Multilevel Approach to Measuring Societal Vulnerability due to Failure of Critical Land Transport Infrastructure

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ABSTRACT

Societal vulnerability is a part of a disaster risk assessment and crucial information necessary for supplementing hazard and mitigation assessments. Identification and assessment of various vulnerabilities of societies, economies, institutional structures and environmental resource bases are the basic information necessary for improving risk reduction and preparedness to any kind of hazard. This paper outlines our approach to measuring societal vulnerability caused by impacts of extreme weather events on critical land transport infrastructure. We propose to use a multilevel approach where the measure of societal vulnerability is expressed through Vulnerability Index calculated on the basis of selected vulnerability indicators. The higher value of vulnerability index indicates the more vulnerable area. In conclusions the issues of further enhancement of vulnerability identification and measuring are discussed.

Keywords: Risk, Vulnerability, Society, Critical Infrastructure, Land Transport.

1. INTRODUCTION

The critical transport infrastructure is important to serve the national priorities such as economic sustainability and growth, social development, providing security and public order, operational capability of the armed forces, but as well plays important role in disaster management in facilitating assistance during various crisis situations and also in ensuring a mass evacuation and is subject to hazards. Analysis of the critical transport infrastructure should always be viewed in a broader context – with relation to geo-spatial, economic, social, security, environmental context, etc. Reliability and performance of critical transport infrastructure have significant influence on services which are provided by the other sectors of society, and in many instances transport infrastructure spans these sectors. Therefore a functional transport infrastructure is the core of any developed country.

Extreme weather events reflect in the transport sector immediately, intensively and with massive negative consequences: they lead to the increase of freight transport time, prolongation of traveling and the rise of accident probability. Except for the direct above mentioned extreme weather impacts on transport infrastructure, there are also consequential negative societal and economic impacts in population which are caused by the dysfunctionality of transport infrastructure [1]. Among the most serious impacts on population are: unavailability of ambulance and rescue services which causes higher damage of health and loss of lives of a population, unavailability of essential food and goods, problems with providing massive evacuation, insufficient security of population and public order, transport inaccessibility of employer, i.e. longer way to work place. Disruption of transport network due to disasters can cause major problems for the functioning of the whole society and also lead to an increased societal vulnerability. Therefore we argue that the identification and the understanding of the societal vulnerability due to failure of the critical transport infrastructure is essential to (1) risk management, (2) transportation planning, (3) development of society, and in particular critical for (4) the national security.

Our effort is concentrated on research how to measure this societal vulnerability to be usable mainly for improving risk management (risk reduction) during the all phases of the disaster management cycle. For this purpose we propose to use the multilevel approach for measuring societal vulnerability. We argue that the use of the multilevel approach can address important aspects of the societal vulnerability: (1) multidimensional aspect of vulnerability, (2) community (societies) divergences, (3) facilitate knowledge elicitation from human experts through a structured approach to the problem.

2. BACKGROUND AND RATIONALE

The vulnerability is used in many research areas, but its definition is often ambiguous. Commonly is vulnerability expressed as the extent to which people or things are likely to be affected [2] (in Flanagan [3]) and similarly vulnerability can be briefly defined as the propensity or predisposition to be adversely affected [4]. In connection to the transport network or infrastructure we can define vulnerability as the consequential cost of the lack of reliability ([5], [6], [7], [8]), and this consequential cost must compromise not only the immediate toll on the network-users, but the overall socio-economic costs on the community that this vulnerability would entail ([5], [6], [8]). Linking these two characteristics gives us the possibility to describe societal vulnerability as extent to which society is likely to be susceptible resulting from a lack of reliability of critical infrastructure and in our work we follow this trend.

The newer vulnerability concepts and assessments approaches do not solely focus only on one specific aspect, e.g. susceptibility (as was mentioned) but they address various factors of vulnerability and their interplay [9]. According to Birkmann [9], core factors of vulnerability encompass, e.g. susceptibility and coping or adaptive mechanisms as factors to systematize societal response capacities to deal with adverse environmental or weather conditions which cause a lack of the reliability of the critical infrastructure. System susceptibility to extreme weather events and adaptive capacities and planned response options are important factors in assessing vulnerability. Early consideration of these elements will provide the maximum opportunity for a timely and effective response to extreme weather events.

