Remediation and Monitoring of Unstable Slope of Railway Cut

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Abstract. As part of the railway tracks modernization in Slovakia, a cut with a maximum depth of approximately 11 meters and a length of approximately 200 meters was built in the vicinity of the capital Bratislava. During the realization of the cut, in complicated engineering-geological and hydrogeological conditions, several instabilities and landslides occurred. This resulted in several remediation measures on a 200-meter long cut which were not considered in the original design proposal. After construction, geotechnical monitoring is carried out on the slope. The geotechnical monitoring aims to verify and control the effectiveness of remediation measures to maintain the safe operation of the rail transportation. This paper evaluates the results of 3-year geotechnical monitoring and analyses its relationship to the given warning level.

1. Introduction
The construction site of the railway tracks between the railway stations Devínska Nová Ves and Zohor at stationing 5,016 - 6,130 is located near Bratislava, the capital of the Slovak Republic. This part of the track is also part of IV. Pan-European Railway Corridor Dresden - Prague - Bratislava / Vienna - Budapest - Arad - Istanbul. The main reason for the reconstruction of the railway cut was to increase the track speed in the track curve from the current 120 km.h⁻¹ to 160 km.h⁻¹ ([1]. The reconstruction of the curve required the abandonment of the existing railway body at a length of about 500 m. Most of the relocation of the track was led trough a cut. It was the new routing of the railway track through a cut, with a maximum depth of approximately 11 m which required several remediation measures to be taken and which could not be taken into account in the original design proposal and are the subject of that article. After the implementation of the remediation measures, 3-year monitoring was carried out, the results of which are also analysed in the article.

2. Geological and hydrogeological conditions in the railway cut area
The area is relatively complicated from the point of view of geological settings because the Quaternary and Neogene sediments of various grain size and character alternate here irregularly. In addition, the complexity of the geology is also emphasized by two tectonic faults passing through the assessed area [2]. Generally, the lower parts of the cut’s slopes are formed by Neogene clays to sandy clays and the higher parts of the cut’s slopes are Quaternary sands and gravel (Figure 1). Contact between clay and sand is very complicated and often takes the form of depressions or elevations oriented perpendicular to the direction of the railway cut.
Hydrogeological conditions of the railway cut are strongly related to the geological conditions of the rock environment. There are 2 horizons of groundwater in the area:

a) first groundwater horizon is bound to a surface layer of sand with thickness from 5 to 12 m. It shows only a slightly pressures character caused by local clay layers in the sands (buoyancy up to approx. 2 m) and was detected mostly 1-2 m above the clay impermeable subsoil,

b) second groundwater horizon is related to sandy lenses in impermeable clays (Figure 2). The ground water pressure level rise to 10 m.

Ground water level (GWL) is bound to the positions of sand or gravel about 5-12 m thick. The direction of groundwater flow is influenced by the dip of the impermeable subsoil formed by clay. From the general point of view, the groundwater recharge area is in the area above the slope of the cut. The construction of the railway cut in the past has partly affected the groundwater regime, the cut was a local drainage.
On the basis of GWL measurements in the boreholes, we assume that even in the axial profiles of the groundwater flow is affected by the dipping of the impermeable subsoil. The axial geological profile (Figure 1) shows that in the section between 20 - 27, where the impermeable clay bed forms an elevated part, the groundwater level is the contact of sand and clay bed. From here to the north and south (i.e. to Zohor and Bratislava) groundwater flows in the direction of descending clay bedrock (Figure 2), while the general direction of the ground water flow is into the foot of the slope of the cut (i.e. to the west, where nearby river Morava flows).

3. Methods of static remediation taken on the railway cut slope

The method of increasing the stability of 200 m long slope of the railway cut responded to the engineering-geological and hydrogeological conditions identified during the construction (Chapter 2). In the areas where a contact of clays and sands reached above the cut bottom, instabilities occurred on the slope cut, which had to be solved by more massive static measures. The most significant instability (landslide) occurred on 12.10.2013. The area of the landslide was approximately 50 x 40 m, while the accumulation part of the landslide (the slip area exit) reached beyond the first railroad track. The maximum thickness of the landslide was approximately 10 m (Figure 3). The landslide has developed at a predisposed site. On the one hand, the clay underlying layers has steep dipping, and the second the pressurized water emerges from sandy positions. The slip surface has developed in Neogene clays and it has a circular shape. The landslide was remediated by the retaining pile wall (Figures 3 and 4).

In other parts of the cut, the method of landslide stabilization responded to newly identified engineering-geological and hydrogeological conditions and the slope stability of the cut. These were mainly slopes with nailed steel grid and drainage components, locally also jet grouting with ground rope anchors (Figure 5).

