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INVESTIGATION WORKS AND REMEDIATION DESIGN OF A ROAD LANDSLIDE IN HRVATSKO ZAGORJE

KRISTINA VULIĆ [1], LOVORKA LIBRIĆ [2], MARIO BAČIĆ[3], STJEPAN MATIĆ[4]

[1] *University of Zagreb, Faculty of Civil Engineering, Croatia, kristina.vulic@unizg.grad.hr*

[2] *University of Zagreb, Faculty of Civil Engineering, Croatia, lovorka.libric@unizg.grad.hr*

[3] *University of Zagreb, Faculty of Civil Engineering, Croatia, mario.bacic@unizg.grad.hr*

[4] *Center of the Faculty of Civil Engineering, Croatia, stjepan.matic@unizg.grad.hr*

Abstract

The area of Hrvatska Zagorje is the most prone to landslides in the Republic of Croatia, with landslides occurring practically every day, caused either by natural or anthropogenic factors. Many of these landslides are activated along the network of state and local roads that pass through numerous cuttings mostly without any or with inadequate slope stabilization measures. Implementation of investigation works, and remediation design are all accompanied by numerous challenges. Designing effective landslide remediation measures requires a thorough understanding of geological, hydrological, and environmental factors influencing slope stability. This paper deals with investigation works and remediation design of a road landslide in Hrvatska Zagorje providing an overview of the landslide that occurred on the state road at the entrance to residential area Tkalci. The investigation works and remediation solution were implemented considering the spatial restrictions for remediation works (i.e. considering the proprietary and legal relations) and without any alternative road route which could be used during the implementation of remediation works. Also, a comprehensive overview of the results of stability analyses of the affected roadway in the cut have been carried out for different scenarios under static and seismic conditions, determining safety factors, and stress-deformation analyses to ascertain displacements and internal forces in the designed structure.

Key words

Road infrastructure, landslide, investigation works, remediation works, Hrvatsko Zagorje

1 Introduction

The area of Hrvatsko Zagorje is characterized by the frequent occurrence of landslides due to natural and anthropogenic influences. The transportation infrastructure in this area often runs through many cuts that lack adequate stabilization protection. This can lead to landslides, among other issues, due to weather-induced changes in slope geometry and the presence of seepage water, which can compromise the strength of the material in which the transportation infrastructure is built (Kim et al., 2018). Addressing landslide problems involves extensive investigation works and designing remediation solutions, both with numerous challenges. For an optimal remediation solution, a detailed understanding of the geological, hydrological, and meteorological impacts on slope stability is necessary. This knowledge is the basis for the proper dimensioning and implementation of stabilization measures, such as retaining walls, drainage systems, or other slope stabilization measures. This paper will provide an overview of the landslide situation that occurred on the state road in the Hrvatsko Zagorje area at the entrance to residential area Tkalci, with presentation of investigation work carried out at the site, and will provide a detailed insight into the chosen landslide remediation measure. The location in question is situated on the route of the state road between the residential area of Petrovsko and Tkalci. The planned remediation is in the area of road subsidence, specifically around a landslide on the downhill slope at km 9+327 of the State Road DC206, as shown in Figure 1.

