ROAD NETWORK SEGMENTS AT RISK AND VULNERABILITY ANALYSIS AND NATURAL HAZARDS ASSESSMENT

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Abstract

Risk analysis of a road network includes the evaluation of both hazards along the roads and the vulnerability of road segments. We propose the approach to natural hazards assessment related to natural phenomena which have occurred in the Czech Republic. Road vulnerability can be assessed in two ways: direct losses from the damage to a road segment or indirect losses due to additional expenses for longer alternative routes. Risk analysis is calculated for individual road segments. The risk can be reduced on both parts of the risk graph (hazards × vulnerability). This risk analysis approach is demonstrated on the example of a road network within the Luhacovice region of the Czech Republic.

Key words
Natural hazards, road network, robustness, vulnerability, risk assessment.

Since the beginning of civilization people have had to face threats coming from natural disasters and their consequences. In the past the territorial vulnerability used to be related exclusively to developed settlements whose restoration was considerably costly. Nevertheless, most settlements could have been moved to other places, where the danger from natural hazards was not imminent.

The territory, as a result of the society development, has gradually changed. The cities with complex infrastructures have been built, the buildings have been higher and more costly. Roads which have connected these settlements were already paved and more and more perfect and costly. This society development was, however, connected with the growth of territorial vulnerability. A highway interrupted due to a vast landslide cannot be simply left and built, as it used to be in case of an unpaved road, somewhere else.

This paper is focused on the description of a procedure which can be applied for the identification of the most vulnerable segments within a road network. We demonstrate that besides the identification and enumeration of the probability of the occurrence of a natural disaster in a specific place, it is equally important to evaluate the impact and the damage which are caused by a negative phenomenon. As long as a road network is in danger, then it is necessary to know the importance of this road network for the functioning of the whole network. At the end of this contribution we introduce the application of the risk assessment supported with the example from the Czech Republic.

Natural Hazards in Time and Space

The most frequent natural disasters in the Czech Republic which influence the functioning of road communications are first of all floods, landslides, falls trees, and heavy snowing.

Some of these phenomena are more frequent (snowing, fall trees) than others (floods, landslides). It also proved that higher frequency of a phenomenon is connected with minor
consequences. In order to evaluate the degree of a danger which might be expected, it is important to obtain complete and reliable data as much as possible.

Data on Natural Disasters

Floods

The data on the extent of floods are available in the form of the space GIS (shape-file) as "the floodplain of five-year water, twenty-year water and centennial water." It is a theoretical extent resulting from a digital model of the area. Besides this, it is possible to obtain the extent of the largest recorded natural flood (the real overflows). The data provider is the Department of Geographical Information Systems and Cartography of the Water Research Institute of TGM, Prague.

Landslides

In case of the slope deformation we can rely on the data which are administered by the Register of Slope Deformation by the Czech Geological Service. This database contains thousands of records on the position of landslides and other negative slope phenomena including their detailed description.

Snow

Heavy snowing is snowing when during a short period of time the total thickness of snow is quite high. These values are given by the grid layer "the height of new snow." These are the averages of seasonal totals of the heights of new snow (elaboration period 1961–2000). The provider is the Czech Hydro-meteorological Institute.

In order to be able to count with the danger of a natural disaster we have to determine the probability that a phenomenon (e.g. flood) will occur in a specific place and time. For this, therefore, we need the overview on the areal extent of the threat which is usually available, see above. Furthermore it is necessary to be informed on the frequency of the occurrence of these phenomena in time which again calls for the sufficiently long time series. At the same time it is necessary to include the intensity of a phenomenon or its extent, e.g. the size (n-year water) of the flood.

Impacts of Natural Disasters on Road Network

A flood does not have to cause any significant damage to property and at all does not have to be related to road infrastructure. However, as long as road communications are in floodplains of water flows and as long as they do not have sufficiently high embankment, it is likely that they will be flooded from time to time.