Susceptibility (sometimes also called sensitivity or fragility) characterizes the predisposition and likelihood to suffer harm when a hazard strikes a community or a system is exposed. Even if a community or system is exposed to hazard, this does not necessarily mean that it is high susceptible, since susceptibility refers primarily to the conditions of the community or the system exposed. E.g. the hazards and vulnerability literature reveals that categories of people living in a disaster-stricken area are not affected equally [3]. Susceptibility generally describes deficits and problematic conditions that might manifest themselves through people's defenselessness due to poverty or the lack of awareness about risks and so on [9].

Adaptive capacity is the combination of the strengths, attributes, and resources available to an individual, community, society, or organization that can be used to prepare for and undertake actions to reduce adverse impacts, moderate harm, or exploit beneficial opportunities [4]. It also reflects the ability of a system to change in a way that makes it better equipped to deal with external influences [10].

Some authors (e.g. [11], [12]) define an additional factor – exposure because in terms of spatial and temporal influences of a hazard event is important to assess the extent to which a society is exposed. Generally exposure refers to the extent to which system or a unit of the assessment (society, infrastructure, buildings, etc.) falls within the geographical range of a disaster [9]. If society is actually or potentially not exposed to hazards or impacts arising from the lack of critical infrastructure reliability, it is also less important to assess their susceptibility to such a phenomena.

In our work exposure is seen as own factor next to vulnerability (similarly as in concept of Intergovernmental Panel on Climate Change [4] and Institute for Environment and Human Security of the United Nations University [13]). It is defined as the presence of people, livelihoods, environmental services and resources, infrastructure, economic, social, or cultural assets in places that could be adversely affected [4].

In that context we can define societal vulnerability as a function of three elements (Fig. 1):

1) exposure to disasters,
2) susceptibility to change,
3) capacity to adapt to that change.

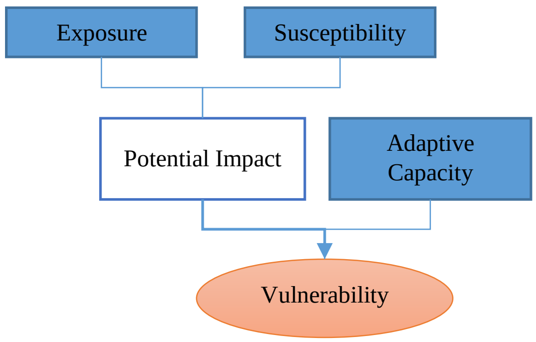

Fig. 1 Vulnerability and its core factors (Adapted from [10])

Based on above mentioned definitions and partial conclusions a system or society that is highly exposed, susceptible and less able to adapt is more vulnerable. Following these relationships a societal vulnerability can be calculated.

3. MULTILEVEL APPROACH TO SOCIETAL VULNERABILITY MEASURING

Societal vulnerability is composed of various dimensions (Fig.1) and is affected by vast number of factors. These dimensions and factors are so different that it is not possible to use them for direct Societal Vulnerability measurement. On the other hand, these dimension and factors have some characteristics and aspects in common, hence, it is possible to assort them into groups. This way we can gradually define the overall level of societal vulnerability. Therefore, we suggest the use of multilevel approach for the measurement of societal vulnerability (Fig. 2) which, by gradual defining of concrete levels, will lead to the determination of overall Societal Vulnerability. We propose to define the level of Societal Vulnerability by the use of **Vulnerability Index - VI**.

The method was formed by gradual splitting (division) of Societal Vulnerability into lower levels (downwards):

- Vulnerability Core Factors (3 factors),
- Vulnerability Societal Categories (9 categories),
- Vulnerability Indicators (31 indicators).