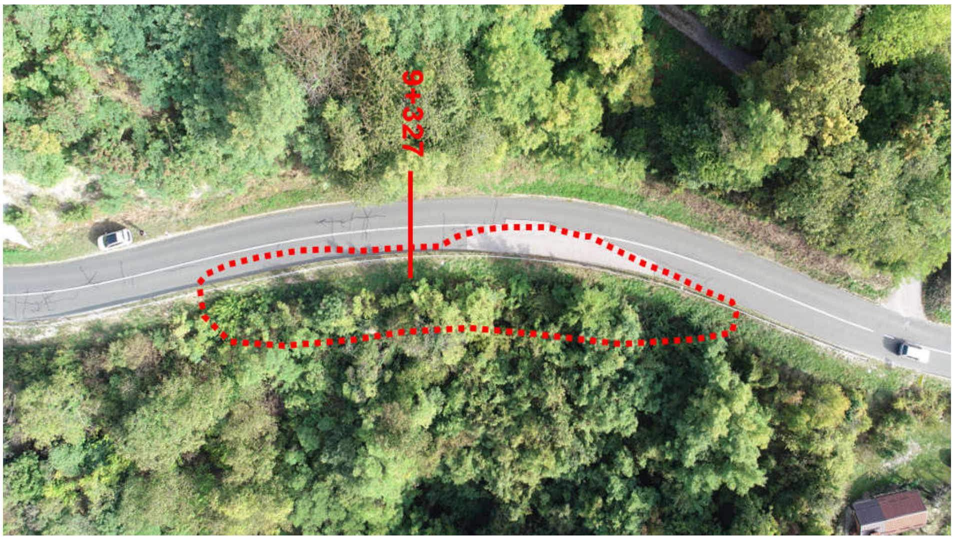

Figure 16. Area of instability and planned remediation, State Road DC206

The road is located at an altitude between 346 and 349 meters and has a width of 6.5 meters. At the location in question, there is a very steep slope of 8 meters on the uphill side, which is protected by a steel mesh and anchors. The downhill slope, covered with forest and dense vegetation, is also steep with a gradient of 30°, while along a smaller section of the road, the gradient reaches up to 50°. The landslide has affected approximately 80 meters of the road, with the most pronounced cracks appearing over a length of 30 meters. In this road section, significant shallow subsidence of the downhill lane has been observed, with visible cracks extending from the road axis towards the downhill slope.

An engineering visual inspection revealed that there was no rainwater drainage, instead, water is partially drained via curbs along the uphill edge of the road, directing water along the longitudinal gradient. Most of the rainwater flows down the slope, driven by the transverse gradient of the road. Surface drainage is further hampered by accumulated material in the narrow area next to the curbs. The accumulation of material on the uphill side is a result of water erosion and the washing away of cover material. Figure 2 shows a crack about 15 meters long, observed on the western part of the intervention area, located 1 meter from the edge of the road. The figure also shows a very steep slope covered with dense vegetation on the uphill side.

Figure 17. Western part of the road with developed crack about 15 meters long

It is predicted that shallow and slow sliding could occur on the mentioned site. As observed around the world, shallow landslides can be very destructive phenomena, with the potential for considerable loss of human life as well as property damage (Postance et al. 2017). Some examples of catastrophic translational landslides that occurred due to heavy rainfall include those at Mt. Umyeon in Japan, which resulted in 18 deaths and infrastructural damage (Lee and Park 2015), in eastern Liguria and northwestern Tuscany, which caused 13 casualties (Bartelletti et al. 2017), and in Macedonia, which is generally affected by landslides impacting infrastructure and the population (Peshevski et al. 2017; Haque et al. 2016). Therefore, appropriate landslide susceptibility, hazard, and risk assessments are needed in areas such as mentioned above or Hrvatsko Zagorje, which is prone to shallow landsliding, and any other locations affected by landslides around populated areas and infrastructure.

2 Geological and geotechnical conditions of the location

To gain a comprehensive understanding of the spatial distribution of engineering-geological environments at the site, as well as their physical-mechanical characteristics, the application of multiple soil investigation methods is required. Detailed engineering-geological investigations determine the morphological, geological, hydrogeological, and engineering geological characteristics of the location, including defining micro-locations for boreholes, inspection of drilled core, as well the selection of samples for laboratory testing.

Due to the very dense vegetation covering the terrain and hindering accessibility, no clear contours of the landslide or pronounced cracks were observed during the mapping of the downhill slope. It is presumed that shallow and slow sliding is occurring, affecting a narrow strip along the road for approximately 80 meters. The data on the distribution of individual lithological units were obtained through drilling, core determination, and geological mapping. An engineering geological map was developed, and it is shown in Figure 3. It is assumed that the sliding involves cover layers, specifically fill material and weathered rock. Leaning trees were occasionally observed on the slope, which occurs because of the very steep slope. The adverse morphological characteristics of the terrain and the action of rainwater, which flows over the slope, soaking the cover layers and reducing the shear strength of the material, are factors that contribute to the landsliding at this location. In the eastern part of the road, cracks and subsidence extend to its center, while in the western part of the area, the cracks are less pronounced, likely indicating road fill material sliding.

