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Remediation of landslides on railway line between Karlovac and Mrzlo Polje stations

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Professional paper

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A number of landslides occurred soon after construction (in 1963) of the section of the railway line M202 Zagreb Main Station - Rijeka, between the Karlovac Main Station and Mrzlo Polje. These landslides have been protected using various local remediation measures. As the sliding intensified in early 2013 due to increased precipitation, quick action was needed to preserve the functionality and safety of the railway section and the structures on the platform above the cutting. This paper therefore chronologically presents landslide remediation phases, starting from investigation works, design preparation, and construction work.

Key words:
landslide, remediation, railway line M202 Zagreb GK-Rijeka, reinforced soil, material replacement

Stručni rad

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Sanacija klizišta na željezničkoj pruzi između kolodvora Karlovac i Mrzlo Polje

Nedugo nakon izgradnje dionice željezničke pruge M202 Zagreb Glavni kolodvor – Rijeka (1963.), između kolodvora Karlovac i Mrzlo Polje, pojavila su se klizišta koja su tijekom godina štićena različitim lokalnim mjerama sanacije. S obzirom na to da su se klizanja intezivirala početkom 2013. godine uslijed povećanih oborina, nužno je bilo brzo djelovati da se ne bi ugrozila funkcionalnost i sigurnost te dionice i građevina na platou iznad usjeka. U radu su stoga kronološki prikazane faze sanacije klizišta, počevši od provođenja istražnih radova, izrade projektne dokumentacije te same izvedbe.

Ključne riječi:
klizište, sanacija, pruga M202 Zagreb GK – Rijeka, armirano tlo, zamjena materijala

Fachbericht

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Erdrutschsanierung auf der Bahnlinie zwischen den Stationen Karlovac und Mrzlo Polje

Kurz nach dem Bau des Bahnabschnitts (im Jahre 1963) Polje der Linie M202 Zagreb Hauptbahnhof – Rijeka ist zwischen den Stationen Karlovac und Mrzlo eine Reihe von Erdrutschen aufgetreten, die im Laufe der Zeit durch verschiedene lokale Eingriffe saniert wurden. Da sich seit Anfang des Jahres 2013, aufgrund erhöhter Niederschläge, die Erdrutschgefahr intensiviert hat, sind prompte Eingriffe notwendig, um die Funktionalität und Sicherheit des Abschnitts und der Objekte, die sich auf dem Plateau über dem Einschnitt befinden, nicht zu gefährden. In dieser Arbeit werden die Phasen der Erdrutschsanierung, einschließlich Forschungsarbeiten, Erstellung der Projektdokumentation und Ausführung, chronologisch dargestellt.

Schlüsselwörter:
Erdrutsch, Sanierung, Bahnlinie M202 Zagreb GK – Rijeka, bewehrter Boden, Materialersetzung

1. Introduction

In 1963, the construction work started on a new 3 km long section between Karlovac and Mrzlo Polje stations, on the railway line M202, Zagreb Main Station – Rijeka. This railway section was built so as to avoid a number of railway - road crossings, and to improve train operating parameters at this railway section.

However, most parts of the section were affected by landslides that formed on cutting slopes a short time after the end of construction work. Thus, eight year after the railway was built, i.e. in 1975, the remedial work, involving RC piles and prefabricated walls, was carried out on five locations. Other five locations along the said section, where the landslide occurred at a later time, were remediated by makeshift remedial measures including foundation soil removal, and construction of a temporary protection wall formed of rails and wooden sleepers. These local remedial actions are presented in Figure 1.

As safety and functional aspects of the railway were put into jeopardy due to acute deterioration of temporary protection structures, and considering the fact that the stability of privately owned homes and facilities situated along the top platform of the cutting would be greatly endangered by the sliding, the Client, Hrvatske Željeznice d.o.o., engaged the company Geoekspert d.o.o. to conduct laboratory and in-situ investigations [1] and to prepare preliminary design for the remedial work [2]. This activity was completed in November 2010. In the late 2011, the terms of reference were prepared for the landslide remediation detailed design. This detailed design was prepared by the Faculty of Civil Engineering of the University of Zagreb.

However, before completion of the detailed design documents, in the early 2013, the sliding action intensified to such an extent that the functionality and safety of the railway section and the private property units on the platform above the cutting were gravely imperilled. The landslide activity increased following the period marked by intense precipitation, i.e. heavy rain and snow. The combined action of intensive precipitation and saturation of the surface layer with waste water generated in the nearby housing units situated near the crown of the slope, called for urgent remedial activity. The completely deformed prefabricated concrete wall is shown in Figure 2.a. In order to temporarily stop further degradation, various improvised protection measures were implemented, such as the ones presented in Figure 2.b, involving 8 driven rails supporting makeshift protection elements.

