PLANNING 'ROBUST' ROAD NETWORKS FOR FLOOD RISK MANAGEMENT: A LITERATURE REVIEW

Gopal Chandra Banik[1], Subrata Kumar. Paul[2], Sudip Kumar. Roy[3]

[1]Ph.D Scholar, School of Ecology, Infrastructure and Human Settlement Management (SEIHSM), Indian Institute of Engineering Science and Technology (IIEST), Shibpur, Howrah, India 711 103.

[2]Assistant Professor, Department of Architecture, Town and Regional Planning Department, IIEST, Shibpur, Howrah.

[3]Professor and Head, Civil Engineering Department, IIEST, Shibpur, Howrah.

[1]gopalchandrabanik@gmail.com , [2]subrata2412@gmail.com , [3]royksudip@gmail.com .

Abstract

The concept of 'robustness' is comparatively a new thought in transportation studies. The current article, based on literature review, seeks to systematically examine the concepts and perspectives of 'robustness' as applied to transportation networks in general, and to planning of road networks exposed to flood-hazard, in particular. The findings of the review draw attention to the necessity for formulating frameworks and strategies for planning road networks in flood-prone areas with 'robustness' as a major consideration that would lead to successful flood risk management.

Key words: *Robustness; Road Network Planning; Flood-risk management.*

1. Introduction

Flood is a frequently occurring natural disaster that imposes serious threats to human lives and habitations across the globe. The devastation of flood is often widespread over a large regional scale. Besides abrupt traffic-disruption, one of the worst consequences of flood, reported in literature (Mens et al. 2011), is isolation of several nodal components (settlements) owing to reduced or completely lost capacity and serviceability of road links resulting from physical damage caused by inundation (Konstantinidou et al. 2014).

The task of disaster management calls for assessing the risks and, accordingly getting prepared for mitigating the adversities of the catastrophic events that essentially involves evacuation of victims and providing vital facilities (food, clothing and medicines) to the affected areas. Thus, road networks, have a vital role to play in disaster mitigation in general and, are identified as critical lifelines for flood risk management in particular, for two fold reasons: first, it remains the major, if not sole, means for ensuring physical access to the affected communities by providing supply line of vital facilities and evacuation path of victims; second, the survived network supports the flow of traffic without breaking down the connectivity with the rest of the region. Thus, planning of a road network, which is 'robust' against flood-risk, is imperative for proceeding towards disaster mitigation goals and, it involves a chain of activities ranging from performance evaluation and pre-disaster improvement of network resilience to post-disaster response, recovery and reconstruction (Peeta et.al. 2010).

'Robustness' is one of the fundamental concepts, often relied upon to demonstrate a system's performance at any operational condition. Ziha (2000) defines 'robustness' as the capability of a system to respond to all possible random failures uniformly. For the present study, a road network ('system') may be regarded as 'robust' against flood-hazard, if the loss of connectivity and accessibility, due to disruption of its segments during inundation ('possible random failures'),is insignificant.

With the above background, this paper aims to systematically review the concepts and perspective of ‘robustness’ as applies to transportation networks in general, and how it has been adopted and dealt in discourses for planning of road networks exposed to flood-hazard, in particular.

The Google and Google Scholar search engines were used to search articles, research papers and documents using English keywords. Literatures were also located through ‘snowballing’ a method that uses bibliographies as the means to find other pertinent resources. The documents selected were written in English.

The remainder of this paper is organized as follows: Section 2 elucidates the concepts and perspectives of road network robustness with particular reference to disaster mitigation; Section 3 identifies the requirements of a road network to be robust against flood risk; Section 4 furnishes the salient findings from the review leading to identification of the tasks in planning of a road network that is robust against flood hazard, followed by concluding remarks.

2. Road network robustness and disaster mitigation: concepts and perspectives

The term ‘robust’ originates from the Latin word ‘robustus’, meaning ‘strong’ or ‘hardy’ (Mens et al, 2011). According to the Merriam Webster dictionary (2015), ‘robust’ means having strength, being strongly constructed, or performing without failure under a wide range of conditions.

