Risk Analysis of the Motorway Routes in Landslides Area

Miloslav Kopecky 1, Martin Ondrasik 1, Martin Breck 1, Viktor Jantak 1

1 Dept. of Geotechnics, Faculty of Civil Engineering, Slovak University of Technology, Radlinskeho 11, 810 05 Bratislava, Slovakia
miloslav.kopecky@stuba.sk

Abstract. During monitoring measurements of the slope stability performed before construction of the D1 motorway in central Slovakia, a significant activation of landslides was observed in a motorway section long about 2 km. Such deep and active landslides were not taken into consideration during design stage. Therefore, it was decided to reassess the realization of the motorway in the originally designed route and to assess the possibility of choosing more favourable alternative route. To decide which alternative is the best one, a risk analysis of feasibility of the original (surface variant V1) and a newly proposed route (tunnel variant V2) were performed. In the article, the risks are assessed in detail - such as qualitatively or quantitatively expressed functions of probability of occurrence of certain hazards and magnitude of its adverse consequences on vulnerable motorway sections and objects (vulnerability) within a certain time period (exposure). The considered exposure is usually the construction period or the service life of the motorway and its objects. The analysis focused on geological, geotechnical and hydrogeological risks. However, the decisive risk was the interference of the motorway route with the landslide area. Risks of the variant V1 were evaluated for 10 sections and in the V2 variant four sections have been evaluated. The results of the risk analysis revealed that 35.5% of the V1 route was classified to the highest risk, grade 5. In variant V2 only 8% of the route was classified to grade 5. So, it was advisable to consider changing the original motorway route with the alternative one. In the present, works to begin building the motorway in the new route, which was also recommended by the risk analysis, are underway.

1. Introduction
Slovakia is a country with a young geology and therefore there are ongoing problems with many geological hazards in civil engineering activities. These are primarily landslides that cover up to 5.3% of the Slovak territory [1], tectonic movements or collapsible soils [2], [3]. Especially, road constructions are often in contact with the landslides and their remediation [4], [5] and monitoring.

The course of the D1 highway in Central Slovakia is designed through the area with extremely deep slope deformations [6]. Especially risky is the section in km 2.0-4.0, where the highway was led on the surface in the form of cuts, embankments and bridges. The total area of the unstable slopes in this section is approximately 2 x 2 km and the altitude increase between the D1 highway and the highest parts of the slope deformation is up to 1500 m (Figure 1). The slope deformations that are developed almost on the entire slope in question (from the valley to the ridge of the hills) are of different character and activity. The development of the individual forms of slope deformations was linked to the erosive activities of the Váh river during its gradual erosive cutting and modelling the valley. The slope geology allowed to create huge slope deformations. Stronger dolostones and limestones (the top part of the slope) lie on the "soft" siltstones (the lower moderately dipping parts of the slope). The plastic character of the marly
limestone enabled the gravitational movement of the blocks of dolostone and limestones down the slope. Approximately at the contact of dolostone and marly limestone, block field have been created, where large blocks of limestone and dolostone sink in to the marly limestone and slide down along them. In this way, relatively large rock blocks (thickness over 50 m) could travel along the slope on distances up to 500 m (Figure 1).

During the construction of the highway, information on the activity and depth of the slope deformations in the original D1 route in km 2.0-4.0 was improved (Figure 2). On the basis of the updated information, the design and extent of the remediation of the unstable solution were gradually changed. It was verified by the analysis that the original proposal of the unstable slope remediation in the highway course would be ineffective and even unrealistic [7]. Therefore, abandoning the original highway surface variant (Variant V1) began to be considered and moving the highway into tunnel into the rock massif to bypass the landslides (Variant V2). One of the criteria for selecting the suitable variant was assessing both variants by risk analysis.

