Highway construction in fossil landslides zones – Lessons learned from the Grdelica Gorge, Serbia

Biljana Abolmasov, Marinos Skempas, Svetozar Milenković, Janko Radovanović, Miloš Marjanović

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5TH REGIONAL SYMPOSIUM ON LANDSLIDES
IN ADRIATIC–BALKAN REGION

Landslide Modelling & Applications

Proceedings of the 5th ReSyLAB

Editors

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Proceedings of the
5th Regional Symposium on Landslides
in the Adriatic-Balkan Region

Croatian Landslide Group
University of Rijeka, Faculty of Civil Engineering
University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering

Under the sponsorship of International Consortium on Landslides (ICL)

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Foreword

The Regional Symposium on Landslides in the Adriatic-Balkan Region (ReSyLAB), organized under the auspices of the International Consortium on Landslides (ICL), has reached its fifth edition. This is an important milestone for ICL and for its Adriatic-Balkan Network (ABN).

Ten years ago, the ICL has encouraged the establishment of thematic and regional networks in the framework of its ten-year strategic Plan. The ABN was promptly launched in 2012, gathering together scientists, researchers, engineers, professionals and decision-makers, from the Adriatic and Balkan region and elsewhere, concerned with landslide hazard and risk, their reduction and impact on society.

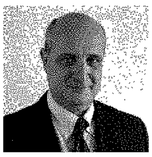
Today we can say that this has proved to be a successful strategy and the ABN is perhaps the best example of successful regional network. Since its foundation in the year 2012, the ABN has regularly organized its regional symposium every two years, dedicated to specific issues, in various countries of the Adriatic-Balkan area: Croatia, Serbia, Slovenia, Bosnia and Herzegovina and Croatia again.

Participation has gradually expanded to other countries, throughout Europe and elsewhere. This year the Symposium sees the participation of scientists from ten countries, providing an effective platform to achieve fruitful cooperation among landslide researchers.

The ReSyLAB represents a successful contribution to the Kyoto Landslide Commitment (KLC2020) launched by ICL in the year 2020 for the global promotion of understanding and reducing landslide disaster risk. The main purpose of the KLC2020 is to build a common platform for sharing ideas, good practices and policies with key actors and stakeholders concerned with landslide risk at the global level. One of the main priority actions of KLC2020 is to facilitate and assess progresses through the organization of meetings at the regional and national level, to take place in respective countries, in order to show deliveries and performances made towards the achievement of objectives for landslide risk reduction on a global scale.

The general theme of the 5th ReSyLAB is "Landslide Modelling & Applications", which clearly shows the close interplay between scientific research and its application in the engineering practice and for supporting risk reduction policies.

For these reasons, I am convinced that the example of the ABN and the ReSyLAB should be valued and exported in other geographical contexts.



Nicola Casagli
President of the International Consortium on Landslides
Florence, Italy

Foreword

The International Consortium on Landslides (ICL) was established in January 2002 in Kyoto, Japan, to promote landslide research for the benefit of society and the environment, and capacity building, including education, notably in developing countries.

In January 2005, the second UN World Conference for Disaster Reduction was organized in Kobe, Japan. ICL, UNESCO, WMO, UNU, IAHS etc. jointly organized a thematic session on Landslides (IPL) and Floods (IFI). The Letter of Intent on Earth System Risk Analysis and Sustainable Disaster Management was agreed in the session and signed by global partners (ICL, UNESCO, WMO, FAO, UNU, UN-ISDR, ICSU, WFEO within 2005. Participants included Professors Ognjen Bonacci from Croatia, Kyoji Sassa, Hideaki Marui, and Kaoru Takara from Japan.

In January 2006, ICL and its global partners (UNESCO, WMO, FAO, UNU, UN-ISDR, ICSU, WFEO etc.) organized the Round Table Discussion for the IPL and adopted the 2006 Tokyo Action Plan strengthening research and learning on landslides and related earth system disasters for global risk preparedness. In 2007, Science and Technology Research Partnership for Sustainable Development (SATREPS) program to promote international joint research for global issues based on the needs of developing countries was founded by the Government of Japan. This programme was very timely to promote the 2006 Tokyo Action Plan. The Croatia-Japan Joint SATREPS Project "Risk identification and land-use planning for disaster mitigation of landslide and floods in Croatia" was proposed in 2007 and accepted as one of the initial SATREPS projects in 2008.

In order to support this SATREPS project, the Ministry of Foreign Affairs of Japan organized a workshop in Tokyo aiming at regional cooperation in South-Eastern Europe on disaster management by inviting Professors Željko Arbanas, Matjaž Mikoš, Snježana Mihalić, Biljana Abolmasov, Sabid Zekan and others from Adriatic-Balkan Region on 14-17 December 2010. This workshop contributed to the establishment of the Adriatic-Balkan Network of International Consortium on Landslides (ICL ABN) in January 2012 and also its biannual regional symposium; the 1st ReSyLAB in March 2013 in Zagreb (Croatia), the 2nd in May 2015 in Belgrade (Serbia), the 3rd in October 2017 in Ljubljana (Slovenia) and the 4th in October 2019 in Sarajevo (Bosnia and Herzegovina), and 5th in March 2022 in Rijeka (Croatia). The ICL has launched the Open Access Book Series "Progress in Landslide Research and Technology" for Kyoto Landslide Commitment 2020 which is published twice a year. I wish to invite all participants of this symposium to contribute articles to this new open access book series. The target readers of the book series are practitioners and other stakeholders who apply in practice the most advanced knowledge of science and technology for landslide disaster risk reduction. Articles must be written in a simplified way easily understandable by practitioners and stakeholders.

The Adriatic-Balkan Network of International Consortium on Landslides (ICL ABN) is the most successful network of the ICL and its biennial symposium and its publication contributed to boost the regional potentials for reducing landslide disaster risk. I am very grateful for this tremendous effort to organize the fifth regional symposium of the International Consortium on Landslides. I wish the Adriatic-Balkan network a very successful meeting and a very good publication.

Kyoji Sassa
Secretary-General of the International Consortium on Landslides and the Kyoto Landslide Commitment 2020
Editor-in-Chief of the Open Access Book Series of the ICL
Kyoto, Japan

Preface

The 5^{th} Regional Symposium on Landslides in Adriatic-Balkan Region (ReSyLAB) will be held in the year of two important anniversaries: 20 years of establishing of International Consortium on Landslides (ICL) and 10 years of establishing regional and thematic networks of ICL. The regional Adriatic-Balkan Network (ABN) is one of the most active networks and this 5^{th} ResyLab2015 will contribute to regional cooperation and widening the Network by the new members in the region. Just for reminder, the 1^{st} ReSyLAB was held in Zagreb, Croatia, 2013; 2^{nd} ReSyLAB in Belgrade, Serbia; 3^{rd} ReSyLAB in Ljubljana, Slovenia and 4^{th} ReSyLAB in Sarajevo, Bosnia and Herzegovina. The 5^{th} ReSyLAB will be held three years after the last Symposium, disrupting the biannual schedule due to Covid-19 pandemic and will be held as hybrid event, but we believe that this will not diminish the significance of this Symposium.

This book contains peer-reviewed papers that will be presented at the 5^{th} Regional Symposium on Landslides in the Adriatic-Balkan Region entitled "Landslide Modelling & Applications". The Symposium will be held in Rijeka, Croatia from March 23^{th} to 26^{th}, 2022. A wide range of landslide topics are presented in the Symposium sessions that include landslide monitoring, landslide investigation, landslide mapping, landslide susceptibility zonation, laboratory testing, physical and numerical modelling of landslides and landslide case studies. This collection of papers is beneficial to practitioners, researchers and other professionals dealing with landsides. The proceedings reflect the ongoing response of researchers and practitioners from 10 countries from the region and around the world. Unfortunately, the Covid-19 pandemic situation disables landslide scientists from Japan that were present at all previous ReSyLABs, to join us in Rijeka.

We would like to thank all authors and participants for sharing their ideas and research results in the area of landslide science and practice. We wish to acknowledge the help from all the reviewers in advising and refining the contributions to their final version published in this book.

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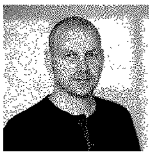

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Highway construction in fossil landslides zones – lessons learned from the Grdelica Gorge, Serbia

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Abstract During the E75 Highway construction in the Grdelica Gorge in Serbia (Corridor X), complex fossil landslides were reactivated in two cuts. The geotechnical investigations were performed in several phases from the Preliminary through the Main Design, but comprehensive remedial measures were developed after additional geotechnical monitoring and re-design in the final stage of highway construction. Both fossil landslides were formed in complex geological settings, i.e. extremely anisotropic albite-chlorite-muscovite schists from early Paleozoic. Engineering geological conditions were determined by lithological composition, presence of highly weathered and tectonized zones, as well as presence of local torrential streams and surface erosion. In this paper two case studies of fossil landslides reactivated during highway construction in complex geological conditions and lessons learned after several phases of investigation and design will be presented.

Keywords fossil landslides, highway construction, geotechnical investigations, design

Introduction

Construction-induced landslides usually occur in slopes/cuts mostly due to excavation, which can cause many problems and delays in transport infrastructure projects realization. It is not unusual that large volume excavations for highway construction lead to massive instabilities in particular when complex morphological and geological settings prevail. Zhang et al. (2012) discussed a case of repeated failures on a high cut due to multi-excavation for G212 highway in China. The analysis shows that the excavation-induced repeated failures was related to the exposure of the weak bedding plane and the toe unloading of the slope cut. Solberg et al. (2008) reported reactivation of large, prehistoric clay slides due to the construction of a new highway (E39) in Buvika, mid-Norway. Unexpected instabilities in the flysch and molassic formation caused by Egnatia Odos highway construction in the Greece were explained in Christaras (1997). Skempas (2017) describes some case histories with slope instability problems at various sections of the Egnatia Odos Highway Project in Greece and the methods that have been applied for overcoming these events and constructing the highway. In recent years, China's road infrastructure projects expansion causes many landslides triggered by engineering activities because of complicated and misinterpreted geological features (Zhang et al. 2021; Yu et al. 2020).

