K4+830-K5+160 was selected for in-depth analysis, and its deformation characteristics, instability mechanism, stability evaluation and treatment strategies were systematically explained (see Fig. 1).

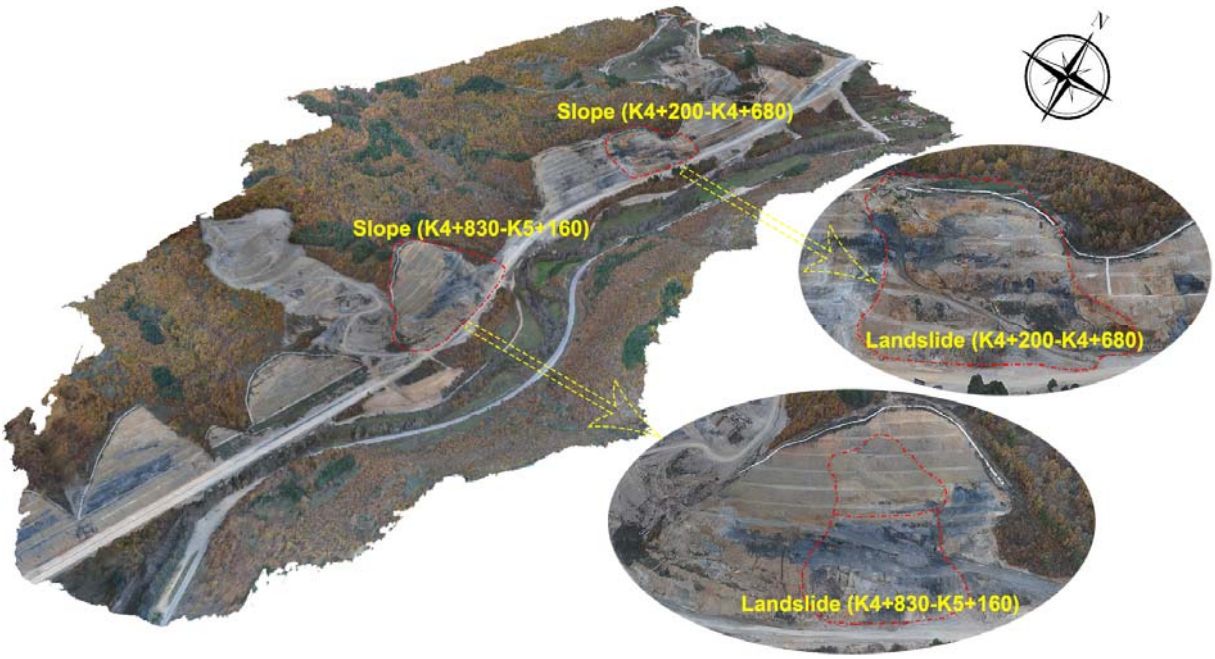


Fig. 1 Aerial view of the slope along the section from K4+000 to K6+000 in the study area.

3 Landslide characteristics and instability mechanisms

3.1 Landslide Types and Morphological Characteristics

The landslide is nearly horseshoe-shaped with a well-defined boundary. Cracks on both sides have connected and undergone displacement. The shear outlet is located at the contact between strongly weathered phyllite and strongly weathered graphite schist in the middle of the slope. Local water seepage is observed on the slope surface, indicating a typical failure mode of "overlying soil displacement + underlying rock layer creep". The leading edge of the landslide is approximately 106 m wide, 92 m long, and 2–17 m thick, with an average thickness of about 10 m. The landslide volume is approximately 7.9×10^4 m^3, classifying it as a medium-sized landslide, with a slope aspect of 91°. The rear edge of the landslide is arcuate in shape, with a maximum elevation difference of about 0.5 m, located on the slope platform at an elevation of 811 m (see Fig. 2(a-d)). The shear outlet is located at an elevation of 774 m on the middle part of the slope, where water seepage is observed near the outlet (see Fig. 2(e-g)). After the slope cracked, the lower three benches of the slope had not yet been excavated. However, since the highway alignment has been finalized, further excavation down to the designed road elevation is required, which will likely lead to further expansion of the landslide. Meanwhile, field investigations revealed numerous seepage points on the unexcavated slope below (see Fig. 2 (h~k)), strongly suggesting the presence of potential weak sliding zones and posing a risk of deep-seated sliding. For the purpose of distinguishing between the two types of sliding zones in this study, the sliding zone with its shear outlet located in the middle of the slope is referred to as the shallow shear zone, while the sliding zone with its shear outlet located at the slope toe is referred to as the deep deformation zone.