The method of remediation the individual parts of the railway cut is shown in Table 1.

| Section - Building Profiles no. | Geology of the cut slope, groundwater | Method of remediation of the cut slope | Figure |
|-------------------------------|--------------------------------------|----------------------------------------|--------|
| 1-14                          | the slope consists of sands, GWL under the track level | nailed slope, steel grid, drainage pipes | 5      |
| 14-25                         | the upper part of the slope consists of sands the lower of clays; groundwater flow and discharge at the contact of clay and sand | jet grouting, ground rope anchors, drainage pipes on the contact of sands with clays | 5      |
| 25-31                         | the lower part of the slope consists of clay with lenses of sand and with pressurized groundwater | pile wall (length = 61 m, \( \phi \) piles = 900 mm, length of the piles = 12,0 m, spacing of piles =1,2m) 3 horizontal drainage boreholes, a longitudinal deep draining trench in front of the pile wall | 4      |
| 31-38                         | railway cut slopes consist mostly of sands | reinforced ground slope - slope dipping 1:1 |        |
Figure 3. The course of the slip surface and remediation of the landslide by the pile wall

Figure 4. Pile wall in the landslide area - building profiles 25-31
4. Drainage of the cut slope
The presence of aquifers (sand and gravel) lying on clays with low shear strength parameters were the prerequisites for the formation of the slope instability. But the decisive initiator of the movement on the cut slope was the effect of groundwater.

It follows that the main measure to increase the slope stability was, in addition to static measures (retirement wall, pile wall, etc.) drainage of the slope. This has been done in several ways:
- in the area of the nailed slope and jet grouting, the drainage was provided by drainage gravel located at the groundwater discharge sites. The water leaking from the contact of sand with clay has been caught by pipes and is currently being flowing behind the wall and springs from the pipes at the bottom of the wall to the drainage trench,
- a longitudinal drainage trench has been built in the pile foreground to drain the groundwater springs flowing from behind the piles (Figure 6). The trench collects the water from the springs and is drained by an inclined sub-horizontal pipeline under the track to the inspection shaft on the other side of the railway cut, where the discharge rate can be measured. The water thus collected is finally drained by a deep trench drain along the left slope of the cut into the nearby water stream. The discharge rate from the trench mouth is also measured,
- three horizontal drainage boreholes of 18 m length were drilled between the piles.

All drainage elements implemented during construction caused a decrease of GWL, which permanent effect is currently verified by long-term monitoring [3].
5. Geotechnical monitoring of the cut slope

During the reconstruction of the railway cut instabilities has occurred, which subsequently led to a need for remediation measures performed on the slope. Geotechnical monitoring was also part of these measures. The aim of the geotechnical monitoring was to verify and control the effectiveness of remediation measures to maintain the safety of the railway operation.

In 2013 – 2014, a monitoring system was gradually built in the area of interest to monitor:
- groundwater levels in piezometers and boreholes for siphon drainage,
- discharge rate from the drainage elements,
- deformations of the cut slope in inclinometric boreholes,
- surface deformations at geodetic points.

The monitoring also includes a regular visual inspection of the condition of individual structures on the cut slope, as well as the condition of individual monitoring devices and surface signs of any possible instability (erosion, cracks, etc.).

Measurements of geotechnical monitoring on the slope of the cut have been carried out by several organizations for more than 3 years in accordance with the approved monitoring schedule.

5.1 Measurements of GWR and drainage discharge

Monitoring measurements for about 3 years show a clear relationship between GWL and climatic conditions (precipitation, snow melting, etc.). The main result of the monitoring is the fact that GWL during the whole monitoring period did not reach the maximum levels of GWL from November 2013, when the greatest slope instability occurred (landslide). The dependence of drainage on GWL states is also important. The discharge rate from the drainage responds to the level of ground water in the area, keeping GWL at a lower level. Three pieces of horizontal drainage boreholes also contribute to the reduction of GWL [4] in the area of boreholes SD-13 to SD-17, as shown in Figure 3.
5.2 Inklinometric measurements – stability evaluation of the soil massif of the railway cut

The total number of inclinometer boreholes is 10 and the measurements are performed twice a month. Based on the evaluation of inclinometric measurements, the following stability or activity was recorded in the individual building profiles, as shown briefly in Table 2.