During the Corridor X highway construction through the Republic of Serbia many instabilities were caused by excavation frequently in combimation with unforeseen or poorly investigated ground conditions on both the Corridor X sections (E75 and E80). Georgalas et al. (2017) explains geological and geotechnical conditions during construction of E80 highway from Niš to Bulgarian border, and noticed that out of 20 excavated cuts, 18 have faced sliding failures, resulting in suspension of the works, awaiting remedial geotechnical designs. The implications of the insufficient geotechnical investigations that caused delays and a significant increase in the project costs and schedule overruns on E75 section of Corridor X were presented in Berisavljević et al. (2016) and Berisavljević (2018). The most demanding section along the E75 highway was the one through the Grdelica Gorge, where Cut 3 and Cut 5 were found to be crossing two fossil landslides which were reactivated during highway excavations. In this paper we will present lessons learned after several phases of investigation, design and highway construction in complex geotechnical conditions.

General data

Corridor X Project

The integration of the Serbian transport network into the regional and Trans-European Network (TEN-T) remains critical for Serbia's economic and social development. Corridor X is the longest and busiest road transport corridor in the Western Balkans. It passes through Serbia and the Republic of North Macedonia, connecting Croatia and Hungary with Bulgaria and Greece. The total length of the Corridor is 726 km, 531 km of which are in Serbia. As the most important transport route for Serbia, Corridor X enhances regional connectivity through linkages to the TEN-T Orient/East-Med Corridor and represents the shortest link to Europe (through Croatia and Hungary), and to the Middle East, Asia, and Africa (through Greece and Bulgaria). In 2008 the Government of the Republic of Serbia (GoRS) committed to completion of the core road infrastructure on Corridor X.

Construction activities started in 2012, but both sections (E75 and E80) were opened for traffic in 2019 after almost two years delay. Geographical position of E75 section and position of critical cuts (CUT3 and CUT5) are presented in Fig. 1.

Study area

The Grdelica Gorge is a part of the South Morava River basin, located in the southeastern part of Serbia. In the mid-1950s, the Grdelica Gorge was identified to belong to the areas most endangered by soil erosion in Europe. Namely, there are 137 torrential streams, direct tributaries of the South Morava river, registered on the small area, along 26.6 km of the Grdelica Gorge length (Kostadinov et al. 2018). After the Second World War numerous erosion control works had been performed in the Grdelica Gorge, as well as the entire South Morava river basin, which resulted in significant reduction of soil erosion by the end of the 1980s. The bedrock predominantly belongs to Paleozoic Serbo-Macedonian Massif (SMM). SMM in Serbia and North Macedonia represents an entirely metamorphic belt comprising a structurally lower unit (the Lower Complex) and an upper unit (the Vlasina Unit), as originally proposed by Dimitrijević (1997). These units are commonly differentiated on the basis of their metamorphic grade, with the Lower Complex predominantly metamorphosed at medium to lower amphibolite facies, and the Vlasina Unit at greenschist facies (low-grade cristaline). The Vlasina Unit consists of the pre-Ordovician greenschist facies represented by chlorite, biotite, muscovite, sericite and epidote schists (Antić et al. 2016).

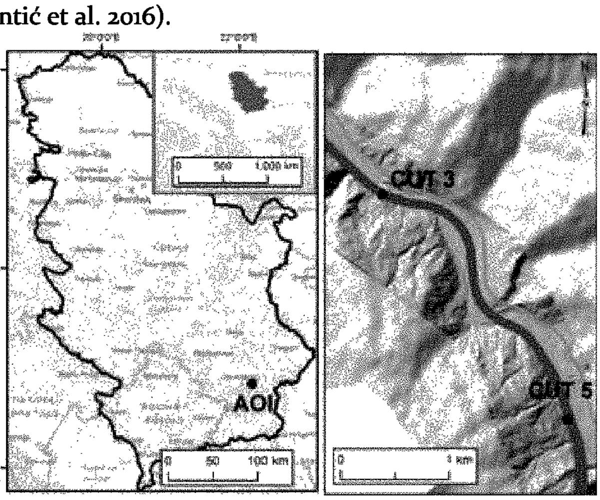


Figure 1 Geographical position of Grdelica Gorge (Area of Interest - AOI) and position of CUT3 and CUT5 within AOI.

Both fossil landslides are formed in highly weathered and tectonized albite, chlorite, muscovite, and sericite schists from the Vlasina Unit on the left bank of the South Morava river.

Evolution of landslides

The highway construction on E75 section Grabovnica-Srpska Kuća started in 2012 according to the FIDIC Conditions of Contract for Construction, the Red Book form, which meant that technical documentation was provided by the Investor (the Republic of Serbia). The Main Design assumptions were based on very limited knowledge from site investigation together with the prepared engineering geological mapping and laboratory testing. The lack of access roads to the location of cuts was one of the main reasons for the limited scope of site investigations, as well as the very short time available for preparing technical documentation for the final design and tendering of the project (Berisavljević, 2018).

Initial instabilities in both fossil landslides (CUT3 and CUT5) started in 2014 during excavations for the highway construction according to the Main Design. Shallow landslides occured at that time and additional geotechnical investigations were performed in 2015. Re-design of a frame supporting structure and micropile walls as remedial measure were suggested by Contractor and accepted by Investor in 2016. Implementation of the proposed measures started in mid 2016, but displacements progressed and escalated in both cuts during late winter of 2017 and early spring of 2018. More geotechnical investigations were performed again – including LiDAR survey, numerous boreholes, laboratory testings and geotechnical monitoring, which started in 2017. Table 1 shows geotechnical investigation works conducted for the Main Design and during highway construction on the CUT3 and CUT5 from 2014 to 2019.

Landslides features

CUT3

The first shallow instabilities on CUT3 begun in 2014, but the large fossil landslide was not recognized after additional geotechnical investigations performed in 2015, as well as in the Main Design (2010). According to the new design from 2016, construction of micropille wall was executed, but micropille wall monitoring showed uniform cumulative displacement of 45 cm from December 2017 to March 2018. High-resolution LiDAR scanning from 2018 had detected indicators of earlier occurrences flow-like landslide on high-resolution terrain surface model, as well as displacement of the South Morava river because of deep-seated landslide which probably blocked the river in the past (landslide dam). All installed inclinometers (2017-2018) showed displacement depth between 8 m and 43 m, i.e., up to 15 m below the highway platform. Landslide was aproximatelly 600 m long and 200 m wide, and average slope angle was 15°.

Table 1 List of geotechnical investigation conducted from 2010-2019.

Name of CUT and chainage	Geotechnical investigation for Main Design (2010)	Additional geotechnical investigations 2014-2016	Additional geotechnical investigations 2017-2019
CUT3 km 876+510 to km 876+740	5 trial pits	(2015) 7 boreholes in total length 134 m; laboratory, geophysics, piezometer (1) and inclinometer (1) installation	(2017) 12 boreholes in total length 433 m, only piezometers and inclinometers installation (2017) 3 available boreholes logs in total length 140.3 m, geophysics (2018) 3 boreholes in total length 150 m, laboratory, and inclinometers installation (3)
CUT5 km 879+350 to km 879+775	12 boreholes (max depth 17 m) in the zone of retaining structure at toe of the slope, laboratory (mainly index tests)	(2015) 10 boreholes in total length 116 m; laboratory, piezometer (1) and inclinometer (1) installation	(2017) 21 boreholes in total length 284 m, only piezometers and inclinometers installation; (2018) 30 boreholes in total length 708 m, geophysics, laboratory, inclinometers installation (8); (2019) 11 boreholes in total length 260 m, laboratory, inclinometers (7) and piezometers (4) installation

Type of landslide material is predominantly sandy/silty clay (completely disintegrated schists-S***) in the upper part of landslide body and highly weathered schists (debris and boulders in fine-grained silty/clay matrix – S**- S*) in the lower part of landslide body. Basic material properties of landslide body and stable ground are presented in Table 2. The residual strength parameters from direct shear tests proximal to the zone of sliding surface were φ_r'= 13-16° and c_r'=3-6 kPa. Failure mechanism was a combination of sliding (in the lower parts), and flowing in the upper parts of the slope.

Simplified map of the landslide is shown on Fig. 2, while representative cross-setion is shown on Fig. 3a. In general, the entire slope has a high groundwater table. Saturation on the ground surface was recognized during all field campaigns and it was caused by inflow from two gullies located on the upper part of slope, but fluctuation of piezometric groundwater levels were not significant, except in December 2017-February 2018 period (Fig. 3b).

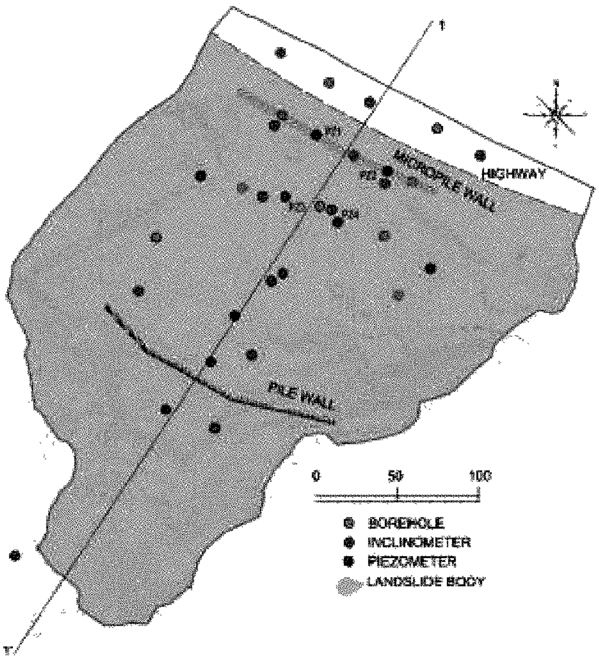


Figure 2 Simplified map of landslide area (CUT3).