3.2 Analysis of landslide elements

3.2.1 Sliding Soil

To investigate the stratigraphic structure and deformation zone distribution of the landslide, an engineering geological profile (1-1′) was established along the main sliding direction. This profile is based on three control boreholes: BH08, BH09, and BH10 (Gjorgjevski H et al. 2025). The strata revealed by the profile mainly consist of landslide materials and underlying bedrock. In borehole BH08, the boundary between phyllite and graphite schist is located at 11.8 m. In the 11.8–12.5 m section, the graphite schist is severely weathered, with the core sample being blocky and relatively fragmented. In the 15.2–15.5 m and 16.3–16.5 m sections, the core sample consists of highly fractured rock debris that easily disintegrates into mud upon water immersion. In borehole BH09, the stratigraphic boundary between phyllite and graphite schist is located at 8.5 m. Below this, multiple zones of highly fractured rock debris are developed within the graphite schist, located at 14.0–14.4 m,

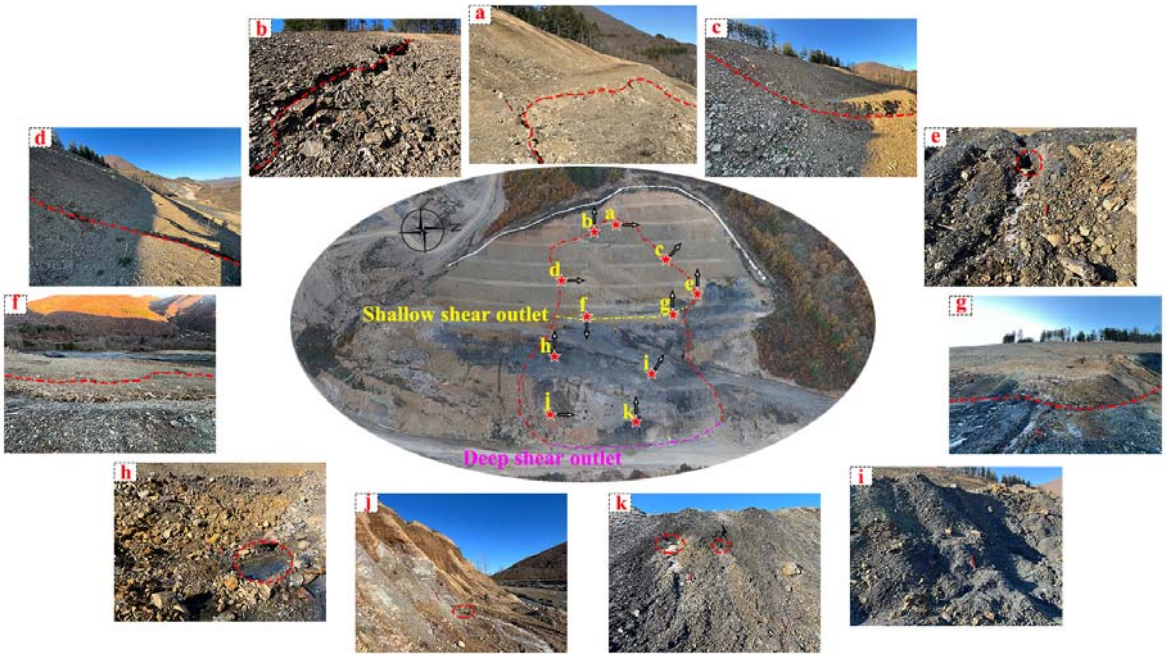


Fig. 2 Panoramic and detailed view of the landslide section K4+830~K5+160: (a) Crack at the rear edge of the top; (b) Crack at the rear edge of the south side; (c) Crack at the rear edge of the north side; (d) Crack at the southern side edge; (e) Seepage point; (f) Shear outlet on the south side; (g) Shear outlet on the north side; (h) Spring; (i) Seepage point on the slope surface; (j) Seepage point on the south side of the slope toe; (k) Seepage point on the north side of the slope toe; Arrows indicate mirror direction.