Flooding causes limited traffic which disappears as soon as water subsides and goes back into its bed. In some cases, after the flood, there is a layer of silt such as mud or other coarse-grained material. In mountain areas or where there is a sufficient bottom slope, the water has enough energy to erode with drifted material not only its bed but during the overflow also places through which it temporarily flows. The effects on roads are in the form of partial or complete destruction (Fig. 1).

Equally destructive can be the effects of slope deformations (Fig. 2). In these cases the situation is somewhat more complicated as the stability of the whole slope is affected. Subsequent reconstruction must include also the adjustment of the terrain along the road and the security of larger surrounding of the impacted segment.
Example of a damaged road by side erosion of a water flow in Liberec region in August 2010

Fig. 1

Road II/432 near Korycany affected by a landslide

Fig. 2
Sudden snowfall and high total snow in a short time usually definitely interrupts the road traffic. Nevertheless, it does not mean the infrastructure failure. Yet, the maintenance of roads in the winter is difficult and therefore the roads with low traffic intensity and little importance for transport are not maintained in winter (according to approved Plan of Winter Maintenance of Roads).

As far as the tree falls is concerned, they are in places with prone vegetation and with sufficiently strong winds. These phenomena interrupt the traffic, but there is no evidence that they would affect in some way the technical condition of road communication.

In case of a natural disaster and the danger in delay, the owner of a relevant part of a road segment is obliged to close it and label it at least by an improvised way. Before the re-opening of a closed road it is indispensable to carry out an extraordinary inspection of this road.

The data on the damage of a road network have not been available in a unified form so far. Only within the project *Quantification of the Threat to Road Infrastructure by Natural Hazards* (trisk.cdvinfo.cz), we carried out the analysis of the available data suitable for the evaluation of vulnerability, natural hazards and risks of threat to roads and highways in the Czech Republic. We also created the *Database of Damaged Communications in the CR*.

In order to obtain the overview on real interruption of roads we also use the database of traffic information which is displayed within the JSDI (Unified System of Traffic Information). This a joint project of the Ministry of Transportation, Ministry of Interior, the Directorate of Roads and Highways of the Czech Republic and a range of other authorities, organizations and public administration institutions, public and private persons and entities from the whole CR (www.dopravniinfor.cz). This application also serves (besides the archive of historical events) for the collection, elaboration, sharing, distribution and publication of traffic information and traffic data on actual traffic situation and information on road communications.

Thanks to the information on time and place of every interruption, we are able to analyze specific situations. For example the flood which affected the CR in June 2013, according to the data from JSDI, affected 542 road segments (493 due to floods, 43 due to tree falls, 6 due to landslides). Besides this, in the territory of the CR extra 526 road segments due to other causes were interrupted (Fig. 3).

It is obvious that as soon as there is available a longer time row of JSDI data, it will be possible through the analysis of these data to determine the probability that there will be not only the interruption of the road function, but the threat to the road communication itself (Fig. 4). However, for such analysis we need a really long time row which cannot be obtained from the JSDI data for the present (the beginning of the delivery of information has been from 2009). Therefore we addressed individual regional workplaces of Road Administration and Maintenance and Directory of Roads and Highways and asked for the data availability on roads infliction in years 1997–2010. This way we obtained necessary data in required quality and in time from the vast majority of them.

The range of the database was chosen in order to cover the largest natural disasters which affected the Czech Republic. The first and so far the most significant natural disaster afflicted the Czech Republic in July 1997 in the form of intensive rainfalls (Sofjakova, 2000) which caused extreme floods and consequently landslides of an unusual extent (Krejci et al, 2002). It was after a long time when the territory of a state was impacted by the event of such an extent and intensity. The latest event of a similar range goes back to 60ies of the 20th century. After 1997 the CR territory was significantly affected also in years 2002 (Hladny et al., 2005), 2003, 2006 (Bíl and Muller, 2008), 2009 (MZP 2009), 2010 (Kubat et al., 2010 and 2013).