Figure 1. Remediation by: a) prefabricated concrete wall; b) wall made of driven rails and wooden sleepers

Figure 2. Degradation of implemented remediation measures: a) completely deformed prefabricated concrete wall; b) makeshift slope protection structure

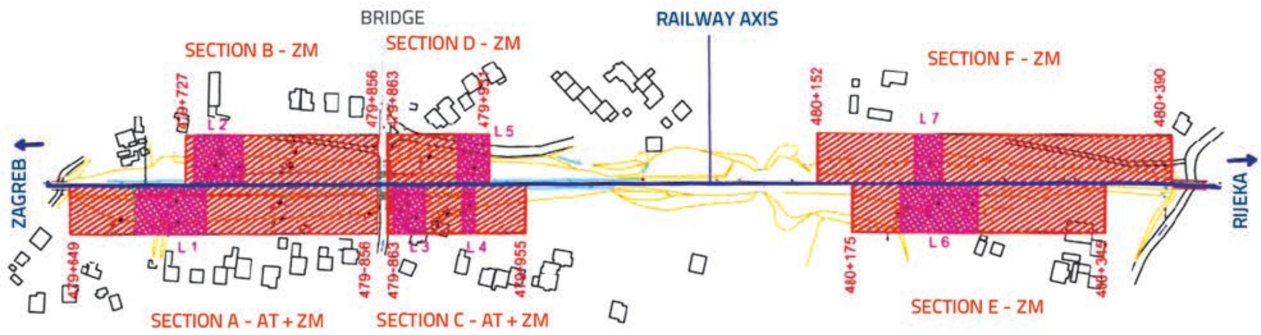

Figure 3. Remedial work status (AT – reinforced earth wall; ZM – material replacement)

Table 1. Comparison between remediation works planned in the preliminary design and those actually conducted in accordance with the detailed design

		Preliminary design			Detailed design		
		Chainage [km]	Location	Length [m]	Chainage [km]	Length [m]	Volume [sections]
DIRECTION (Toward higher chainages)	D	479+693 do 479+740	L1	47	479+649 do 479+856	207	1 [A]
	L	479+733 do 479+765	L2	32	479+727 do 479+856	129	2 [B]
	D	479+867 do 479+888	L3	21	479+863 do 479+955	92	3 [C]
		479+914 do 479+921	L4	7			
	L	479+910 do 479+931	L5	21	479+863 do 479+931	68	4 [D]
	D	480+210 do 480+260	L6	50	480+175 do 480+345	170	5 [E]
	L	480+220 do 480+235	L7	15	480+152 do 480+390	238	6 [F]
				Σ 193		Σ 904	

The influence of climate change on landslides, such as the landslide depicted in the section under study, is a highly topical issue that has been thoroughly investigated both at European and worldwide levels. For instance, the COST (European Cooperation in Science and Technology) Action TU1202, entitled *Impact of climate change on engineered slopes for infrastructure*, calls for urgent evaluation of the impact of weather change on transport infrastructure, and places emphasis on the need to plan measures that will improve safety and reduce rehabilitation costs.

Highly aware of the seriousness of the new situation, the Faculty of Civil Engineering divided, in concert with the Client, the detailed design documentation into several stages [3-8] so that a particular stage can be implemented as soon as the corresponding design activity is completed. Thus the current stage of construction work was carried out in parallel with the design of the oncoming stages. The construction works were realized by the Rijeka-based Monterra d.o.o. company.

Already at the stage of preliminary design, the entire project was divided into several sections for which slope remediation activities were considered necessary. However, due to intense precipitation, the sliding affected an area that is much greater than that anticipated in the preliminary design. In addition, further detailed engineering-geological site investigations were carried out before the design preparation and, according to results obtained in the course of these investigations, the instabilities defined during previous investigations progressed significantly, and new instabilities were noted in the body of the slope. That is why the sections, i.e. remediation segments, marked as unstable in the preliminary design, were additionally extended after consultations with the Client. The view of the extended sections is shown in Figure 3, while the comparison of sections planned in the preliminary design with sections included in the detailed design is given in Table 1. At the time this paper was being prepared, the remedial work was completed at landslide sections A, B, C, and D, while the remediation of the remaining two sections, for which design documents are ready, is soon to be undertaken.

Basic stages of the project will be presented in the paper: from preliminary investigations and preparation of design documents for all sections, to the realization of remediation works at sections A, B, C, and D.

2. Preliminary investigations

The following works were conducted in the scope of preliminary investigations: visual inspection of the terrain, on-site borehole drilling, piezometric measurements, inclinometer measurements, and laboratory testing. The investigation results are described in the corresponding report [2]. Additionally, engineering-geological site investigations was conducted, two boreholes were drilled and samples from these boreholes were tested in laboratory [9]. This enabled establishment of engineering-geological sections showing appropriate physicomechanical properties of materials, which were used in the design work.

2.1. Visual inspection of landslide and existing remediation measures

Active zones, approximately 20 m in width, and the presence of tensile joints in the part behind the front of the sliding body, are visible at Section A (right-hand side, before the bridge, Figure 3). The temporary protection concrete grillage structure was realized at the landslide toe of the Section A. This structure was insufficient to provide a more durable stabilisation, and the movement of material from the sliding body, and all the way to the drainage channel, was registered at several occasions during auscultation measurements. The section B is situated on the side opposite to section A (left-hand side, before the bridge, Figure 3). It is at this part of the railway that first landslides were registered, and so the first temporary protection structures, consisting of driven rails (I-sections) and wooden sleepers (Berlin-type retaining wall), were used at this section. This structure proved relatively good in stopping the sliding action, and so it did not reach the sliding intensity registered at Section A. Somewhat wider active sliding zones, measuring about 30 m in width, can also be seen at the right-hand side, after the bridge (Section C). A temporary protection structure made of steel rails and wooden sleepers was realized at the landslide toe. However, it proved insufficient for a more durable stabilisation. The temporary protection structure situated at the start of the Section D cutting, composed of driven rails (I-sections) and wooden sleepers (Berlin-type retaining wall), and continuing as a concrete fence, did a relatively good job in stopping the landslide, which did not reach the intensity registered at the neighbouring sections. However, this protection structure was still unable to ensure a more durable stabilisation of the slope. A public road called Ulica Galović brdo is situated at the top platform of the cutting above the Section D. It is located in front of the private property units whose stability has been compromised by the sliding actions. No landslide protection structures were registered at sections E and F.
According to the type of sliding action, it can be concluded that this is a potentially multiple retrogressive landslide, which occurs through reiteration of a number of individual relatively thin-shallow sliding surfaces, or shear zones. It should be noted that intensive sliding at the location under study is the result of intense precipitation and waste water disposal.