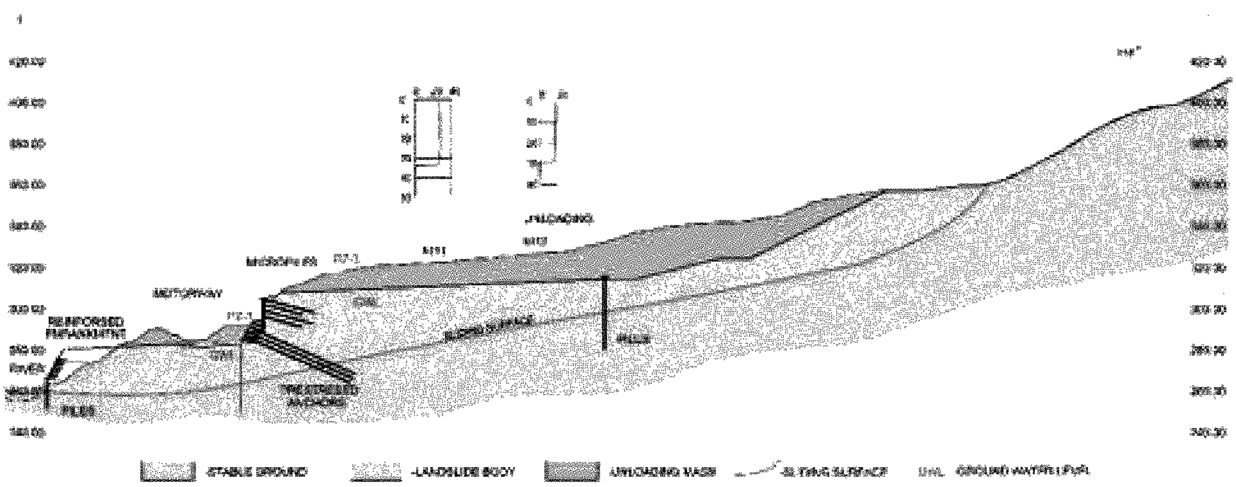


Figure 3 Simplified cross section of landslide and proposed remedial measures on CUT3.

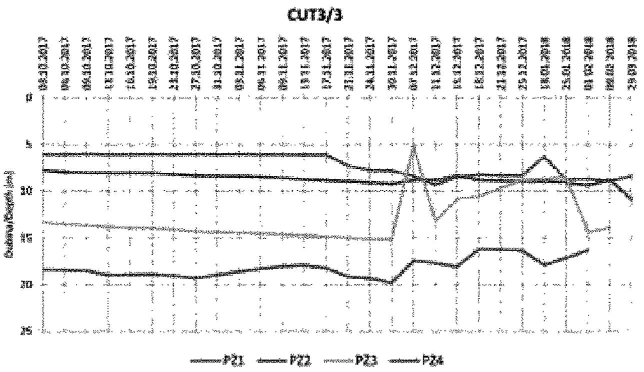


Figure 4 Ground water level on CUT3 from October 2017-March 2018.

CUT5

Potential instabilities on CUT5 were recognized within technical documentation for the Main Design and area was marked as "marginaly stable slope". The first displacements started in October 2014 during excavations in the slope toe area, and construction of micropilles was implemented according to the re-design of initial remediation measures available from the Main Design. During 2016 the landslide was widening and was retrogressing upslope and beyond the expropriation line.

Landslide width was 200 m in the zone of main scarp and 400 m in the zone of the landslide toe, while landslide lenght was 350 m in January 2018. Landslide material predominantly consists of Quaternary elluvial-dilluvial silty clays and completely disintegrated and highly weathered schists (S***- S**). Average slope angle was about 25°, but many local morphological indications of previous movements and steeper parts of the landslide surface were indicated.

Engineering geological mapping, analysis of borehole logs, and morphological analysis of high-resolution LiDAR image had confirmed the presence of a complex fossil landslide in reactivation stage. Inclinometer readings showed several sliding surfaces (9-15 m), with the deepest sliding surface at 22 m, indicating a translation mechanism of sliding and "blocky" movements.

A simplified engineering geological map is presented in Fig. 5, while a representative cross-section is given in Fig. 6. Basic material properties of landslide body and stable ground are presented in Table 2, while residual values of shear strength parameters from direct shear tests in the zone of sliding surface were φ_r'= 20-23° and c_r'=3 kPa.

The diagram of piezometric ground water level fluctuation showed slight influence of sesonal inflow from precipitation (from June 2017-March 2019), except the period from December 2017-March 2018 when snow and snow melting caused rising of ground water level in several piezometers (Fig. 7).

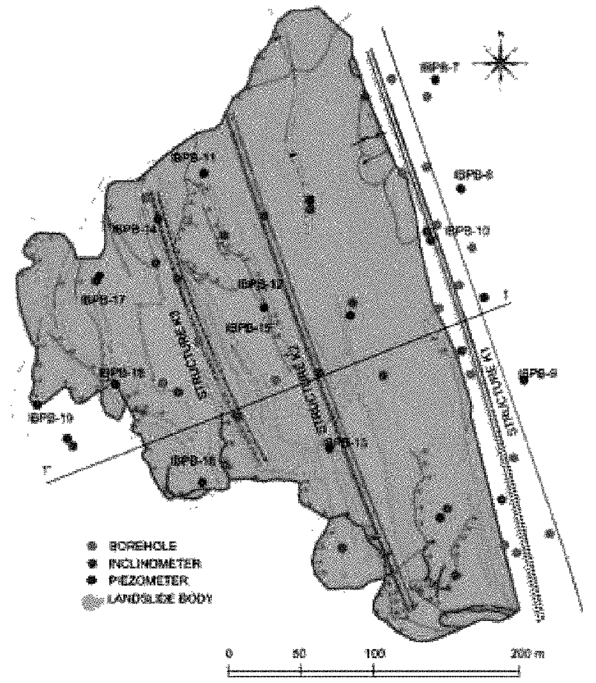


Figure 5 Simplified map of landslide on CUT5.

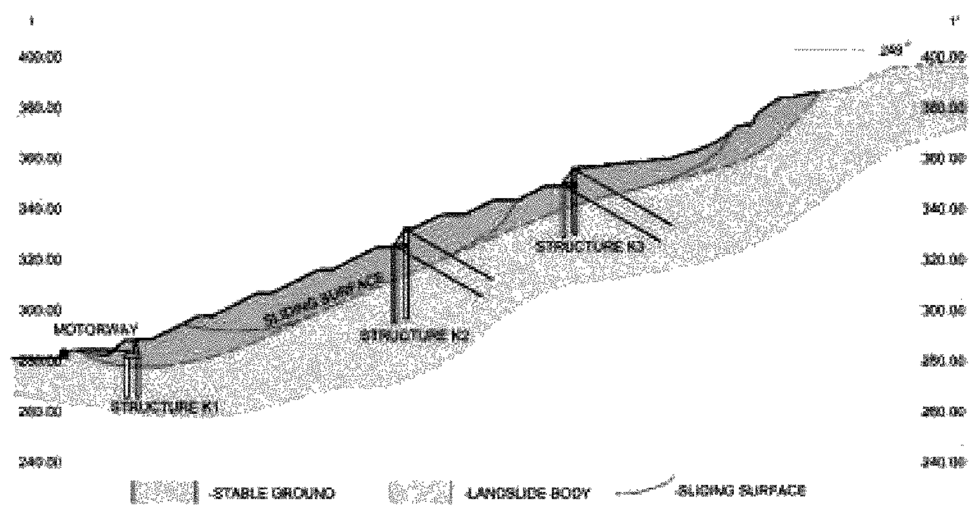
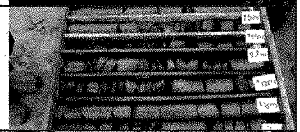


Figure 6 Simplified cross section of landslide 1-1' and proposed remedial measures on CUT5.

Table 2 Material properties of engineering geological units identified on CUT3 and CUT5.

Description of Engineering geological units on CUT3 and CUT5	RQD	Laboratory results γ (kN/m³)	c (kPa)	φ (°)	Photos of borehole logs
S*** Completely weathered and disintegrated shists – mainly surface parts of the slope and a part of landslides bodies		18-22	3 -14	13-23	
S** Highly jointed and weathered schists – mainly below S*** and part of landslides bodies	< 20	20-23	5-20	20-23	
S* Medium jointed shists – partially weathered along joints, structure is preserved and part of landslides bodies	20-50	25-27	17-40	29-37	
S Jointed non-weathered shists – grey to green albite-muscovite-chlorite schists, structure and texture are preserved – stable ground	>50	27-28	>250	45-55	

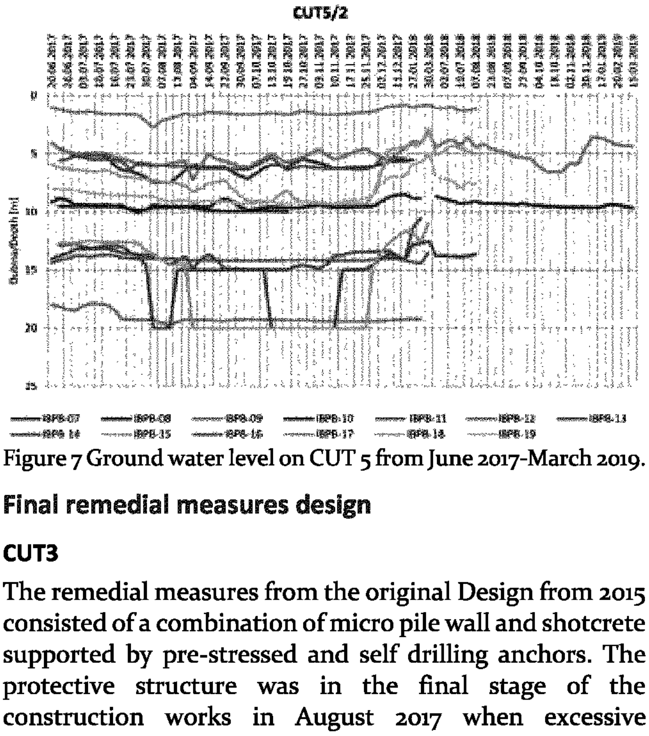


Figure 7 Ground water level on CUT 5 from June 2017-March 2019.

Final remedial measures design

CUT3

The remedial measures from the original Design from 2015 consisted of a combination of micro pile wall and shotcrete supported by pre-stressed and self drilling anchors. The protective structure was in the final stage of the construction works in August 2017 when excessive movement of the supporting structure had been reported after excavation of the last stage and the starting of construction works on road and pavement. As mentioned earlier, additional geotechnical investigations and airborne LiDAR scanning were performed in the next few months.

The new remedial measures proposed consisted of various works planned in three phases of construction. The first phase (as the most important), had consisted of 200.000 m³ landslide material unloading behind existing retaining structure of micro-pilles and construction of drainage trenches for surface drainage. The second stage consisted of large diameter pile wall (∅ 1200 mm) next to the South Morava river side in the toe of landslide with a reinforsed embankment. In the third phase the construction of vertical reinforced concrete beams along the micropile wall had been involved. The beams were supposed to be anchored with long (55 m) pre-stressed anchors in stable rock layer behind sliding surface. On the platform of the berm a 6 m gabion wall is designed in order to stabilize the existing support structure with micro piles. During implementation on the third phase of remedial measures and after continuous monitoring by inclinometers and geodetic bench marks additional large diameter pile wall (∅ 1500 mm) is designed in the upper part of landslide. Simplified cross-section with remedial measures is presented in Fig. 5, while panoramic view of remedial works on CUT3 is presented in Fig. 8.