The concept of ‘robustness’ has been adopted in transportation studies form the discipline of communication and networking (such as, telecommunication, computer science) and also from physics, mathematics and biology (Stringer, 2006). Robustness is the ability of a network to continue performing correctly across a wide range of operational conditions, when it is subjected to failures or attacks. (Ellens, W. and Kooij, R. E., 2013; Gribble, 2001; Li, 2008; Snelder, 2010). According to Matisziw, Grubesic and Guo, (2012) network robustness refers to a network’s resilience to stress or damage. Sullivan, Novak, Aultman-Hall and Scott(2010) defined network robustness as the degree to which the transportation network can function at ease similar to the earlier best condition in spite of various capacity disruptions of links. According to Sullivan et al. (2010) a ‘‘robust” network can compensate for disruptions on network links with relative ease and with only slight increases in overall system-wide travel times. A ‘‘non-robust” network does not adjust well to disruptions on network links and is subject to substantial increases in system-wide travel times. Knoop et al., (2012) consider robustness as the network’s ability to preserve its functionality under conditions that “deviate from the normal”. Snelder, et al., 2012 noted that “robustness is the extent to which, under pre-specified circumstances, a network is able to maintain the function for which it was originally designed”. They further state that robustness is related to impacts of a disruption rather its occurrence probability and argue that robustness relates to less frequent events of increased impacts. According to Boccaletti et al. (2006), robustness refers to the ability of a network to avoid malfunctioning when a fraction of its constituents is damaged. In city road system robustness refers to the ability to maintain the functionality under attacks or failures (Duan and Lu, 2014). Thus, it follows from the aforementioned literatures that ‘robustness’ is one the important attributes of a road network system that determines its performance at wide-ranging operational conditions.

Existing discourses on road networks robustness are scattered over different objectives (Table 1), such as identifying vulnerable/critical links in a road network for traffic-disruption and short term fluctuation in traffic-flow, designing reliable supply chain, analyzing accessibility of an entire network or its part in post-disasters scenario etc., which relate to two broad categories of problems frequently dealt in transportation planning: first, traffic congestion that may result due to ephemeral disruption in a road segment and second, disaster mitigation and management.

Table 1: Overview of road network robustness studies

Objectives	References
Identifying vulnerable links/sections	Scottetal.(2005); Sullivan et al.(2010); Snelder, (2010); Kaysi etal.(2003); Visser and Molenkamp (2004); Yperman and Tampe`re (2006); Bell (2000);Cassir and Bell (2000); Murray-Tuite and Mahmassani (2004).
Accessibility robustness	Berdica and Eliasson,(2004); D'Este and Taylor,(2003);
Post-disaster network analysis	Chang and Nojima,(2001); Sakakibara et al.(2004); Mens et al., (2011).
Robustness and link failure	Dekker and Colbert (2004); Zhang and Levinson (2004); Yinet al.(2005); Jenelius et al.(2006); Zhang et al., (2011)
Robustness and reliance of transportation network	Boccaletti et al.(2006); Derrible and Kennedy,(2010); Knoop et al.(2012).

While the concept of robustness has been widely deployed for evaluating performance of transportation networks under varied traffic scenario and developing models for reliable supply chains in the studies of Grubesic et al. (2007); Snyder and Daskin (2007); Wilson (2007); Dong (2006); Scott et al. (2006), the necessity of a robust road network for minimizing casualties, economic losses and maintaining connectivity for evacuation and supply of relief-work during natural disasters are well acknowledged in several earlier studies (Li,2008; Sakakibara et al, 2004; Kurauchi et al. 2009).