2.2. In-situ investigations and laboratory testing

An overview of in-situ investigations carried out at individual sections is given in Table 2.
Inclinometer measurements conducted in 2010 pointed to the fact that the landslide is constantly active. Some displacements (although less pronounced) were also noted at the parts of the landslide that were considered to be fully remedied. Slip planes are relatively shallow, measuring from 1 to 3 m in depth along the entire section, which corresponds to other parts of the landslide with the same type of soil, and to laboratory test results (soil layer with greatest liquid limit and a small consistency index).
The terrain classification was made in the course of the drilling. Cores extracted from boreholes were photographed, and samples for laboratory testing were selected. The following tests were made in laboratory: identification tests aimed at determining general properties – dry density, grain density, natural moisture content, liquid limit, plastic limit, and plastic index, grain size distribution, as well as tests aimed at determining shear strength and uniaxial compressive strength, including compressibility testing in oedometer. The groundwater was registered in piezometers at sections A and B (sections before the bridge), and this at a relatively great depth (from about 8 to 9.5 m), in silty-sandy-gravelly materials in the substratum. A consistent level of groundwater was not registered within the reachable depth at piezometers at other locations, although the piezometers ended in the same type of soil as in sections A and B. Considering the situation in a wider area, groundwater may be expected as greater depths. As no increase in the groundwater level above the expected range was noted, it may be assumed that there is no pressurized water of subartesian character in the area under study.
Based on investigations conducted on the project site, it was established that the soil composition on the railway section to be remedied is of mostly uniform composition along the entire railway stretch. Layers of highly plastic very firm clay, which are locally silty, were found under the topsoil 20-30 cm in thickness. The thickness

Table 2. Overview of in-situ investigations, by sections

		Number of boreholes / preliminary design	Drilling length in m / preliminary design	Piezometers /preliminary design	Inclinometers /preliminary design
SECTION	A	5	50	1 x 10 m	2 x 8 m
	B	5 (1)	46 (20)	1 x 10 m	2 x 8 m
	C	5	48	2 x 10 m	2 x 8 m 1 x 12 m
	D	2 (1)	18 (20)	1 x 10 m	1 x 8 m
	E	3	26	1 x 10 m	1 x 8 m
	F	1	8	-	1 x 8 m
		Σ 23	**Σ 236**		

of the mentioned clay layers vary depending on the locality. Thus at Section A (right side, before the bridge), the clay thickness at the top of the cutting varies from 5 to 8 m, and gradually reduces (wedges out) as the cutting height reduces. At Section B (left-side, before the bridge), this clay layer varies from 3 to 5 m in thickness, its thickness is about 3-6 m at Section C (right side, after the bridge), and about 4-6 m at Section D (left-side, after the bridge). At higher railway chainages, at sections E (right side) and F (left side), the clay layer thickness varies from about 4 to 6 m, and the layer also wedges out as the height of the cutting decreases.

Under the said clay layer, fine-grained densely compacted gravels, with an excessive quantity of clay or silt, alternate with compacted sand layers, also with an excessive quantity of silt or clay, while thin intercalations of described clay formations can also locally be observed (Section D). A typical engineering geological section for Section B is shown in Figure 4.

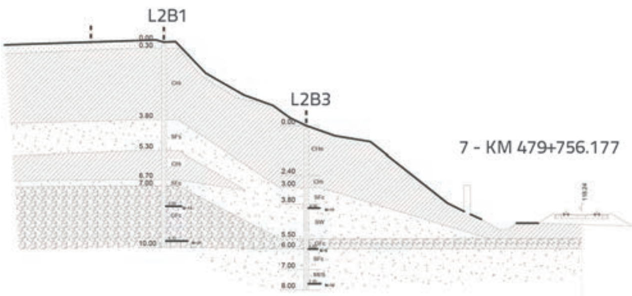

Figure 4. Typical engineering-geological section for Section B

3. Landslide remediation design

The design for remediation of the landslide on this location [3-8] was prepared at the main design and detailed design levels, based on investigation results [1, 9] and the landslide remediation preliminary design [2].

Three alternative solutions were analysed in the preliminary design [2] and the designers adopted at that stage the solution involving replacement of the existing material with the new stone material. This solution was related to all sections on which the remedial work was planned. However, before preparation of the detailed design, the Client instructed the designers that the remedial work must be carried out within the area that is not affected by the existing underground TD and PNK cables, and signalling-telecommunication cables (STKA). As in some segments of remedial work, defined in the preliminary design, the said cables were within the analysed cross sections, new calculations had to be made taking into account the above mentioned Client's instruction. It should also be noted that all analyses were conducted in accordance with guidelines given in Eurocode 7, which had not been done in the preliminary design.