The resulting database contains at present almost 3000 records from the whole CR. Together with the interruption of communications which were damaged as a result of mentioned natural hazards, the databases contain also the data of partial damage of a road communication segment which enabled at least minimal traffic and also the records on traffic interruption due to e.g. flooding of the roadway and caving (Fig. 5).
Note: The points are places where the road network was damaged. The color of the points differentiates the cause of the damage.

**Fig. 3**
Illustration of the area affected by flood in June 2013

Note: It is a complete interruption which does not mean, however, that the road communication was interrupted physically.

**Fig. 4**
Frequency of the interruption of road network segments in the period of December 2012 – July 2013
Note: The data have not been provided by all road administrators yet.

**Fig. 5**  
The range of a database of damaged road segments in years 1997–2010

**Combined Threat of Natural Disasters**

In order to create the layer of threat (in terms of GIS) encompassing and quantifying all real natural disasters it is necessary to apply a multi-hazard approach, e.g. Kappes et al., 2012. This means that all disasters must be standardized (in terms of intensity and frequency) so that it was possible to merge them into one layer. The result is a GIS layer which enters the risk analysis together with the layer of the vulnerability network.

**Evaluation of Natural Disasters Consequences in Road Network ich Calculation of Vulnerability**

Let’s have a closer look at the extent of the damage of a road segment. The road segment can be affected in three degrees: it can be a total destruction when the segment must be reconstructed, or partial damage which can cause its temporary decommissions and the repair is required. The third type is blocking of a road due to e.g. mud, but more significant repairs are not necessary. Our analysis is focused only on the destruction states of road communications and partial damage which requires long-term repairs. Cases when there is only blocking of a road are many e.g. due to tree falls on a road or flooding, but usually after a few hours or tens of hours the road segments are open to traffic. For this reason we omitted the events when the territory of the Czech Republic was affected by the crossing of deep, low pressure areas, windstorm Kyrill (2007) and Emma (2008). They resulted in a number of interrupted roads and especially railways due to tree falls (e.g. Kurkova et al., 2008; Kolejka et al., 2010).
The impacts of mentioned events can be divided into direct and indirect ones.

Direct Costs

Direct costs include first of all reconstruction costs of damaged roads. At the same time they may include the reconstruction of landslide areas or the adjustment by erosions entrained banks.

Indirect Costs

As long as the road communication is interrupted and there is a detour, then it is definite that these detours are always less favorable. They are either longer or more time consuming (e.g. Berdica, 2002). These extra costs are then a part of indirect costs. According to the Act No. 13/1997 Coll., on Road Communications as amended in § 24 article 1 that no one is entitled to compensation for any losses that incurred as a result of closures or detours. Other indirect costs can be formulated as lost opportunities as long as the planned trips were not carried out or another means of traffic was chosen.

Vulnerability of Networks

It is typical for the networks that when their vulnerability is searched, it is necessary to assess their geometry and topology at the same time. Geometry is related to real conduction of a segment, its length, gradient, etc. (it is different whether the interrupted segment is 100 or 10,000 meters long). Topology means the connection of nodes by edges which expresses the neighborhood of individual network nodes. The nodes which have only one neighbor are most threatened by the cutting off because they are connected (usually) with the rest of the network only by one edge.

Furthermore it is typical for the networks that despite the same number of nodes and relatively similar number of edges they may substantially differ as far as resistance is concerned. Resistance is the capability of the network to cope with various types of catastrophic events represented by the set of impassable edges and preserve at the same time the connection (e.g. Latora and Marchiori, 2004). For example if the network has the topology of a tree (in terms of information, thus network = graph), the interruption of a random edge results in the division of this network into 2 parts. Such network is then very little resistant (Bíl and Vodak, 2013).

It is not easy to determine how two different roads differ from the viewpoint of resistance to catastrophes. The complexity of this role lies in the fact that each comparison of networks is very demanding in terms of the calculation and therefore it is necessary to apply or develop stochastic methods and algorithms. Furthermore it is important to develop a method which will enable the comparison of these different networks.