The concept of robustness in planning of road networks for flood risk management has been found to be pertinent in two different perspectives: first, robustness in network design and second, robustness in routing (Bigdeli, A., 2012). The basic goal in robust network design is to constitute the best topologies for a communication network, and to assign suitable capacities to the links to attain the maximum robustness against various changes in the network composition namely link failures. On the other hand the robustness in routing, deals with traffic engineering algorithms that are not affected dramatically by environmental changes, specifically variations in the traffic matrix, network topology and source destination pairs of interest. For the present study, the focus is on the discourse dealing with robustness in network design.

3. Requirements of a road network to be 'robust' against flood risk

The multi-faceted importance of road infrastructure for progress towards prosperity of aregion is well documented in several studies (Patrasuk, 2013; Burman and Rietveld, 1999; Deichmann et al., 2005; Gutierrez and Urbano, 1996; Bourdet, 1998; Windle and Cramb, 1997; Jacoby, 2000; Airey, 1992; Fan and Chan-Kang, 2005; Bourdet, 1998; Lampe, 1983). However, literature dealing with the roleof a road network in flood disaster management is limited. Iida et al (2000) identified the essential roleof road infrastructure for disaster management operations in two sub-phases, which indicates the requirements of a road network to be 'robust' against flood, as outlined below:

First, ***Response sub-phase*** (During flood operation) - Shortly after onset, and during inundation, it is expected that the road network would support emergency operations. The focus should be given towards operational efficiency of road networks in such a way that the emergency response unit can access easily to provide rescue to the affected people and help them for evacuation. At this phase, normal community activities are more or less disrupted and regular transportation needs are minimal. At that time the road networks need to establish emergency response and efficient evacuation routes.

Second, ***Recovery sub-phase*** (After flood operation): In the post-flood phase, road networksoften suffer severe damages to its elements (highways, bridges, embankments, tunnels), ranging from degradation to full collapse, which partially and fully encumber the network's performance and limit its connectivity, serviceability and functionality. During this period community activities would gradually recover to its earlier state, and thus, the surviving network would be expected to remain operational enough to support the recovery process and other needs for post-disaster services, such as evacuation of population, supplying reliefs, providing quick responses to emergencies etc.In addition, the remaining network is expected to support recovery activities for its restoration to the pre-flood situation and to handle a sizeable volume of outbound traffics, which are likely to divert from other disrupted roads in a post-flood scenario.

4. 'Robust' road networks for flood-risk management: Planning tasks

According to Peeta et al, (2010) "disaster management is a multi-stage process that starts with pre-disaster mitigation and preparedness that focus on long-term measures for reducing or eliminating risk, and extends to post-disaster response, recovery and re-construction" (Figure1). Thus, the tasks in planning of 'robust' road networksfor flood risk management, in pre-disaster stage, include risk assessment and decision making in connection with infrastructure development that would result in reduced vulnerability and hence,enhanced resilience of the networksunder adverse situation. The same in the post-disaster stage call for performance estimation and, tactical and operational decision-making for providing critical emergency, recovery and re-construction services.