2. Risk analysis methodology
The risk analysis is the process of quantifying the identified risk or assessing the significance (weight) of its factors. Risk quantification also demonstrates the level of knowledge about possible risks and, when comparing several variants of the highway course, makes it possible to compare them in terms of feasibility in a given, mostly complex, geological environment. In assessing the risks arising from the geological environment we have taken into account:

- geological conditions – presence of geodynamic phenomenon (geological risk),
- impact of geotechnical intervention on the stability of the rock environment (geotechnical risk),
- the impact of the construction on hydrogeological ratios as well as the impact of hydrogeological conditions on the construction (hydrogeological risk).
The term geological risk in this risk analysis is understood as possible losses and damages associated with geohazards. We understand geological hazard as the occurrence or possibility of occurrence of a dangerous natural geodynamic phenomenon (e.g. earthquake, landslide, erosion, groundwater runoff, etc.) in a given environment over a certain period of time. We understand the term geotechnical risk as the possibility of creating dangerous phenomena caused by the impact of a highway construction (geotechnical intervention) on the rock environment. The term hydrogeological risk is understood as the possibility of influencing the hydrogeological conditions of the territory by realization of the construction (e.g. lowering of the underground water table) and at the same time as the risk resulting from the hydrogeological conditions on the realization of the construction (e.g. the inflow of the underground water into the tunnel under construction).
In the selected methodology of the risk assessment of the two variants of the highway section, we assume that the aim is not the perfection of the evaluation but its adequacy and complexity within the current time and data possibilities.

The risk assessment is an assessment of a possible (future) extraordinary event and its consequences. It is based on considerations of sources and types of danger and the resulting risks in the area concerned for the highway objects (roads, embankments, cuttings, bridges, etc.), engineering networks, line constructions such as power lines, water pipes, sewerage, etc., and in the case of the assessed area, also the municipality of Hrboltová with its infrastructure. Risk, defined as the possible consequence of extraordinary events for the risk taker, it is an economic category. Unlikely extraordinary events, but with significant consequences, may present the same risk as highly probable events but with relatively lower consequences.

Most of the definitions characterize the risk as a qualitatively or quantitatively expressed function of the likelihood of occurrence of a certain hazard (dangerous phenomenon) and the magnitude of its adverse consequences on vulnerable sections and objects (vulnerability) within a certain period of time (exposure), usually the period of construction or life time of the construction objects:

\[ \text{Risk} = \text{Hazard Occurrence} \times \text{Vulnerability} \times \text{Exposure} \]

2.1. Probability of hazard occurrence

In hazard identification, it is necessary to estimate with certain probability the location as well as the intensity of its expression and the trigger mechanism. Dangerous event location predictions can be made with a high probability if based on an analysis of relevant background data. For the purposes of risk assessment, however, it is usually sufficient with the likelihood of a potential hazard occurrence. The likelihood of hazard occurrence was evaluated semi quantitatively in five levels (Table 1), with the lowest level representing minimal or no likelihood of occurrence of the hazard. The highest level represents a very high probability of occurrence of the hazard within the defined space.

| Table 1. Grades of probability of occurrence of hazards |
|--------------------------------------------------------|
| 1 | Very low       |
| 2 | Low            |
| 3 | Moderate       |
| 4 | High           |
| 5 | Very high      |

2.2. Vulnerability of the environment (impact on technical work)

In case of vulnerability, it is necessary to determine the possible extent of damage of the work (object) or destruction from the point of view of the given type of the hazard. With sufficient experience, risk index values can be grouped into certain limits to provide a semi-quantitative representation of risk values at specified intervals from 0 to 100\% [8]. As well as the likelihood of occurrence, the vulnerability of the environment or the impact on the technical work we evaluate also by semi quantititative five levels.

