
Disaster resilience of transportation infrastructure and ports – An overview

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ABSTRACT

Contemporary literature on disaster resilience of transportation infrastructure and seaports is reviewed. There is a considerable body of literature on disaster resilience in terms of engineering and technical resilience of infrastructure to disasters. Resilience of communities is also a subject of wide research. The impact of disasters on transportation infrastructure and their resilience has been studied by researchers, mainly in the context of the developed world. There is a considerable paucity of such studies on the resilience of transportation infrastructure in the multimodal context, even in the developed world. Studies on the impact of disasters on the interface of maritime transport and land based transport in a seaport centered setting are scarce. Most studies in this context have been spurred in the aftermath of 9/11 and hence are essentially security oriented. In general it is observed that there is still no widely accepted measure for resilience of transportation infrastructure for any mode of transportation. The review also exposes the lack of serious research on the impact of disasters on the resilience of transportation and port infrastructure in the developing countries. Areas requiring further attention from researchers are identified.

Keywords: Disaster, Disaster Resilience, Transportation Infrastructure, Transportation Network, Port.

1. Introduction

We are living in the age of disasters. The more we advance, the greater is the impact of each disaster on our society and the more it becomes necessary for us to build resilience into our communities and infrastructure. We cannot avert most disasters. We can, however, be prepared for them to minimize their impact and return to normalcy within the shortest possible time after a disaster with the help of as little external resources as possible. This is what a resilient society strives for.

Transportation - be it road, rail, air or water – is the lifeline of our society. Serious disruption to transportation infrastructure can have catastrophic impact on the ability of the community, business and economy to recover from a disaster. Hence it is of utmost importance for researchers to address the issue of building resilient transportation infrastructures. Today, more than three quarters of world trade by volume is carried on ships. Hence ports play a very critical role in the overall transportation infrastructure. If port activity is disrupted due to any reason, it will have a direct adverse impact on not only the other transportation functions but also the nation's economy as a whole. This was amply demonstrated by the impact of the 1995 earthquake on Kobe port in Japan.

Disasters know no boundaries. Disaster research too has no boundaries. The multidisciplinary nature of disaster research complicates holistic studies of disasters and also calls for awareness among researchers in diverse disciplines on current research trends across disciplines. To this end, we undertook a literature review in the critical area of disaster resilience of transportation infrastructure and ports, which is not currently available.

2. Approach

Our focus in this review has been on papers published within the last 10 years, with a preponderance of the papers having been published in the last 5-6 years. Most of the papers are from peer reviewed journals. Some important reports and articles have also been included due to their importance to the area under review. In this paper, we first review some papers in the general area of disasters, followed by disaster resilience, transportation infrastructure / network resilience and finally port resilience. We conclude with our observations on the review with recommendations for future research.

3. Disasters

Disasters have been a subject of much research in the last decade. A succinct overview of disasters and their classification in the form of a disaster tree is provided by Shaluf, 2007. Allenby and Fink, 2005, argue that today our society is exposed to a multiplicity of disaster scenarios, ranging from natural disasters and terrorist attacks to epidemics like SARS and AIDS. The range of challenges and the practical impossibility of addressing each type of disaster call for a comprehensive system perspective to disaster management. They suggest that “this should be on the principle of enhancing social and economic resiliency as well as meeting security and emergency response needs, and to the extent possible, developing and implementing dual use technologies that offer societal benefits even if anticipated disasters never occur.” Proper handling of disaster situations holds the key to minimizing its impact. To this end, most countries have their own versions of Incident Management Systems (IMS) at the state, county or subdivision level. Perry, 2003, traces the evolution of IMS in the US context and examines how it could be used effectively in disaster management at the local administrative level.

Hurricane Katrina was one of the most devastating disasters in recent history. Its impact and consequences were subjected to several detailed studies. A broad summary of the principal findings of the US Interagency Performance Evaluation Task Force is provided by Link, 2010. A study conducted by the University of Madras and Kyoto University provides an assessment of the resilience Chennai city to climate related disasters. The study, Chennai Zone Profile: Climate and Disaster Resilience, 2010, was based on a questionnaire covering five dimensions of resilience – Physical, Social, Economic, Institutional and Natural. A key finding of the study was that of the five dimensions, natural resilience was the lowest. The impact of climate change and consequent disastrous flooding in low lying areas of third world countries like India is highlighted by Ranger et al., 2011, in their study of flood impact on Mumbai. The role of insurance in disaster mitigation and management from an Indian perspective is provided by Atmanand, 2003.

Rodriguez et al., 2006, explore the societal impacts and consequences of the December 26, 2004 Indian Ocean tsunami. The importance of generating early warning systems and strategies for sustainable recovery and building disaster resilient communities has been highlighted. Moe and Pathranarakul, 2006, propose an integrated approach for effectively

managing natural disasters from a public project management perspective. Their research had the 2004 Indian Ocean tsunami that hit Thailand as the backdrop.

