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Interaction of transport infrastructure with natural hazards (landslides, rock falls, floods)

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Abstract. The significance of the transport infrastructure is going strongly up during last period. It is connected with two aspects. Firstly the interest is connected with energy consumption as about 40% of overall consumption is consumed for transport infrastructure. Secondly the interest is focused on securing the serviceability of transport infrastructure also during nonstandard conditions. Between these conditions belong not only cases elicited by human factor, as transport for example the blockade caused by transport accident, but also by cases elicited by external factors, mostly by natural hazards. The paper is focused on securing serviceability during natural impacts - hazards. Floods, landslides, rock falls are natural hazards typical for middle Europe. Therefore natural hazards like tsunami, typhoons, hurricanes typical for coastal zones, or avalanches typical for alpine zones, respective earthquakes for seismic prone zones are not included in. The paper is therefore focussed in more details on the interaction of transport infrastructure with floods, landslides and rock falls with the main aim to guarantee at least limited serviceability during such events. In doing so the view of geotechnical engineering is playing primordial task.

Keywords: Landslide; Rock fall; Flood; Critical infrastructure

1 INTRODUCTION

Currently there are more documents in Europe, which are specifying the significance and orientation of transport infrastructure for coming decades. The following can be mentioned, (Vaníček, Jirásko, Vaníček 2017):

- Horizon 2020 Transport Advisory Group (TAG), May 2016
- FEHRL Vision 2025 for Road Transport in Europe
- ECTP reFINE (2012)
- ELGIP position paper (2016)

In principle they are focused on three aspects: sustainability, availability and affordability.
With respect to affordability the attention is directed on long term functionality of the transport infrastructure, taking into account the structure ageing, demands on the maintenance. (Generally speaking on the decrease of demands for life time expectancy).

In relation to the natural hazards, the aspect of availability is having priority. 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: (Vaníček and Vaníček 2013), (Jirásko, Vaníček 2017), (Jirásko, Vaníček and Vaníček 2017).

With respect to sustainability the attention is directed on the protection of natural environment. Decrease of consumption of energy, raw materials, natural aggregates and agricultural land are the main component of this effort, (Head et al 2006), (Vaníček 2011), (O´Riordan 2012).

Availability aspect is getting higher significance with up to date demands on the mobility of people and goods, products. Good accessibility on the working place, health care, recreation, people meetings and so on should be ensured (even in little bit limited size) also during nonstandard situations, as are created by natural hazards.

Natural hazards generally represent a significant impact on human life, inductive of serious social consequences and large economical damage. Natural hazards constitute the limitation of sustainable development, affecting its three main components: economic, social and environmental, (Vaníček and Vaníček 2008).

Despite the steps taken during last decades (e.g. The international decade for natural disaster reduction), the number of natural hazards are in fact increasing; causing at present-day, in average yearly damage, about 50 billion US dollars or 40 000 human lives, (Kalsnes, Nadim, Lacasse 2010).
All the above mentioned is the reason why the interaction of natural hazards with transport infrastructure (TI) is getting such prominence. Therefore the individual examples of such interaction will be investigated independently with the main aim to eliminate theirs impact on the functionality of TI. However, not only the prevention component will be underlined but also the increase of structure resistivity. The resistivity will be discussed with respect of limit states of earth structures of TI, as ultimate limit state and serviceability limit state.

2 FLOODS

The impact of floods on inhabitability and their belongings were always in the forefront of publicity as roughly one third of all damage caused by natural hazards are floods. Presently, the problem of floods is even more sensitive due to two reasons. Firstly it is higher usability of the flood prone area, with higher population, higher development, including critical infrastructure, of which TI is part of it. So it means that floods can create higher damage than in former times.

Climate changes are the second reason of this higher sensitivity, as they can increase the number and extreme of floods. The increase of average temperature is well documented, namely during last half century – Fig. 1. For example the increase of average temperature in the Czech Republic is higher than 10° C during last half century. This fact is causing higher drying of the surface layers. This factor is causing lower infiltration during rainfalls on one side and higher flow-off on the other one. Average sum of rainfall is still roughly the same, however there are greater differences between period of rain surplus and period of rain deficit. These differences are as for rainfall peaks and bottoms so for duration of dry and wet periods.

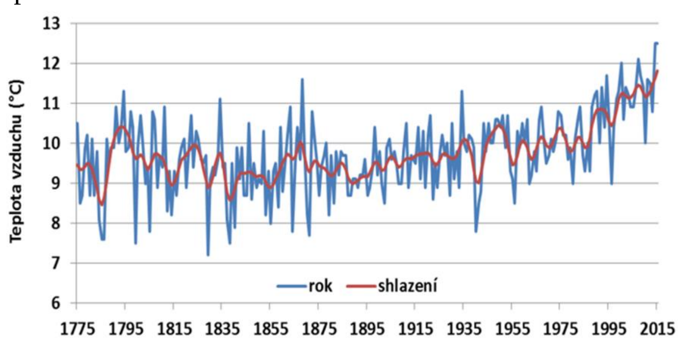

Figure 1. Change of air temperature with time for the Czech Republic.

Generally three basic types of floods can be distinguished:

- Regional floods – affecting 1 or more river-basins, coming usually in summer and are caused by long term heavy rainfall;
- Local floods – affecting small area, for relatively short period and are caused by extremely high local rainfall (storm) – so called flash floods;
- Floods in foothills – during spring, when the soil is still frozen – and floods are caused by combination of snow melting and rain.

Most difficult from the forecast point of view are flash floods, they have local impact, very often without any previous experience for people living there. From this point of view the floods in foothills are best predictable with respect to time and place and there are long-term experiences.

For both above mentioned cases the lateral (sideward) erosion of TI, running in parallel with watercourse is the typical case of this interaction. Exposure of small bridges crossing these watercourses is also significant. Protection against spring floods has already some history, as the construction of large dams in mountains and foothills started at the end of the 19th century.

The regional floods are most dangerous from the point of view of damages caused during the flood interaction with TI not only in Europe but also in Czechia. This type of floods created many problems. During last period the floods in 1997, 1998, 2002, 2006, and 2010 were recorded from which floods in 2002 had largest impact. Floods in 2002 were created by heavy rainfalls, which had two peaks close to each other. Significant part of country was affected due to the fact that the largest rainfalls were on the south, and most of the rivers flow out in north direction. Therefore not only capital Praha was heavily affected but also industrial zones along river Labe (Elbe) in the north part of the country.

Basic protection against regional floods has also long term character.
Roughly 75 000 of small dams were constructed in the upper part of water courses in middle Ages. Storage capacity of reservoirs make possible the out flow retardation, brought down the flood peak. Reservoirs are also used for fisheries, therefore they are without water at the end of each year, enabling the dam control. Still about 25 000 of these historical small dams are successfully operating at the present days. Dam crest height is between 3 and 15 meters and these earth-fill dams were constructed as nearly homogeneous dams from the local soils.

Roughly at the same period, in middle Ages, construction of dikes along significant rivers started and practically still continues. And again the fill dams are the most often-used protection element during extreme hydrological situations. For Europe, namely Central Europe, the typical and big problems are connected with the Danube River. Significant floods occurred there in 1954, 1965, 1997, 2002 and 2006, e.g. (Peter 1975), (Brandl and Blovsky 2003), (Hulla and Kadubcová 2000), (Milerski et al. 2003). The construction of dikes in large cities is nearly impossible, therefore during few last decades construction of mobile barriers started. Mobile barriers applied in Prague on the river Vltava help to protect historical part of the city during floods in 2002, Fig. 2.

The construction of large dams on the main rivers is concentrated in 20th century. Large dams are either fill dams or concrete dams. The functionality is connected with flood protection, with energy utilization and with river navigability. As they were constructed with utilization of modern and safer knowledges the probability of failure – connected with significant situation worsening – is less probable. On the other hand another construction is strongly limited. The appropriate dam profiles are nearly exploited and the pressure of some initiatives against new construction is another limiting factor.

Figure 2. Mobile barrier used in Prague during floods in 2002.

