Practical example of the infrastructure protection against rock fall

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Abstract. The protection of transport infrastructures against rock falls represents for the Czech Republic one of the sensitive questions. Rock falls, similarly as other typical geo-hazards for the Czech Republic, as landslides and floods, can have negative impact on safety and security of these infrastructures. One practical example how to reduce risk of rock fall is described in the paper. Great care is devoted to the visual inspection enabling to indicate places with high potential to failure. With the help of numerical modelling the range of rock fall negative impact is estimated. Protection measures are dealing with two basic ways. The first one utilize the results of numerical modelling for the optimal design of protection measures and the second one is focused on the monitoring of the rock blocks with high potential of instability together with wire-less transfer of measured results. After quick evaluation, e.g. comparison with warning values, some protection measures, mostly connected with closure of the potential sector, can be recommended.

1. Introduction
In the field of Transport Infrastructure some priorities during last years were defined, e.g.

- FEHRL Vision 2025 for Road Transport in Europe [1];
- ECTP reFINE (2012) [2].

Basically all are emphasizing three aspects: sustainability, availability and affordability. Availability is putting an accent on increase of infrastructure capacity not only for current but also for expected changes in future, e.g. from the weather change point of view. Therefore the interaction of transport infrastructure with natural hazards as e.g. landslides, rock falls, floods are studied very intensively – e.g. European project INTACT, as well by authors: [3].

Therefore the paper is focused on one such example, describing the infrastructure protection against rock fall.

The slopes above the road II/102 in section Strnady-Štěchovice represent a substantial risk for the traffic on the road from its construction in 18th mid-20th century [4]. An increasing number of cases of falling stones and blocks on the road have been observed in recent period. Fortunately it was without any casualties. Road management and maintenance office in Kladno decided to solve this alarming situation. They contacted the Department of Geotechnics of the Faculty of Civil Engineering, CTU in Prague with a request for assessment of the risk and recommendations for its elimination.
The main aim of the assessment was determination of the risk areas which was based on our own site survey. The second aim was to propose risk reduction measures, together with the proposed long-term monitoring of the selected rock objects (the places with the highest potential risk), using wireless data transmission system with connection to the warning system.

2. Description of the site

Assessed section is 12.45 km long, and there were four defined surveyed subsections with the high risk, Figure 1. These are the sections: Strnady, Vrané nad Vltavou, Štěchovice 1 (Žižkův vrch) and Štěchovice 2 (Šlemín - Hradiště).

Rock slopes above the dam Vrané nad Vltavou was evaluated as a riskiest part - Figures 2 and 3. Vltava river valley runs parallel to the direction of layers having tendency ca 40-50° to the SE. This tendency is identical with the inclination of most studied slope and forms the majority of its surface.

A typical characteristic of this section are four clearly visible smoothed rock surfaces - "plates" of shale. Inclination of the layers is oriented down toward the valley. A huge rock falls of volcanic tuffs occurred along these shale plates in the past as a result of excavation of the foot of the slope for road construction in the twenties of the last century. Principle and chronology of the landslide is shown in Figure 4 [4].

In addition to this typical feature there are large rock blocks of various sizes with various stage of weathering situated on the main scarp of the landslide above a rock plates – Figure 5. These blocks represent a significant risk of fall on the road. Progressive weathering occurs along parallel discontinuities which can result in possibility of their loosening and subsequent movement or even fall down into the valley.

![Figure 1. Assessed sections.](image1)

![Figure 2. Vrané nad Vltavou – section with highest risk above the dam.](image2)
Figure 3. View on the section with highest risk - Vrané nad Vltavou section above the dam reservoir.

Figure 4. Principle of landslide occurred in Vrané nad Vltavou [4].

Figure 5. View on main scarp above rock plates.
3. Risk reduction
Evaluated section of most risky rock slopes along the road II/102 Strnady - Štěchovice is in indifferent equilibrium. It is almost impossible to guarantee required slope stability (usually expressed as a factor of safety $F = 1.3$ to $1.5$) by cutting and reduction of steepness of the slopes, because it would mean a huge excavation of rock mass, which would also affect land in the upper edge of the slope.

The solution to this potential risk can have several approaches, depending on the acceptable risk. This risk is given by direct threat of falling released rocks from small fragments to large blocks, which directly threaten the traffic on a road at the foot slope or nearly situated buildings and water structures. Recent cases where the fall of loose blocks and their collision with vehicles occurred mean that a danger is very high.

