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Landslide behavior interpretation based on inclinometer and surface monitoring at cut & cover 6, Railway corridor 8

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Abstract

A landslide affecting the Cut & Cover 6 (Tunnel 6) section of Railway Corridor VIII (Beljakovce–Kriva Palanka, North Macedonia) represents a critical geotechnical hazard due to the presence of highly weathered andesitic tuffs and a previously identified large fossil landslide. Although initial failures during excavation were local, construction activities posed a significant risk of reactivation, necessitating systematic monitoring of both subsurface and surface displacements. A comprehensive landslide monitoring program was implemented, combining inclinometer measurements and geodetic surveying of surface benchmarks. An inclinometer casing was installed in a strategically positioned borehole within the potential sliding zone, enabling long-term monitoring of subsurface deformations and identification of active shear horizons. Periodic inclinometer readings provided insight into displacement magnitude, depth, and temporal trends, supporting assessment of landslide activity state during excavation and stabilization works. In parallel, surface movements were monitored using precisely surveyed benchmarks, allowing detection of horizontal and vertical displacements of the slope and correlation with subsurface behavior. The integration of inclinometer data with geodetic measurements proved essential for distinguishing between local excavation-induced movements and potential reactivation of the larger fossil landslide. The monitoring results formed a key basis for design decisions, verification of slope stability analyses, and timely adaptation of temporary support measures. This case study highlights the importance of integrated landslide monitoring systems in complex geological settings, particularly for alignment infrastructure projects where construction activities may alter pre-existing marginally stable conditions.

Keywords

Cut and cover structure, Paleo landslide, Monitoring, Inclinometer, Geodetic surveying.

1 Introduction

Landslides represent one of the most significant geohazards affecting infrastructure development, particularly in mountainous regions where geological and geomorphological conditions often predispose slopes to instability. Linear infrastructure projects (alignments) frequently require extensive excavation works that may disturb the slopes natural equilibrium and potentially trigger or reactivate landslides.

Geotechnical monitoring is widely applied for risk management in landslide-prone areas. Monitoring systems enable early detection of ground movements and evaluation of slope behaviour. Common techniques include subsurface displacement monitoring using inclinometers and surface deformation monitoring through geodetic surveys. The integration of these techniques allows a comprehensive understanding of slope deformation mechanisms by deep-seated and surface movements.

This paper presents the interpretation of geotechnical monitoring results obtained at the Cut & Cover 6 (Tunnel 6) site along the Beljakovce – Kriva Palanka railway section. The monitoring system included inclinometer measurements within a borehole located in the potentially unstable zone and geodetic surveying of surface benchmarks positioned across the slope. The study focuses on the analysis of inclinometer and geodetic monitoring data to evaluate slope behaviour, identify active shear zones, and assess the influence of excavation works on landslide activity.

2 Project location and geological setting

2.1 Project overview

Railway Corridor (RC) VIII is a strategic infrastructure project connecting the Adriatic and Black Sea regions through Albania, N. Macedonia, and Bulgaria. The section between Beljakovce and Kriva Palanka is the second section (LOT2) of the Eastern part of RC VIII and follows the valley Kriva River with 34 km in length. The project consists of many half-constructed structures and cut sections. The first construction stage has been started in 1996 and continued until 2004, when the project was suspended. In this period most of the earthwork studies, some tunnels and some bridges have been completed. A new design stage has been performed in 2016 for the remaining studies of the project and later the second construction stage has been started in 2023.

The study area corresponds to the location of Cut & Cover 6 (Tunnel 6), constructed using the cut-and-cover method, which involves excavation followed by construction of the tunnel structure and subsequent backfilling. This construction technique requires extensive excavation of slopes along the tunnel alignment, potentially disturbing the natural stability of the surrounding terrain.

The most significant aspect of the terrain morphology in this area is the occurrence of local slope failures at the cut, which was partially excavated during the previous phases of railway construction. Furthermore, earlier geological investigations conducted for the preparation of the Engineering–Geological (EG) Map of Macedonia (1977; scale 1:200,000) identified the presence of a large paleo-landslide affecting the area, indicating that the slope had undergone past mass movement processes. Field observations confirmed that the landslide is currently fossil (inactive).



Fig. 1 Location of the study area (LOT2).