2.1 Limitation of TI functionality during flooding

Flooding during higher level of water in rivers is the most typical case of interaction of floods with TI and is connected with all basic types of floods. Transport infrastructure cannot be used for limited time when is flooded by water. This time is usually relatively short, after water level decrease TI can be generally used again, usually without special effort. Fig. 3 is such example, after 5 days the bridge over river Labe in town Ústí nad Labem was fully functional again.

Situation during floods was more complicated in Praha during floods in 2002. Town district Karlin was completely flooded, Fig. 4. In this case not only road transport but also tram transport was affected.
Special attention at these days was focused on metro stations and lines as metro system is the basic element of city transport in Praha. Some stations and part of lines were flooded as well, Fig. 5. However in this case the interruption of transport was significantly longer, in months order. However this problem is little bit out of this presentation. Some aspects connected with metro lines flooding were described by (Soga, Vaníček, Gens 2011).
The different countermeasures are applied to decrease the range of flood prone areas. Instead of technical ones as construction of dams (historical small dams or modern large dams) and dikes the agricultural steps are very important. They have to increase the water infiltration and decrease the surface water outflow.

Figure 3. Flooded bridge in town Ústí nad Labem over river Labe (Elbe). Flood wave shorter than 5 days.

Figure 4. Flooded TI in Prague during floods in 2002.

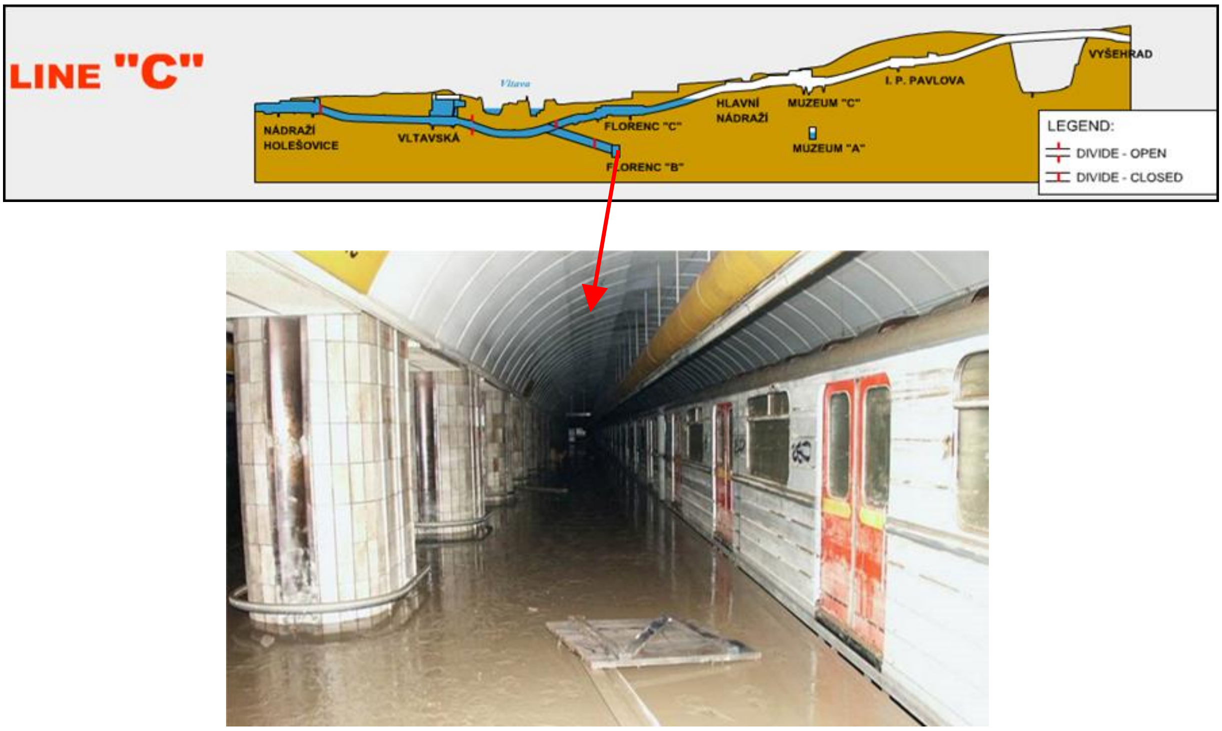

Figure 5. Flooded metro station Florenc in Prague.

2.2 Immediate flood interaction with transport infrastructure

The first form of this interaction is direct failure of road and railways following water course. During higher water level and speed of flowing water its erodibility is going up. Side walls of this infrastructure are eroded resulting up to final collapse. Fig. 6 shows such typical case. However there is a chance to appreciate weak places and to reinforce the resistance to erosion in advance. Similarly the same approach can be used during reconstruction of damaged segments. The problem is that very often the demand on quick reconstruction prevails and classical methods are used again. Therefore the new methods, accepting the principles of affordability and availability, should be prepared in advance to be able to reduce the probability of the failure at the same place in future, during next floods.

Figure 6. Typical case of damage of road following the water course.

Bridges crossing the river are second example of such interaction. With respect to scouring the bridge piers foundation create most sensitive place. This is especially valid for old, historical bridges, as there the foundation depth is relatively low. Charles Bridge in Praha from 14th century is such example. During centuries nearly all bridge piers failed as the result of shallow foundation of bridge piers and sequentially were reconstructed – Fig. 7. However it is possible to mention another historical bridge in town Písek, which survived in relatively good shape a complete flooding during floods in 2002, Fig. 8.

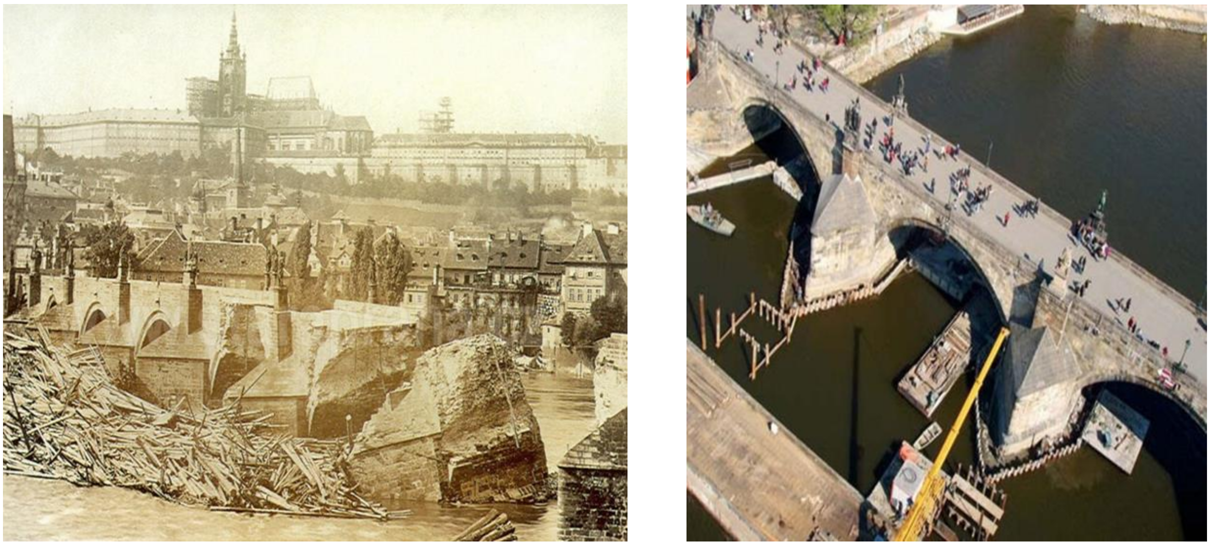

Figure 7. Prague - Charles bridge - failed piers in 1890 and the reconstruction of last two piers after 2002 floods.

Figure 8. Historical bridge in Písek during floods in 2002.

The problem of scouring is also sensitive for modern bridges. For example (Malerba 2011) describes this type of interaction for bridges on the river Po in Italy, constructed between years 1908 to 1967. Significant floods were recorded there in years 1926, 1951, 1994 and 2000. After last floods in 2000 Italian Agency for Roads promoted a campaign to survey the state of piers, of the basements and of the foundations of the main bridges crossing the Po River and serving roads of national interest. Closer view into this multidisciplinary problem is given e.g. by (Hamill 1999), respectively by (Federal Highway Administration in USA 1993).