CUT5

According to the Main Design in the zone of CUT5 a simple 7 m high concrete wall was originally designed. The total length of the cut was approximately 500 m and around 7 m high. During excavation and construction of the wall, in the last 100 m of the cut a small landslide was activated in 2014. After two years of investigations and monitoring it was concluded that the entire cut area was a pre-existing landslide.

New remediation design was prepared by the Institute for traffic and transportation (CIP) in November 2017. Remedial measures included construction of three stiff structures (K1, K2 and K3) consisted of two rows of large diameter piles (∅ 1500 mm), long pre-stressed anchors (40 m) and additional excavation in between. Simplified cross-section with remedial measure is presented in Fig. 6, while a panoramic view of remedial measures on CUT5 is presented in Fig. 9.

view on CUT3 from August 2021
(a

view on from August 2021
a

Conclusions

In this paper two case studies of fossil landslides reactivated during E75 highway construction in Serbia under complex geological conditions are presented. Both fossil landslides on CUT3 and CUT5 are formed in highly weathered and tectonized albite, chlorite, muscovite, and sericite schists from the early Paleozoic Vlasina Unit on the left South Morava river bank. After several phases of investigation and design some conclusions can be summarized as follows:

- Lack of understanding of the prevailing complex geological settings in the Feasibility study resulted to the wrong selection of the highway corridor alignment; it is recommeneded that advanced remote sensing techniques should be introduced for the future planning of infrastructure corridors
- Insuficient geotechnical investigations during the early phases of highway design (Preliminary and Main design) resulted to cut slopes instability problems during excavations, which subsequently neccessitated additional geotechnical investigations
- Additional geotechnical investigations should had been extended beyond the expropriation line by the Investor and fine-tuned according to complexity of ground conditions
- Advanced geodetic survey, like LiDAR scanning should had been performed before construction excavations and combined with detailed morphological analysis, especially in the zones of fossil or dormant landslides
- A geotechnical monitoring system should had been recognized by the Investor and Contractor and installed early enough and systematically, for the accurate detection of the sliding surface(s) and the mechanism of movement
- Design solutions should be climate resilient and conservative when applied in complex geotechnical conditions; insufficient measures always lead to re-design and significant increases of project costs and schedule overruns.

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Remediation measures of mandslides on State roads in the Republic of Croatia – Presentation of case studies

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Abstract Landslides are common on roads, which directly affect the flow of traffic and the connection and functioning of the population in surrounding area. Therefore, it is necessary to investigate them in the shortest possible time and to determine and carry out the remediation solution. Functionality of the state roads is immensely important so it is necessary to ensure that the traffic is maintained during remediation activities. Therefore, design solutions and remediation execution technology should be adapted to these requirements. Landslides are frequently formed in the road embankments and cover materials on the top of the bedrock due to exceeded soil strength parameters as a result of groundwater flow.

The paper presents experiences from practice on landslides remediation in the Republic of Croatia: landslide Laz 18 on state road D29 in section 38+254, landslide Dedin on state road DC3, section 015 in section 2+060, landslide Vranja on state road DC500, section 001 in section 2+400, landslide Dubravci on state road DC3, section 012 in section 4+400. The cause and mechanism of landslides, design solution for remediation measures and experience during the execution of works are presented. Landslide remediation measures mainly consisted of pile walls with cap beams or retaining walls and geotechnical anchors or rod anchors where necessary. In addition, in the impact area of each landslide a reconstruction of stormwater drainage system was carried out. After the completion of remediation works, monitoring equipment was installed to monitor the geotechnical structure and to verify the design solution.

Keywords landslide, remediation measures, stability

Description, cause and mechanism of landslides

State roads are public roads that have the function of connecting the territory of the Republic of Croatia into the European transport system as well as interconnecting regions within the Republic of Croatia (counties, larger cities) and enable traffic transit. Continuous and safe traffic is of significant interest to the country, and landslides are one of the dangers that can temporarily or permanently disable it. Landslides are common on roads, where the most common triggers are geologically unfavourable terrain structure, excessive traffic load, inadequately constructed or unmaintained road drainage, inadequate drainage of surrounding terrain that directly affects the roads, clogged culverts, and drainage canals, etc.

When landslides occur on state roads, it is necessary to perform an inspection in the shortest possible time (up to 24 hours), and to start with geotechnical investigation works and preparation of the design documentation for the landslide remediation as soon as possible.

In the event of instability, the safe flow of traffic is endangered. One of the frequent requiwemwnts by the investors is to allow permanent or temporary traffic in at least one lane. These roads are often the only way for buses, supplies, firefighters, and ambulances to operate.

The paper presents four different landslides on state roads (Laz 18, Dedin, Vranja and Dubravci), and for each landslide the causes and mechanism, geological structure, and remediation solution are described.

Description, cause and mechanism of landslides (comparation of different geological conditions and landslide initiators/triggers)

Landslide Laz 18 on state road DC29 km 38+254

Laz 18 landslide was located on the northern edge of the City of Zagreb, south of Krapina-Zagorje, between the settlements of Kašina and Laz Bistrički. The landslide was formed on a forested unstable slope (approximately 30 - 35 °) to the southwest, while the left side of the landslide passes along the edge of state road DC 29, in section 38 + 254. The Suhopot stream flows in the toe of the landslide (Grošić 2019a). On the part of the unstable slope, along the northwestern edge of DC 29, a landslide of about 20-40 m wide and about 150 m long was started.

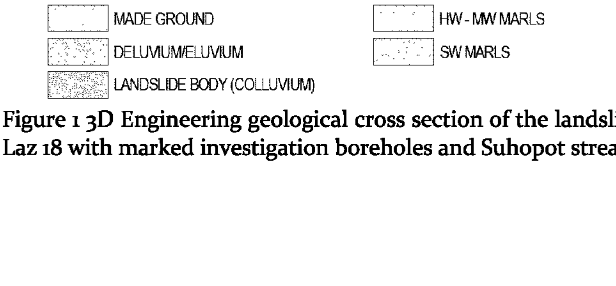

Figure 1 3D Engineering geological cross section of the landslide Laz 18 with marked investigation boreholes and Suhopot stream.

Elements of secondary sliding were determined within the investigated Landslide. There was a possibility of further expansion of the landslide on the sides, which directly affects the stability of the road embankment.

Detailed engineering geological and geotechnical investigation works were carried out. Investigation drilling was performed and 13 boreholes with a depth of 3.0 to 8.0 m (total of 66.0 m) were performed (Fig 1). In the boreholes, the groundwater level was continuously measured, and ranged from 0.4 m to 3.7 m from the ground level. Laboratory tests were performed on disturbed and undisturbed samples from boreholes.

The whole location consists of Miocene limestone marls covered with a continuous deluvial-eluvial cover (Fig. 1). Investigation works determined the leakage of groundwater at the contact between the landslide colluvium and the deluvium/eluvium or at the contact between the landslide colluvium and the substrate. A constant groundwater level was determined around the existing Suhopot stream on the southwestern edge of the landslide toe.

The landslide main body was defined by the contact of materials of different physical and mechanical characteristics. This was an active landslide that tended to expand in several directions: in the direction of the landslide movement (downwards), in the direction opposite to the direction of movement (upwards) and on both sides of the landslide.

Based on all conducted research as well as reinterpretation of previous investigations in the area, a geotechnical model of the landslide was developed, which was used for the analysis and development of a project solution for road rehabilitation.

Landslide Dedin on state road DC3 (section 015) km 2+060

The Dedin landslide was located in Dedin, which is part of the city of Delnice in the Primorje-Gorski Kotar County. The existing section DC 3 state road was constructed partly by cutting and backfilling on natural terrain – northeast part of the hill. The road structure is reinforced by stone supporting structure with existing culverts (at two locations).

Due to the landslide, the pavement was damaged by tensile cracks, which affected traffic safety. The location consists of deposits of upper triassic breccia conglomerates covered with cover material and deluvial-eluvial deposits.

Stormwater was drained by existing culverts, but mostly it naturally infiltrated into the ground through well-permeable gravel deposits and the deluvial-eluvial cover and very weathered substrate.

The landslide body is formed in the cover material and deluvial/eluvial deposits. The landslide is most likely triggered due to exceeding the strength of the near-surface materials, traffic vibrations (frequent heavy vehicle traffic) and local disturbance of physical and mechanical characteristics of deluvial-eluvial cover due to continuous atmospheric actions (Fig. 2).

Figure 2 Photo of the state road DC3 (section 015) at km 2+060 before remediation works. Tension cracks at the crown of the landslide Dedin are visible on the asphalt.

The landslide body passes through several different geotechnical units. The width of the sliding body was 15.0 m, the length was 10.0 m, and thickness was about 2.0 m. The volume of the sliding body was estimated to be about 300 m^3.

Due to unfavourable hydrogeological and geomorphological conditions, as well as terrain and road configuration (part of the road was constructed in the slope and part of the road was on the embankment), further instabilities of cover deposits (deluvial/eluvial deposits and landslide deposits) were possible. Also, new landslides could be triggered on lateral and higher parts of the slopes due to unloading (Grošić 2018a).

Landslide Vranja on state road DC500 (section 001) km 2+400

The location of Vranja landslide was in the Istria County, on the state road DC500, at km 2+400. The area of Vranja landslide is located north of the settlement of Vranje and passes through an uninhabited area along its entire length of the road. In the southwestern part of the road, there were tensile cracks 40.0 m long and 2.50 m wide.

The landslide was approximately 45.0 m wide and approximately 80.0 m long and included the lower part of the state road . The landslide also affected the slope below the state road. The road has a slight slope to the northeast, while the terrain below the road has a steep slope of up to 30° to the southwest and is forested. On the north-eastern side of the road, there are surface outcrops of rock mass. Part of the road was constructed as embankment on the slope.