As robust (or resistant, little vulnerable) networks are those when divided into two or more parts, relatively high number of edges must be interrupted. From the traffic viewpoint it is definitely convenient to have robust networks. Nevertheless it is important to realize that vast networks require high costs for their construction and also their subsequent maintenance. Understandably, there is lack of means for both. In reality it is usually necessary to accept a certain degree of vulnerability, namely of those parts which are not for the serviceability of the whole, substantial.

Risk Analysis

Risk is the product of vulnerability and probability of a natural disaster threat (Fig. 6).
Fig. 6
Scheme of the procedure of the risk assessment of the damage of the segment of a road network by natural hazards which were used for the purpose of this essay

Fig. 7
Diagram of risk is the result of the combination of the probability of the occurrence of a disaster and the damage vulnerability of a territory

Risk probability can be embodied graphically in a diagram of risk. As it is obvious from the diagram, we can consider four extreme conditions marked with numbers (Fig. 7):

1. Phenomena which might occur with low probability and their consequences are only minor. Basically it is an ideal state. We do not have to deal with them.

2. Phenomena which will occur with very high probability, however, their consequences are mild. Precipitations of low intensity and short duration are typical. Also this includes yearly winter snowing which causes problems with traffic flow but usually with low damage to infrastructure.

3. Phenomena which will occur with high probability and at the same time their consequences are very serious. We can mention an extreme case of a hypothetic construction
of large agglomeration at the foot of an active volcano *knowing about its activeness*. In the past, just as a result of the lack of information on the background of a volcano activity, the existence of towns in these places was not an exception. Unfortunately people encountered the consequences of unexpected eruptions (e.g. Vesuv in year 79, Mt. Pelée in 1902) when people were not able to evaluate this threat with sufficient time-ahead.

Disasters which will occur with low probability and at the same time they result in very serious consequences. For example tsunami of extreme height which is capable to destroy vast coastal areas (Indonesia 2004, Japan 2011).

Regarding the risk assessment and strategic planning, the phenomena in number 3 do not occur, or the paramount interest is to eliminate them as soon as possible. The phenomena in number 1 and 2 do not represent serious impacts, therefore no measures are taken against them. The most disturbing are the phenomena in number 4 because there is only very low probability of their occurrence; however, they are with potentially very destructive impacts. Our society usually tends to underestimate these phenomena.

Another fact is worth mentioning. Provided that we carry out risk assessment and place into the graph the result of the analysis as a point, its position is not constant in time. For example the phenomena originally included in number 1 can, within the graph, gradually transfer along the diagonal to number 3. Regarding the natural hazards we can mention the increased frequency of serious floods whose number has been in recent years much higher than for example 50 years ago. Therefore, it is necessary to observe permanently as many factors as possible which might influence the probability of the occurrence of an event with negative consequences.

Together with the development of society, also the investment in the territory has been higher and higher, the infrastructure has been more perfect and therefore more costly. The damage to most urbanized territories would be, at present, much higher than several tens of years ago. At the same time the built-up areas cover at present a much larger part of the territory than before which results in the increased number of recorded events.

### Potential of Risk Reduction

Reducing the risk of a specific segment of a road network means to influence the occurrence, frequency or intensity of disasters on one hand, and reducing the vulnerability of a given segment on the other hand.

In case of the decrease of the probability of the occurrence of a natural disaster, we can apply remediation measures directly on slopes (in this case there is in the Czech engineering geology a long tradition, eng. Zaruba and Mencí, 1969). Furthermore we can install nets to catch falling stone blocks, carry out monitoring for timely warning, carry out flood control modifications in beds of water flows, choose appropriate planting of forest cover etc.

Regarding vulnerability reduction of a road segment we can proceed in two directions:

1) **Enhancement of a road segment resistance**

Road segments endangered by a natural disaster must be adjusted to enhance their physical resistance. For this purpose we carry out various construction adjustments e.g. converting communications on embankments or deeper foundation of roads on slopes. This vulnerability reduction is carried out sometimes together with the reduction of another threat. For example anti-flooding measures can represent at the same time the reinforcement of the original road. Anchoring of a slope is accompanied by the repair of an adjacent road etc.