The characterstic and design values of geotechnical parameters were selected using the design approach 3, which is in full accordance with guidelines from applicable standards relating to the design of geotechnical structures HRN EN 1997-1:2012 Eurocode 7: Geotechnical design – Part 1: General rules [10], and the national annex to this standard HRN EN 1997-1:2012/NA:2012 Eurocode 7: Geotechnical design – Part 1: General rules – National annex [11].

The combined realization of the reinforced earth wall in the bottom part, and the material replacement in the top part, together with an appropriate evacuation of rain water and other waters, was selected as an optimum remedial solution for Section A, at the right side of the railway before the bridge (Figure 6). The reinforced earth wall is composed of modular blocks, geogrids, and stone material courses. The same remediation solution was used at the right side after the bridge, at Section C. A part of this section, marked in preliminary design as L3 and L4, was to be remediated by combined realisation of a sheet pile wall (piles 40 cm in diameter, spaced at 1.2 m intervals) on top of the slope, and by replacement of material. However, after analysis of the on-site situation, it was established that the realization of the sheet pile wall from slope crown would be very difficult due to restricted access to a private plot, preventing the use of heavy machinery, which is why a solution with the reinforced earth wall, combined with material replacement, was finally adopted.

At other parts of the route, the remedial work is finished (Section B and Section D), or is to be conducted (Section E and Section F) by material replacement, as proposed in the preliminary design. However, the solution (Figure 8) has been adapted to new geotechnical analyses, to the planned technical implementation of the solution, and to the future permanent way design (planning od drainage to be connected with the drainage system via channel elements, according to the permanent way remediation design) "New double track combined-transport railway line M202, Goljak – Karlovac – Skradnik".

The control of ultimate limit states of the said geotechnical structure was conducted using the limit equilibrium method, by means of the GeoStudio-Slope/W 2007 software [12].

3.1. Remediation design based on reinforced earth wall

The combined method involving reinforced earth wall and material replacement was selected as the instability remediation solution for the right side, 207 m before the bridge (Section A), and 92 m after the bridge (Section C). The design work for the remediation of these sections was conducted using engineering-geological soil sections determined on the basis of preliminary investigations. The analyses included the following activities:

a) control of the external (global) stability of the reinforced earth wall (block), and control of bearing capacity of the soil;
b) control of the internal (local) stability of the reinforced earth wall, where the control was made for the slopes generated in the potential failure zone.

Considering that the project is realized in stages, these controls were made for every individual phase as follows:

1. excavation for approach road;
2. excavation for reinforced earth wall;
3. construction of reinforced earth wall;
4. construction of material replacement