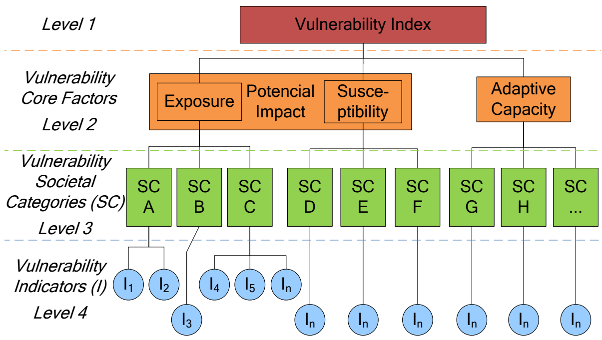

Fig. 2 Multilevel Approach to the Vulnerability Index Identification

Vulnerability Index is formed by three Vulnerability Core Factors (Exposure - E, Susceptibility - S, and Adaptive Capacity - AC, while Exposure and Susceptibility together create Potential Impact - PI). Each of these three factors is formed by three different Societal Categories. Societal Categories are formed by several Vulnerability Indicators.

Each Vulnerability Core Factor (CF) stands for one component of vulnerability which describes the eventual state in target region. According to the assessment of eventual state, it is possible to subsequently determine the level of vulnerability in given region. Those components of society are taken into consideration which can be in danger (Exposure), components which are more sensitive to extreme weather (Susceptibility), as well as capacities (Adaptive Capacity) which are in assessed region in disposal of in order to manage the impacts of extreme weather events.

For each Vulnerability Core Factor it is necessary to define sub-categories – we call them Societal Categories (SC). Societal Categories stand for those parts of society which form the main interest/centre of our research. They concern mainly transport critical infrastructure and society dimensions (social, economic, security, environmental, institutional, etc.) hence, the management of transport infrastructure operation for society.

Individual Societal Categories are formed by Vulnerability Indicators (I). These Indicators describe concrete specific characteristics of each society which are significant considering their vulnerability to extreme weather impacts.

Vulnerability Index (VI) is calculated by retrospective assessment of the mentioned levels (upwards). By the assessment of Vulnerability Indicators and the integration of Vulnerability Societal Categories and henceforth, within Vulnerability Core Factors, we will get the resulting value of VI. Vulnerability Index represents unlimited value (we assume values from 1 to 5). Increasing values indicate increasing vulnerability. VI values have no strict interpretation, but if the given approach is applied on more sectors (areas) simultaneously, it is possible to compare them and it allows the identification of more vulnerable areas.

Authors [14], [15] argue that a system might be vulnerable to certain events but be resilient to others therefore it is important that while defining vulnerability one must consider hazardous events characteristic to the area under consideration.

Societal Vulnerability is so complicated to define in regard to society and transport that it was necessary to consider many factors and relations which affect this vulnerability. We have found out that Vulnerability Indicators are so different content wise that it was not possible to find a unifying unit to express the societal vulnerability (e.g. determination through money or other). Therefore, we suggest the use of point's assessment for each Vulnerability Indicator. Thereby, the unity of determination of each indicator will be ensured and will enable further operation.

Each Indicator will be given a value from 1 to 5. Indicators will be given also weight **(w_I)** apart from the given value because the relevance of indicators does not need to be the same, i.e. the evaluators in given country can assess the weight of relevance according to their preferences. Weights are given to indicators separately within each Societal Category according to the principle that indicator weights must have the value of 1 within one Societal Category. Indicator weights will be determined by subject matter experts based on their assumptions.

To set the resulting value of Vulnerability Index, it is necessary to assess the weight of all Core Factors, Societal Categories as well as of all indicators (w_I, w_{SC}, w_{CF}). These weights (together with given values) will be gradually counted into the resulting value of VI (Fig. 3) and also, they were defined according to subject matter expert's assumptions. There is a principle for these weights which sets the sum of Exposure weight (w_E) and Susceptibility weight (w_S) to the value of 1. Similarly, the sum of Potential Impact weight (w_{PI}) and Adaptive capacity weight (w_{AC}) results in the value of 1.