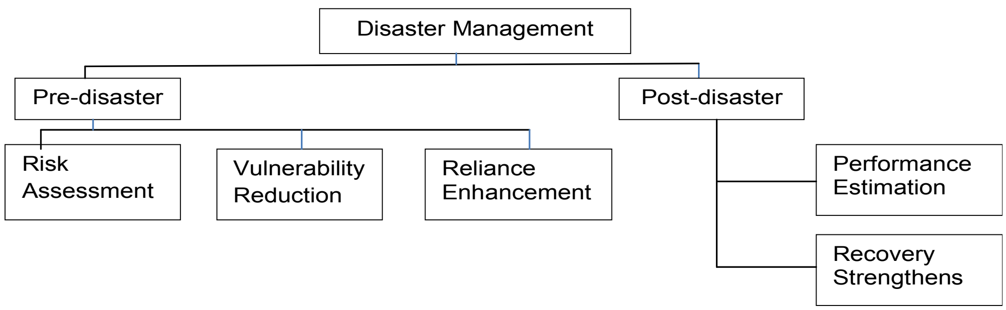


Figure: 1: Multi-Stage process in flood management

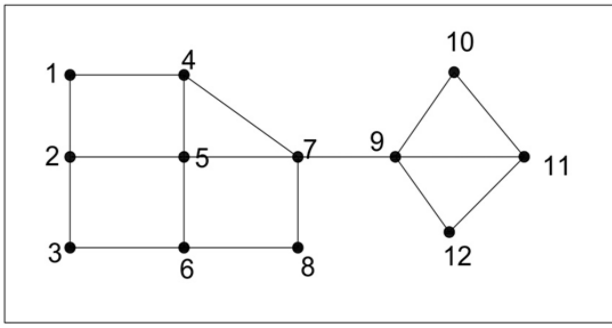
The following sections indicate the salient findings from the review in connection with the planning tasks as identified above:

4.1 Ascertaining disaster type:

Ascertaining the severity of the hazard or disaster under consideration is a prerequisite for preparing risk-management plans. Cirianni et al, 2012, Sohn et al, 2006reportedthatwhile discourses dealing with earthquake preparedness plans are available in significant volume, literatures on flood-risk management are limited.

4.2 Characterization of networks and links:

The topology of a road network has significant bearing on its resilience to disaster hazard. Balijepalli et al, 2014noted that not all road links of a network are equally critical to its functioning - some of the links have a greater importancefor network performance than the rest and, the former are called critical links. Disruption of the critical links may result in significant deterioration in network flow and/or accessibility in the disaster affected area.Link(s) in network(s) can be characterized in two ways: first, a link may be indispensable for sustaining connectivity with some areas because it is the only one which connects two circuits; second, a link may be the most important to sustain performance of the network because there are many shortest paths, which passes through it.



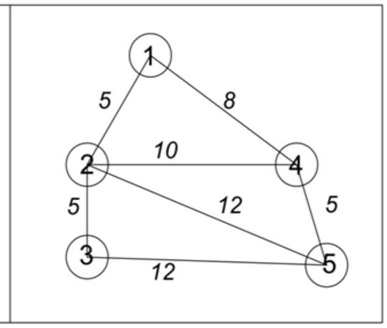


Figure 2a: Indispensible link **Figure 2b: Most important link**

In Figure 2a, the link (7-9) is an example of indispensible link because it connects the set of vertices 1-8 with that of 9-12 and, if this link is removed from the network both the sets of nodesbecome isolated from each other. On the other hand, the link (4-5) in Figure: 2b is an example of most important link being in the shortest paths between nodes 1-2, 1-3, 1-4, 1-5, 2-3, 2-4, 2-5, 3-4, 3-5 and 4-5. If this linkis removed the connectivity still sustains but the impedance in the shortest pathsincrease significantly - for example, if the shortest path 1-4-5 (between nodes 1-5) is replaced with 1-2-3-5 the impedance between the nodes increases from 13 to 22 units.

Therefore, characterization of networks for identification of critical links is an important task in planning for flood risk management under pre-disaster stage.

4.3 Assessment of vulnerability, risk and reliability:

Assessment of vulnerability, risk and reliability has been referred in many literatures in context of characterization of road networks based on the consideration of robustness (Immers et al 2004; Snelder, 2010; li, 2008).

Vulnerability describes the weakness of a network while robustness describes the strength of a network (Snelder, 2006).Vulnerability, in road network system, results considerable reduction of serviceability (Berdica, 2002; Chen et al 2007). The serviceability describe the possibility to use a link, route or road network during a given time period (Snelder, 2006). D'Este and Taylor (2001) define vulnerability as the possibility of severe adverse consequences if a small number of links (or possibly a single link) is degraded. Holmgren (2004) defined vulnerability as "sensitivity to threats and hazards". Vulnerability is often associated with accessibility, which represent the ease of approaching a destination (Niemeier, 1997). In flood situations, due to isolation of links accessibility of nodes became reduced. Jenelius(2006) introduce two terms for interpreting network vulnerability: "link importance" and "exposure". The first one incorporates the impacts of link failure on costs and capacity and the second one describes the probability of link isolation and their impacts on travelers. Later, Jenelius,(2009) introduces "regional importance", "expected total exposure" and "expected user exposure" as terms expanding his previously proposed terminology.