2.3 Interaction of floods with historical dams

Historical dams have dominant significance from the view of interaction of dams with floods, especially in the Czech Republic. The main aim of such dams with its reservoirs is water retention during its surplus and its accumulation for dry seasons. The crest of these historical dams, referred to as fish dams, as the reservoirs are used for carp farming, are used also for transport communication. Whereas historically the crest was unpaved, however later on some of them are covered by asphalt carpet. Ageing of such dams is connected with more unfavourable phenomenon. Higher transport loading with dynamic effect, atrophy of old trees on upstream and downstream slopes of embankment are typical cases of these phenomenon. Especially dynamic effect is having negative effect on the contact of soil with original timber bottom outlet.

During heavy floods the number of damaged dams is in the order of units up to tens. Most often case of failure is connected with surface erosion during crest overflowing. For dams with long crest the downstream slope eroded along all length and the breakthrough starts in most weak place, sometimes simultaneously in two places – Fig. 9. Asphalt pavement has positive effect during crest overflowing, as speed of erosion is decreasing. Therefore the time of flood wave duration doesn't need to lead to the total collapse, which would create dangerous addition flood wave under this dam. – Fig. 10.

Failures during floods event caused by internal erosion over a period of higher hydraulic gradient are less frequent. Failures by piping or by suffusion are not the cases for nearly homogeneous historical dams. The failures are mostly connected with some preferential path. The contact of the bottom timber outlet with surrounding soil is typical case of this preferential path. In some cases it is unsuitable technical solution performed in history. Fig. 11 shows old timber outlet, which was left in the dam body (when new outlet was set in another place). Ends of this outlet were sealed by soil, however this plug failed due to high hydraulic gradient and this preferential path was the initial point of internal erosion.

Fig. 12 shows the dam which failed during floods in 2002 at the same place, where was reconstructed at the end of eighties with the help of new technology – with jet injection. However the connection of this sealing wall with boulder subsoil was very sensitive place as internal erosion started there during higher hydraulic gradient. Classical failure due to slope instability was not observed.

Figure 9. Typical case of the surface erosion during crest overflowing.

Figure 10. The result of surface erosion of the crest with asphalt pavement.

Figure 11. Old timber outlet – the reason of internal erosion.

Figure 12. Failure of dam by internal erosion as the result of bad connection of sealing wall with subsoil boulders.

The reconstruction of these historical dams deserves a special attention. The attention is focused on the selection of appropriate soil, preferable similar as the remaining undamaged part of the dam. Local granitic eluvium creates frequently the body of these historical dams. The grain size distribution is usually on the boundary with acceptable conditions valid today. Therefore it was necessary to control filtration characteristics. However they were mostly fulfilled due to higher content of mica. After that the main attention during the selection of the construction technology was devoted to the connection of the new, reconstructed part, on the old one or on the existing side slope and subsoil, especially when containing large boulders.

2.4 Interaction of floods with dikes

The interaction of floods with dikes constructed along rivers is probably most sensitive problem. If even small part fails the claims can be extremely high. These claims are attributes to the 2 D effect. For example the failure of dikes on the river Danube below Bratislava close to Gabcikovo had extensive consequence, even when there were only two wide gashes (water outbreaks), Fig. 13. Generally it means that 99% or more of the total length of dikes can be safe, even conservative from the view of safety. Damages are connected with weakest places from the combination of dike quality and subsoil point of view. One thousand square meters of high quality agricultural soil was flooded, 3 910 houses were destroyed and another 6 180 houses were damaged.

Figure 13. River Danube below Bratislava – example of dike failure, 1965.
Source: David Ištok, TASR.

Heavy floods in July1997 in the Czech Republic, mostly in Moravia, affected 538 towns and villages; about 136 km of protection dams were damaged, with 55 failures, mostly due to overflow, leaving 50 death, damages around 60 milliard CZK. 946 km of the railway track were destroyed as well as 1850 km of roads and 2151 houses.

The failures along Danube River had common character – were triggered off by the internal instability of fine sand induced by the high hydraulic gradient. Fine sand particles were washed out from the sandy gravel layer, causing a higher water velocity and also higher hydraulic gradient there. This higher hydraulic gradient washed out higher particles and so progressively created seepage canal, (Vaníček and Vaníček 2008).

Two dominant reasons of the dike failure development are usually mentioned, (Vaníček and Vaníček 2008):

- The failure of the protection dam body – highest erosion hazard is connected with the internal erosion starting at the downstream toe of dam – at place at which the depression curve is reaching downstream face – this is valid for old dams, for new ones the toe drains are not missing. A certain danger potential is connected with animals, preferential path for seepage can be caused by otters, beavers.

- The failure of dam subsoil – failure starts behind the dam on downstream side - either by uplift, when the water pressure on impermeable layer is higher than geostatic pressure there or at even higher distance from the dam where impermeable layer is missing and where upward seepage pressure is able to erode fine particles. Process of piping start there leading in the final phase to the dam collapse, the case described also for protection dams below Bratislava on Danube River.

In principle two basic ways are used for increase of dikes safety. The first one prefers the elongation of the seepage path for lowering hydraulic gradient. Second one is using different possibilities how to cut across the seepage path by sealing element. Different ways of increasing safety are presented for schematic cross-section in Fig. 14.

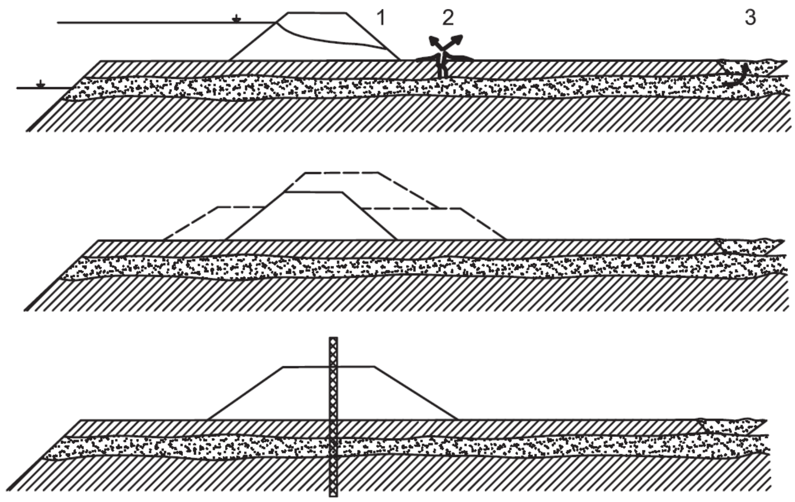

Figure 14. Protection against internal erosion. Different possibilities of safety increase.

Now it is appropriate to stress the fundamental specificity of the dikes by which they differ from the classical fill dams:

- Loading by water is strongly time limited - therefore during the flood the soil is partly saturated, seepage is limited by air bubbles. The demands on permeability are not as high as for classical small dams, allowing constructing dikes from more permeable, local soils.
- Localisation – roughly the line of dikes is predestined (whereas for classical dams the profile is carefully selected according to the quality of subsoil). Therefore the subsoil conditions are often very complicated because quality of river sediments are changing from gravels up the sullage (organic silt).
- Construction materials – local soils are preferred which can caused some problems with high heterogeneity and after that with possibility to influence the seepage path in future,
- Dimensions – the third dimension – dike length is extreme – one weak place can cause large catastrophe.

2.5 Special interaction problems

7 historical dams failed on small river Lomnice during floods in 2002, from which 5 failed completely – Fig. 15. Higher resistivity of the remaining two dams is ascribed to asphalt pavement of the dam crest. It is interesting to note that during floods on the same small river in 1890 all these 7 dams completely failed, even this historical floods was little bit smaller. Authors already this type of failure denoted as domino effect of failure due to cascade arrangement of these dams. During failure of dam situated at the beginning of the catchment basin the additional flood wave is generated (especially when having reservoir with large volume) and dams situated below, close to each other, have limited chance to survive, (Vaníček and Vaníček 2004).