During the terrain inspection of the state road and surrounding area, the elements of the landslide were determined. The crown of the landslide was represented in the form of tensile cracks on the southwestern edge of the DC500 road, while the toe of the landslide, ridges and accumulation are not clearly visible due to the vegetation and forested terrain. The sliding surface along the slope is covered with landslides colluvium and is not clearly visible. On the natural slope below the road there are traces of landslides/soil creep (irregularly inclined trees, irregular slope relief etc.). Frequent tensile cracks were observed within the road below the slope (Grošić 2020a).

According to the conducted geotechnical investigations, translational sliding of the slope southwest of the state road DC500 was determined, at km 2+400, in the part of the embankment and deluvium deposits with a sliding surface at the depth of approximately 4.5 - 9.0 m below the road embankment. This type of landslide (consequent landslide) includes deposits of cover material and deluvium whose sliding surface is formed within deluvial deposits, in contact with the bedrock made of alveolar limestones (Hungr et al. 2014). The landslide at the state road DC500 is retrogressive and the rupture surface could be extended in the direction opposite to the movement of the displaced material. Also, the deposits of the road embankment are additionally loading the landslide body. The sliding of the natural slope is conditioned by the destabilization of deluvial deposits and by the action of groundwater that seeps through at the contact of deluvial deposits and the rock base of alveolar limestones.

Landslide Dubravci on state road DC3 (section 012) km 4+400

The Dubravci landslide was located west of the Dubravci settlement, on the state road DC3, section 012 at km 4+400, Karlovac County. On the investigated part of the location, the DC3 road is passing in the general northwest-southeast direction and is formed by cutting transversely to a natural slope of approximately 25° to the southwest. The route of the road was made by partial cutting and partial filling of the existing terrain, which formed cuts along the left edge of the road and embankments along the right edge of the road. The existing embankments and cuts are unprotected, and no retaining structures are present at the location. At the left edge of the road, there are unregulated canals for drainage of rainwater, which redirect it towards the existing concrete culvert. There are numerous layers of asphalt and repaired cracks on the existing road, which indicate the systematic creeping of materials over a long period of time.

The earthquake in Banovina on 28th and 29th December 2020 caused the activation of the landslide of already potentially unstable material of the road and caused the opening of a tensile crack with a vertical height of approximately 3.5 m (Grošić 2021a).

After the terrain inspection and mapping of the location more signs of sliding were observed: open cracks, new tensile cracks in the asphalt, progress of the accumulation in the southwest direction, seepage of water at the bottom of the accumulation, dredging of the terrain and irregular sloping of the trees – Fig. 3.

The sliding body and accumulation of the material consisted of three cascade like terraces with a height of about 1.5 m between each terrace and was represented by light, water-soaked material which, due to the large mass of running material, causes the fall of trees at the base of the landslide (Fig. 4).

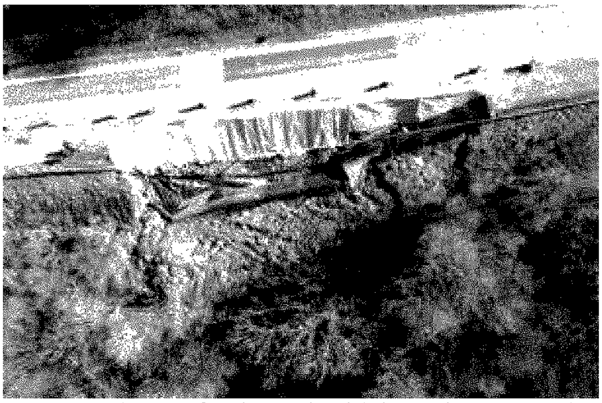

Figure 3 Aerial view of Dubravci landslide on the state road DC3 (section 015) at km 2+060.

Figure 4 Main scarp of the Dubravci landslide.

Geotechnical investigation works consisted of investigation drilling, engineering geological mapping of whole terrain and boreholes cores, and laboratory testing of samples.

On the existing road, tensile cracks were observed above and around the main crack of the landslide, inclined trees were observed on the slope below the road along the entire location, in the width of approximately 85.0 m. The width of the landslide was approximately 35.0 m and the length of the landslide was 35.0 m. Due to the weather conditions, it was possible that the landslide would further progress in the horizontal and vertical directions of the current landslide body. The depth of the sliding body at the deepest point was approximately 9.0 m from the level of the road and was located at the contact of deluvial-eluvial deposits and completely to highly weathered marls.

Based on the performed geotechnical investigation works at the location, a rotational landslide with a sliding surface of approximately 9.0 m depth was determined. The landslide included a part of the pavement structure and a part of the slope below the road. The sliding surface is formed at the contact or in the immediate vicinity of the deluvium/eluvium contact with high to medium weathered clastics. These types of landslides include deposits of cover material, cover layer and deluvial-eluvial deposits, and due to the action of water and the weight of the sliding mass, it deepens to the horizon of completely to highly weathered marls (Hungr et al. 2014). The cause of the initial activation of terrain sliding is most likely inadequate slope drainage and overloaded high frequently traffic. After the earthquake the landslide progressed rapidly and there was a final failure of the whole terrain.

Remediation measures design

Landslide remediation works along state roads need to be approached with increased attention and regarding requirements from investors. As these are state roads, they present the roads and connections of particular importance that connect the territory of the Republic of Croatia with the network of major European roads.

One of the conditions for remediation is to leave at least one traffic lane permanently or temporarily open (when it is possible), because these roads sometimes represent the only way for buses, supplies, firefighters, and ambulances to pass.

Following chapters of the paper, present stability analysis of the landslides and remediation measures (Popescu 2001) with a technical description of remediation works for each of the mentioned landslides.

Landslide Laz 18 on state road DC29 km 38+254

Remediation measures for the Laz 18 landslide were divided in two zones - zone I (includes remediation works of the upward part of the slope above the road curve) and zone II (includes protection of the side part of the road curve).

The stability analysis was carried out in Plaxis 2D software two phases and was carried out separately for the two zones. First, the current state was modelled, and a reverse stability analysis was performed to obtain the actual strength parameters of the geotechnical units. In the following phase, the proposed design solution was modelled and verified to confirm the stability and to determine the forces and moments for dimensioning of the structural elements (piles, walls, anchors). The model used for stability analysis of the remediation measures for zone I is presented in Fig. 5 (Bentley Systems 2020).

Remediation measures of zone I consisted of reinforced concrete bored piles, in two rows, with a diameter D = 600.0 mm at a horizontal distance of 1.0 m. Designed pile length was from 5.0 m to 8.0 m . Above piles, a reinforced concrete "L" pile cap was constructed as foundation structure for a retaining wall – Figs. 5 and 6. Remediation measures of zone II consisted of a pile wall of bored piles in one row with a diameter of D = 600.0 mm, length from 5.0 m to 8.0 m at a horizontal distance of 1.80 m each. A reinforced concrete pile cap was constructed above the piles. Self-drilling anchors with a length of 12.0 m at an axial distance of 3.60 m were installed through the pile cap (Grošić 2019b).

Landslide Dedin on state road DC3 (section 015) km 2+060

As a design solution for the remediation measures of the landslide Dedin, the construction of a reinforced concrete

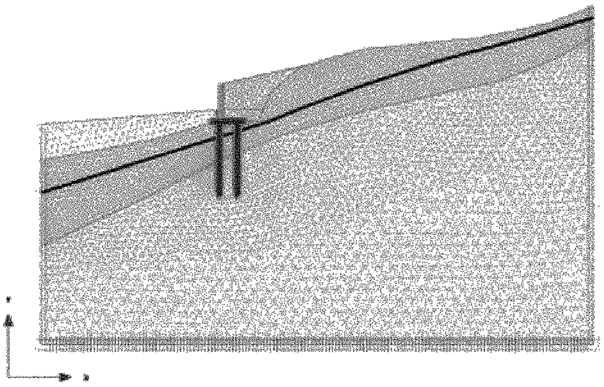

Figure 5 Numerical model used for geotechnical analyse of zone I (reinforced concrete wall with piles) for landslide Laz 18, performed in Bentley Plaxis 2D software.

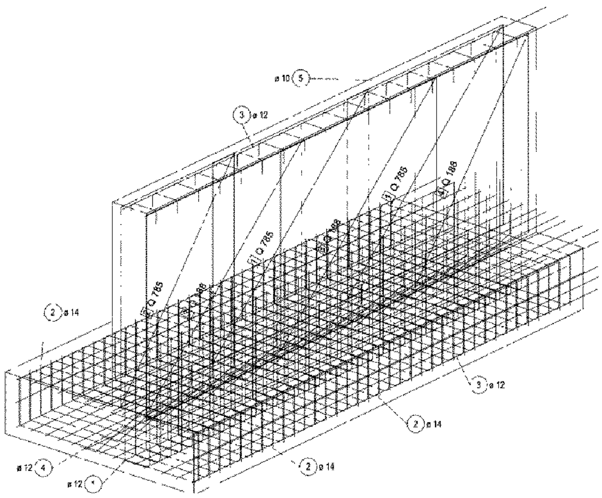

Figure 6 3D BIM model of reinforcement plan of the concrete pile cap and wall of zone I for landslide Laz 18 created in Allplan (Allplan Nemetscheck Group GmbH 2020).

retaining wall was chosen, which was constructed on bored piles. The pile wall was made of reinforced concrete bored piles with a diameter D = 400 mm, pile lengths were L = 3.50, 4.50 and 5.0 m respectively.The horizontal distance of the piles were 1.0 m and piles were embedded into the rock base at least 1.50 m. In this way, the stability of the retaining structure was ensured, and the pile wall was used not only for the foundation of the retaining wall but also for ensuring higher slip resistance of the whole geotechnical construction. Piles, with their whole length, passed through the landslide body and thus significantly contributed to the increase of the safety factors of the whole slope. Additional stability was provided by the construction of self-drilling rod anchors with a total length of L = 12.0 m with an anchor bond length of L_b = 6.0 m.

As part of the remediation measures works, the whole drainage system of the road (transverse and longitudinal slopes of the road, drainage channels) was completely reconstructed, and a new culvert was built. The outflow part of the new culvert with channels were constructed and water was drained from the impact area of the landslide area – Fig. 7 (Grošić 2018b).

Figure 7 Dedin landslide on state road DC3 (section 015) at km 2+060 after remediation works.

Landslide Vranja on state road DC500 (section 001) km 2+400

The length of the landslide remediation work was 65.0 m, and it consisted of bored piles D = 600 mm in one or two rows (depending on the remediation zone and geological conditions of the site). At the start of work, a temporary barrier was installed (New Jersey bumpers) and temporary traffic control was established. Temporary excavation for the construction of a pile wall and retaining wall was excavated at a slope of V:H = 2:1.