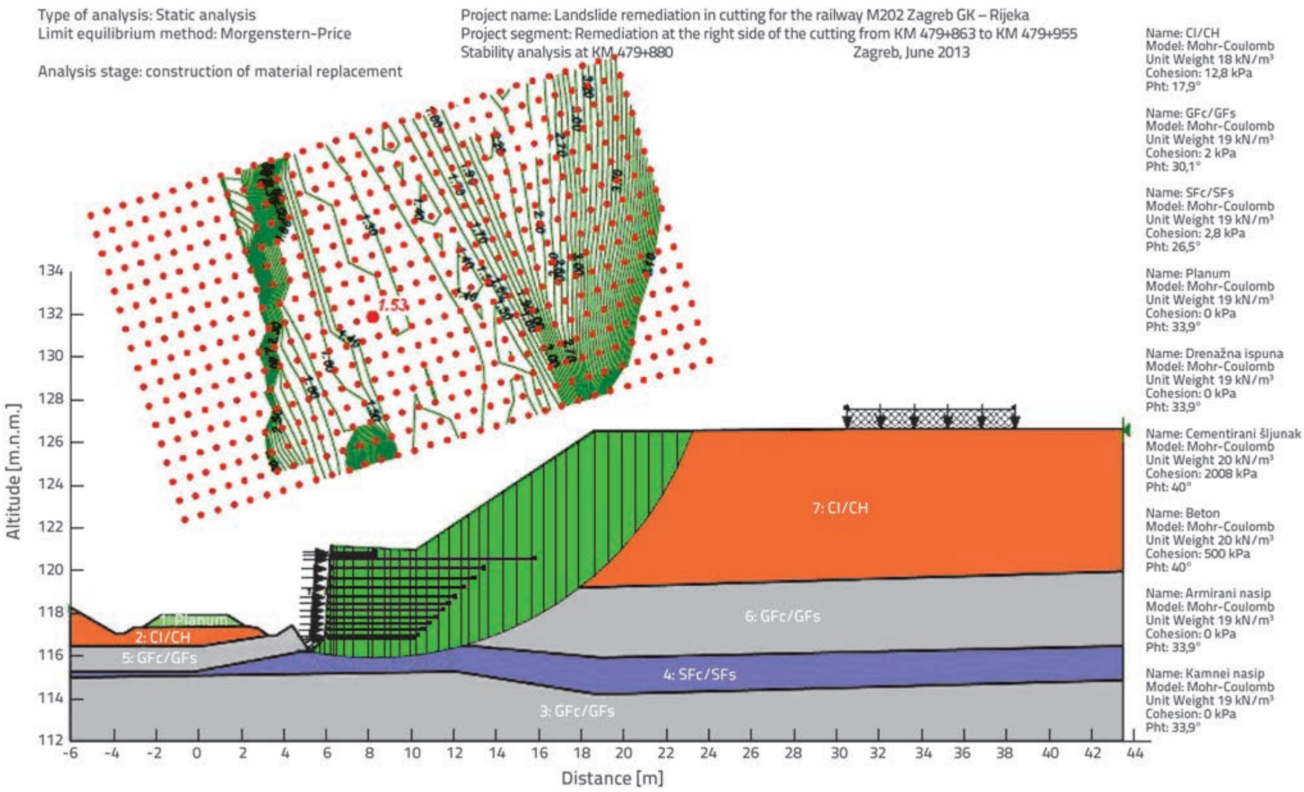

Figure 5. Stability analysis results after reinforced earth wall construction and material replacement (F_s=1.53 > $F_{s,min}$ =1.00)

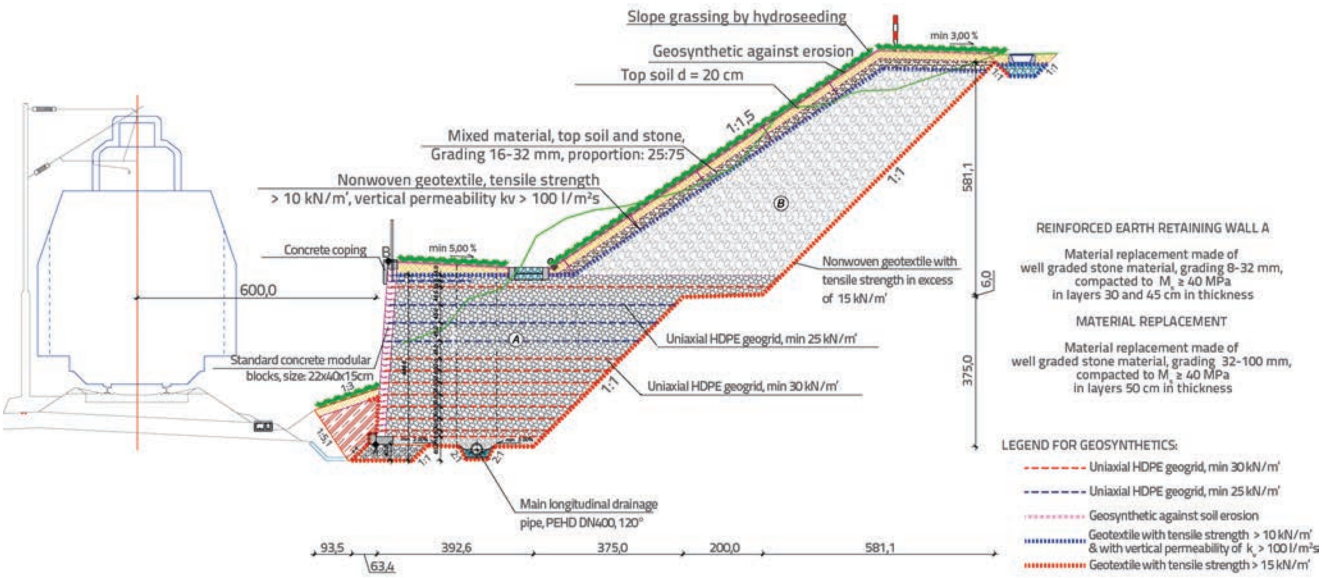

Figure 6. Typical cross section of remediation measures at Section A

5. construction of passive wedge in front of the reinforced earth wall;
6. grade separation (change of level) in front of the reinforced earth wall (because of oncoming railway renovation and construction of the new water evacuation channel).

Static analyses were conducted for each individual construction stage, while the analysis of seismic influence on the stability of reinforced earth wall (dynamic analysis) was carried out for the final stage. An appropriate traffic load due to use of machinery (occasional, unfavourable), presence of housing units situated at the top platform of the slope (permanent, unfavourable), and presence of a temporary structure (permanent, unfavourable), was also taken into account in the analyses.

Uniaxial geogrids, belonging to two strength classes, are planned for reinforced earth wall. The design resistance of min