Subsequently a great attention was devoted to this type of domino failure also for another catchment basins in the Czech Republic. Cascade arrangement (with most important dam at the beginning) was registered for more cases. The potential risk was evaluated from the view of flood wave numerical modelling between individual dams, (Vaníček, Vaníček and Pecival 2016). At first the character of flood wave leaving failed dam is modelled and subsequently its size is modelled as function of time, distance and flooded area character, Fig. 16. The interaction of this wave with transport infrastructure (with transport embankment) crossing the route can play also positive role, as can flatten this wave. However only up to situation to which the embankment is able to hold this wave.

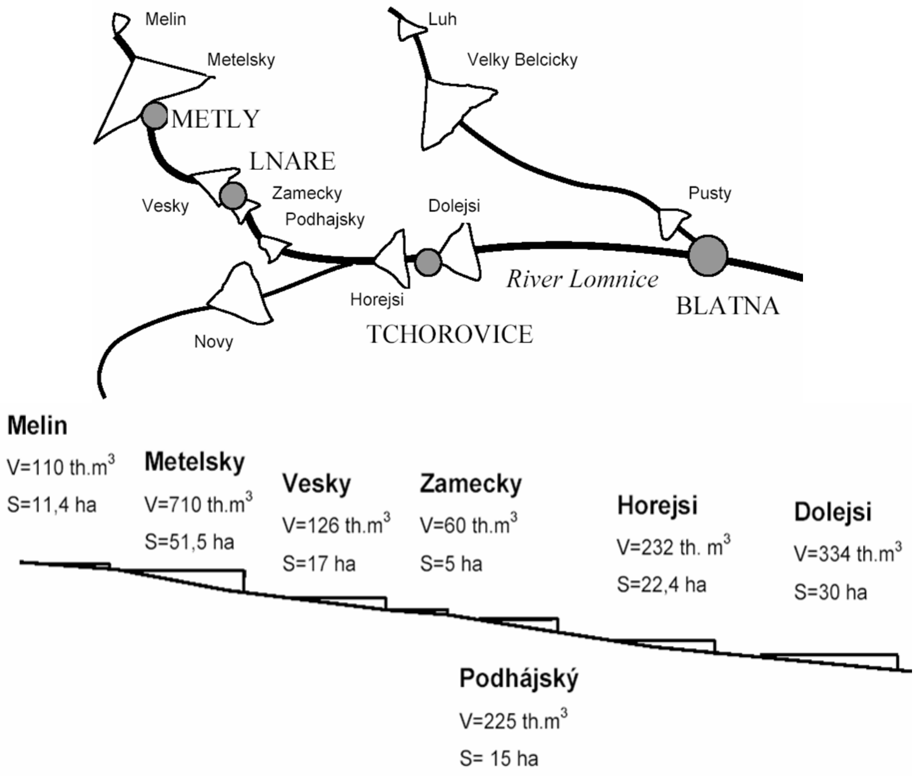

Figure 15. Domino effect of dam failure for cascade arrangement.

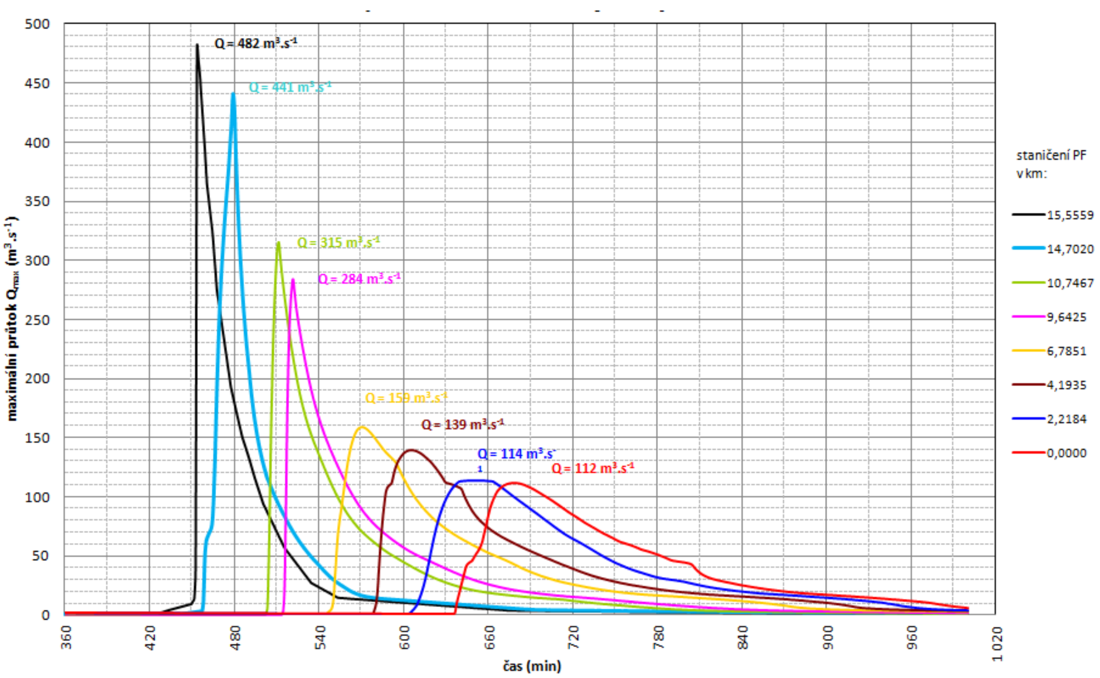

Figure 16. Numerical modelling of flood wave propagation in time and distance from failed dam.

Usually when the transport embankment is crossing the river (brook) water is flowing through culvert. During higher flow rate and especially when outflow is obstructed by carried vegetation (bush, tree) the water front of embankment is uprising and subsequently can be the reason of embankment failure. Fig. 17 is showing such failures, the event happened on already mentioned small river Lomnice, the second one - Fig. 18 - is from Italy, (Burdo 2016).

Figure 17. Failed railway embankment on small river Lomnice.

Figure 18. Embankment failure on the railway track Bari – Taranto.

During the discussion about the character of failure the type of soil of the embankment adjacent to the bridge abutment was stressed. For very permeable soil the seepage is very quick and the outflow on the downstream face can initiate the internal erosion. When the embankment permeability is very low after that the seeping water is not able to reach downstream face. After the quick flood wave falling off the water inside of embankment can create by reverse outflow the slope instability of the upstream face. However this type of failure was not observed for above mentioned two examples.

Therefore our attention was focused on soil with average permeability, roughly of the sand type. In this case the water is penetrating embankment only from the upstream face but also as rain-water from the downstream face. The air inside the embankment for primordial partly saturated soil is trapped between developed two saturated zones. The air pore pressure is increasing as time goes on. Finally this pressure can be sufficient for lifting the downstream face. The displacement (slide) of this face can evoke internal erosion leading up to total collapse.

Therefore we simulated the behaviour of air trapped in soil pores in laboratory. Dry sand was placed into glass tube, only upper part was composed from fully saturated sand. Lower part of tube was put in tank with water, enabling to rise by capillarity forces. The crack, the separation of the two sand parts, was observed, as the result of air pressure increase between two saturated parts – Fig. 19. This experiment demonstrates the estimated character of failure described above. At the same time is pointing at partly saturated sand which can be most sensitive for described type of embankment failure.

Figure 19. Upheaval of saturated sand layer by pore air pressure increase in partly saturated sand.

3 LANDSLIDES

Landslides are causing large damages on both properties and human lives every year worldwide. Therefore, extreme attention to the landslides is devoted in the literature. With respect to (Kalsnes, Nadim and Lacasse 2010) the amount of damages caused by natural hazards is at least 17%. From the transport infrastructure point of view, it is possible to pick two general types:

- Landslides caused by new construction of civil infrastructure in the areas prone to landslides
- Landslides caused by the changes to external conditions (mainly climatic ones) that affect the stability of slopes adjacent to civil infrastructure.

3.1 Landslide prone areas

The area prone to landslide can be characterized as area, where both old and recent slope movements were identified. In many countries such areas occupying large tracts. Therefore, civil infrastructure projects shall accept such reality and make account of those areas. Identification of landslide prone areas is a general assumption. For the identification map records and databases of local geological services could be used. Special maps that indicate slope instabilities exist in some countries. For example, (Baliak et al. 1996) present the map of Slovakia where several hundred places of coincidence between slides and transport infrastructures roads are indicated.