A total of two boreholes, were drilled to a depth of up to 14 meters, as shown in Figure 4. The exploratory drilling involved the identification and engineering description of the borehole core, standard penetration testing (SPT), and the collection of disturbed and undisturbed soil samples. The soil samples were transported to the laboratory for testing. Laboratory tests conducted included determining the natural moisture content of the soil, classification tests such as Atterberg limits and grain size distribution, as well as shear strength tests using the direct shear test and the determination of the compressibility modulus using the oedometer test.

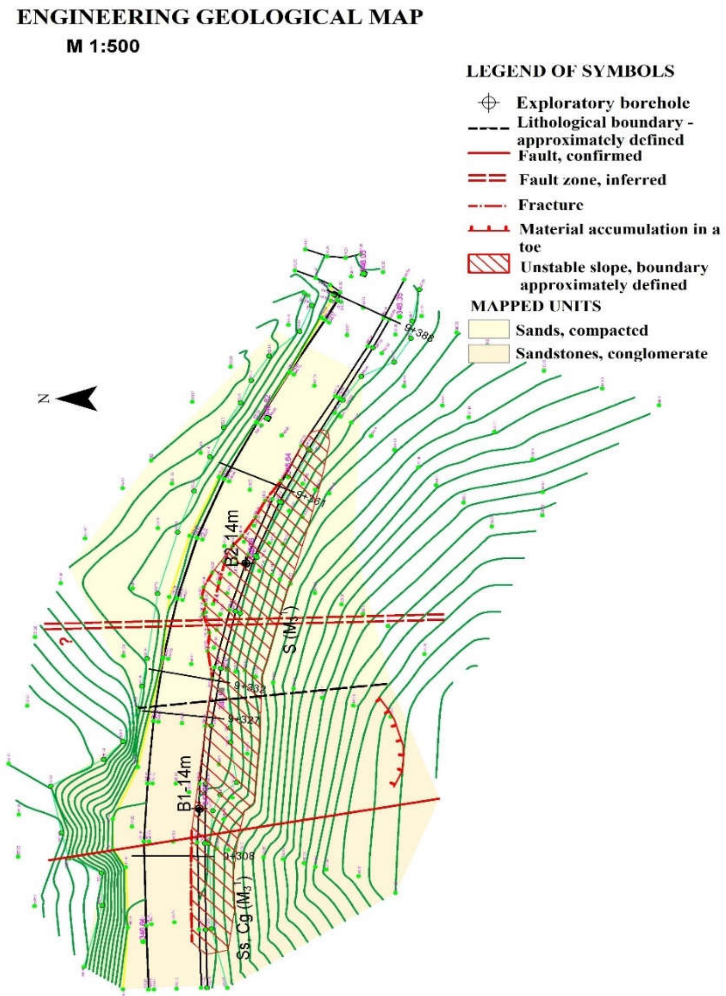

Figure 18 Engineering geological map of the area

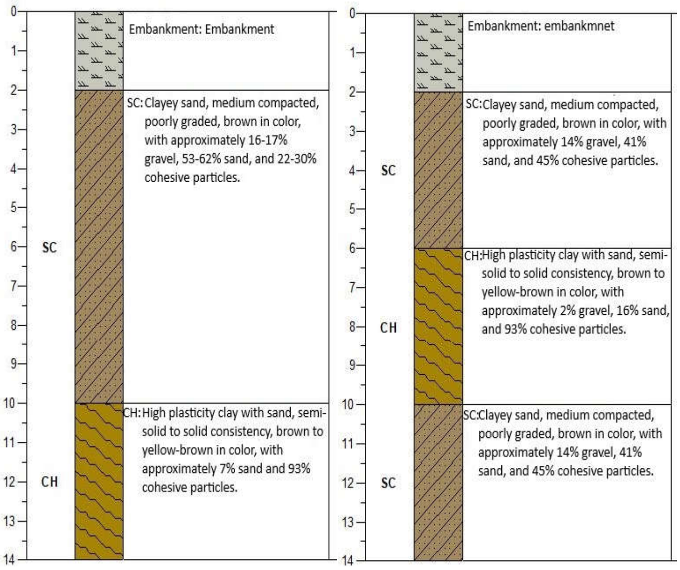

Figure 19 Display of core samples from exploratory boreholes B1 (left) and B2 (right)

Based on the field determination and classification of the borehole core, considering the results of laboratory testing, the soil profile at the site was determined. The soil profile consists of an anthropogenic road fill layer of 2.0 meters thickness composed of non-cohesive material, gravel, and sand, gray brown in color. Beneath this layer, there is a deposit of clayey sand that is medium dense, poorly graded, and brown in color, consisting of gravel, sand, and cohesive particles in different percentages. Under clayey sand the soil transitions into a layer of highly plastic clay with a firm consistency, brown to yellow brown in color, containing gravel, sand, and cohesive particles. The clay exhibits high plasticity, which affects its stability and deformation characteristics. Under high plasticity clay there is another layer of clayey sand, which is also medium dense and poorly graded, brown in color.. The geotechnical properties of the soil profile show a unit