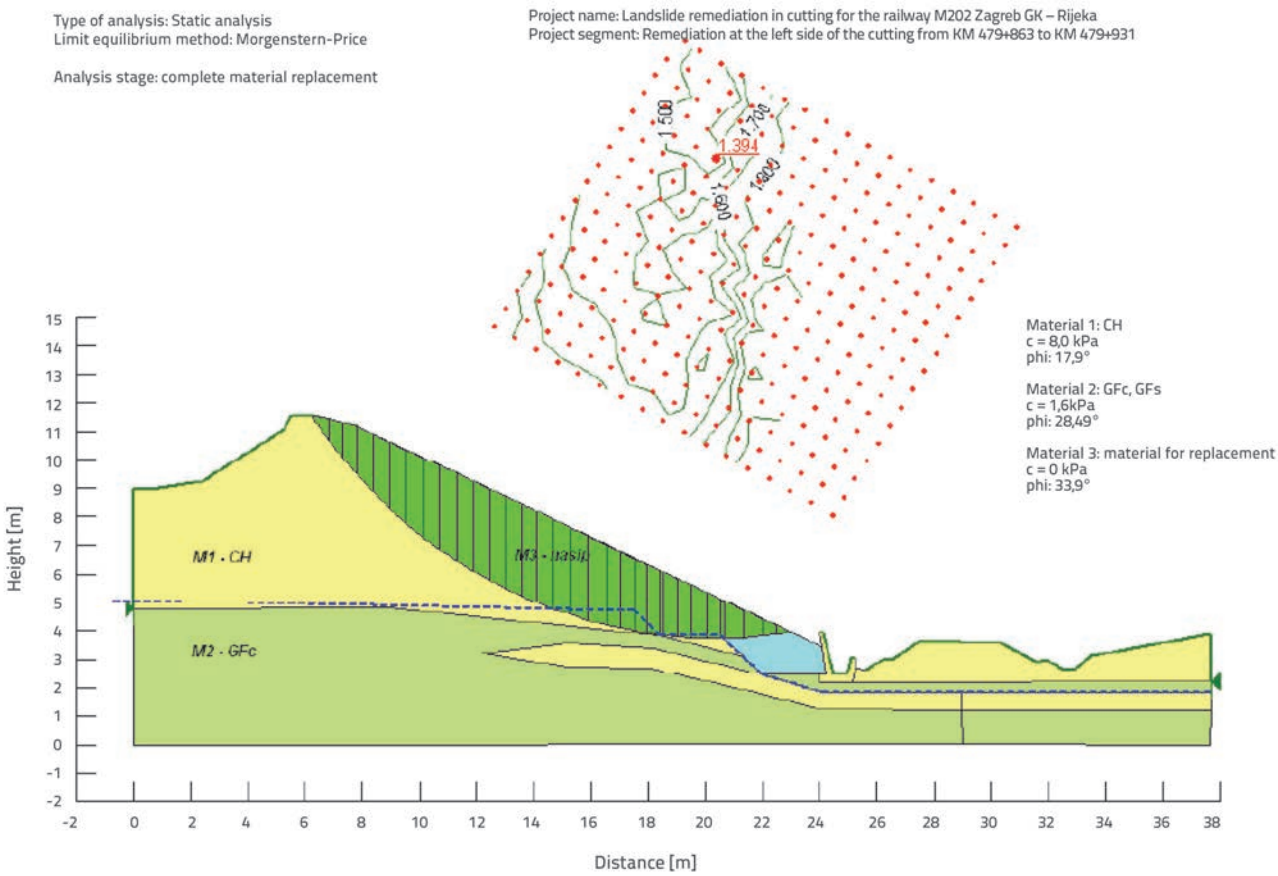

Figure 7. Stability analysis results after replacement of material (Fs=1.39 > Fs,min =1.00)

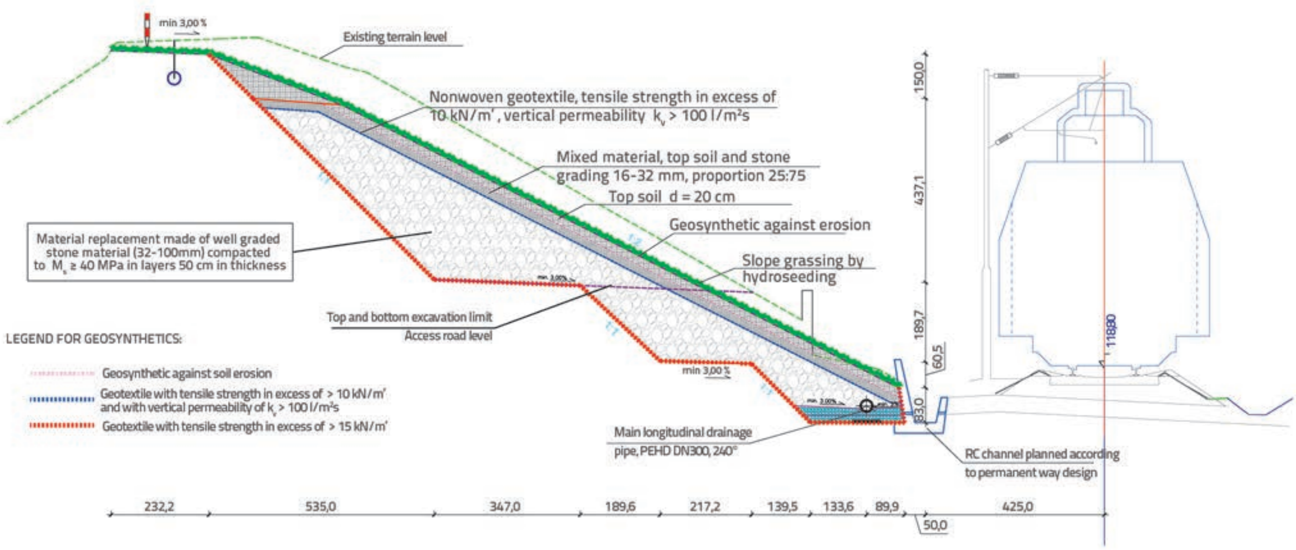

Figure 8. Typical cross-section of remediation measures at Section D

25 kN/m' was required for the first class (top part of the wall), while the design resistance of min 30 kN/m' was required for the second class (bottom part of the wall). Characteristic strength parameters of c = 0 kPa and ϕ = 40° are used for the reinforced earth wall material and soil replacement material.