Table 2. Characteristics of current slope stability according to inclinometric measurements

| Building stationing – profile no. | Remediation - type of measures | Inclinometric boreholes | Deformation (movement) | Figure no. |
|----------------------------------|-------------------------------|-------------------------|------------------------|------------|
| 1-14,5                           | nailed slope                  | INK-6, INK-7            | tilting Movement towards rail | 7          |
| 14,5-25                          | jet grouting, anchors         | INK-8, INK-4A, INK-2 a INK-9 | minimal movement up to 1 mm | 8          |
| 25-31                            | pile wall                     | INK-5A, INK-10, INK-12 | small movement on old slip surfaces | 8          |
| 31-38                            | slope leveling                | INK-11                  | minimal movement up to 1 mm | 8          |

Figure 7. The course of deformations and motion vector with tilting pattern (A + is in the direction of the slope towards the rail) in the INK-7
The realization of inclinometric measurements shows that no movements greater than 3mm were recorded on any inclinometer. However, continual attention should be paid to 2 areas:
- the area between profiles no. 1 and 14.5, where a small tilting of the inclinometric boreholes is permanently recorded, in a direction toward the railway track,
- the area between the profiles 20 and 25 - the area of the old landslide - there is small movement on the old slip surfaces

5.3 Geodetical measurements
The above mentioned geodetical measurements serve mainly for the measurement of the surface displacements of newly built geodetic points in 4 selected construction profiles. Furthermore, the originally built points on the pile wall and on the foundations of the traction line masts are measured. The points on the pile wall and masts do not show any movement. At the geodetic points placed on the wall, relevant movements in 2 profiles were recorded, where movement towards to the rails was observed.

These observed shifts are caused by the pressure of water behind the wall infiltrating here from a spring and leaking unpaved trench above the edge of the railway cut during each spring. The solution is to build a paved trench for quick drainage of water from the springs above the cut.

The basic objective of monitoring is to compare the actual development of the monitored system (rock mass - building structure) with the assumptions of the implementation documentation of the relevant building object or structure. The information collected from each measurement is continually evaluated, i.e. compared with defined warning states [5].

The warning states were determined by stability calculations and represent:
- values of critical GWL states in the selected observation wells,
- critical deformation values for inclinometric and geodetic measurements

The warning states were calculated for 4 characteristic building profiles, i.e. one profile for each certain type of supporting structure. The critical value of the measured parameters was designated as "P". The individual warning states and measures prepared are listed in Table 3.
Table 3. Warning states and prepared measures [5]

| Warning state | Description of the state | Measures prepared |
|---------------|--------------------------|-------------------|
| 1 State of high level safety | No or stable deformations over time are achieved below 60% "P" | No action is necessary. |
| 2 State of acceptable changes | Stable deformation over time is achieved below the value of "P". Since 60% of the "P" is reached, appropriate measures need to be put in place. | Calling a coordination meeting - increased visual control, shortening the interval of selected measurements, etc. |
| 3 State of limit acceptance | The deformation does not stabilize over time under the value of "P", but it is possible to assume (extrapolation) that the deformations will stabilize to the value of 125% of "P" according to the recorded development. | Decrease of train speed in adjacent track when filling condition at selected points. |
| 4 Critical state | The deformations do not stabilize over time even at the value of 125% "P", above the value of "P" there is a constant speed of the deformation process. | Stopping traffic when meeting the condition at designated points in the checklist, or speed reduction at other points. |
| 5 Emergency state | Suddenly accelerating the deformation process anywhere above the level 60% "P" | Stopping the traffic on the adjacent or both rails |

As an example of alert states, the results of the GWL monitoring from December 2013 to October 2017 can be presented (Figure 9). In the piezometer SD-11, GWL is monitored every hour, i.e it works as an online warning system.

![Figure 9. Relation of GWL in SD-11 and SD-13 piezometers to critical levels (red lines)](image-url)
Figure 9 shows that, at present, according to the GWL data obtained, a "State of high level safety" is achieved on the site.

However, the piezometer SD-11 (building profile no. 28) lacked about 0.8 m in spring 2015 to achieve the 2nd warning state "state of acceptable changes" - a red dashed line.

6. Conclusion
Road and railway constructions are often in contact with the landslides [6] and monitoring in Slovakia. The railway cut in stationing 5,600 - 5,800 km is an example of how complicated geological conditions can significantly influence the construction. The complex geological settings are reflected in the complexity of groundwater flow in the soil environment. And this caused the occurrence of a landslide in a certain narrowly predisposed site. In the end, the complicated geology on a 200 m long cut required several remedial measures that could not be taken into account in the original design. Therefore, the geotechnical monitoring is ongoing on the slope of the cut, the aim of which is to verify and control the effectiveness of remediation measures to secure the safety of the train transport. Based on the results of geotechnical monitoring, which took place in the cut of the railway until October 2017, we can state that on the remediated slope the “state of high safety level” was reached in terms of warning conditions. However, the climatic extremes of 2013 when the landslide occurred during the construction have not yet been achieved.

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