2) **Optimization of a road network**

The construction of new roads significantly burdens the budget of every country. Expenses on the construction are not, however, the only ones which are spent on the growth of the road length. Also the item for the road maintenance has significantly grown. Therefore it is
not appropriate to build road communications which are maximally resistant but, on the contrary, it is necessary to ensure detour routes which could be used, in case of a failure.

Optimization algorithms can help find such combination of network nodes which are connected as much appropriately as possible in order to ensure maximal growth of the resistance of the road networks against catastrophes (Bil, Vodak, 2013).

For this reason it is necessary to define objective function which is capable to measure the resistance of a road network against various, mostly accidental events. One of the typical examples of the values of such function is the average number of components to which a road network falls apart when interrupting specified number of segments i.e. if \( n \) is a total number of segments, \( k \) the number of interrupted segments and \( m_i \) is the number of components to which the network falls apart when interrupting \( i \)-, \( k \)-edges, then

\[
\bar{M} = \frac{1}{\binom{n}{k}} \sum_{i=1}^{\binom{n}{k}} m_i.
\]

The problem of these measurements is their calculation demandingness. For this reason it is possible to consider the values \( m_i \) as accidental quantities and through repeated accidental impassability of roads (actually application of Monte-Carlo method) to calculate the approximation of the value \( \bar{M} \). Values calculated in this way can be used when designing newly added segment into a network. We are interested only in those segments which maximally reduce the value \( \bar{M} \). With regard to the fact that it is a task with discrete state space, it is desirable to go through all admissible edges which can be added to this network. This admissibility is given by practical requirements for a new segment, among which there are for example the impossibility to cross an already existing edge, limitation of the length of a new segment, prohibition of parallelization with existing edges etc.

If we focus on the reduction of probability in terms of that the selected locality will not cut off the rest of the network, i.e. it will always be available, we do not have to count the robustness of a network as a whole, but we will build up a standby connection. It will be advantageous if it does not go along the same valley which decreases the chance that it would be affected by the same flood as the former connection.

If the weak place is a bridge, it is appropriate, instead of the construction of a parallel bridge, rapidly available standby in the form of a substitute temporary bridge. As Dalziell and Nicholson (2001) proved, indirect costs spent on the detour might be overall higher than immediate construction of new spanning. It is related first of all to those situations when the connection is considerably used for the transportation, e. g. transit traffic.

**Risk assessment based on the case from the Czech Republic**

The above mentioned procedure for the determination of the threat to a road segment is demonstrated on the case of the district Luhacovice (Fig. 8). It is one of the 13 districts in the territory of a Zlin region. Its area is 178 km\(^2\) and it has a population of 19,270 (Czech Statistic Authority, 2013). The entire area is in the area of flysch Carpathians which is the area very prone to landslides (Krejci et al., 2002). Morphologically they are highlands (Vizovice Highlands) where individual ridges are separated by relatively narrow valleys. Only a small part of the surroundings of the village Sanov reaches White Carpathians. Right here there is the highest point of the territory spot height Na Koncich its height is 655 meters. The lowest point is in the valley of the Stavnice river in the local part Polichno (222 meters). Maximal vertical distance amounts to 433 meters then.

Most of the relief area of a district reaches middle inclination of 8 -15°. The most important water
flows are the rivers Stavnice flowing through Luhacovice and flowing into the Olsava river and the river Rika which flows through Slavicin and in the district territory flows into the river Vlary.