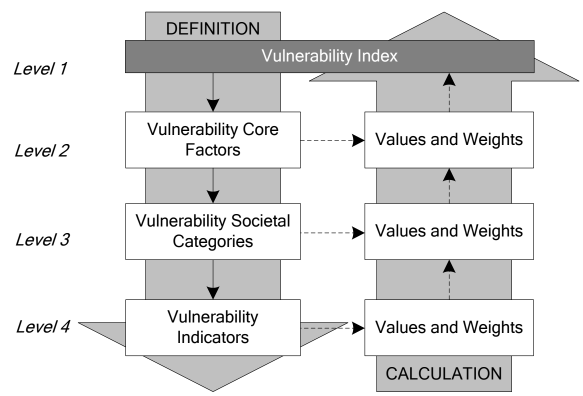

Fig. 3 Multilevel definition (downwards) and calculation (upwards) of Vulnerability Index

By summing the values of Vulnerability Indicators and considering indicator weights, values of Vulnerability Societal Category will be calculated according to the relation (1):

$SC_x = \sum_{n=1}^{i} w_{I_n} I_n$	SC = Societal Category x = designation of Societal Categories i = number of indicators within Societal Category (from 1 to n) w_I=weight of Indicators I_n = value of Indicators	(1)

Similarly, values of Societal Categories will be added to the value of Core Factor. As in the case of other indicators, even all Societal Categories needed their weight (w_{SC}) to be assessed. Aggregated value of Core Factor is calculated according to the relation (2):

$CF_y = \sum_{n=1}^{j} w_{SC_n} SC_n$	CF = Core Factor y = designation of Core Factors j = number of Societal Categories within Core Factor (from 1 to n) w_{sc} = weight of Societal Category SC_n = value of Societal Category	(2)

Resulting value of VI is obtained in a similar way as it was done in previous steps. The final calculation of VI is preceded by one extra step which lies in the calculation of Potential Impact **(PI)**. Potential Impact represents possible level of impacts on society after considering all aspects which can be in danger (Exposure) and after considering all societal groups which are more sensitive to extreme weather impacts (Susceptibility). The weights of Exposure and Susceptibility **(w_E, w_S)** are counted as well. Potential Impact is calculated according to the relation (3):

$PI = w_E E + w_S S$	PI =Potential Impact E = Exposure S = Susceptibility w_E = weight of Exposure w_S = weight of Susceptibility	(3)

Resulting value for VI is the sum of PI weight value and weight value of Adaptive Capacity (4):

$\boldsymbol{VI} = w_{PI} PI + w_{AC} AC$	VI = vulnerability index AC = Adaptive Capacity w_{PI} = weight of PI w_{AC} = weight of Adaptive Capacity	(4)

As it was mentioned in the theoretical part, vulnerability is dependent on specific hazard. Hence, target region can be more vulnerable to a certain kind of threat but much more resistant, i.e. less vulnerable to another kind of threat. We incline to this idea and therefore, it is necessary to evaluate vulnerability for each threat or danger separately.

4. CONCLUSIONS

Understanding and assessing multifaceted nature of societal vulnerability is a great challenge since the social, economic and environmental conditions of people as well as the hazards that affect them are still changing. In particular, understanding of distribution of societal vulnerability due to a failure of the critical land transport infrastructure may help to identify most vulnerable parts of the society.

Exploring societal vulnerability to extreme weather events can help to protect the most vulnerable parts of a society e.g. (1) by continual increasing of risk awareness aimed on the target groups (children, elders, disabled, etc.), (2) by more effectively preparing responsible authorities at all phases of the disaster cycle, (3) by incorporating subject of vulnerability into a typological disaster plans, (4) by allocating necessary resources within regions to address potential negative impacts of disaster, (5) by ensuring evacuation compliance, (6) by contributing to successful long-term recovery, etc.

The concept of vulnerability is still a subject of active interest from both practitioners' and academic communities. In recent years, an increasing number of initiatives have been launched to measure vulnerability with a set of indicators and indices. We can find them in the literature especially in the form of case studies. They include quantitative and qualitative approaches and are an important basis for further enhancing and disaster-risk reduction before a disaster occurs. Basically, existing approaches are based on the identification of the appropriate indicators which describe relevant system's (societal) characteristics and at the same time indicate differences within region.

Proposed approach will be validated on actual examples of regions in the Slovak Republic. In order to provide needful and appropriate information to local and national decision makers more transparency and more information about the most vulnerable areas and groups are needed. The more we will concentrate on the research how to improve and adjust existing indicators approaches for specific events and purposes the better results concerning the risk and vulnerability reduction we can expect.

5. ACKNOWLEDGEMENTS

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