weight of 18.0 kN/m³ in the upper and lower layers, with a slightly higher 21.0 kN/m³ in the clay layer. The cohesion of the clay is 7 kPa, with an internal friction angle of 20° and a compressibility modulus of 10 MPa. The clay's liquid limit is 56.7 %, while plasticity index is 37 %, and consistency index is 1.0, highlighting its significant plastic behavior and potential challenges for engineering applications.

3 Remediation design methodology

The optimal solution for stabilizing landslide has been selected, involving the installation of a pile wall in two rows that are connected by a cantilever wall as the pile head beam. Since the cantilever wall acts as the head beam rather than a retaining structure, the load is transferred to the piles, which then transmit it further into the deeper soil layers.

The chosen solution consists of two rows of piles with a diameter of Ø 60 cm and a length of 10 meters, along with a concrete cantilever wall with a base depth of 60 cm and a total wall height of 250 cm as shown in Figure 5. The two rows of piles are installed with the same diameter and length but with different spacing. The spacing for the front row of piles, in the zone of the roadway subsidence over a length of approximately 39 meters, is 1 meter, while the remaining piles of the first row are spaced 2 meters apart. The second, or rear row of piles, is installed with a spacing of 2 meters throughout its entire length. It should be noted that the remediation is implemented on the state road where usually there is no alternative route for traffic during the works. Therefore, road managers insist on implementing solutions during the traffic operation. In this case, to secure the safe implementation of works, as well the traffic operation along the one lane, the sheet pile wall is installed to secure the construction pit (Figure 5).