Bored piles were installed through the cover material and embedded into the rock base. Piles of length L = 4.50 and 7.0 m were constructed in one or two rows at an axial distance of 1.80 m – Fig. 8. The transverse distance of two rows of piles was 1.20 m. Request for minimal depth of embedding into the rock mass (limestones) was 1.80 m to ensure required load and moment transfer into the bedrock (Grošić 2020b).

Landslide Dubravci on state road DC3 (section 012) km 4+400

Remediation works on Dubravci landslide were performed by the combination of pile wall and a mechanically stabilized earth (MSE) retaining wall. Bored piles had a nominal diameter of D = 880.0 mm and length of 10.0 m. An axial distance between the piles was 2.50 m in the longitudinal and transverse directions. For the proposed remediation solution stability analyses were performed – Fig. 9 (Bentley Systems 2020). As part of the preparation phase, temporary excavation was conducted for approaching of machines for piles installation. The excavation, and whole remediation works, were conducted in several phases to avoid further instabilities on the slope

Figure 8 Remediation works on pile wall at Vranja landslide.

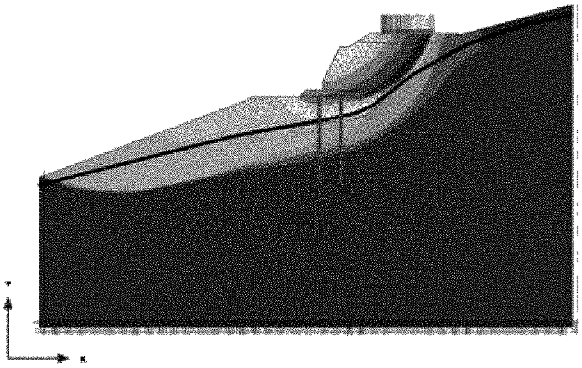

Figure 9 Results of stability analyses for factor of safety of proposed remediation solution for Dubravci landslide performed in Bentley Plaxis 2D software.

and road. After the excavation and construction of piles, the foundation of the soil was prepared and improved by mechanical compaction (Ms>20.0 MN/m^2) and geotextile installation. Two layers of a mechanically stabilized granular stone material (granulation of Ø0-63 mm) was installed with a total thickness of 75.0 cm. Between two layers of mechanically stabilized granular stone material, the layer of geogrid was installed.

Above the mechanically stabilized granular stone material, a gabion support structure with tensile elements was constructed. An embankment of stone and mixed material with a final slope of V:H = 2:1 was made behind the gabion retaining structure (Fig. 10). Hydro seeding was applied on the surface of the slope.

In the part of the location where there were no significant instabilities, the construction of a pile wall consisted of bored reinforced concrete piles with length L = 10.0 m, nominal diameter D = 620.0 mm in one row at an axial distance of 2.25 m, Piles are connected with a reinforced concrete pile cap 0.50 x 0.80 m. Together with the landslide remediation works, the reconstruction of road layers and reconstruction of a stormwater drainage system was performed (Grošić 2021b).

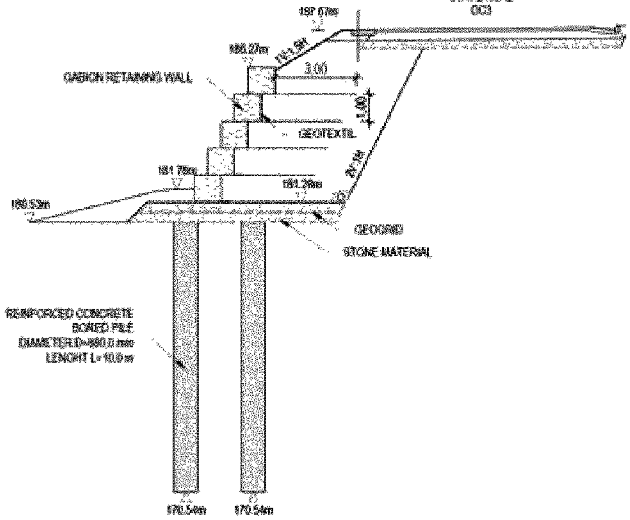

Figure 10 Characteristic cross section of remediation measures for Dubravci landslide.

Discussion

The paper presents the geotechnical investigation works and remediation solutions for 4 landslides on state roads in Republic of Croatia: landslide Laz 18 on state road D29 in section 38+254, landslide Dedin on state road DC3, section 015 in section 2+060, landslide Vranja on state road DC500, section 001 in section 2+400, landslide Dubravci on state road DC3, section 012 in section 4+400.

The causes of landslides are conditioned by unfavourable geology, inadequate drainage systems, earthquakes, excessive traffic loads and usually a combination of these conditions. Among these landslides we also participated in the numerous remediation projects of state roads, and it can be concluded that a special and frequent trigger of landslides cannot be isolated. In most cases it is a combination of one or two unfavourable causes that trigger landslides.

For each of these landslides, detailed geotechnical investigation works were conducted to determine the landslide mechanism, the layout of geotechnical units and the parameters required for the geotechnical numerical analysis. Remediation measures mainly consisted of bored piles (diameter from 600 mm to 900 mm) in a combination with a pile cap or/and retaining wall. Sometimes, anchors are used for additional protection and safety. The pavement structure and complete reconstruction of drainage system in the impact area were always performed alongside the geotechnical remediation works. This type of reconstruction is most common along not only the state roads but also on the other roads because it has proven to be an ideal combination of performance technology and design solution.

Acknowledgements

This landslide remediations case studies were made to protect and ensure stability of state roads and to ensure safe traffic for the investor Hrvatske ceste d.o.o., Vončinina 3, HR 10000 Zagreb. The geotechnical investigations, geotechnical report and slope protection design were carried out by Geotech d.o.o., Ciottina 21, HR 51000 Rijeka.

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Deep landslide in the jointed flysch sediments on the Bar-Boljare Highway, Montenegro

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Abstract The subject of the paper is a case study of a deep landslide that formed in the jointed flysch sediments on the Bar-Boljare highway, Smokovac-Mateševo section, Montenegro. The landslide has affected 140 m of the left highway lane in the cut and has endangered the Uvač 4.1 bridge abutment. The landslide displacement first occurred in May 2019 and continued to intensify in early June of the same year. The cause of the instability occurrence is in the unsecured temporary subvertical cut (approximately 15 m high) constructed between left and right lane of the highway. The landslide was formed in the flysch formation, which consists of an alternation of sandstones and siltstones with a developed joints system. The landslide was initiated in the northern part of the site, where a wedge failure occurred (average block size 4 – 6 m), resulting in the formation of a 50 m wide unstable zone. The instability further propagated along the slope towards the southern part of the site, where a second sliding body was formed, the movement of which caused the displacement of the retaining wall and the bridge abutment. The total length of the landslide along the slope is about 80 m. This was further confirmed by a simple kinematic analysis. One of the unfavourable circumstances is the presence of a 2 to 3 m wide fault zone, so that the landslide zone partially propagated through this weakened zone. The whole mechanism of the process caused appearance of a clearly visible frontal scarp in the rock mass about 110 m long and a transverse crack separating two unstable masses (northern and southern) about 70 m long. Assessment based on the geotechnical investigation and inclinometer data suggests that the deepest points of sliding zone vary are between 17 and 22 m. Slope stability analysis was performed on typical cross-sections to confirm the assumed sliding mechanism and to obtain numerical parameters for design of remediation measures. The analysis was performed using Slide and RS2, Rocscience software. Based on the results of the geotechnical investigation, inclinometer data and numerical analysis it was concluded that the unfavourable position of discontinuities in the rock mass was a predisposing factor for the landslide occurrence. This refers primarily to the joint sets, since the orientation of stratification is relatively favourable from the aspect of slope stability, which is atypical for this zone and is rarely the case for unstable flysch slopes. One of the characteristics of the landslide is also a high-quality rock mass composed mainly of sandstones and also affected by sliding. The landslide was remediated in 2021 through a combination of several types of remediation measures that included construction of bored piles with a diameter of 150 cm and a depth of 20 m with a cap beam, prestressed geotechnical anchors up to 30 m long connected with a reinforced concrete grid, 6 m long bolts, and surface and underground terrain drainage.

Keywords flysch, landslide, mechanism, remediation

Introduction

The subject of the paper is a case study of a deep landslide formed in the jointed flysch sediments on the Bar-Boljare highway, Smokovac-Mateševo section, Montenegro. In flysch terrains, Quaternary layer usually slides over the bedrock (Živaljevic et al. 2021), while in this case, due to the unfavourable orientation of discontinuities in the rock mass, sliding occurs through a more solid rock mass.

After a brief description of the site morphology and geologic conditions, the paper focuses on a detailed description of the key elements of the landslide and sliding mechanism. The paper presents the results of numerical analysis of the slope stability on a typical profile as evidence of the sliding mechanism that has been assumed based on the geotechnical investigations and inclinometer data. A brief description of the remediation solution is also provided.

Study area

Topography and landform

The landslide is located on the left slope of the open route of the Bar-Boljare highway, Smokovac-Mateševo section, on the chainage from km LK 33+280 to LK 33+420 (Fig. 1). The right lane extends along the bridge Uvač 4.1. The site is located on the eastern mountainside of Vitanovica above the Tara river.

From the aspect of geomorphology, the overall terrain route is quite complex and rugged and can be generally classified as hilly and mountainous relief. At the micro location, morphometrically, it is a slope with an inclination of 35° to the east.

During the period of the landslide activation, the morphometry of the natural terrain changed due to the executed earth works for the construction of the highway. Seen from above, the following morphometry parts can be identified: a plateau at an elevation of about 1104 m a.s.l., from which the abutments of Uvač 4.1 bridge on right lane rise; a steep rock section formed between the left and the right lane with a height of 20 m; a 14-15 m wide plateau within the area of the left lane of the highway at the elevation of about 1124 m a.s.l.; a 7-8 m high retaining wall along the left edge of the left lane with an inclination of about 5:1. Three benches are constructed above the wall: first bench is 5 m high with an inclination of 3:1, and the other two benches are 5-7 m high with an inclination of 3:2. The berms are constructed between the benches; the slope crest is at an elevation of 1144 m a.s.l., followed by a natural slope with an inclination of about 35°.