The lowest level represents the minimal vulnerability of the environment and the highest level represents a very high vulnerability due to the influence of the hazard (Table 2).
Table 2. Grades of impact on technical work

| Grade | Name                              | Scope of damage                  |
|-------|-----------------------------------|----------------------------------|
| 1     | Minimal or no impact              | (minimal or no impact)           |
| 2     | Little impact                     | (extent of damage <6%)           |
| 3     | Moderate impact, possible delay    | (extent of damage 6-7%)          |
| 4     | Impact can cause a significant slowdown in works | (extent of damage 7-10%)         |
| 5     | Additional solutions are needed    | (extent of damage >10%)          |

2.3. Exposure (hazard duration)
In exposure the frequency of the hazard occurrence or its duration is evaluated [9], [10]. For the purpose of assessing the hazards or the risks of construction of the two variants of the assessed highway section, we have chosen a three-grade exposure assessment (table 3):

Table 3. Evaluation the duration (exposure) of hazard in the assessed area

| Grade | Exposure | Description                                                                                                                                 |
|-------|----------|---------------------------------------------------------------------------------------------------------------------------------------------|
| 0     | None     | Hazard is not present in the assessed zone. One-time or permanent occurrence during construction. The implementation of the designed measures makes the hazard safe and the implemented measures are expected to be effective. |
| 1     | Short-term| Permanent occurrence during the life of the work. If designed or additional measures to stabilize the hazards were implemented, the effectiveness of the measures will be known only if long-term monitoring will be provided. |
| 2     | Permanent| Permanent occurrence during the life of the work. If designed or additional measures to stabilize the hazards were implemented, the effectiveness of the measures will be known only if long-term monitoring will be provided. |

2.4. Level of knowledge about the hazard
In addition to the likelihood of hazard occurrence, environment vulnerability or impact on the technical works and exposure; the risk assessment needs to indicate also the level of uncertainty about the hazard and the vulnerability of the components of the geological environment. Proven knowledge must be clearly distinguished from the estimates. The level of uncertainty is assessed by dividing the hazard knowledge into two levels (Table 4):

Table 4. Assessment of knowledge about the hazard (uncertainty level)

| Level | Level of knowledge | Description                                                                                                                                 |
|-------|--------------------|---------------------------------------------------------------------------------------------------------------------------------------------|
| 1     | Sufficient         | Existence and activity of hazards verified in space and time (there are available results of detailed and complementary engineering geological survey and monitoring) |
| 2     | Inadequate         | Existence of hazard verified with insufficient accuracy, supplementary survey required                                                    |

2.5. Zoning of the assessed area
The risk assessment was performed on homogeneous zones (sections of the highway and tunnel respectively) of variants V1 and V2. When we made the zoning of the territory, we did not consider only the spatial distribution of the hazards (e.g. individual landslides) or rock environments with homogeneous properties (the tunnel sections out of the landslides), but also the distribution of the potentially endangered technical objects (cut, embankment, bridge, portal, tunnel, etc.)

The surface variant V1 is divided into 10 zones based on the distribution of 6 landslides (Figure 2) and ten building constructions representing various geotechnical interventions in the rock environment.
The tunnel variant V2 is divided into 4 zones based on the distribution of the landslides no. 1 and 2 and the position of the tunnel and its portal against these two landslides.

2.6. Risk assessment
In the final evaluation of the risk of construction of the two comparative variants of D1 highway section Hubová - Ivachnová, we have used two-element evaluation risk matrix (Table 5). In this matrix the rows represent level of probability of risk occurrence and the columns represents the impact grade on the technical work. By combining rows and columns, we got the level of risk for the V1 and V2 variants. There are five levels of risk. This applies to surface variant V1 and tunnel variant V2. The definition of the five risk levels for both variants is different, adapted to the surface construction and tunnel construction, but the weight of levels of the risks is the same (Table 6 and 7). In Table 5 in addition to the numerical risk classification also a risk-based semaphore colours are used for better risk level resolution. This three-color risk range was used not only in the tables, but also in the schemes of the two considered highway variants.

The exposure (time) during which the area is exposed and the level of knowledge (uncertainty) about the hazard is also affecting the risk level. These, if they reach a value of 1 or 0 respectively, have no impact on the risk assessment. However, if the exposure or the level of knowledge has a value 2 (Table 3 and 4), the level of risk deteriorates by one degree, even if the value 2 would have both evaluated factors.