14.7–15.0 m, 17.5–17.7 m, 19.5–21.0 m respectively. The core samples are highly fractured and rock debris-like, with a structurally fragmented texture. In borehole BH10, the 0–5 m section consists of miscellaneous fill accumulated from the previous construction access road. The 6–9 m section is dominated by fully to strongly weathered graphite schist. The core samples from 9 m to 12.8 m are relatively intact, with the 10–10.3 m section being highly fractured rock debris with a fragmented structure. Below 12.8 m, the core samples are blocky and fragmented. No obvious phyllite overburden is observed in this borehole. The stratigraphic characteristics revealed by these boreholes reflect the spatial variability of lithological assemblage and weathering degree in the landslide area (see Fig. 3).

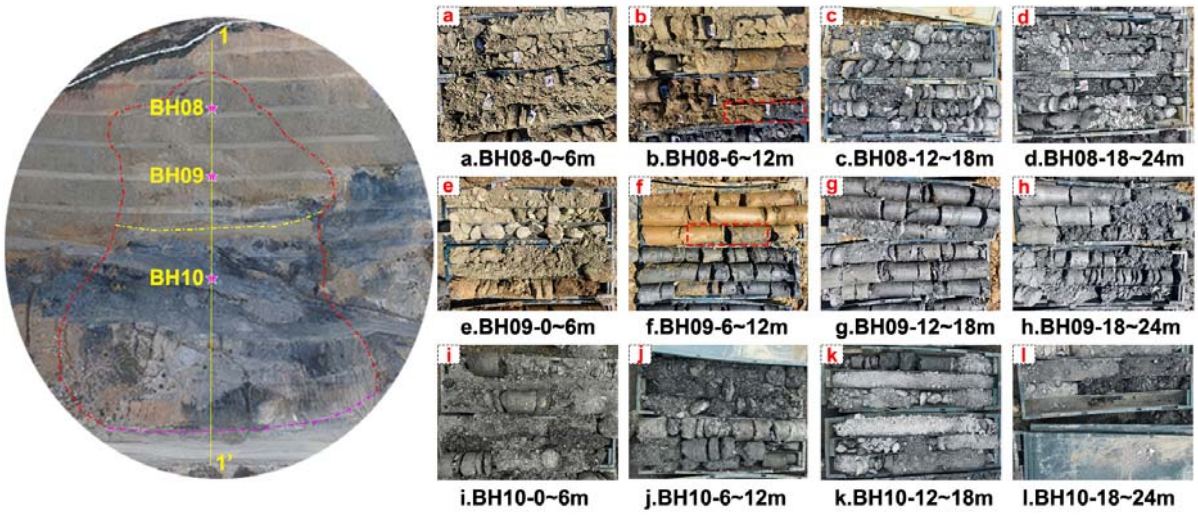


Fig. 3 Engineering exploration points and core photographs.

3.2.2 Sliding Zone

The locations of displacement concentration zones are mainly determined by comprehensively considering factors such as lithological abrupt change interfaces, fracture zone development characteristics, core integrity variations, and the development of weak interlayers. According to drilling results, a shallow shear zone in borehole BH08 is identified at 11.8 m, which marks the boundary between completely to strongly weathered phyllite and the underlying strongly weathered graphite schist. In borehole BH09, a similar shallow shear zone is identified at 8.5 m, also at a

lithological abrupt change interface between phyllite and graphite schist. These shallow zones represent potential sliding interfaces between the landslide body and the underlying stable strata. Deep deformation zones are mainly determined by the depth of fractured zones within the graphite schist and the characteristics of weak interlayers. In borehole BH08, a deep shear zone may be located within the 15.2–15.5 m and 16.3–16.5 m sections, consisting of highly fractured rock debris that easily disintegrates into mud upon water immersion, exhibiting extremely low shear strength. Borehole BH09 contains multiple highly fractured zones distributed between 14.0 m and 21.0 m (at depths of 14.0–14.4 m, 14.7–15.0 m, 17.5–17.7 m, and 19.5–21.0 m), making it difficult to pinpoint a single depth. In borehole BH10, a deep shear zone may be located within the 10–10.3 m highly fractured rock debris interlayer. All of these deep zones are situated within graphite schist, and their fractured, mud-prone characteristics indicate significant shear deformation.