2.2 Geological and geotechnical conditions

The investigated area is located within the *Kratovo–Zletovo volcanic region*, which is characterized by extensive volcanic formations composed mainly of andesitic rocks and associated pyroclastic deposits (Petrusev et al. 2021). Engineering-geological investigations performed at the site included geological mapping, drilling of investigation boreholes, laboratory testing of taken samples, and detailed geological logging of the extracted cores. The geological structure of the site is dominated by andesitic tuffs, which represent the base of the younger effusive volcanic complex in this region. These rocks occur in various stages of weathering and alteration and form the main geotechnical unit within the slope. Based on field observations and borehole investigations, the following lithological units were identified:

Diluvial deposits (PG_d): the ground surface is covered by a relatively thin layer of recent diluvial deposits. These deposits consist predominantly of clayey and sandy materials with occasional fragments of volcanic rock. Their thickness is generally limited and does not exceed 2 m.

Andesitic tuff (θ): the underlying bedrock is represented by andesitic tuff. Fresh andesitic tuff occurs as a relatively strong and compact rock mass characterized by massive or thickly bedded structure and relatively low fracturing intensity.

Weathered and altered andesitic tuff (θ'): in most parts of the investigated terrain the andesitic tuff is significantly weathered and altered. Depending on the degree of alteration, several transitional materials were identified ranging from partially weathered rock to soil-like materials. These materials commonly appear as clayey sand, silty sand, or clayey gravel containing fragments of andesitic tuff. Such materials exhibit transitional characteristics between hard soils and soft rocks, and their mechanical properties vary significantly depending on the degree of weathering.

Andesitic breccias (Θ): at greater depths, particularly in some investigation boreholes, andesitic breccia was encountered. This rock is composed of angular andesite fragments embedded within a volcanogenic cementing matrix. The rock fragments typically have sizes between several centimetres and are strongly bound.

Field investigations indicate that weathered andesitic tuffs dominate the slope profile, forming a relatively thick zone of soil-like material above the less weathered rock mass. This weathered material exhibits reduced mechanical strength and is particularly susceptible to deformation when subjected to changes in stress conditions or increased moisture content. Such geological conditions represent an important factor contributing to slope instability in the investigated area.

3 Landslide monitoring program

In order to evaluate the stability of the slope and detect potential landslide reactivation, an integrated monitoring program was implemented, which included: subsurface displacement monitoring using inclinometer measurements, and surface displacement monitoring using geodetic surveying of benchmarks. The combination of these monitoring techniques allows for a comprehensive understanding of landslide behaviour by correlating subsurface shear movements with surface deformation patterns.

3.1 Inclinometer monitoring

Subsurface deformation monitoring was carried out using an inclinometer installed in borehole TN06-BH03i located within the suspected sliding zone (Figure 2). The inclinometer system used for the monitoring was the Digitilt AT inclinometer system, which measures changes in the inclination of the borehole casing to determine lateral ground displacements. The inclinometer probe contains two tilt sensors oriented orthogonally, allowing measurements in two perpendicular directions. Measurements were performed at regular intervals of 0.5 m along the borehole depth. The monitoring program began with an initial reference measurement in June 2023. Subsequent measurements were carried out periodically from November 2023 to December 2024 in order to capture displacement trends during the excavation period.

Data obtained from inclinometer measurements were processed using specialized software that generates several types of plots used for interpretation. These plots enable identification of active shear zones, evaluation of displacement magnitude, and analysis of temporal trends in slope movement.