Civil infrastructure placement into this type of area requires first of all very detailed geotechnical site investigation. The geotechnical investigation shall identify in wider strip, where transport infrastructure could be placed, which sections have been subjected to any slide movements and which have not. Naturally, the infrastructure alignment selection is attracting the non-sliding sections. The reason being is the reduction of soil shear strength along the old slippages down to residual strength and therefore appropriate measures will be required. Investigation points shall be located as such that they result in relevant information about the old sliding movements from both surface and depth point of view.

Evaluation of the civil infrastructure influence on the slope, which was affected by old slippage, is the second important step. For this evaluation (Hutchinson 1977) defines so called principle of neutral point (line). According to Hutchinson this point (line) is located as such that the change in stress field generated by the infrastructure placement (embankment, cut or pore pressure) will not cause any change to stability what so ever. In other words, slope stability after the new construction F_1 is the same as before F_0. The authors derive the neutral point using the simplified Bishop's method. The location of a neutral point is affected by the angle αn of the slide area from horizontal, see Fig. 20:

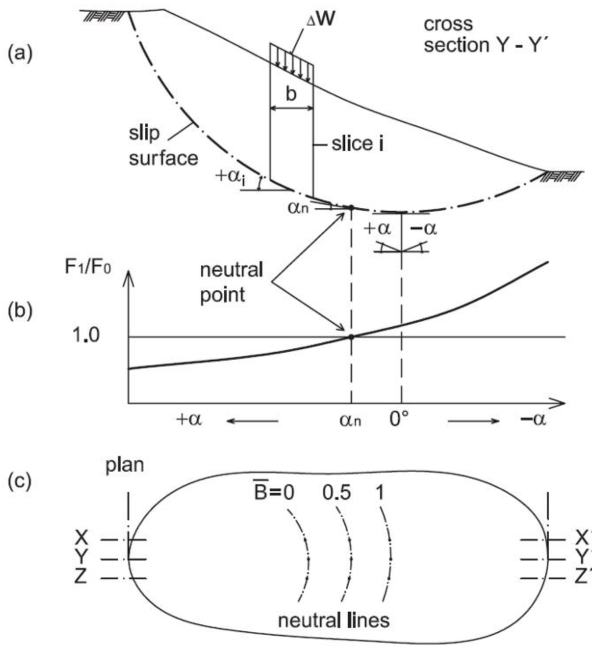

Figure 20. The influence of additional loading on slope stability – explanation of neutral lines and neutral point (according to Hutchinson). (a) Cross-section of a landslide with an influence of load acting; (b) Influence line (diagrammatic) for the effect of load on overall factor of safety of the landslide; (c) Plan of the landslide, showing diagrammatically the position of the neutral lines for different B¯ values.

$$\tan\alpha_n = (1 - \bar{B}\cdot\sec^2\alpha_n)\cdot\tan\varphi'/F_0 \tag{1}$$

Where the parameter of a pore pressure B¯directs the change of pore pressure:

$$\Delta u = \bar{B}\cdot\Delta\sigma_1 \tag{2}$$

From the given above it is obvious, that αn descends with a growing parameter $\bar{B}$. For $\bar{B}$= 0 it is valid that tan α_n = *tg* φ'/F_0 (for an old landslide φ'_r) namely for $\bar{B}$= 1 → α_n = 0. From this view Hutchinson puts a big stress on the size of a parameter of a pore pressure, because it significantly influences the position of a neutral line. That is why the embankment has a positive effect if it is realized under the neutral point, and in contradistinction the drainage cut/incision is positive in effect above this point. The condition in the second case is the prevention of surface infiltration – saturation by water of a landslide area.

Slope stability of the embankment (where short-term stability is decisive) or stability of cutting (where long-term stability is decisive) composes the main geotechnical problem, which is however outside of the scope of this paper.

3.2 Landslides caused by a change of conditions in time

It is natural that with time some conditions affecting the slope stability are changed in time. Within those conditions it is possible to count both natural changes and man-made changes.

At first, we think about the natural, climatic changes, which have direct impact on rainfalls and so on groundwater levels and pore pressures. The prognosis of groundwater levels in time is therefore highly important and is one of the required initial assumptions. The issue of climatic changes is sensitive mainly for rather steep slopes with only partly saturated subsoil most of the time. Negative pore pressure has a positive effect on the stability, which guaranties relatively steep slopes. Pore pressure change from negative values to positive ones significantly affects the stability. Change is the main factor for slope movement development. These movements are with respect to theirs's time frame very quick.

Secondly, we think about man-made changes. These changes are linked with ground movement, either with embankment or cutting construction. The impact of ground movement is falling under the main task of soil mechanics and therefore will not be covered here. After all in agreement with previous chapter 3.1 we can conclude that negative impact on the slope stability has not only surcharge in the upper part of the slope but also unloading (by cut) in its lower part.

Process, causing the change of chemical composition of liquid phase, is also connected with natural changes. These changes of chemical composition of liquid phase have direct impact on the interaction in between individual grains, mainly on clay minerals, respectively on the interaction of solid particles with liquid phase.

Soils, denoted as quick or sensitive clays, went through such serious changes in chemical composition. According to the Geological Survey of Norway (NGU) quick clay (and other types of sensitive clay) is formed in Norway in areas where clay was deposited in a saline marine environment, and subsequently lifted near or above sea level due to post-glacial uplift. Groundwater flow has gradually washed out the electrically charged particles from the sediment pore water. These particles helped to stabilize the loose grain structure, so the leaching leads to instability.

These quick clays have relatively high strength until the internal structure is affected by external impact, which leads at the end to its total collapse. Overloading or digging is in most cases the reason of such external impact. For example (Broms 1980) describes the case when vibrations caused by blasting in the close quarry initiated such internal structure collapse of mudflow character.

3.3 Practical example

The motorway D8 connecting Prague with Dresden has a great importance for the Czech Republic, as providing the connection with the north German motorway network. The construction of this motorway was very demanding from the technical aspect point of view as it is passing on the Czech side via Krušné hory Mountains and also via České středohoří Mountains. Therefore, many tunnels and bridges are there, often side by side. The decision between application of tunnels or surface route for the section between towns Lovosice and Ústí nad Labem passing via České stredohoří Mountains was connected with many discussions. Not only with technical discussion but also with environmental one. Finally, for some sections, the surface route was prioritized with classical embankments and cuts, situated on inclined surface, perpendicular to the motorway alignment.

The main reason that the example of the landslide close to the village Dobkovičky was selected for presentation is the combination of both basic factors. Firstly this wider area was known for slope instability, however the final instability was caused not only by natural, climatic aspects but also by man-made activities, (Jirásko, Vaníček and Vaníček 2017). The motorway in the discussed section is in stepped cut, in two different levels, each for one direction.

The geological conditions are relatively complicated there. Subsoil is composed by complex of Mesozoic sediments as sandstone, calcareous clay, marlstone, with small islands of older crystalline rock as gneiss. On many places these rocks are break through and overlaid by tertiary neo vulcanite rock, as basalt. Slope inclination above the motorway is rather gentle, with average inclination of about 8°. The old railway track is running 250 m in parallel above the motorway D8. Basalt layer rises to the surface only in the upper part of the slope, at about 500 – 600 m above the motorway, where the platform of the basalt quarry is situated. The slope inclination is rather steep in this part, 30° or more, and the surface is created by spoil heap from the finest fraction of the quarry, overlaying weathered rock massif.

The landslide occurred at the beginning of June 2013. The excavation for motorway roadways was finished about 3 years ago, only final pavement was missing. From the beginning the landslide was described as areal shallow one with length of about 500 m, width of 200 m and depth of 5-7 m. The railway track moved downhill by about 50 – 60 meters. Landslide mass overlaid the motorway roadways, Fig. 21. The depth of the landslide corresponded with the interface between weathered surface of calcareous clay and quaternary soil cover. Quaternary materials are characterized as colluvial deposits, fine soils with high up to very high plasticity.

The authors were involved in this problem as consultants of the investor - Czech Directorate of roads and motorway since the spring of 2014. The main aim of this involvement was the verification and observation of remediation measures, to guarantee theirs long term functionality, in order to have a safe operation of the motorway D8.