To accurately identify the distribution of potential displacement concentration zones, deep displacement monitoring was performed in boreholes BH09 and BH10 on three dates (June 13, June 19, and July 4, 2025) (see Fig. 4). BH10 data were discarded due to external interference. The monitoring curves from BH09 show a first displacement offset at 7.5–9.5 m depth, with a maximum displacement of approximately +0.6 mm at 8.5 m. This depth corresponds to the lithological transition between phyllite and graphite schist, exhibiting small displacement and weak activity. This zone is interpreted as a shallow shear zone. Within the depth range of 17.0–26.6 m, the curve exhibits complex deformation features. A main shear zone is identified between 17.0 and 18.5 m, with a peak displacement of +2.2 mm at 17.5 m. Below this, from 22.0 to 26.6 m, an S-shaped shear zone is developed, characterized by alternating positive and negative displacements (from +2.2 mm to -2.2 mm and back). The interval between 18.5 and 22.0 m shows negligible displacement, separating the two shear zones. This pattern indicates distributed shear deformation rather than a single slip surface. Based on borehole lithology (fractured graphite schist with well-developed foliation) and the slope structure (shear outlet at the toe), these two zones are collectively interpreted as a deep deformation zone, accommodating multi-level shear and possible bending or buckling of rock layers. The peak displacement at 17.5 m marks the most active part of this zone. Below 26.6 m, minor fluctuations are considered stable.

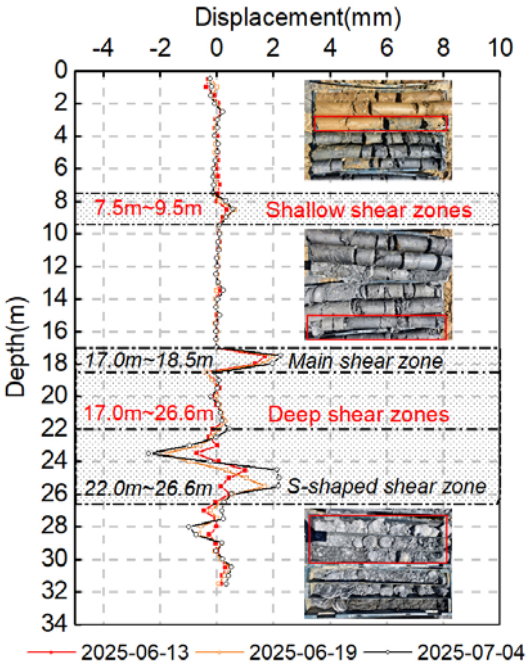


Fig. 4 Line graph of deep displacement monitoring of BH09.

3.3 Analysis of Landslide Instability Mechanism

Based on the comprehensive drilling results, deep displacement monitoring, and soil and rock strength parameter test results, the instability mechanism of this landslide is mainly characterized by progressive composite failure involving shallow and deep shear zones. Its formation and evolution are influenced by the coupling of multiple factors such as lithological combination, weathering differences, groundwater action, and engineering disturbance.

(1) Lithological combination and weathering differences provide the material basis for landslide formation

The study area is characterized by widespread coexistence of carbonaceous phyllite and graphite schist. The carbonaceous phyllite, after complete to strong weathering, becomes earthy, exhibiting strong water sensitivity and disintegration, and constitutes the main material of the landslide body. The graphite schist, rich in scaly graphite, has smooth foliation surfaces, extremely low friction angles, and relatively strong resistance to weathering, forming a potential sliding control surface for the slope. Spatially, the two rock types are interbedded or transitional, forming a unique complex slope of "alternating soft and hard rock, soil-rock coexistence," which provides material conditions for the development of shallow and deep shear zones.

(2) Rainfall infiltration is a key triggering factor for landslide instability

The study area receives 700–1000 mm of annual precipitation, concentrated in winter and spring. During rainfall infiltration, the overlying weathered phyllite layer becomes saturated and its strength decreases; infiltrating water accumulates on the top surface of the graphite schist, softening the foliation surfaces and lubricating the graphite minerals, significantly reducing the shear strength of the shear zones. Shallow shear zones, located at lithological interfaces, are significantly affected by groundwater infiltration, but the overlying mass thickness is relatively small, resulting in limited displacement. Deep deformation zones, located in groundwater-rich areas, remain constantly moist, exhibiting a significant graphite lubrication effect, larger displacement, and greater activity.

(3) Engineering excavation and stress release accelerated landslide evolution

During highway construction, more than 50 deep-cut slopes were designed. The slope ratio adopted for the initial excavation was 1:0.2, which is relatively steep. Excavation and unloading led to stress redistribution in the slope, with stress concentration at the slope toe causing shear deformation and opening of internal structural surfaces, providing preferential pathways for rainfall infiltration. Although subsequent slope reduction treatments were implemented in some sections, they failed to completely block groundwater infiltration, and the slopes continued to experience creep deformation.