Risk assessment is another concept closely related to network characterization in connection flood-risk management. Risk is associated with the probability of a disruptive event and its impacts (Berdica, 2002) and is defined as the product of hazard and vulnerability. In context of flood-risk management, hazard quantifies the severity of inundation, while vulnerability computes the probability of reduction of the serviceability of the road network.

For a road network, the operational conditions can be classified into two sides: supply conditions and demand conditions. Any disruption in a road network ultimately results in the changes of its supply (such as link capacity) or /and its demand. The operation status of a road network is often evaluated with some indicators for its network level performance, such as average speed, network throughput. Thus the study of network robustness can be simply understood as the analysis of the performance of the road network under the situations with considerable changes in its supply or/and demand compared with its normal or desired performance. From this point of view, the concept of robustness is closely related to the concept of reliability and is very easily confused with the concept of network reliability, which also focuses on analyzing the network performance under certain operational conditions (Li, 2008).

Several understandings about road network reliability exist from different interests in the research objectives. For Bell and Iida (1997), reliability is the degree of stability of the quality of service, which a system normally offers. According to Billington and Allan (1992) and Wakabayashi & Iida (1992) reliability is the probability of a road network performing its proposed service level adequately for the period of time intended under the operating conditions encountered.

The initial studies on network robustness focused on two concepts of reliability. The first, connectivity reliability, considers the probability that two network centers (nodes) remain connected when one or more links are cut (Wakabayashi and Iida, 1992; Bell and Iida, 1997). The second, travel time reliability, considers the probability of making a trip between two network centers within a specified time interval given daily stochastic travel demand variation (Asakura and Kashiwadani 1991; Clark and Watling 2005). Chen et al. (1999) introduced the concept of capacity reliability, which is concerned with the probability that a network can accommodate a certain travel demand at a given level of service. Yang et al. (2000) compared capacity reliability and travel time reliability, and suggested that they should be used together on comprehensive road network design.

4.4 Performance measures:

Performance measure is an important criterion in planning of robust road networks for flood-risk management under post-disaster stage. According to Nojima (1998), performance measures may be categorized as flow-dependent or flow-independent. Through flow-dependent measures attempt to capture congestion phenomena in the post-disaster stage whilst the latter requires only data on the physical state of the network. Chang and Nojima (2001) conclude that due to the lack of available data the use of flow-dependent measures are limited in assessment of disaster mitigations. In contrast of flood management, flow- independent measures are more suitable measure at characterization of networks at regional scale. They use three different flow-independent measures to estimate performance; total length of network open and total and areal distance-based accessibility. Component length participates in the calculation in all cases but under different concepts. The first measure is the fraction of the network open to traffic in the post-disaster stage in terms of length, irrespective of the actual allocation of the open segments and their connectivity. In the second measure, initial component length, damage state and connectivity are combined to provide an estimate of accessibility based on the minimum distance paths for every origin – destination (OD) pair. In the final measure the concept is similar, but accessibility is based on both minimum distance paths and weighting factors for the nodes according to pre-disaster OD data.

4.5 Recovery strength:

It is another indicator of network robustness and generally follows performance measures studies. The network will be considered more robust if it recovers soon at its earliest form.

5. Concluding Remarks

The present article focuses on the concept of 'robustness' and its applicability and implications in connection with road network planning in general, and particularly for flood risk management. A number of literatures enlightened on the application of robustness criterion for measuring performance of road networks on different disaster situation in real world scenario and argued its importance in preparation of management plans for achieving a minimum-disruption goal. In India a vast geographical area suffers from flood hazard every year with significant loss of lives, infrastructure and properties. Future research works may focus on formulating frameworks and strategies in Indian context for planning of road networks in flood-prone areas with 'robustness' as a major consideration that would lead to successful flood risk management.

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