Figure 21. Character of landslide covering the constructed motorway D8.

From the beginning the climatic conditions were denoted as the main reason of the landslide. For the reference period between years 2007 and 2010 the rainfalls were lower than average ones. Ground water table in quaternary soil cover was significantly below the ground surface. On the contrary the rainfalls for the period between years 2010 and 2013 were above-average, and namely the extreme rainfalls few days before critical event, which were also denoted as the main reason of floods in the wider territory. Ground water table practically reached the surface. For the average slope inclination of 8° it was obvious that the landslide occurred along the surface of previous movement, where the residual angle of internal friction was lower than 16°. The first results of the residual strength measurements for the interface of the weathered subsoil with quaternary deposits approved this assumption when the measured angle φ_{res} = 14,4°. It is obvious that for dry quaternary sediments the stability was sufficient, corresponding for the classical factor of safety F = 2. However for each meter of the ground water table above this interface (in the depth of about 5m) the stability is significantly decreasing.

For the cut section, with maximum depth around 8 meters, the situation was also worsening with time. The first signals of instability were observed already during the phase of excavation (2009 – 2010). But at this time the instability was connected only with local, very shallow slope movement. After the realization of short drainage trenches and small berms at the slope toe no other instability was observed between years 2011 and 2013. But also in this section the slope stability is influenced by pore pressure increase due to ground water table increase above old slip plane. Therefore there is justifiable assumption that this section was close to instability just before the main landslide occurred.
The similar situation was also valid for the upper part of the slope created on the surface by fine fraction of basalt from the stone crushing plant. Height of the slope was roughly 30 m and already mentioned inclination was about 30°. It is another example of the man-made activities influencing slope stability, as the total slope is surcharged in its upper part. Even when the slope inclination of the last (30 m high) part of slope is close to the expected angle of friction of this material as the deposition was by free fall no special problems were observed there. The reason is that the deposited material is partly saturated with time and capillary forces are adding some strength. However with moisture content increase due to extreme rainfalls and also due to additional saturation from the surface water from the quarry platform this additional strength is decreasing. For fully saturated material as can be expected at the slope toe this additional strength is equal to zero.

This significant factor leading to slope stability decrease was simulated by authors in lab for given material. The angle of freely spilled material was between 32 and 35 degrees for dry material. For wet material the created sample can have even vertical walls and such sample was finally disturbed only by significant external load, Fig. 22. However for no-load condition the sample failed very quickly when flooded from the bottom, Fig. 23.

From the above mentioned reasons, it was finally concluded that all decisive sections of the whole slope (middle one with railway truck, lower one with motorway cuttings and upper one with spoil heap from freely deposited fine material) were close to the state of indifferent equilibrium just before the discussed landslide occurred.

After that there was and still is very sensitive discussion at which part of the slope the great landslide started. Authors are pointing out on the upper section. As the supporting arguments they are using the character of the landslide. The part of the landslide above railway track is strongly compressed, not only the surface but also vegetation on it, what is straightforward from the Fig. 24. Under the pressure from the upper part also movement of the railway embankment started even though this embankment had little bid higher stability than the surrounding terrain. When this embankment started to move also the remaining part did the same. From the photo – Fig. 25 - it is visible that the lower part under railway embankment is undisturbed, does not contain any cracks implying the retrogressive failure from the bottom upwards.

Figure 22. High bearing capacity of wet unsaturated sand.

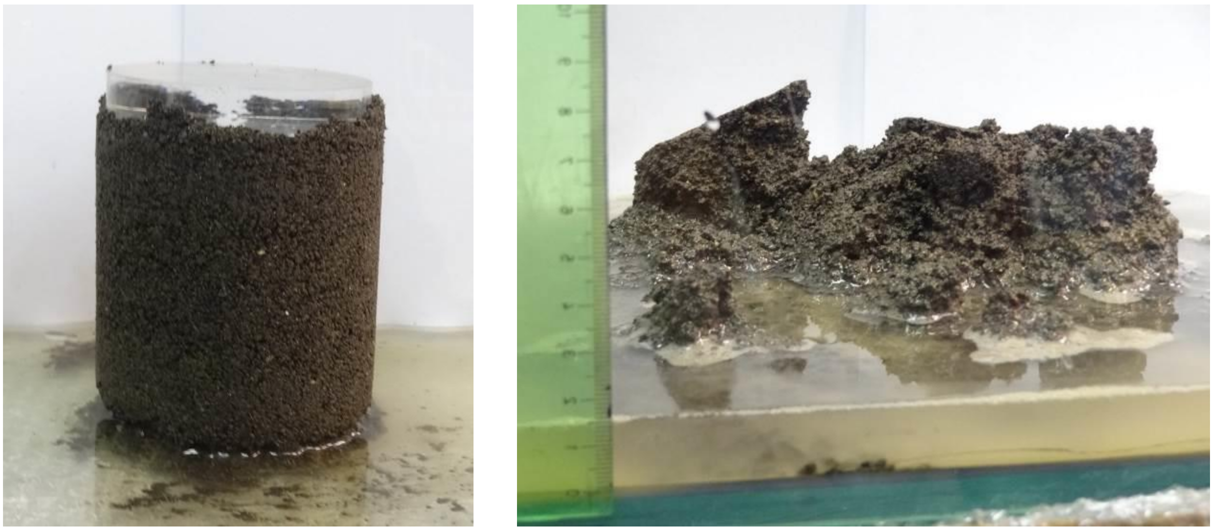

Figure 23. Initial phase of failure of sample loaded by water.

Figure 24. Compressed upper part of landslide.

Figure 25. Undisturbed surface of the lower part of landslide.

Very briefly some notes to the remediation process. Firstly the slope was deforested and its surface slightly levelled for the elimination of water infiltration as well to guarantee the access for additional investigation. After the realized analytical and numerical analyses the individual steps of the remediation process were proposed and performed:

- Removal of the loose material in the upper part of the slope up to the basalt bedrock.
- Limitation of the surface water infiltration into slope from the quarry platform as well construction of drainage trench in the upper part to eliminate the infiltration into central part of the slope, Fig. 26.
- Construction of retaining elements – embedded retaining walls just above the motorway cut, guaranteeing the safe removal of the landslide mass covering motorway roadways but also long term stability of the motorway cutting slope.
- The performance of the drainage system in the central and lower parts to limit maximum ground water table there.

Numerical modelling was used by the authors for the design of retaining wall, taking into account different design situations, (Jirásko, Vaníček and Vaníček 2017). From the different alternatives for the retaining structure the one composed from the elements of diaphragm wall was finally constructed – Fig. 27 and 28.

Figure 26. Drainage ditch in upper part of slope.

Figure 27. Retaining elements in the lower part of slope.

Figure 28. Armature for reinforcing element.

4 ROCK FALLS

Rock falls differ from the previous natural hazards mainly by speed by which can endanger the transport infrastructure. Falling rocks detached by sliding, toppling, or falling from cliff can not only block up TI but also directly endanger human lives. Geomorphological condition, location of transport infrastructure in the vicinity of steep rock slopes, is the basic premise of its interaction with rock falls. Therefore rock falls are typical for regions with high mountains. Nevertheless even for country as the Czech Republic is this problem very sensitive. It is caused by location of TI and human residences along rivers, whose river-basin is bounded by steep slopes – Fig. 29.

Figure 29. Combination of housing with road and railway traffic in steep valley.

In addition to slope steepness, very significant role have geological and climatic conditions as gradient of layers, orientation and number of discontinuities, sensitivity to weathering etc. Process of weathering is mostly influenced by physical changes as freezing and thawing, or by impact of surface and ground water. Vegetation on rock slopes is helping to the process of weathering by its roots. Trees turn up can directly release the individual rock blocks.

4.1 Protection measures

In principle the protection countermeasures can be divided into two basic groups:

- protection measures applied directly on rock slope;
- protection measures applied at the toe of slope, front of transport infrastructure.