All analyses comply with the minimum safety factor of 1.0, and one of calculation results (global stability analysis after the reinforced earth wall and soil replacement construction) is shown in Figure 5. The selected typical cross section of remediation at Section C is shown in Figure 6.

3.2. Design of remediation by material replacement

Material replacement is planned at sections B, D, E and F. As the work will be realized in stages, these controls were made for each stage as follows:
1. excavation for approach road;
2. excavation of the bottom part of slope;
3. material replacement at the bottom part of slope (below the approach road level);
4. excavation of the top part of slope;
5. material replacement at the top part of slope (above the approach road level);

Static analyses were conducted for each individual construction stage, while the analysis of seismic influence on the stability of the newly formed slope was carried out for the final stage. All analyses complied with the minimum safety factor of 1.0. One of the calculation results (after material replacement at the top part of slope) is shown in Figure 7. The selected typical cross-section of remediation measures at Section D is shown in Figure 8.

4. Landslide remediation works

Remediation stages were selected depending on the method chosen. All works were realized in accordance with the design documentation, and individual construction phases are presented in the following sections.

4.1. Landslide remediation using reinforced earth wall and material replacement

The following construction stages were conducted at Section A and Section C at the right side of the railway:
1. Preliminary works.
2. Setting out of the approach road.
3. Excavation for approach road.
4. Construction of approach road platform.
5. Setting out of excavation for reinforced earth wall.
6. Excavation for reinforced wall.
7. Mechanical compaction of foundation soil.
8. Geotextile placement.
9. Construction of cemented stone material, as foundations for the reinforced earth wall.
10. Realisation of drainage system.
11. Installation of manholes.
12. Construction of footing for reinforced earth wall.
13. Construction of reinforced earth wall.
14. Material replacement.
15. Geotextile placement.
16. Installation of surface drain.
17. Placement of mixed material.
18. Placement of top soil.
19. Placement of geosynthetic material against erosion.
20. Hydroseeding.
21. Backfilling area in front of the wall using material from excavation.
22. Realisation of the peripheral drainage system.

A temporary approach road had to be built at both sections (A and C) where the reinforced earth wall was to be realized. As a high humidity of foundation soil was expected, a geotextile material was placed on the approach road. The road was additionally strengthened with 30 cm of stone material so as to ensure proper base for the movement of machinery.
After excavation for reinforced earth wall, the foundation soil was compacted so as to achieve favourable physicomechanical properties. Then the non-woven geotextile (15 kN/m' in tensile strength) was placed onto the soil compacted in this way. At its plane, the geotextile also assumed the role of a drainage medium, i.e. it conducted the seepage water to the perforated pipe situated at the bottom of the reinforced earth wall. This was followed by construction of the footing using stone material and cement, and by construction of the drainage ditch in which a perforated pipe PEHD DN400, 120° was placed. After this, the construction continued with realization of the reinforced earth wall, i.e. with placement of geogrids, backfilling of stone material 30 cm in thickness, and its compaction to 40 MPa. The reinforced earth wall consisted of modular concrete blocks (without any load carrying function), polymeric connectors, and geogrids. The geogrid was placed onto cleaned blocks via a groove in the block, and each end of the geogrids was connected with the connector, which provided for a proper link between the geogrids and modular concrete blocks. Geogrids 2 m in length were installed at the top of the wall (final two modular blocks) in order to ensure stability at the wall crown level. The concrete coping was placed on top of the final modular block, and this coping was fixed with anchor to modular blocks. Geogrids manufactured by Tema Xgrid 60/30 kN/m' were used. The construction was realized in sections 20 m in width.
A surface drain was installed at the top of the wall, and its stability was ensured by a peripheral channel with transverse beams. A special attention was paid to the installation of manholes that are situated within the reinforced earth walls, and to the placement of geogrids around the manholes. The wall construction was followed by realization of the material replacement, which was made in layers 50 cm in thickness, with compaction of each layer to 40 MPa. This was followed by placement of geotextile 10 kN/m' in tensile strength, and 100 l/m^2s in vertical permeability. The activity continued by placement of mixed material (stone and top soil 25 cm in thickness, with compaction to 30 MPa), placement of top soil 20 cm in thickness, placement of geosynthetic material against erosion KMat, and by slope hydroseeding. The peripheral drainage by means of concrete channels was made on top of the slope. As the existing cables were situated at approximately 1.5 m from the channel axis, a special attention was paid during excavation work at the top of the slope. Individual remediation stages at Section A are shown in Figure 9.

Figure 9. Landslide remediation at Section A

The construction work for Section C consisted of the same elements as for the Section A, the only difference being a perforated pipe PEHD DN250, 240° that was installed into the drainage ditch, and this at the beginning of the zone (i.e. until the overpass) 44 m in length. This was followed by installation of the perforated pipe PEHD DN300, 120°, 42 m in length, and by installation of an ordinary pipe PEHD DN300, about 146 m in length.