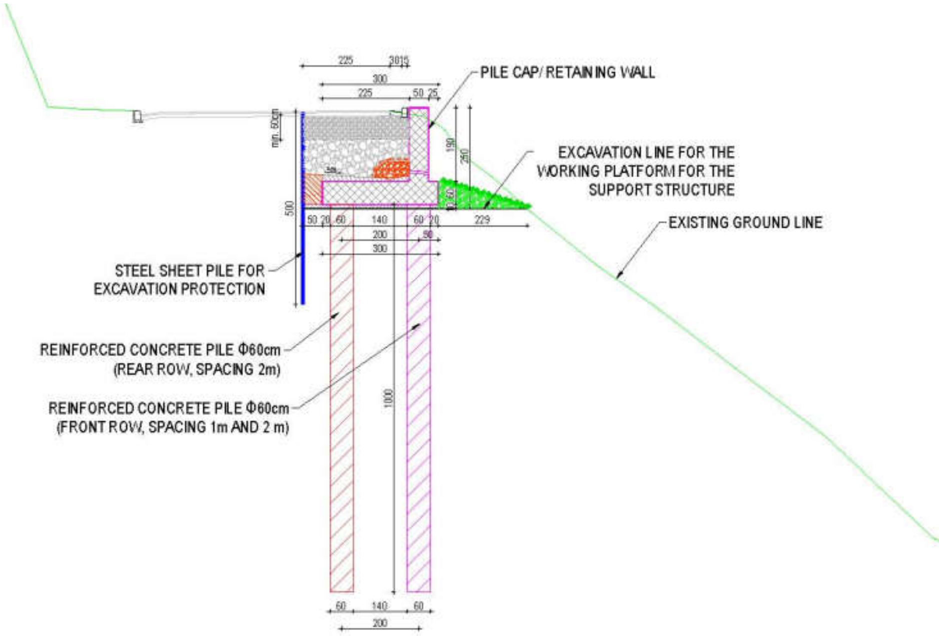

Figure 20. Cross-section with the planned landslide remediation solution

In preparing the geotechnical calculations according to the guidelines of HRN EN 1997-1:2012 Eurocode 7: Geotechnical Design and HRN EN 1998-5:2008 Eurocode 8: Design of Structures for Earthquake Resistance, and relevant Croatian national annexes, checks for both ultimate and serviceability limit states are conducted. Stability analyses of the affected roadway in the cut have been carried out for different scenarios under static and seismic conditions, determining safety factors and conducting stress-deformation analyses to ascertain displacements and internal forces in the structure.

When checking the stability of slopes and determining the safety factor of the sliding mass, the sliding mass is not predetermined; instead, it is necessary to find the one with the smallest safety factor, as this will be the critical sliding mass for evaluating slope stability (Burman, 2015). This safety factor is used as a measure of the stability of the entire slope. It follows that the practical application of the limit equilibrium method involves analyzing and finding the sliding mass with the smallest safety factor (Burman, 2015). During the stability analysis, following design situations were examined: current stability of the slope, pile installation and excavation for the retaining structure with installation of temporary sheet pile wall, installation of two rows of piles and the cantilever wall with backfilling and removal of the sheet piles, end of construction with operational vehicle loading, and application of seismic loading.

Stress-strain analyses are conducted for the ultimate limit state (ULS) for determining shear forces in structural elements, and as part of the serviceability limit state (SLS) for determining displacements. Stress-strain analysis is based on the finite element method, which is used to analyze stress and deformation relationships (Burman, 2015). For the described analysis, a hyperbolic constitutive model was used. The hyperbolic model analyzes soil behavior by checking if yielding or exceeding the shear strength occurs and assigns appropriate value of the soil stiffness.

For the purposes of conducting stress-strain analyses within the framework of ultimate and serviceability limit states at characteristic profile, the following design situations were considered: end of construction, operational conditions with traffic, sliding of the downhill slope (as a possibility), and seismic loading. Figure 6 shows the computational model with all elements of the planned remediation solution. The design situation in which the sliding of the downhill slope occurs after the implementation of the remediation measures is analyzed, as these measures do not have impact on potential downhill sliding. This is a common situation when implementing remediation measures along the road infrastructure where the infrastructure managers usually own the land where the road itself is located and immediately next to it. This means that stabilization of whole downhill slope would include implementation of measures across the slope, which is usually considered too costly, as well not allowable since it is not land owned by the road managers. Therefore, the analyses should verify that the road and remediation solutions are stable and resistant to loads even in the case if downhill slope sliding occurs.