(4) Progressive failure mode involving shallow and deep shear zones

The landslide instability manifests as a progressive, composite failure mode characterized by traction of the shallow shear zone and dominant movement of the deep deformation zone. Initially, shallow shear zone activity dominated, with cracking at the slope crest and bulging at the slope toe, resulting in relatively small displacement. As rainfall continued to infiltrate, groundwater penetrated deeper, intensifying the softening of fractured zones within the graphite schist. This gradually activated the deep deformation zone, which then became the dominant feature controlling slope deformation. Once the deep deformation zone fully developed, overall stability decreased sharply, leading to complete landslide failure under continuous rainfall or engineering disturbance. Deep displacement monitoring curves showed that the shallow shear zone (at ~8.5 m depth) had a cumulative displacement of 0.6 mm, while the deep deformation zone (within 17.0–26.6 m depth, peak at 17.5 m) had a cumulative displacement of 2.2 mm. The significantly larger displacement of the deep deformation zone confirms its dominant role in the overall stability of the landslide.

4 Conclusion

(1) The landslide in the study area exhibits a typical complex structure characterized by "interbedded soft and hard layers with soil-rock coexistence". The completely to strongly weathered carbonaceous phyllite is soil-like and highly water-sensitive with strong disintegration characteristics. The graphitic schist is rich in flaky graphite, with smooth foliation surfaces and extremely low residual friction angles. The two rock types are interbedded or transitional in space, forming the material basis for landslide development.

(2) The landslide develops shallow and deep shear zones. The shallow shear zone is located at the lithological boundary between phyllite and graphitic schist, exhibiting relatively weak activity. The deep deformation zone is located within the fractured zone of the graphitic schist (approximately 17–27 m in depth), showing large displacement and strong activity, and plays a dominant role in the overall stability of the landslide. The accuracy of these interpreted zones is verified by deep displacement monitoring.

(3) The failure mechanism of the landslide is characterized as a progressive composite failure mode involving shallow shear zone traction and deep deformation zone dominated movement. Rainfall infiltration leads to saturation and softening of the weathered phyllite layer, reducing its strength. The infiltrating water accumulates at the top of the graphitic schist, softening the foliation surfaces and triggering a coupled failure of overlying soil thrusting and underlying rock bedding creep. Engineering excavation and unloading further accelerate the deformation and evolution of the slope.

References

Brideau M, Yan M, Stead D (2009) The role of tectonic damage and brittle rock fracture in the development of large rock slope failures[J]. Geomorphology, 103(1):30-49. DOI: 10.1016/j.tecto.2013.04.029

Dong Jiao (2013) Research on the formation mechanism and prevention and control strategies of landslides in phyllite mass in southeastern Yunnan [D]. Kunming University of Science and Technology

Zheng Bin (2015) Study on the failure mechanism of bedding-parallel phyllite slope in Qinba Mountain Area [D]. Chang'an University

Cai Guojun, Cheng Yuhang, Zhong Chuang, et al (2021) Experimental analysis of softening effect of phyllite under water saturation state [J]. Science Technology and Engineering, 21(08):3032-3038

Janevski B, Jovanovski M (2021) Stability evaluation of cut slopes in highly weathered schists using limit equilibrium, kinematical and empirical methods[J]. IOP Conference Series: Earth and Environmental Science, 833(1):12006. DOI: 10.1088/1755-1315/833/1/012006

Liu, Li (2021) Strength characteristics of completely weathered phyllite soil in Longsheng, Guilin [D]. Guilin University of Technology

Deng Tao (2022) Study on the structure and shear strength characteristics of fully weathered phyllite under reservoir immersion [D]. Chengdu University of Technology

Liang Zongji (2023) Shear strength and slope stability analysis of phyllite residual soil [D]. Guilin University of Technology

Stanev S, Penchev P(2025) Challenges for the Implementation of the Pan-European Corridor No. 8: Proceedings Of The International Conference On Business Excellence[Z]. 19th International Conference on Business Excellence (ICBE) - Leading Change in Disruptive Times, 19, 1798-1807. DOI:10.2478/picbe-2025-0139

Gjorgjevski H, Veljanovski B, Miloshevikj A, et al (2015) Factual report for performed geotechnical investigations and tests at cut km4+830 - km5+160, section 4, Kičevo-Ohrid motorway (Technical No. 78/25). GEOING MK Doo., Skopje, North Macedonia