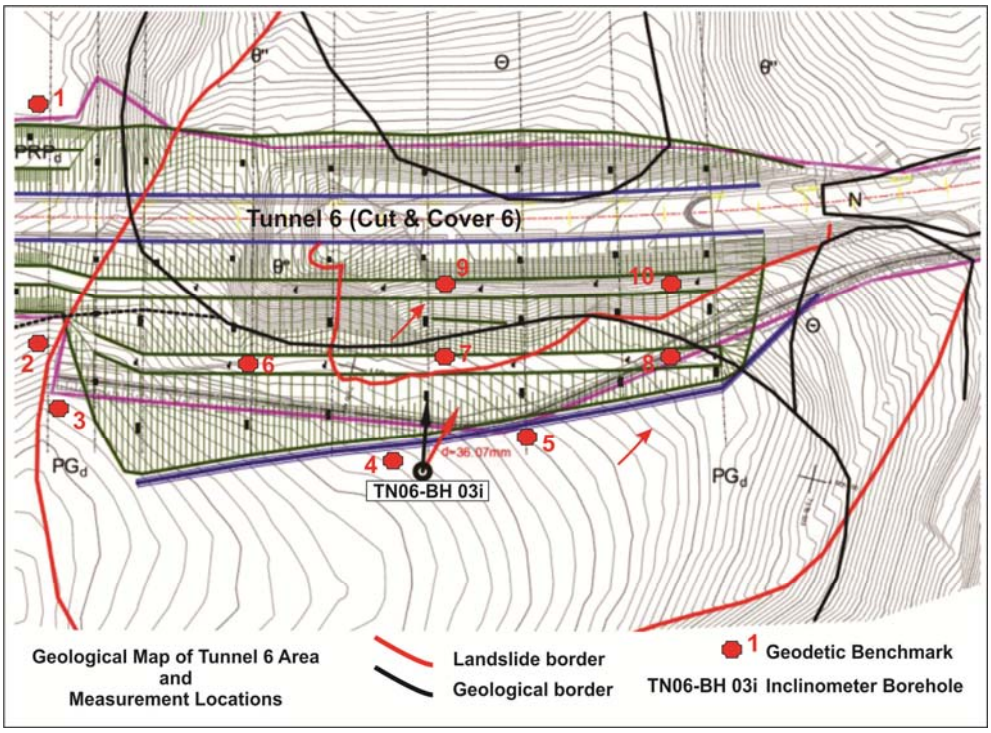


Fig. 2 Geological map of the study area and location of inclinometer borehole TN06-BH03i (red lines represents mass movements, black arrow shows A0, red arrow shows movement directions).

3.2 Surface displacement monitoring

Surface displacements were monitored using a geodetic surveying system based on precisely measured benchmarks installed across the slope and along the tunnel excavation area (see Figure 2). Measurements were conducted periodically using high-precision total station equipment, enabling detection of both horizontal and vertical displacements of the ground surface.

Monitoring of the upper slope section, where the landslide mass was identified, commenced in March 2024 following completion of the excavation stage. In the lower chainage section, characterized by solid andesitic rock mass, monitoring began in September 2024 after excavation works had been completed.

4 Monitoring results

4.1 Inclinometer results

The analysis of inclinometer data revealed the presence of two distinct zones of deformation within the monitored borehole. The first and most significant shear zone is located at a depth of approximately 14–14.5 m (Figure 3). This zone represents the main sliding surface of the landslide. Cumulative displacements measured at this depth reached approximately 32.6 mm in the primary movement direction (A) and about 15.5 mm in the perpendicular direction (B) during the monitoring period.

A second zone of deformation was detected at approximately 7.0 m depth. This shallower shear zone developed during the excavation phase and shows cumulative displacements of approximately 36.0 mm in direction A,while no significant movement was detected in direction B. This indicates that the deformation is directly related to excavation.

The displacement vectors are predominantly aligned with the natural slope direction, indicating movement toward the excavation area. Temporal analysis shows that displacement rates increased following intensive excavation works initiated in early 2024, whereas previous movements were negligible and likely represented background deformation within the fossil landslide mass.

The average displacement rate during the monitoring period was approximately 3 mm/month, classifying the landslide as very slow according to the classification proposed by Cruden and Varnes 1996. Polar analysis of displacement vectors also indicates a slight change in movement direction during the monitoring period, from predominantly eastward to northeastward movement, likely caused by progressive excavation and modification of slope geometry.