Geological conditions

In the wider area of the landslide, the highway extends through flysch sediments of the Cretaceous-Paleogene age. The thickness of these sediments is about 500 m.

In terms of lithology, the micro location is dominantly featured by the engineering-geological (EG) unit 2d, which means that it has a similar ratio of sandstone and alevrolite.

Figure 1 Landslide position.

The prevailing presence of sandstone (EG unit 2a) is found at greater depths and eventually at lower thickness in the upper zone. The thickness of the silty-clayey materials varies from 0.5 m in the steeper parts of the slope to 4 m in the higher parts of the slope with lower inclination. The deluvium is absent from the large part of the micro location, because of the executed cut and major earthworks in this zone of the highway.

General bedding orientation is favourable from the aspect of the slope stability. This was further confirmed by EG mapping which registered bedding planes orientation of 215-310/10-35, indicating a southwest-northwest orientation of bedding, sufficient for stability of the east-facing slope. Alevrolite (siltstone) is platy and tabular and sandstone is thin bedded to bedded. Where laminae occur in the rock mass texture, they have orientation of the bedding dip.

The joint system is clearly defined and shown on EG map (Fig. 2). According to the mapping, the bedding discontinuities are followed by two more dominant steep joint sets. A zone between boreholes BIP-5 and BIP-2 is typical and is considered to be the zone where the sliding process has been initiated, as two joint sets were registered with dip direction/dip angle (EP) 40-55/55-70 and a subvertical set which falls at very steep angle either on direction 130° or on 310°. The two joint sets can cause sliding of blocks down the slope; hence this occurrence is considered to trigger the slope instability. In addition to these two dominant joint sets, with deviations of up to 20°, there are also joint sets in the zone of the abutments of the Uvač 4.1 bridge of 165/70 and 95/87, as well as 325-335/35-50 in the zone of BIP-7 and BI-1 boreholes. The geotechnical category P represents a deluvial-eluvial zone which is very thin, while category F represents the exceptionally poor flysch rock mass, i.e. a degraded and altered zone of the bedrock which is mainly present at the first (highest) bench of the slope excavation. Further on, the second and third benches are dominated by an E category rock mass, which is represented by clear texture properties of rock mass without zones that would characterise it as a rock to soil transition. Geotechnical categories F and E are related to the EG unit 2d.

Thereafter there is a dominant presence of sandstones (2c) that, due to their resistance, are automatically less fractured with two joint sets at larger distance and with a bedding plane also at larger distance. This is a D category of the rock mass.

Overview of the landslide and landslide mechanism

The information about the landslide development and the problem of slope instability was obtained from the Contractor of works. The first deformations occurred in May 2019 and intensified in early June.

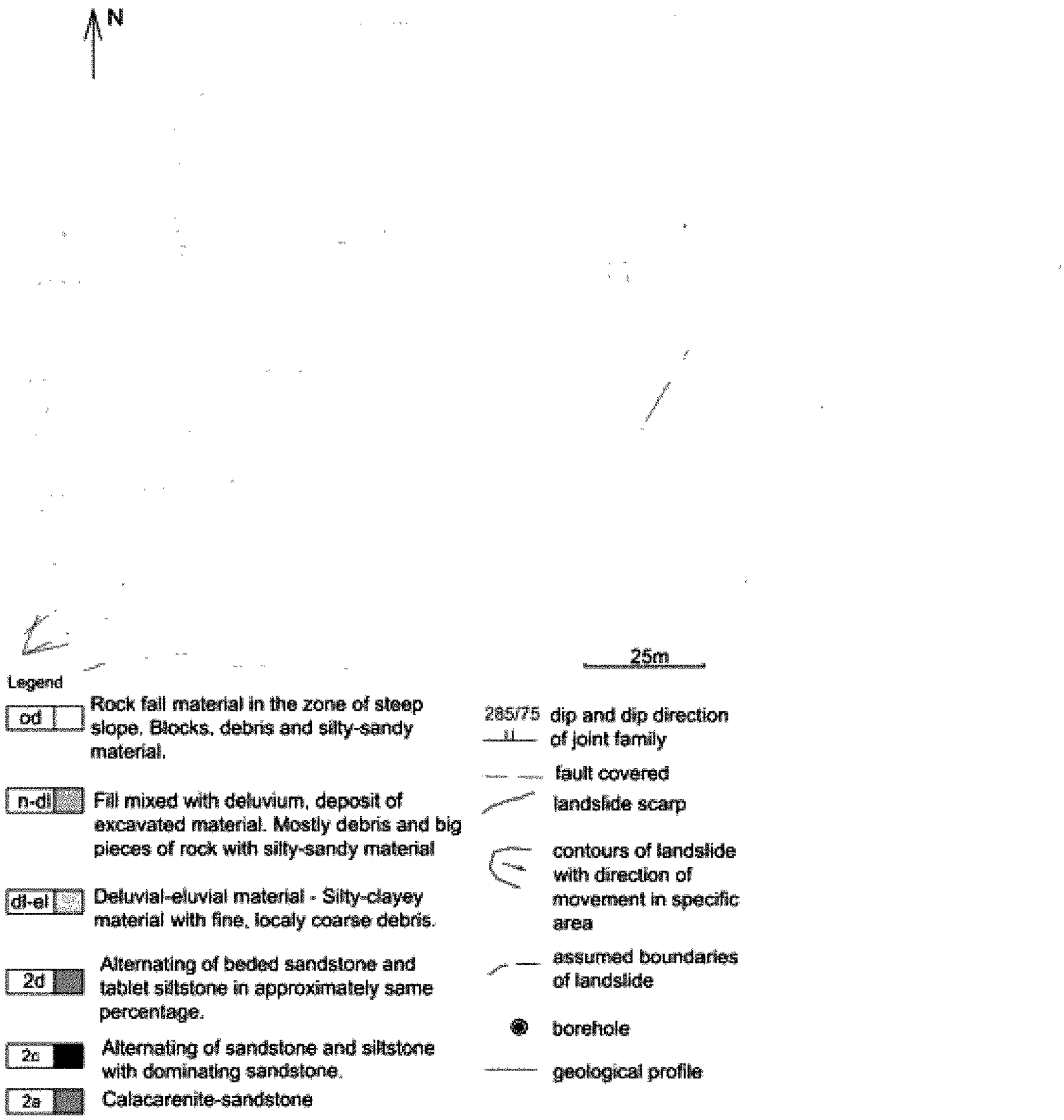

Figure 2 Simplified engineering-geological map with characteristic photos from the site: a Scarp, b Fallen rock blocks due to wedge failure, c Abutment of Uvač 4.1 bridge (Međedović 2019).

Based on the analysis of the data relating to the affected landslide, it can be said that the sliding of a rock mass with an estimated volume of about 50000 m^3 has started, which can be attributed to the unfavourable rock mass discontinuity set and inadequate cut-and-fill slopes, as well as the absence of any kind of terrain protection measures in the northern part of the micro location behind the retaining wall (Fig. 2) and also between the left and the right lane of the highway (Fig. 2c). The cause of the instability is not the cut in the open route, but the subvertical cuts between the left and right lane as well as the temporary cut in the northern part of the site. Namely, the cut between the left and right lane of the highway is steep to subvertical, with a height of about 15 m. The cut in the northern part of the location behind the retaining wall also has a similar geometry. The length of cut between the two lanes is approximately 70 m, while the length of cut-and-fill slope behind the retaining wall is approximately 50 m. No support measures were provided for these two cuts. This means that the uncontrolled earthworks had crucial impact on activation of the sliding process, which endangered the slope, the retaining wall and the bridge abutment. About 25-35 m above the slope, a scarp is formed at the contact with the huge calcarenite block within flysch. The scarp is about 90 m long with locally clearly visible jump from 1.5 to 3.0 m and spreading of up to 1 m. Number of secondary scarps with a jump of up to 1.5 m is observed between the slope and the main scarps. Some vertical joints are visible on the third bench. A very significant scarp in the length of 70 m is registered at some 10 to 12 m from the top of the cut, beyond the highway zone (above borehole BIP-5), Fig. 2a. This scarp extends even to the retaining wall where it affects the last two benches that have displaced the most. A joint is clearly visible on the third bench of the slope.

Kinematic analysis of the rupture composition, inclination and orientation of the slope determined the wedge forming and rock block falling in this zone. The block falling because of the wedge forming is a common phenomenon, however, in this case blocks of enormous dimensions are formed, which would probably initiate the instability of the entire zone (Fig. 2b). Based on the kinematic analysis, the central part of the hillside and the slope is also prone to the block falling, which is further confirmed by the kinematic analysis in that zone.

Mapping the zone around the bridge abutment on the south hillside (abutment L1O2) recorded a fault zone extending from the abutement towards the top of the hillside. This fault zone can be tracked on all cut-and-fill slopes of the access road in the southern part of the hill. The zone width ranges from 2 to 3 m. The material consists of debris with dusty-sandy component. The elements of the fault dip are approximately 95/60.In addition to the instability that occurred in the northern part of the site, this fault also presented a very unfavourable situation in this part of the site, and it is considered that the sliding plane has partially formed through this weakened zone, as shown in the cross-section 3-3' (Fig. 3).

The south edge of the landslide is defined by subvertical joints with EP 20/90 that are formed on the slope between the two lanes of the highway. These joints are located at about 15-20 m from the abutment towards north.

The EG terrain composition based on the investigation works is shown on the EG cross-section 3-3' (Fig. 3). The figure clearly shows the main and secondary scarps which have been determined by the EG terrain mapping. The toe area of the landslide is not defined considering this part of the site is covered with backfill material. Based on the geodetic monitoring and the inclinometer structures built in the boreholes, the slip surface has been interpreted as marked by the red line. Considering that the inclinometer BI-1 measured certain deformations (not necessarily suggesting the slip surface) at greater depth (approximately 20 m), the magenta colour has been used to mark the unfavourable slip surface at the greater depth, so that this input could be considered in the construction design as the unfavourable scenario when defining protection measures. Precise defining of these deformations required a longer period of time and additional inclinometer measurements. However, considering the urgent nature of the slope stabilisation subject to the timeline of the highway construction, the Designer was instructed to also consider the protection measures for the unfavourable scenario.