The quality of the works, i.e. the quality of compaction (stiffness) of the reinforced earth wall and material replacement layers, was controlled by a bearing plate (contractor's tests) and using the SASW surface wave analysis method (verification tests), where the modulus of elasticity was determined, for small strains, based on the velocity of shear waves passing through individual layers. All tests have shown that the stiffness values required in the design were actually achieved during the construction work. In addition, the usability of the reinforced earth structure was continuously checked by measuring deformation within the wall body using horizontal deformeters 7 m in length, and by measuring displacements of the deformeter entrance (at modular brocks) and wall crown through geodetic bench marks, and this during and after wall construction. These verification tests were carried out at 6 profiles at Section A, and at 3 profiles at Section C. Furthermore, three blocks measuring 20x20x10 cm were installed at the crown of the top slope, where they served as fixed points for monitoring material settlements over time. The measurements will be made for twelve months and this every week during the first month following the end of the wall construction work, while the other measurements will be made after the third, sixth, and twelfth months. Measurements carried out so far have shown that settlements are negligible.

4.2. Landslide remediation by material replacement

At sections B and D, the slope remediation was conducted by replacement of material. The work was realized in stages as follows:

1. Preliminary works.
2. Setting out for the approach road.
3. Excavation for approach road.
4. Construction of approach road platform.
5. Setting out of the bottom part of excavation for material replacement.
7. Mechanical compaction of foundation soil.
8. Geotextile placement at the bottom part of excavation.
9. Realisation of drainage system.
10. Material replacement at the bottom part of excavation.
11. Setting out of the top part of excavation for material replacement.
12. Top part of excavation for material replacement.
13. Geotextile placement at the top part of excavation.
14. Material replacement at the top part of excavation.
15. Placement of mixed material.
16. Placement of top soil.

Figure 10. Landslide remediation at Section D

17. Placement of geotextile (erosion prevention)
18. Hydroseeding.

As approach roads at sections B and D fully passed through softer coherent material layers, the geotextile was placed on the road subgrade, and the compacted stone material 30 cm in thickness (with grading similar to that used for replacement) was placed on that geotextile. In longitudinal direction, the access road followed the grade of the railway and, in transverse direction, it presented the cross slope of 5 % toward the railway. The axis of approach roads was situated, throughout the length of these roads, at about 2.05 m above the railway axis. The work had to be divided into the top and bottom parts because of the overall height of the work and soil characteristics.

The work was conducted in sections 20 m in width. However, a special care was paid during channel excavation at the bottom part, where maximum width of sections amounted to 5 m.

After the full excavation in a particular segment, and prior to construction of replacement, perforated drainage pipes (PEHD DN300, 240°) were placed onto the cemented stone material bedding covered with geotextile. These pipes were connected via appropriate connections with the new concrete channel. The drainage slope amounted to 0.5 % out of which 0.3 % follows the slope of the railway axis (i.e. the fall of the channel axis), while an additional 0.2 % was obtained by varying the depth of the bedding under the drainage pipe. Before construction, the entire face of the excavation was covered with geotextile, which was placed onto the previously compacted subgrade, and which carried the seepage water to perforated pipes at the toe of the slope. Because of vicinity of the existing underground cables, the works on top of the slope were carried out with utmost care, and even by hand, when necessary.

The material replacement was made of well graded stone material, with the grain size ranging from 32 to 100 mm, placed in layers 50 cm in height, with compaction of each layer to the stiffness modulus of $M_S > 40$ MPa. The inclination of the finished slope was 1:2 in the entire work zone. The realization of the entire material replacement was followed by placement of the geotextile with the tensile strength of 10 kN/m', and with the vertical permeability of 100 l/m^{2}s. This was followed by placement of mixed material (stone and top soil) 25 cm in thickness, with compaction to the stiffness of 30 MPa, The work continued with placement of pure top soil 20 cm in thickness, laying of geosynthetic material (erosion prevention), and with slope hydroseeding. Individual remediation stages at Section D are shown in Figure 10.

The quality of works, i.e. the quality of compaction (stiffness) of layers, was checked by bearing plate (contractor's tests), and using the SASW surface wave analysis method (verification tests). All these tests have shown that the stiffness values specified in the design were successfully met at the construction stage.

4. Conclusion

A landslide formed on cutting slopes of the 3-km railway section between the Karlovac and Mrzlo Polje, on the railway line M202, Zagreb GK – Rijeka, very soon after completion of this railway section. Although various remediation measures were implemented over time at this section, they failed to stop the landslide activity. As the landslide action intensified due to strong precipitation, the detailed design for landslide remediation had to be prepared as soon as practicable. At some parts of the section, the remediation measures included construction of a reinforced earth wall and material replacement, while on other parts only slope material replacement was anticipated. Such different solutions were adopted taking into account the fact that remedial work should not cut into the area where underground cables and installations are situated, because of the different distance from the structures located on top platform of the slope, and due to required compliance with all elements defined in Eurocode 7. The solutions were also adapted to the future permanent way remediation design on the railway "New mixed-traffic double track railway line M202 Goljak – Karlovac – Skradnik". Remediation solutions were realized in full compliance with the design documentation, and they constitute a permeant solution providing full functionality and safety for the railway section, and for the structures situated on the platform above the cutting. This remediation project is characterized by a high level of cooperation between the Client, Designer and Contractor, which was indispensable considering the urgent need to find a high-quality solution to the problem.

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