From the total number of 15 municipalities, the last two mentioned are the biggest – in Slavicin there are about 6,916 inhabitants and it is an industrial and business center. Smaller Luhacovice (5,368 inhabitants) is focused on spa activities and tourism. The length of a road network is 142.2 km. There are only roads of class II (53%) and III (47%). The busiest road communications are roads no. II/492 going from Uhersky Brod through Luhacovice to Vizovice and no. II/493 going from Pozlovice through Slavicin to Brumov-Bylnice (RSD, 2013). Railway connection is ensured by the railway no. 341 from Uherske Hradiste to Bylnice and its detour railway no. 346 ends in Luhacovice.

The road network of the Directorate of Roads and Highways inside the district Luhacovice is completed by detour routes beyond the borders of this district in the places where they used to be. If we did not do it, there would be unreal blind segments which would distort the vulnerability analysis of the road network inside this territory.

Note: Road network in district Luhacovice is formed by roads of class II and III. Detour routes are defined in the way that the rise of blind segments is prevented. Neither the threat nor vulnerability is modeled there.

Fig. 8
Definition of the territory

Vulnerability of a road network

As mentioned above, the vulnerability expresses the damage which might occur in the territory if it is affected e.g. by a natural disaster. If we analyze traffic networks, here it is a road
network, then, we assess the vulnerability only with regard to the occurrence of a road communication. We do not deal with other territories for these purposes which can be expressed so that the road network will be maximally vulnerable, other territories minimally, therefore in the interval 0-1. The network analysis is not either focused on the length of a prospective threat to a segment or the place of interruption (bridge, tunnel or just a segment of a route), but only the impact of this interruption of a specific segment on the serviceability of the whole network (nevertheless it is obvious that repair costs will be directly proportional to the length of an affected road communication and they will differ according to the types of objects in the place of interruption – the highest in case of bridges and tunnels repairs etc.). We do not address the estimation of changes in traffic intensity as well, because during the period of natural catastrophes they change a lot and it is not easy to estimate them, let alone determine precisely (Kurauchi, 2009). We are interested, then, only in the reduction of the traffic offer network (serviceability, see Berdica, 2002) in case that a specific segment is not available due to the interruption.

Note: As long as one segment is interrupted, then the numbers represent the reduction of traffic offer of the whole network which means the prolongation of the shortest connection between all or at least several nodes.

Fig. 9
Vulnerability of a road network in Luhacovice district

In fig. 9 it is obvious that the weakest segments are in the middle part of the territory. If they were interrupted, the length of the connection (detour route) between their end parts...
nodes would grow substantially. For demonstration let us say that the length of the shortest detour routes in case of the most vulnerable segments 2534A016  2534A001 (1) and 2534A006 2534A01101 (2) are 27.6 km, or 18.1 km, which means the prolongation of the former segment 28 times or 38 times.

Moreover it is necessary to mention that this calculation of vulnerability takes into account the performance or traffic network as a whole. Other criteria might prefer the availability of the territory or the length of individual detour routes. We neither take into account in this analysis local and purpose-built roads which might be, in some cases, used for detour routes. Their capacities are usually in comparison with other communications low and therefore they are not used in these situations.

Natural disasters

The values of combined threat of natural disaster are the highest in the vicinity of Ludkovice (Fig. 10) which is caused by high frequency of mapped landslide deformations in the vicinity of a road communication and also by the character of both relatively narrow valleys which would be affected in case of floods (Fig. 11). As the valley Stavnice (Luhacovice brook) broadens towards Uhersky Brod and the road follows the embankment, the threat of floods is reduced together with landslides because the slopes are milder in these places. The resulting index of the threat is then lower in comparison with the first example.

![Map of Combined Threat of Natural Disaster](image_url)

**Note:** It is the combination of the threat of slope deformations, floods and a sudden snowfall.

**Fig. 10**

**Values of combined threat of a natural disaster**
Fig. 11

The example of the most threatened segments by natural disasters in the vicinity of villages Ludkovice, Provodov and Brezuvky

Risk

The map of risk is the combination of both preceding results. It is obvious that there, where the segments are evaluated in both partial results by a higher value, the higher is also the overall rate of risk. The most risky segment is the part of the road II/493 going from Slavicin towards Pozlovice (Fig. 12). Segments in the vicinity of Ludkovice where the threats were the most serious, now the overall rate of risk is low which is given by the fact that the detour routes are near each other and they are short.