In both cases the starting point of the decision making process is connected with the evaluation of up to date experiences, e.g. with respect to frequency or range of rock falls, with size of released rock blocks (boulders). The possibility of detailed investigation of the rock slope is another important point even when such investigation is very often connected with some practical problems. The investigation is enabling to determine most sensitive places, including evaluation of the block size, which can dislodged. With the help of investigation the amount of material that will be released can be determined, as well as speed at which this material will be transported.

The investigation can recommend the targeted dislodging of blocks, which were evaluated as most critical. The targeted dislodging connected with free fall is performed under safety measures, mainly with respect to transport operation for given TI. It is a similar case as applied to target dislodging of snow avalanches.

Protection measures applied directly on rock slope should either protect the rock boulders unblocking or their capturing on this slope. In the first case, which is preferred for larger blocks, rock anchors are applied. These rock anchors transfer load from the unstable exterior to the confined (and much stronger) interior of the rock mass. Its length and carrying capacity have to be determined during stability calculations. For smaller detached fraction the combination of nets gripped to the rock slope by shorter anchors or rock bolts is preferred.

When the morphology allow it the preference is given to the second group of protection measures, to the measures at the slope toe, where falling boulders as well smaller fraction are captured. Captured material can be consequently utilized and catchment volume restored. The range of possible protection measures is very wide, starting with classical retaining wall up to overlaying of the transport route. The overlaying is preferred for cases of possible combination of rock falls and snow avalanches.

Dynamic barriers have specific position between different protection measures. 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. However the dynamic barriers cannot be situated only at the slope toe but also on slope, where they are able to catch also larger blocks when they have lower speed of movement (and also lower energy of fall). For this lower energy of fall the different static barriers were applied on the slopes in history. However these smaller barriers, often of wooden type, were able to catch only smaller pieces of detached rock.

4.2 Practical example

The complex approach to the problem of rock falls will be presented on the example of proposed and subsequently realized measures on the road II/102 along Vltava River south of Praha –(Vaníček and Jirásko 2015). 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 1st mid-20th century (Záruba and Mencl 1969). An increasing number of cases of falling stones and blocks on the road have been observed there in recent period. The authors of the paper were responsible for assessment of the risk and recommendations for its elimination.

Rock slopes above the dam Vrané nad Vltavou were evaluated as a riskiest part – Fig. 30 and 31. Dam was constructed in 30-ties of the last century and from these days there are many accidents. One of the main reasons of instability is dip of discontinuities, which are roughly parallel with slope surface – Fig. 32. First huge rockslide occurred in 1927 and was described by (Záruba and Mencl 1976), Fig. 33. After this rockslide protection local protection retaining wall were constructed, however with only limited effect – Fig. 34.

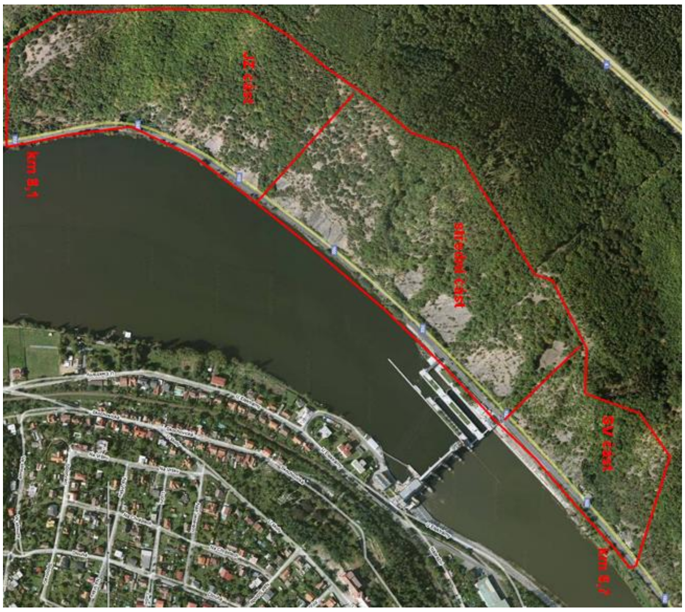

Figure 30. Rock slopes above the dam Vrané nad Vltavou.

Figure 31. Direct impact with road.

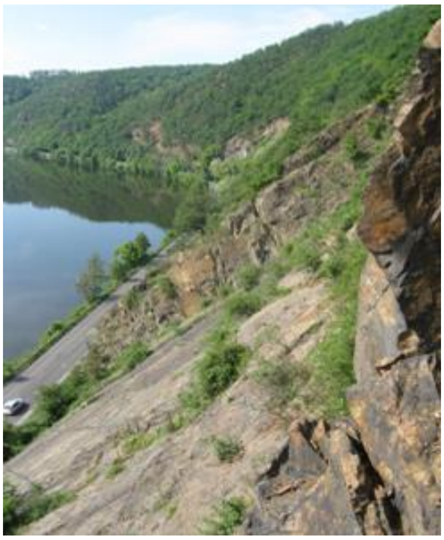

Figure 32. Unfavourable inclination of layers.

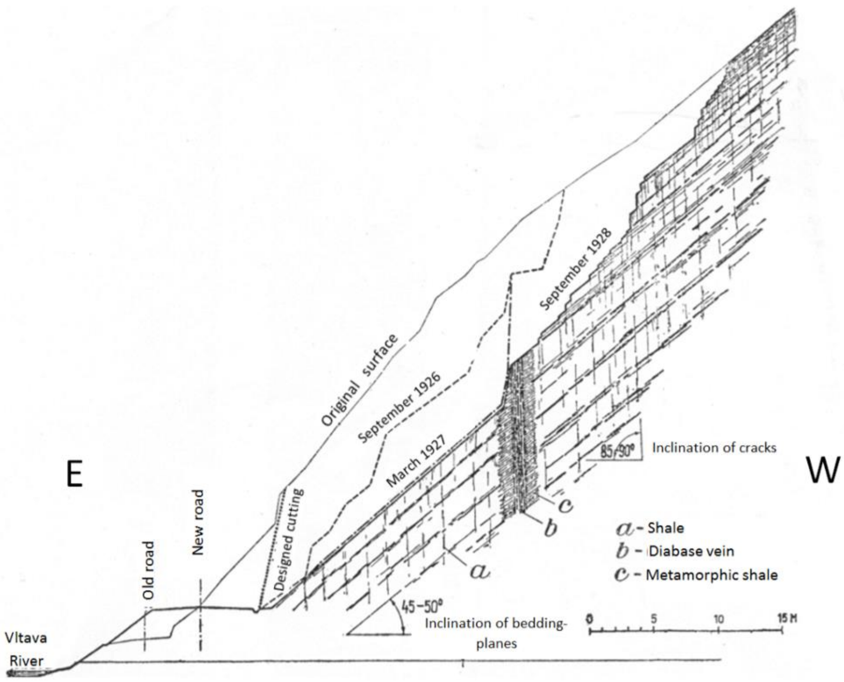

Figure 33. Rockslide after cuts for road.

The solution to this potential risk can have several approaches, depending on the acceptable risk. This risk is given by to 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.

Figure 34. Old masonry retaining wall.

Last investigation was performed at the beginning of the 21st century. The main output of this investigation was connected with risk determination for individual parts of the observed slope. The solution to this potential risk can have several approaches, depending on the acceptable risk, Fig. 35. This risk is given by to 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.

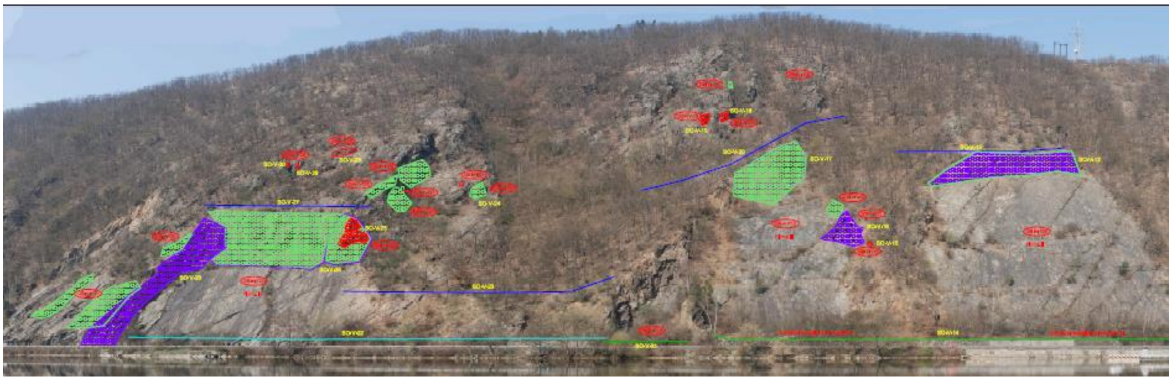

Figure 35. Risk determination of individual part of slope.