One extreme solution is an approach whose main premise is to implement such remedial measures, which would effectively not allow direct impact of falling blocks with the road. It is obvious that this solution can reduce the risk to ensure a high level of safety for several decades on one hand, but also implies the extremely high costs of these remedial measures. But 100% safety can be never reached.

The second extreme solution is based on reduction of remedial measures to the minimum with maximum attention devoted to the limiting the direct collisions of persons and vehicles with falling rocks. This solution has its limits in terms of monitored blocks, where the drivers would be informed in advance about released block by some warning system (traffic lights, gate).

The approach chosen by authors is based on the finding of some optimum between these two extreme solutions. For sections where the potential danger is less, (for example with respect to the small size of possible loosed fragments, or in case where toe of the slope has some retention area) was chosen first passive approach. This approach involves both limiting the movement of loose particles down the slope, and its capture just before the impact on the road. For large blocks (of the order of 10 $m^3$ and more) with the highest potential risk in the event of its release, it is recommended the second approach, i.e. monitoring of behavior of these blocks (especially inclination and displacement in time). For cases with higher potential of release and with relatively demanding measures to dissipate its energy the disintegration or anchoring is recommended (usually for size of blocks 5-10 $m^3$).

4. Proposed measures for risk reduction
Because of variable character of the observed area five types of remedial and protection measures were proposed: retaining reinforced walls, covering of weathered rock surface by mesh and anchoring, dynamic barriers, removal of unstable blocks and monitoring.

Effectiveness of designed protective measures should be evaluated by simulation in rock fall program. The program allows simulations the trajectories of the falling blocks. Designed block with a certain weight, shape and modulus of elasticity is released from a certain part of the slope. Its kinetic energy has to be safely captured by proposed barriers while falling blocks must not jump the barrier. Example of rock fall simulation in GeoRock 2D program for selected sections of Vrane nad Vltavou site is shown in Figure 6.

4.1. Retaining reinforced walls
Retaining reinforced earth walls are recommended in places where there is an enough space between the toe of the slope and the road. Larger stones may be a partially disintegrated during falling and the smaller particles can be captured by retaining walls. We recommended reinforced soil with using old tires, especially on the side toward the slope, which should reduce the impact of fallen rock blocks. Schematic cross section is shown in Figure 7. It seems to be a very effective and low cost measure with great potential for energy absorbing. Therefore, this measure should be implemented wherever the morphological conditions allow it. Moreover, it is possible to increase total protected height by vertical steel fence with fixed wire mesh. This fence is especially very useful for capture of smaller rebounding rock fragments and stones.
4.2. Covering by mesh and anchoring
In principle selected parts of the rock slope is covered by steel wire mesh or high strength geogrid anchored by bolts or short anchors into the rock. The main purpose of this measure is reducing the movement of weathered fragments and even larger boulders of the order of up to 1 m$^3$ to hold them in place during the first stage of the weathering and fix their position until further weathering into smaller pieces. After that weathered particles are targeted removed. This measure is easily realizable on a flat surface slope of the slab character. The measure requires regular inspections and releasing the captured material.

Negatively inclined rock structures that are bounded by discontinuities can be stabilized by anchors or rock bolts. Drilling of boreholes for bolts or anchors will be done by using climbing techniques. All steel elements have to be provided with suitable anticorrosive coating.

4.3. Dynamic Barriers
Dynamic barriers represent special approach. They are most suitable on the places where spontaneously falling boulders and large debris may fall down. In principle dynamic barrier consists of high strength steel mesh which is connected to the steel vertical anchored beams. The connection is made by using brake elements that capture the deformations, absorb energy and stop the block. These barriers represent an effective but demanding system which requires gradual release of captured blocks in order to restore full functionality of the barrier. Therefore, it is recommended only for places where there is a real danger of rock fall, which can impact the road. In our case we assumed that the proposed dynamic barriers have been able to keep the size of boulders up to 1-2 m$^3$. 

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**Figure 6.** Example of the effectiveness of the proposed measures of by rock fall simulation.

**Figure 7.** Schematic cross sections of retaining reinforced earth wall with old tires facing.
4.4. **Disintegration of rock (mechanical loosening)**

Disintegration is very suitable for very danger rock blocks which are unstable and their fall could be expected soon. Blast is usually controlled with micro-second delay and with steel mesh protection, preventing wide spread of loose parts. This measure solves the most problematic cases, and thus significantly reduces the potential risk of falling blocks to the road. The procedure requires safety measures; work on the slope is not easy with respect of difficult access. Hydraulic wedges and lifting bags are most commonly used for mechanical disintegration.