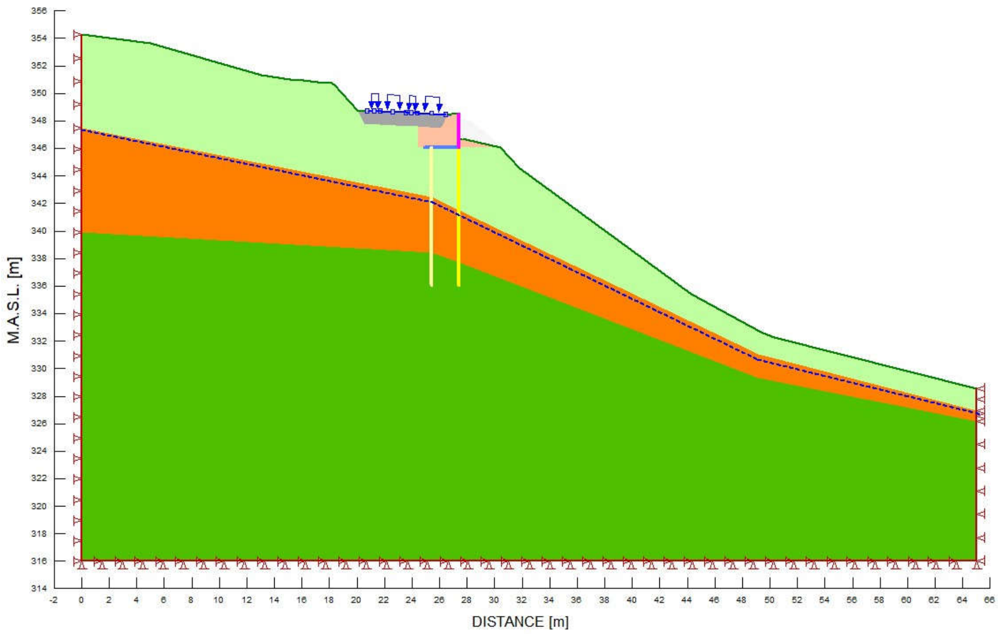

Figure 21 Computational model with elements of the planned remediation solution

For seismic load analyses, a design ground acceleration of a_g = 0.19g was used. The design ground acceleration is relevant for a return period of 475 years. The design ground acceleration depends on the level of seismic risk and is determined based on appropriate seismological studies of the building location or according to adopted seismic maps. The maps with legends are an integral part of the National Annex to several standards HRN EN 1998-1:2011/NA:2011, Eurocode 8: Design of structures for earthquake resistance – Part 1: General rules, seismic actions, and rules for buildings.

4 Results and discussion

The stability analysis of the current (in situ) state showed a safety factor of 0.81. A safety factor less than 1 indicates a stability problem, which aligns with the observed subsidence of the roadway and the appearance of cracks, indicating active instability of the road and the downslope area. During the remediation works, the safety factor in all phases was satisfactory and greater than 1, as shown in Table 1. The same applies to both static and seismic conditions after construction and during exploitation, which signifies the stability of the proposed remediation solution.

Table 5. Factor of safety of Profile 1 for different scenarios

DESIGN SITUATION	Fs
In situ state (before remediation)	0,81
Excavation for the implementation of the remediation	1,12
End of construction and traffic	1,67
Earthquake conditions	1,55

During the stability analysis at the end of the remediation construction, a potential slip surface was observed on the downslope with a safety factor of 0.78, as shown in Figure 7. However, as explained earlier, the goal of the planned remediation solution is to ensure the safety of the road and there was no financial or property-legal justification to stabilize the downhill slope. However, the overall factors of safety of sliding surfaces which affect the road are well above the minimum required factors of safety, even in the case of downhill slope failure. This analysis, however, requires additional stress-strain analysis to check the internal forces and displacements of the structure in such a scenario.