Provided that we draw in a risk diagram all segments in district Luhacovice as points (Fig. 13), we can see that they are relatively near a left bottom corner. It is logical, because the road network in this area is relatively resistant and it is necessary to emphasize as well that we modeled only the case when just one segment in the whole network is interrupted. It is obvious that if we focused on the combination of e.g. pairs or triplets at the same time interrupted segments, the impact on the performance of the total would be considerable. Natural disasters are frequent in this area; nevertheless, their intensity is not high.
Fig. 12
Risk: combination of the probability of the occurrence of natural disasters and vulnerability of road network of the district Luhacovice

Note: The numbers in a graph respond to numbers of the segment in a map of risk in figure 12. It is a cut, the scale on both axes have maximal values 100 %.

Fig. 13
Demonstration of the position of the five the most risky segments in district Luhacovice
Risk Reduction

During the experiment to reduce risk we focused on the proposal of new connections which would at most enhance the resistance of the whole road network in district Luhacovice. The result are three pairs of nodes whose interconnection will ensure the mentioned highest enhancement of resistance (Fig. 14). Interconnection means the construction of a new road communication. This analysis does not take into account the length of a road segment, but just the topology of the network. The length in this model is only a parameter, which might be completed. For simplicity and illustration we only mark nodes whose interconnection is for the risk reduction of the whole network the most advantageous.

![Fig. 14](image)

*Three pairs of nodes – end points of graph edges of road network whose interconnection is for the enhancement of robustness of this network the most advantageous*

Conclusion

This paper specifies the procedures of the calculation of risk affection of a road network by natural disasters which are supposed to be applied in the phase of strategy and planning. In this phase there is enough time for the decision which parts of a road network or a territory are from a given viewpoint (e.g. national security, provision of supplies, availability etc.) important.
After the identification of weak links of networks and the analysis of natural disasters it is possible to specify the risk rate that the road communication will be affected. Afterwards, the procedures to reduce risk should be carried out on both sides: reduction of vulnerability and reduction of the disaster intensity.

It is obvious that when applying a proper analysis of the risk of threat to a road network by a natural disaster, we can prevent the damage which a natural disaster might cause.

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Résumé

Risk analysis of a road network includes the evaluation of both hazards and vulnerability. We present the approach to natural hazard assessment related to the natural phenomena which occurred in the Czech Republic, such as floods, landslides and heavy snowfall. Since 1997 many natural disasters have been recorded, especially floods and landslides which severely affected road networks.

There is, however, no database on historical damage due to natural hazards to roads in the Czech Republic. We therefore collected data from local road administrators and set-up such a database. It contains records of road damage between 1997 and 2010. New data are continuously added to the database through JSDI, which is an on-line system of road information. Based on these data it is possible to calculate the probability of a multi-hazard occurrence along various road segments.

Road vulnerability can be assessed in two ways: direct losses from the damage to a road segment or indirect losses due to additional expenses for usually longer alternative paths. In this paper we analyzed the vulnerability from the viewpoint of the drop in serviceability of the whole network.

Risk analysis was calculated for individual road segments as a product of the probability of hazard occurrence and road vulnerability. The five most risky road segments were depicted in a risk graph.

The aim of the society, represented here by road administrators, should be the effort to minimize the risks. This can be achieved on both sides of the risk graph. It is possible to reduce the hazard or to increase the robustness of a road segment. Reducing hazard is usually a well-known approach based on geo-technical, hydrological or civil constructions. Vulnerability can also be reduced when applying a road network-wide approach. It is possible to add new connections and link up two places within the road network which were not connected before.

The presented approach was implemented on the road network of the Luhacovice region. The respective maps show the probability of a multi-hazard occurrence, network vulnerability and overall risk. The last figure shows three pairs of nodes which should be connected to make this road network more robust.

Literature