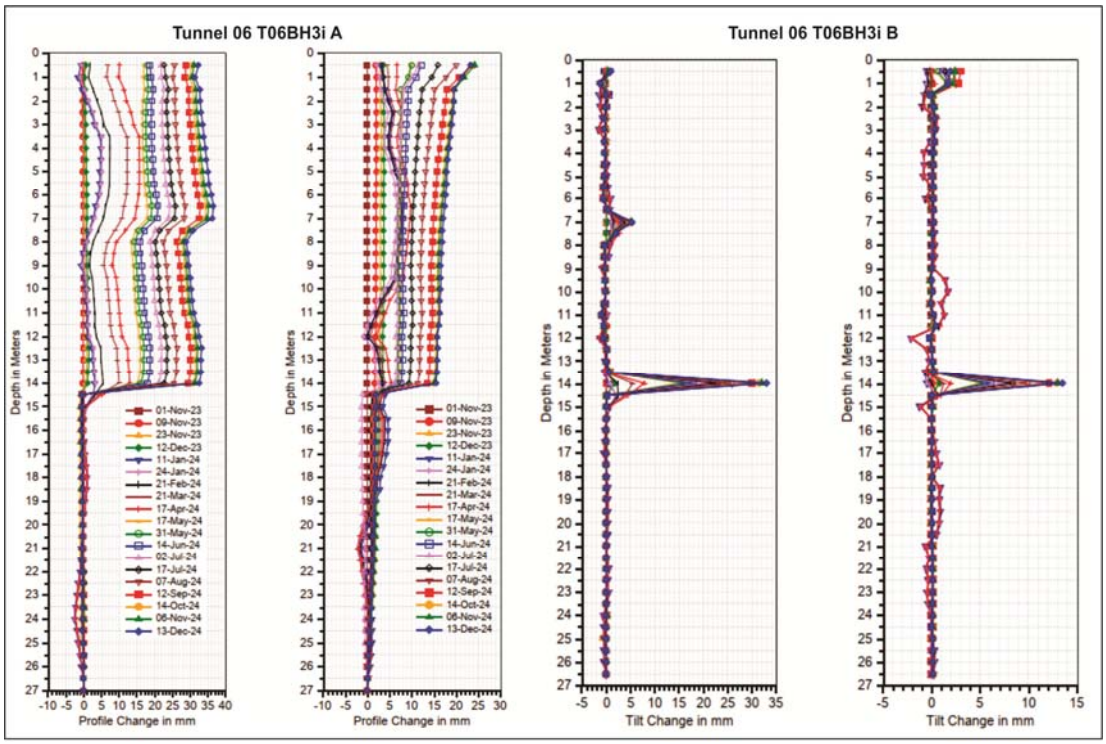


Fig. 3 Inclinometer measurement graphics, cumulative displacement (left) and incremental displacement (right).

4.2 Surface displacement results

Surface monitoring results confirm the general displacement trends observed in the inclinometer data. Benchmarks located on the slope above the excavation area show gradual horizontal displacements consistent with the direction of subsurface displacements toward the excavation, consistent with the detected subsurface movements (Figure 4).