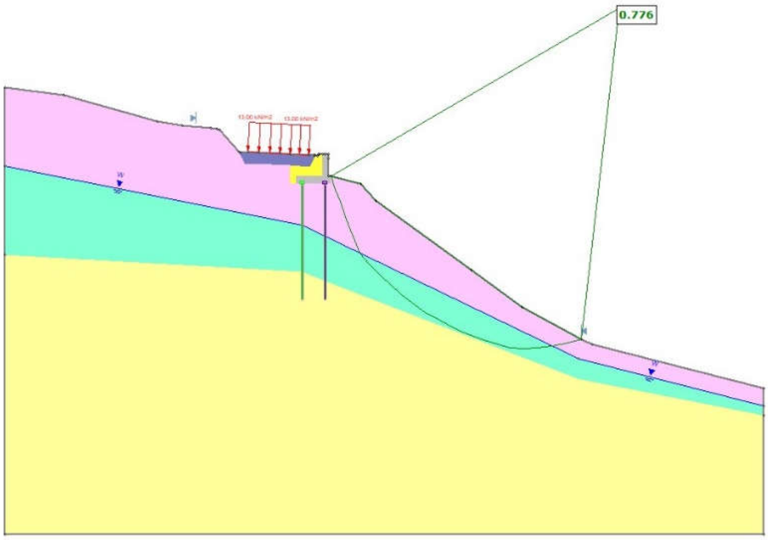

Figure 22 Potential slip surface on downslope with unsatisfactory factor of safety, Fs = 0,78

The analysis of serviceability limit states will be critical for determining the displacements of the structure, while the results of the ultimate limit state analysis are relevant for dimensioning the structural elements. As aforementioned, a model was created where a portion of the slope was "removed" to numerically verify the displacement conditions and the stress-strain relationship during potential landslides of the downslope beneath the road.

Analyzing the internal forces and displacements of the planned structure across different design scenarios showed that the critical values occur exactly in the scenario of a landslide beneath the road. Figure 8 presents the diagram of the internal forces of the pile wall for this critical design scenario. The displacements also have largest values in this scenario, and the structure was dimensioned specifically to accommodate these internal forces and. Figure 9 shows the displacements contours for the downhill slope sliding scenario with maximum displacement of 3.5 cm.

