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Evaluating road network damage caused by natural disasters in the Czech Republic between 1997 and 2010

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ABSTRACT

Road networks play a vital role in maintaining a functioning modern society. Many events perceptibly affect the transport supply along these networks, especially natural disasters such as floods, landslides, and earthquakes. Contrary to more common disruptions of traffic from accidents, or maintenance closures, natural disasters are capable of destroying large numbers of roads and usually cover vast areas. When evaluating network damage no single measure alone is able to describe the full extent of network destruction. In this study, we investigated six highly damaging natural disasters, which occurred in the Czech Republic between 1997 and 2010. They were all induced by extreme rainfall or by rapid snowmelt and resulted in floods and landslides. Their impacts are evaluated with respect to the damage to road networks and decreased serviceability. For mutual comparison of the impacts and their analysis we used several criteria, described in the paper, related to economic impacts, physical harm to individuals and infrastructures, and the effects on connectivity and serviceability. We also introduced a new measure based on the network efficiency index which takes into account the importance of nodes based on their population. Moreover, we provide a detailed analysis of one such event in July 1997 that significantly affected the road network of the Zlín region.

1. Introduction

1.1. Damage to road networks by natural disasters

Natural disasters (e.g. floods, landslides or earthquakes) are frequent causes of road network damage. Compared with other common traffic disruptions, such as traffic accidents and maintenance closures, these natural events may completely destroy transport infrastructure in a given area and cause the long-term cut-off of inhabitants from the main network (Eleutério et al., 2013), as well as appreciable economic losses (e.g. Anbazhagan et al., 2012). Well-known events which have seriously impacted road networks include the Loma Prieta earthquake which hit the San Francisco Bay area in 1989, the 1994 Northridge earthquake in the Los Angeles metropolitan area, and the 1995 disaster in the Kobe region (Chang and Nojima, 2001). The common feature was serious damage to the road network, specifically the highways. A comprehensive overview of road damages due to earthquakes and their classification is presented by Anbazhagan et al. (2012). Besides such exceptional disasters there are others which are caused primarily by heavy rains (and subsequent floods or landslides).

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These produce rather minor overall damage but may also disrupt the road network within a large region (e.g. Vinet, 2008; Hilker et al., 2009).

1.2. Road networks and their resistance to incidents

Road networks can be depicted as a specific kind of communication network represented by graphs. This allows one to study the consequences of various events on their. The events can be caused consciously as a form of intentional attack or unconsciously as natural disasters (see Albert et al., 2000; Dall'Asta et al., 2006). In the second case the events contains certain form of randomness. In this work we pay attention to the second type of events.

The most studied problems cover the concepts of vulnerability and robustness of a road network infrastructure (e.g. Murray and Grubesic, 2007; Matisziw et al., 2009; Reggiani, 2013). The term 'robustness', from the view of the whole road network and its ability to ensure the accessibility of an area, refers to its capability to absorb a certain amount of disrupted links (Berdica, 2002). A robust network should include a certain amount of link redundancy, so that a small disruption would not lead to collapse, defined as a system-wide decline into several disconnected parts. However, there are some limitations on why real road networks cannot have maximal robustness. The problem is that the more robust the network, the more redundant it is. It means that such a network will be more expensive and demanding of maintenance. Moreover, road networks are significantly influenced by the relief topography, which may sometimes become a dominant factor in determining their structure (Rodrigue et al., 2010).

At the opposite extreme, the most vulnerable or 'least robust' (see Berdica, 2002) network will disintegrate into two parts (in graph theory called *components*, e.g. Newman, 2010) after any link is taken away. Mountain valleys are often weakly connected with the rest of a network and the disruption of one or two links often leads to a complete cut-off of nearby inhabitants. Thus, the aim of a vulnerability analysis is to identify those critical links in a network (e.g. Bell, 1999; Berdica, 2002; Jenelius et al., 2006; Sohn, 2006). It is important to say that network vulnerability is not dependent on probability; it represents the consequences of an event (see Berdica, 2002).

It follows from the definitions of robustness and vulnerability of road networks that both concepts are fundamental for the analysis of consequences of natural events. Two features of natural disasters are important to note. First, such natural events are characterized by some randomness in their occurrence. Second, the events can affect the most vulnerable links in the network and thus maximize their impact. Moreover, new weak links may emerge as a result of partial network damage which are necessary for the proper performance of the rest of the network.

1.3. Measuring the network damage

To obtain any information about the robustness and vulnerability of road networks and about the impact of natural events it is necessary to establish some suitable measures. When measuring the impact of a disaster, overall economic losses are generally used for comparison. A loss of connection and reduced accessibility is often a result of such catastrophes, however. Comparison of pre- and post-disaster network performance is therefore possible using suitable indices connected with robustness.

There are numerous studies which estimate and measure impacts of various natural disasters on infrastructure, including roads. When evaluating damage caused by a disaster, direct losses are usually computed (e.g. overall damage to infrastructure). From the view of network performance the indirect losses may be also important (Yee et al., 1996). Versini et al. (2010) evaluated the vulnerability of roads in connection with flooding on the basis of geographic information and actual flooded road segments over the last 40 years in the area around Gard, France. The impact of the earthquake in Haiti on the accessibility of humanitarian aid was summarized by Bono and Gutiérrez (2011). They applied GIS spatial analysis to show changes in accessibility for the affected towns.

Chang and Nojima (2001) evaluated the traffic system performance for the city of Kobe, which was affected by an earthquake in 1995 and compared it with antecedent earthquake events in the USA (Loma Prieta in 1989 and Northridge in 1994). Their study used a ratio of the lengths of damaged and undamaged road networks. They also used an accessibility ratio which is based on distance in computation of the length of a path between two nodes. When the network is broken up into two and more components, however, their measure stretches to infinity, because it is impossible to find finite paths among nodes from these components, and the ratio is therefore unusable.

Another shortcoming of previously published methods is that they compute changes from one simultaneously closed network link (e.g. Jenelius et al., 2006). This could be still used when modeling the effect of traffic accidents or the planned closure of a link. However, natural disasters are capable of damaging many roads at one time. This means the information we have about the current state of a network and flows in it (see for instance Louail et al., 2015; Gallotti and Barthelemy, 2015; Lenormand et al., 2014a,b) are dramatically changed. The common traffic pattern (Gottlich and Klar, 2009; Lammer et al., 2006; Helbing, 2002, 2001) completely disappears and the standard traffic control begins to be useless. The state of the transportation system also differs significantly from common traffic congestions (Treiber et al., 2000) and therefore is not in equilibrium (Kurauchi et al., 2009). This is the reason why there is a need to take a different view of the network after certain events which result in the disintegration of the network. Thus it is also necessary to analyze the resilience of the network (see Cimellaro et al., 2010; Arcidiacono et al., 2012).