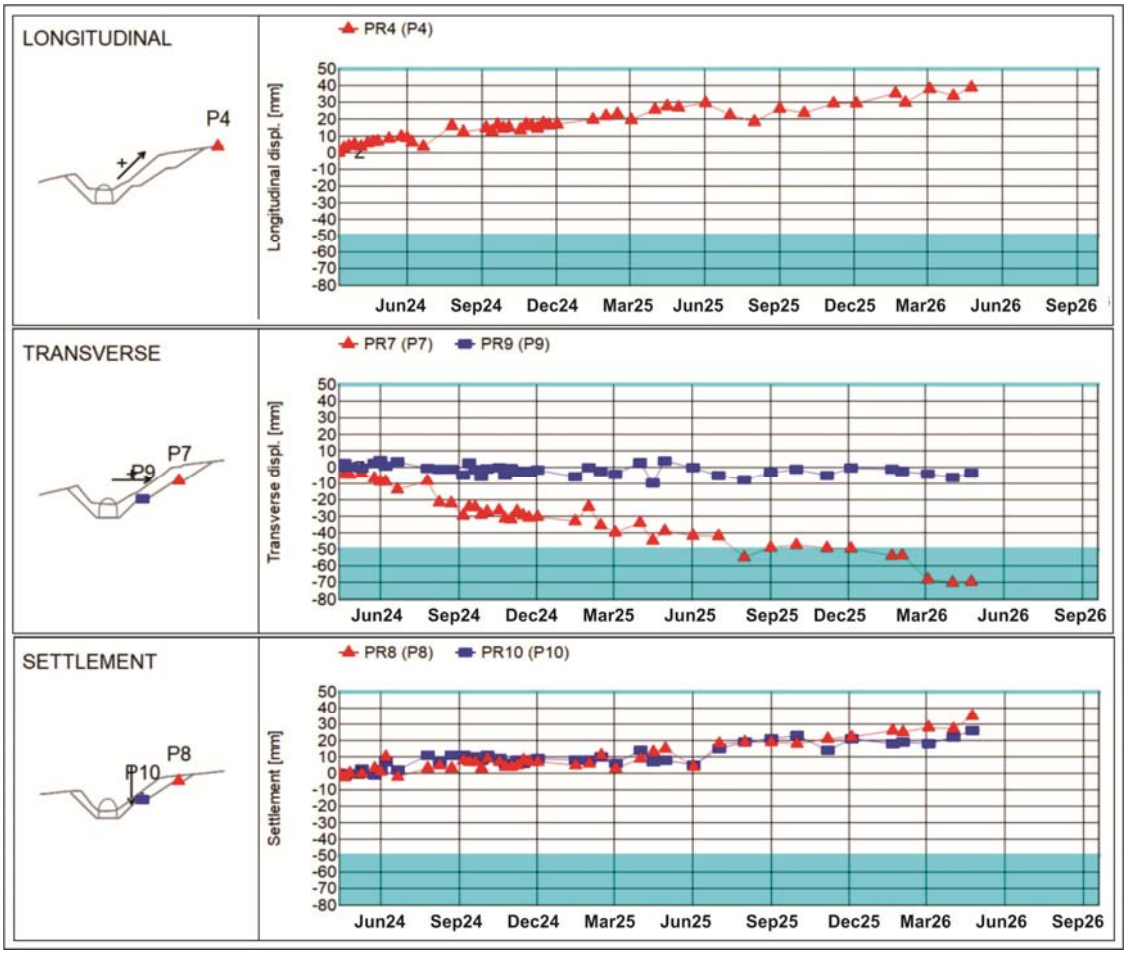


Fig. 4 Inclinometer measurement graphics, cumulative displacement (left) and incremental displacement (right).

The measurements indicate progressive and continuous deformation rather than sudden movement events, confirming that the landslide is currently in a slow deformation phase. The correlation between surface and subsurface monitoring data demonstrates that the observed displacements are associated with the overall landslide mechanism rather than isolated local instabilities.

5 Interpretation of landslide behaviour

Integrated interpretation of inclinometer and geodetic monitoring data indicates that the Cut & Cover 6 area is affected by a large, deep-seated paleo-landslide. The deeper shear zone identified at approximately 14 m depth corresponds to the principal sliding surface of the fossil landslide, while the shallower deformation zone at approximately 7 m depth developed as a consequence of excavation activities.

The absence of significant displacement in direction B within the shallow zone suggests that this movement is directly controlled by slope excavation and stress redistribution associated with tunnel construction. Excavation activities altered the natural equilibrium of the slope and contributed to the increase in displacement rates observed during the monitoring period.

No groundwater was encountered in the investigation boreholes, indicating that pore-water pressure is not currently a dominant controlling factor for slope movement. The relatively low displacement rate is therefore interpreted to be primarily controlled by the large size of the landslide mass, the low inclination of the main sliding surface, and the position of the project area within the overall landslide geometry.

Field investigations indicate that the landslide extends from higher elevations near Ketenovo village down toward the Kriva River valley. The Cut & Cover 6 structure is located near the equilibrium zone of the larger landslide body rather than at its toe, which likely contributes to the relatively stable behaviour observed during construction.

Although deep excavations remained open for an extended period of nearly two years, no rapid or catastrophic slope failure occurred. Nevertheless, such prolonged excavation within an active landslide mass represents a significant geotechnical risk. The observed stability conditions can be attributed to the very slow movement rate and the favourable geomorphological position of the excavation area within the larger landslide system. Continued monitoring remains essential for early detection of any acceleration in displacement that could indicate deterioration of slope stability conditions.

6 Conclusions

This study demonstrates the importance of integrated geotechnical monitoring for understanding slope behaviour in complex geological conditions affected by large infrastructure excavations.

The results show that construction activities within an old landslide terrain can influence the deformation pattern of the slope mass, although the overall movement may remain slow and continuous without signs of rapid instability. The combination of subsurface and surface monitoring proved essential for reliably identifying and interpreting slope response under such conditions.

The findings emphasize that careful monitoring is critical in reactivated or fossil landslide environments, where even limited excavation can modify long-term slope behaviour. Continuous observation remains necessary to ensure construction safety and to support informed geotechnical decision-making.

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