The matrix for risk assessment based on the probability of occurrence of the hazard and its impact on the technical work (modified by the Guide to Risk Assessment, 2006) is presented in Table 5.

### Table 5. Risk assessment using evaluation matrix

| Probability of occurrence | Impact on the engineering object |
|---------------------------|---------------------------------|
|                           | 1 | 2 | 3 | 4 | 5 |
| 1                         | 1 | 1 | 1 | 2 | 3 |
| 2                         | 1 | 1 | 2 | 3 | 3 |
| 3                         | 1 | 2 | 3 | 3 | 4 |
| 4                         | 1 | 2 | 3 | 4 | 5 |
| 5                         | 1 | 2 | 3 | 4 | 5 |

### Table 6. Table of risk assessment of the surface variant V1

| Risk level (number) | Risk level (name) | Description |
|---------------------|-------------------|-------------|
| 1                   | Very low risk     | Construction is realizable, it is situated on a stable slope. |
| 2                   | Low risk          | Construction is feasible, remediation measures without any maintenance and monitoring requirements are needed. |
| 3                   | Moderate risk     | Construction is feasible, remediation measures with regular maintenance and monitoring are necessary. The realization of the construction is technically and economically demanding, threat of destruction of the construction, poor knowledge of the activity and depths of the landslide area. |
| 4                   | High risk         | Construction realization on the boundaries of technical possibilities, regular maintenance of remediation measures needed, threat of construction destruction and threat for the population. |
| 5                   | Very high risk    | Construction is feasible, remediation measures without any maintenance and monitoring requirements are needed. |


Table 7. Table of risk assessment of the tunnel variant V2

| Risk level (number) | Risk level (name)     | Description                                                                 |
|---------------------|-----------------------|-----------------------------------------------------------------------------|
| 1                   | Very low risk         | Tunnel is realized in hard non-pushy sound rocks with little damaged.       |
| 2                   | Low risk              | Tunnel is realized in hard non-pushy sound rocks with little damaged, occasional minimal groundwater spills. |
| 3                   | Moderate risk         | Tunnel is realized in pushy broken rocks, occasional minimal groundwater spills. |
| 4                   | High risk             | Tunnel passes through a tectonic zone with high disturbance and plastic deformations, presence of groundwater. |
| 5                   | Very high risk        | Tunnel face protection needed, possible activation of unstable slopes above the tunnel in case of stress release or rapid drainage of the massif. |

Table 8. Risk assessment of the surface variant V1

| Section stationing (km) | Length | Landslide | Threatened object | Geological risk | HG risk | Geotechnical risk | Percentage of the route | Total risk |
|-------------------------|--------|-----------|-------------------|-----------------|---------|-------------------|-------------------------|------------|
| 2.0-2.3; 300m           | 0.3    | L1        | bridge embankments| 5 2 1 2 2 1     | 1 1 0 2 1 | 5 2 1 2 3           | 11.7%       | 3          |
| 2.3-2.85 550 m          | 0.55   | L2        | cut               | 5 5 2 2 2 5     | 3 4 2 2 4 | 5 5 2 2 8           | 19.6%       | 5          |
| 2.85-3.16 310 m         | 0.31   | L3        | cut               | 5 3 2 2 2 3     | 3 3 2 2 4 | 5 3 2 2 4           | 11.1%       | 4          |
| 3.16-3.56 400 m         | 0.4    | L4        | bridge            | 5 2 1 1 2 3     | 2 2 2 3 5 | 5 2 1 1 2           | 14.3%       | 3          |
| 0.49 – 0.69 200 m       | 0.2    | L4        | cut               | 5 2 1 1 2 3     | 2 2 2 3 5 | 5 2 1 1 3           | 7.1%        | 3          |
| 3.56-3.65 90 m          | 0.09   | L5        | bridge            | 5 5 2 2 2 5     | 3 2 2 2 3 | 5 5 2 2 5           | 3.2%        | 5          |
| 3.65-4.00 350 m         | 0.35   | L5        | cut and embankments| 5 5 2 2 2 3     | 3 2 2 2 3 | 5 5 2 2 5           | 12.5%       | 5          |
| 0.00-0.49 490 m         | 0.49   | L5        | cut               | 5 3 2 2 2 4     | 3 2 2 2 3 | 5 3 2 2 4           | 17.5%       | 4          |
| 3.55-4.00 45 m          | 0.45   | L5        | cut, embankment   | 5 3 2 2 2 4     | 3 2 2 2 3 | 5 3 2 2 4           | 3.9%        | 4          |
| 4.00-4.11 110 m         | 0.11   | L6        | tunnel portal     | 5 3 1 2 4 3     | 2 1 2 3 5 | 5 3 2 1 2           | 3.9%        | 4          |