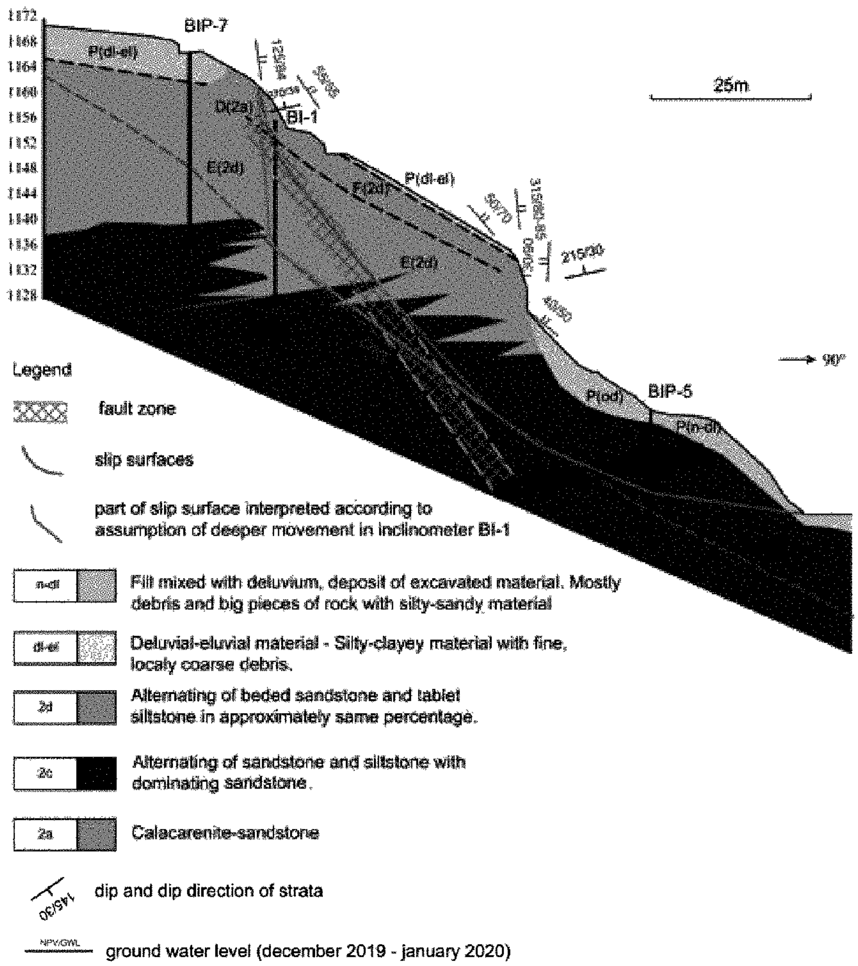

Figure 3 Engineering-geological cross-section 3-3' (Međedović 2019).

Stability analysis

Slope stability analysis were performed on three typical cross-sections to confirm the assumed sliding mechanism and to obtain numerical parameters for design of remedial measures. The analysis was performed by using Slide and RS2, Rocscience software (Rocscience 2021). A standard back analysis based on the method of slices (Bishop simplified, Janbu simplified, Janbu corrected, Morgenstern-Price) with the unfavourable position of the sliding surface was used (Abramson et al. 2001, Rocscience 2021). The back analysis was conducted by varying the shear strength parameters for the slip surface until a factor of safety (FoS) of approximately 1 was obtained. The results of the analysis for profile 3-3' are shown in Fig. 4. It can be seen that the obtained average internal friction angle is about 30° while the adopted cohesion is 0 kPa. The RS2 programme was used to perform the back analysis on a 2D model consisting of linear triangular finite elements by using the shear strength reduction method (You et al. 2018). Tab. 1 shows the physical and mechanical parameters used for the corresponding rock masses. Joints have been modelled by the interface elements. The shear strength parameters for these elements have been varied until Strength reduction factor (SRF) (equivalent to FoS) of approximately 1 was obtained. The adopted joint system has been simplified and represented by 2 joint sets, one out of which with a downslope grade of 80° and the other with a downslope grade of 35°, corresponding to dominantly unfavourable sets on the EG profile 3-3'. The results of the analysis indicate that the sliding mechanism of the trapezoid-shaped sliding surface over the adopted joint sets with the 35° inclined sliding surface and sliding surface depth of 13.80 m (Fig. 5).

Landslide remediation

The landslide remediation was performed in 2021 through a combination of several types of remediation measures that included (Figs. 6 and 7):

- construction of bored piles with a diameter of 150 cm and a depth of 20 m with a cap beam,
- prestressed geotechnical anchors up to 30 m long connected with a reinforced concrete grid,
- 6 m long bolts,
- surface and underground terrain drainage.

Table 1 Computation parameters of rock masses (RS2 software).

Rock mass	γ (kN/m³)	ϕ' (°)	c' (kPa)	Young's modulus (kPa)
D (2c)	25.0	32	2500	2.5e+06
E (2d)	23.5	29	320	800000
F (2d)	23.0	26	50	60000
P3	21.0	30	10	40000
Fault	23.0	21	5	60000

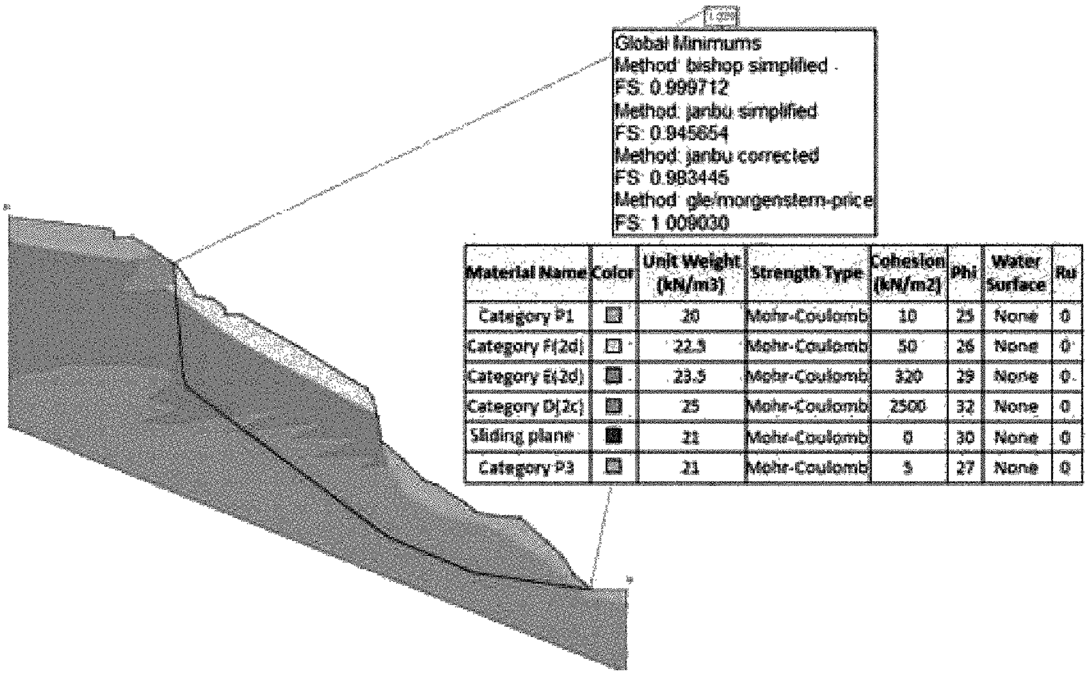

Figure 4 Results of the back-analysis conducted in Slide software.

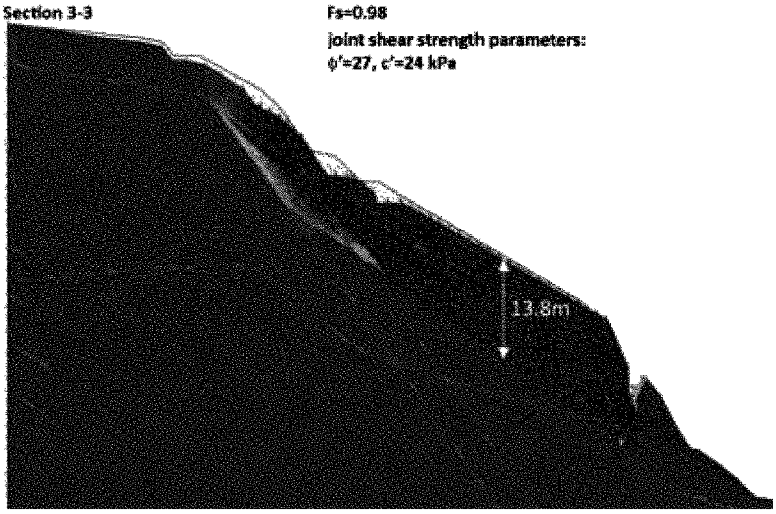

Figure 5 Results of back-analysis conducted in RS2 software.

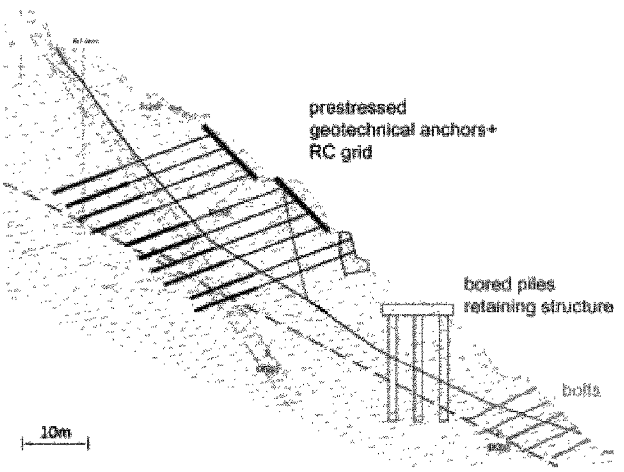

Figure 6 Cross-section with remediation measures.

Conclusions

Case study of a deep landslide formed in the jointed flysch sediments on the Bar-Boljare highway, Smokovac-Mateševo section, Montenegro was presented in this paper. Based on the results of geotechnical investigations, inclinometer data and numerical analysis it was concluded that the unfavourable position of discontinuities in the rock mass was a predisposing factor for the landslide occurrence. This primarily refers to the joint sets, since the orientation of stratification is relatively favourable from the aspect of slope stability, which is atypical for this zone and is rarely a case in unstable flysch slopes. Designed remediation measures are based on conducted stability analysis.

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GEOLOG

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Proceedings of the 5th Regional Symposium on Landslides in Adriatic Balkan Region

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