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 was 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).

The different software can be used for simulation of the trajectory of the falling blocks during the decision making process. Input parameters are not only slope geometry but also weight of rock blocks and also their modulus of elasticity. Obtained energy of block fallout should be safely caught by proposed protection methods. For the discussed case the software GeoRock 2D was selected. The demonstration of obtained results is shown in Fig. 36.

The retaining wall was designed for sectors where is enough space between slope toe and communication road. Non-standard retaining wall from reinforced soil was proposed for final solution. This wall is also using old tyres for energy of fallout absorption – Fig. 37.

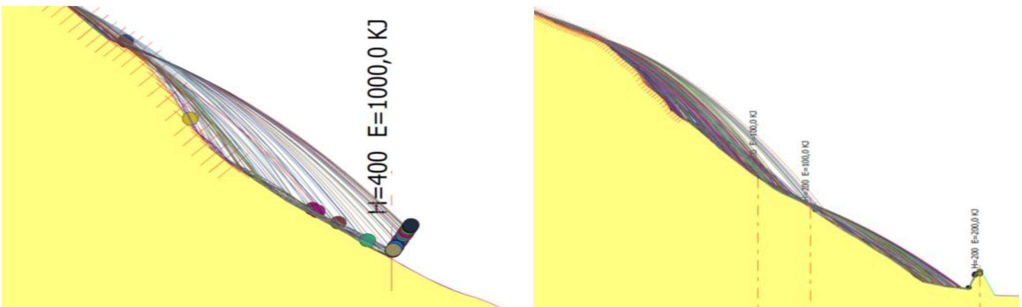

Figure 36. Verification of proposed retaining element by numerical modelling.

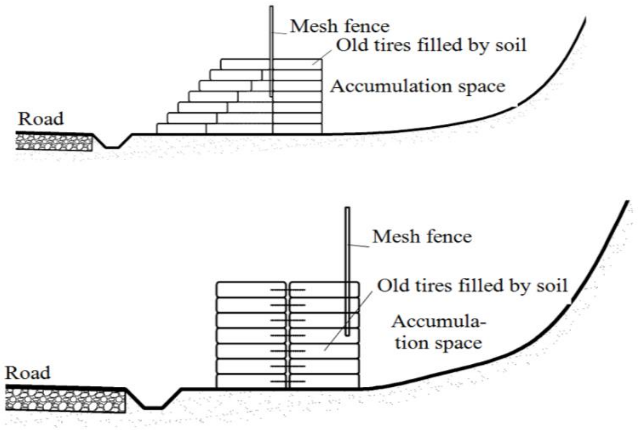

Figure 37. Proposed retaining structure from reinforced soil with old tyres.

The selected sectors were protected by anchored steel net. 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 is done by using climbing techniques. All steel elements have to be provided with suitable anticorrosive coating.

The main aim of dynamic barrier was described already. Finally this measure was proposed 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.
For very danger rock blocks which are unstable and their fall could be expected soon the method of disintegration was proposed. 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.

The application of monitoring of the selected rock blocks connected with high risk was also recommended. Monitoring combined with early warning system is in principle based on deformation measurement of these blocks. Whereas the deformation measurement can be either slide movement or block rotation. 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.

However slope monitoring starts already in the first phase of investigation. Visual inspection is supported by photo documentation subsequently repeated in time. Higher step of monitoring comprises geodetic measurement. 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.

The last step of monitoring is instrumentation of different sensors of deformation and theirs evaluation in time. Wireless data transfer is preferred as 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 have very good experiences with application of this system for monitoring of the quality of metro lining, (Soga, Vaníček and Gens 2011).

After the recommendation of critical limits of the deformation measurement it is possible to adjust the warning system. Scheme of the continuous measurement system using MEMS sensors with wireless data transmission is shown in Fig. 38.

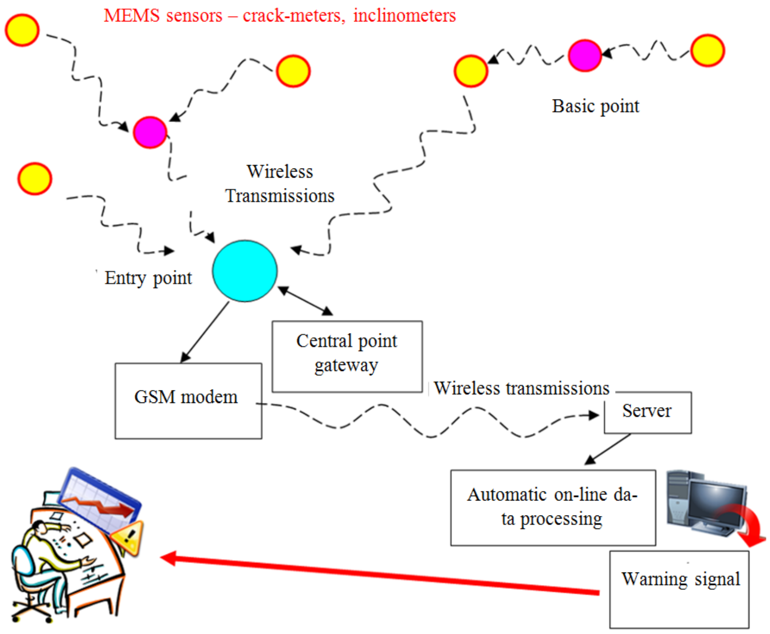

Figure 38. Scheme of monitoring system using MEMS sensors and wireless network.

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, (Jirásko and Vaníček 2017).

It is obvious that the most important measures for reducing the risk of the site are regular visual inspections by experienced geotechnical engineer and using of modern numerical modelling methods together with methods of monitoring system connected to the warning signal.

5 CONCLUSIONS

Natural hazards are phenomenon which are accidental and are hardly forecasted. Nevertheless with the utilization of up to date knowledges and historical records a certain expected development of floods, landslides and rock falls for selected areas can be forecasted, including the range and expected damages. Subsequently with the utilization of new knowledges, firstly in geotechnical engineering, some prevention measures can be recommended, eliminating the potential unfavourable impact of natural hazards on transport infrastructure.

From the view of interaction with floods, the most critical case of failure is connected with surface and internal erosion. Therefore, the possibilities how to decrease the potential risk of failure both embankments of transport infrastructure or dams together with dikes were covered. The attention was focused also on character of embankment material. Special case was mentioned where the grain size distribution can significantly impact the failure, which is caused by air pore pressure increase in partly saturated soils.

Situation, localisation of TI with respect of landslide prone areas is very important, as demands for fills and cuts are different. Second factor is connected with TI interaction for slopes with previous sliding or for slopes which need only demanded increase of slope stability, as shear parameters differs there. The demands on technical measures are for this cases different. Long term monitoring of ground water level as before the construction, so during or after finishing is also very important. Results can be part of the design utilizing the principle of observational method.

Very careful geotechnical investigation is also very important from the view of interaction of TI with rock falls. Effective and economical solution is coming out from the potential risk evaluation for given case. This evaluation allows together with numerical modelling the selection of most appropriate remediation technology.

Problem of interaction of natural hazards with transport infrastructure is particularly sensitive from the view of affordability and availability, from principles which are now prioritized. However this approach should be solved with the help of very good cooperation of the individual partners of the construction process, when the role construction investor is important. Biding price for new construction and first of all for reconstruction of the damaged TI should not be based only on the price of its construction. It should be based on the total price including expenses on TI maintenance and expected climatic changes in future. The designer accepts the more challenging design (and may be more expensive) only in the case that the result of biding will take into account the total price, the price from the view of construction life expectation. Therefore some specification from this point of view was also introduced, when the principle of structure robustness is playing important role there.

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