3. Risk assessment results of the variants V1 and V2
The results of the risk analysis of variant V1 - surface variant is presented in Table 8 and variant V2 - tunnel variant in Table 9. The tables contain a separate assessment of geological risk, geotechnical risk
and hydrogeological risk. Risks of variant V1 are evaluated separately for 10 zones and in the V2 variant four zones have been evaluated. The individual zones are identified by stationing, landslide numbers and numbers of objects within them. The length of the evaluated zones and their percentage of the total length is also stated. The total assessed construction risk for each zone of both variants was determined as the worst risk from the three resulting risk ratings. The five-grade numerical classification of the risk of V1 is given in Table 8 and Variant V2 in Table 9. For a simpler visual risk assessment, semaphore colours were used in these tables.

Table 9. Risk assessment of the tunnel variant V2

| Section stationing (km) | Landslide Threatened object | Geological risk | HG risk | Geotechnical risk | Percentage of route in % | Total risk |
|------------------------|-----------------------------|-----------------|---------|-------------------|-------------------------|------------|
|                        |                             | Occurrence | Impact  | Exposure | Knowledge | Occurrence | Impact  | Exposure | Knowledge | Occurrence | Impact  | Exposure | Knowledge | Occurrence | Impact  | Exposure | Knowledge | Occurrence | Impact  | Exposure | Knowledge | Occurrence | Impact  | Exposure | Knowledge |
| 2.0-2.15               | L1 portal                  | 5           | 3       | 1       | 2         | 4          | 3         | 2         | 4         | 4         | 3       | 1       | 2         | 4         | 7.5     | 4         |
| 2.15-2.30              | L1 tunnel                  | 5           | 5       | 1       | 2         | 5          | 2         | 4         | 1         | 2         | 4         | 3       | 1       | 2         | 4         | 7.5     | 5         |
| 2.30-2.65              | L2 tunnel                  | 5           | 3       | 1       | 2         | 4          | 2         | 80%      | 2         | 20%       | 1         | 2         | 80%      | 2         | 7.5     | 4         |
| 2.65-4.0               | L3 tunnel                  | 1           | 1       | 1       | 2         | 2          | 80%      | 2         | 20%       | 1         | 2         | 80%      | 2         | 17.5    | 4         |

4. Conclusions

During monitoring measurements of the slope stability performed before construction of the highway D1 in the central Slovakia, a significant activation of the landslides was observed in the highway section that was about 2 km long. Such deep and active landslides were not taken into consideration during the highway design stage. Therefore, it was decided to reassess the realization of the highway in the originally designed route and to assess the possibility of choosing more acceptable alternative route. To decide which alternative is the best one, a risk analysis of feasibility of the original (surface variant V1) and a newly proposed route (tunnel variant V2) were performed. The decisive risk is the interference of the highway route with the landslides (Figure 2).

In Chap. 2 and 3 a detailed risk analysis for variants V1 and V2 is given. The total estimated risk for each section of both variants was determined as the highest risk resulting from the three assessed risk. The five-grade numerical classification of the risk of V1 is given in Table 8 and for the variant V2 in Table 9. For a simpler orientation in the resulting risk, the semaphore colors were used in the tables and in the schematic mapping of both variants V1 and V2 (Figure 4).