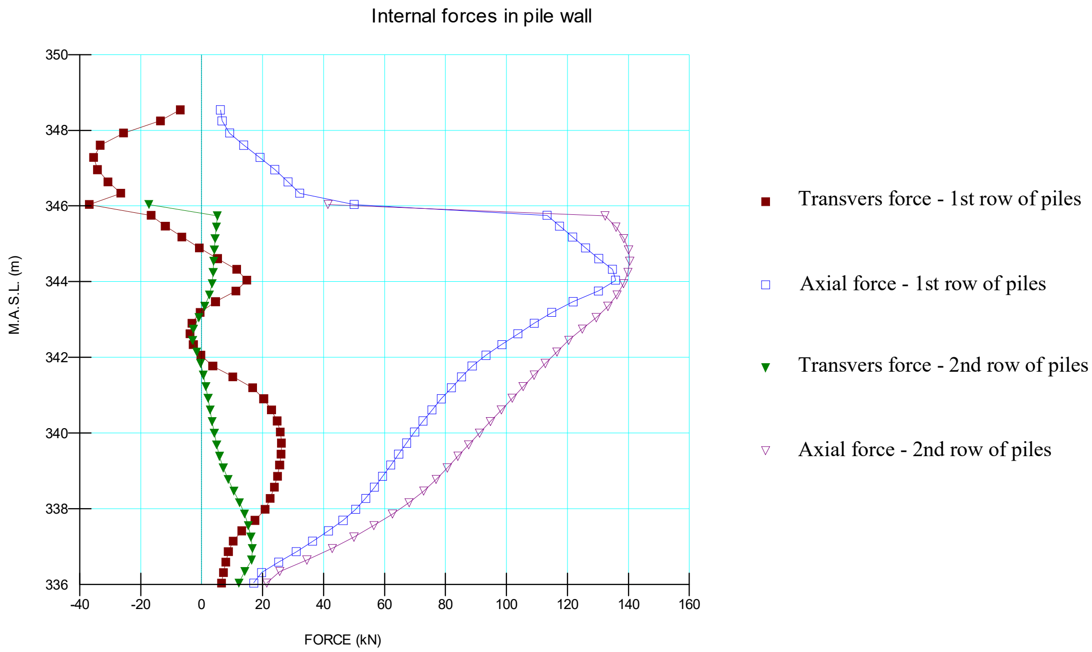

Figure 23 Transverse and axial internal forces of 1st and 2nd row of piles

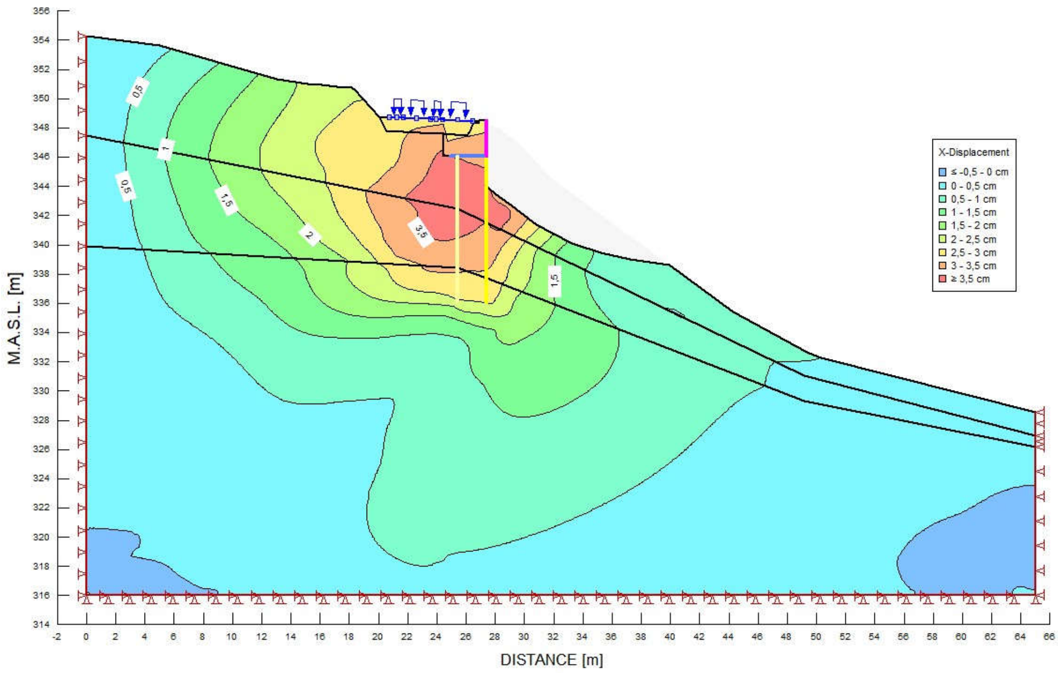

Figure 24 Contours of horizontal displacement

5 Conclusions

The geotechnical investigation and remediation design for the landslide along the state road DC206 have provided a comprehensive understanding of the site's stability issues and the effectiveness of the proposed solution. Detailed geotechnical and engineering-geological analyses were performed, including drilling, laboratory testing, and stability assessments, which were crucial in identifying the problematic areas and evaluating potential risks. The geotechnical findings revealed that the site is characterized by a complex subsurface profile, including layers of loose gravel, clayey sands and high plasticity clay. The stability analysis of the slope identified several design situations, including the existing slope state, conditions during excavation, and post-remediation scenarios under static and seismic loading conditions. The chosen remediation solution involves the construction of a two-row pile wall with a cantilever concrete wall serving as the cap. The stability analysis showed that the factor of safety for the existing condition was below 1, indicating instability, which aligns with observed deformations and cracking in the road surface. However, the proposed solution ensures that the safety factor increases to acceptable levels both during construction and after the completion of the remediation works under static and seismic conditions. The analysis highlighted a potential sliding plane on the downhill slope with a low factor of safety in the post-construction scenario, which necessitates further examination of internal forces and displacements in the structural design to prevent damage due to potential sliding. The final design incorporates measures to address these concerns, ensuring that the constructed solution remains stable and resistant, thereby making the road in question safe and functional for operation. In summary, the integration of geological and geotechnical analyses, structural design, and remediation strategies ensures that the proposed solution effectively mitigates the risks associated with the landslide and provides a robust framework for maintaining the stability and safety of the road infrastructure.

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