4.5. **Monitoring – warning system**

The purpose of monitoring which is associated with the warning system can be divided into several follow-up phases. In principle, monitoring is observation of deformations. Deformation can be understood as a result of cyclic weathering processes - such as the influence of water freezing in rock cracks, crevices, the influence of temperature changes which cause increase or reduction of rock volume, as well as the process of reduction of shear strength on potential slip surfaces. Shear strength is a function of shear displacement. In the first phase shear strength increase with the displacement, but after crossing the so-called peak strength, shear strength can be reduced on shear surface. This second phase may occur as a gradual acceleration of deformation in time, with resulting shear strength excess and followed with sudden shear drop off. The basic character of the expected deformation is illustrated in Figures 8 and 9, when the first case is classical shear and second case is overturning.

![Figure 8. Block with expected translation movement.](image1)

![Figure 9. Block with expected rotation movement.](image2)

5. **Phases of the monitoring**

The following phases of the monitoring are proposed:

- Regular visual inspections of the documentation points or other points that were photographically documented and briefly described. This stage is a rough assessment of the visually observable changes;
- Regular visual inspection of remediation measures - assessment of the status of remedial measures, the volume of captured loose debris, boulders and recommendations for their release, to restore the accumulation space;
- Geodetic observations in the recommended time intervals to monitor relatively large areas on a slope for selected observation points. The aims are to identify places with excessive movements, to assess their development in time, to recommend the installation of additional documentation points or implementation of other remedial measures;
• Instrumentation and monitoring of selected blocks with deformation measuring (displacements of particular blocks, widening of cracks) with using crackmeters and inclinometers with high resolution. Time intervals can be selected depending on the potential danger. It is possible to define critical conditions for increasing deformation rate and provide wireless transmission of measured data to a desk of responsible person.

5.1. Description of continuous monitoring methods using MEMS sensors with wireless data transmission

For monitoring of rock slopes where there is very limited access and where there is a necessity to perform long term monitoring, it is worthwhile to use wireless data transfer. This approach allows connecting various types of sensors used for monitoring via the wireless network. Once the data are recorded they are sent to the central point of the wireless sensor network and afterwards all measured data from a short period of time are together transferred again wirelessly via internet on the server for further processing.

The authors of this paper have a good experience with similar type of monitoring which is designed, installed and operated in the Prague metro [5]. Processing and analysis of data can be operated automatically and measured data can be displayed on a web interface.

At the same time it is possible to create a warning alarm system, which defines the critical value of measured deformation. In the event that the measured value of deformation is higher than critical value, system will automatically send a warning e-mail and SMS messages to the addresses of all persons responsible for safety management of the road. This system can be extended to include an automatic traffic lights and gates on the road. Scheme of the continuous measurement system using MEMS sensors with wireless data transmission is shown in Figure 10.

Wireless technology works in non-licensed band of 2.4 GHz on the ZigBee platform that operates on Intel chips. The whole solution of wireless data collection from individual measuring points that can connect both analogue and digital sensors is supplied by Crossbow Company. Everything is just a question of interconnection of relevant chips (interfaces) for sensing (data collection) with the chip for wireless communication. The heart of the whole system is an embedded computer running the Linux operating system which communicates with the gateway point of wireless ZigBee sensor network via Ethernet or USB interface. This embedded PC acts as well as temporary storage of monitored data before they are sent to the server in the office. Each network point is necessary to program before its installation for specific task, position and connected sensor in the wireless sensor network.

The results can be continuously evaluated and it is possible to define the limit values of deformation, respectively time development of deformation. In case of exceeding of limit deformations, warning system will automatically signal on the road (speed reduction signal, an increased risk of falling rocks, locking the gate etc.), while a group of experts will visit the section on which signal was registered. To check the automatic sensors classic strain gauges with a lower degree of accuracy will be installed as a comparative measurement. It is a classical form of dual control.
Figure 10. Scheme of monitoring system using MEMS sensors and wireless network.

6. Conclusion
The risk associated with a rock fall on the road is currently very topical and much discussed not only in the Czech Republic but also worldwide. Defining and quantifying the risks is very difficult, since the risk depends on many factors and specific condition of particular site.

Paper is therefore focused on rock slope above the road from Prague to Štěchovice. Most dangerous places were described on the base of personal investigation. After that different countermeasures were discussed. Final recommendation for risk reduction is based also on the numerical modeling of blocks up to the size of 2 m³. With the help of numerical modeling we specified protection barrier at the slope toe utilizing waste tires.

One of the most important measures for reducing the risk of the site are regular visual inspections by experienced geotechnical engineer and using of modern methods of monitoring system connected to the warning signal.

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