The resulting comparison of the two variants is shown in Table 10. The total evaluated length of the variant V1 was 2800 m and of the variant V2 was 2000 m. The length of variant V1 is longer, as we had to include the service communications that need to be remediated as they pass through the unstable slopes.
**Table 10.** Comparison of the total risk of construction of variants V1 and V2

|   | Total Length of route V1 |   | Total Length of route V2 |   |
|---|---|---|---|---|
| risk | In meters | In percentage | In meters | In percentage |
| 1   | 0         | 0            | 0         | 0            |
| 2   | 0         | 0            | 675       | 33.8%        |
| 3   | 900       | 32.1%        | 405       | 20.3%        |
| 4   | 910       | 32.5%        | 770       | 38.5%        |
| 5   | 990       | 35.4%        | 150       | 7.5%         |
| Total | 2800     | 100%        | 2000     | 100%        |

Based on table 10, Figure 4, it is clear that for 35.5% of the V1 route, the total risk of the highest grade 5 was determined, and only 8% of the route for the variant V2. Currently, works are underway to begin construction a new highway route, which was also recommended by the risk analysis.

**Acknowledgement**

This article was created with the support of the Ministry of Education, Science, Research and Sport of the Slovak Republic through grant VEGA No. 1/0842/18.

**References**

[1] Kopecký, M. – Ondrášik, M. – Antolová, D.: Atlas of Landslides in Slovakia. *AGH Journal of mining and Geoengineering*. AGH Krakow. Volume 36, No.1. p. 211-217. ISSN 1732-6702. 2012

[2] Klukanova, A., Frankovska, J.: The Slovak Carpathians loess sediments, their fabric and properties. Genesis and properties of collapsible soils. Proc. workshop, Loughborough, 1994, Book Series: *NATO advanced science institutes series, series C, mathematical and physical sciences* 1995, Vol. 468, pp. 129-147
[3] Frankovska, J.: Collapsibility of loess evaluated from field and laboratory tests. *International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management*, SGEM 2016, Vol. 1, pp. 731-738.

[4] Frankovska, J., Zajacová, J., Durmeková, T.: Legislative aspects of landslides stabilization design in Slovakia. *International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management*, SGEM 2016, Vol. 1, pp. 887-89.

[5] Kopecký, M. – Ondrášik, M. – Antolová, D.: Horizontal drains as effective measure for landslide remediation. *Studia Geotechnica et Mechanica* Vol. XXXV, No. 1. ISSN 0137-6365, p. 129-141, 2013.

[6] Malgot, J. – Baliak, F. – Kopecký, M. “Engineering-geological map of slope deformation on route D1 Hubová-Ivachnová, *Department of Geotechnics, Faculty of Civil Engineering, Bratislava*, 2006.

[7] Kopecký, M. “‘Analysis of the feasibility of the planned route of the D1 Hubová - Ivachnová in the km 2.0-4.0 range with regard to the current activity of the landslides and the safe operation of the motorway after the construction”’. *Highway D1 Hubová-Ivachnová, Engineering geological expertise, Department of Geotechnics, Faculty of Civil Engineering, Bratislava*, pp. 38, 2015.

[8] Scavia, C. “Concerted action on forecasting, prevention and reduction of landslide and avalanche risks”. *Landslides: Regional report. Proceedings X-Calar expert meetings Innsbruck 1-3 March, 1999. Draft*. Hofburg center Vienna, Austria. Part 9, 18 pp. 1999.

[9] Molenaar, K. R., Diekmann J., E., Ashley, D., B.: *Guide to Risk Assessment and Allocation for Highway Construction Management*. US Department of transportation, Federal Highway Administration, 2006, 73 p.

[10] Technical requirements of Ministry of Transportations, construction and regional development of Slovak Republic: *TP 02/2011 Risk analysis for Slovak roads tunnels*. 37 p.