Webler and Lord, 2010, suggest an integrative technique for tackling the human dimension of oil spills drawing on social impact assessment, hazard management and vulnerability assessment to portray risks from oil spills and response activities. Lessons learned from Kobe Earthquake are detailed in a number of studies like Menoni, 2001, Chang and Nojima, 2001 and Chang, 2010.

Disasters can not only strike built environment and communities but also the internet. The study of impact of disasters on the internet and possible remedial measures is a field of active study. Sterbenz, et al., 2011, highlight the criticality of the internet and the need to increase its resilience to disasters. They use a combination of analytical and simulation techniques to provide a framework to evaluate the resilience of the future internet.

Altay and Green, 2006, suggest that the randomness of impact of disasters and uniqueness of incidents make the topic of disaster operations management very suitable for OR/MS research. Based on a comprehensive literature survey, they claim that while social sciences and humanities literatures have an abundance of disaster management articles, application of OR/MS in this area is largely unexplored.

Mercer and Kelman, 2010, have shown that in dealing with disasters in tribal and remote environments, indigenous knowledge has both relevance and applicability and scientific knowledge should supplement and not supplant the indigenous community's efforts to cope with disasters. They based their observations on the study of the indigenous community of Baliau living on the island of Manam in Papua New Guinea alongside the active Manam volcano.

3.1 Disaster Resilience

Resilience to disasters has been defined in literature in several ways. Tierney and Bruneau, 2007, define disaster resilience as "...the ability of social units (e.g., organizations, communities) to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities in ways that minimize social disruption and mitigate the effects of future disasters." According to CRN fact sheet, 2009, resilience is "...the process of preparing and responding to the eventual actualization of the multiple and increasingly diverse risks." Cimellaro et al., 2010, define resilience as "... a function indicating the capability to sustain a level of functionality or performance for a given building, bridge, lifeline networks, or community, over a period defined as the control time (T_{LC}) that is usually decided by owners, or society....."

The Multidisciplinary Center for Earthquake Engineering and Research (MCEER) at University of Buffalo has done pioneering studies in the field of earthquake engineering. Tierney and Bruneau, 2007, of MCEER provide a framework for studying resilience of systems and communities based on 4 parameters – Robustness, Redundancy, Resourcefulness and Rapidity (R4 Framework). They have also identified 4 dimensions or domains of resilience – Technical, Organisational, Social and Economic (TOSE). Cimellaro et al., 2010, present a uniform terminology for disaster resilience and its quantitative evaluation based on dimensionless analytical functions. The resilience framework is primarily earthquake focused and builds upon MCEER's terminology. The framework developed is applied to a hospital

building and a hospital network to highlight the implementation issues. Bruneau et al., 2003, present a conceptual framework to define and measure seismic resilience of communities. The key to the proposed framework are three complementary measures of resilience – “Reduced Failure Probabilities”, “Reduced Consequences from Failures” and “Reduced Time to Recovery”. Shinozuka et al., 2004, apply the MCEER framework to model the seismic performance of Los Angeles Department of Water and Power (LADWP) to study the systems’ robustness and resilience based on the data from Northridge earthquake. Concepts of resilience, critical infrastructure, lifeline systems, interdependence of infrastructure and the R4 framework are lucidly explained by O’Rourke, 2007.

Chang, 2009“b”, examines the complexities of infrastructure including societal as well as technical issues. The interdependency of infrastructure and the challenges in understanding the failure consequences of such interdependencies is discussed. Chang points out that designing resilient infrastructure system will require collaborative efforts by engineers and social scientists. The importance of understanding how mitigating lifeline infrastructure systems like water and power systems can improve a community’s overall disaster resilience is stressed by Chang and Chamberlin, 2004.

Disaster Preparedness is an increasingly important measure of a community’s ability to face and survive disasters. The importance of measuring disaster preparedness lies in its ability to help planners allocate resources suitable to disaster mitigation efforts. However, the measures of such preparedness are far from uniform and mostly subjective. Simpson and Katirai, 2006, have proposed a framework for creating a Disaster Preparedness Index and Resiliency Index with a suggested list of measurement indicators.

Building disaster resilience into contemporary building practices is discussed by Boshier and Dainty, 2011, who proffer a set of overarching principles for creating a more resilient built environment. Little, 2003, has observed that making infrastructure disaster resilient requires more than just engineering or technology. It is necessary to look at the effects of hazards beyond a single system onto a more complex system of systems. And these complex systems have critical institutional and human components that need to be understood and integrated into hazard mitigation measures.

Resilience in coastal communities towards coastal hazards and climate change threats is discussed by Gibbs, 2009. Surjan and Shaw, 2009, use the annual monsoon flooding of Mumbai city to study the effectiveness of community participatory mechanisms like Advance Locality Management (ALM) in disaster resilience. Tadele and Manyena, 2009, study the role of capacity building in developing community disaster resilience taking disaster prone Ethiopia as their study’s backdrop.

As security and resilience are becoming increasingly important in urban planning, national security and energy policy, attempts are being made to make the built environment and critical energy infrastructure more resistant to disruptive challenges. Coaffee, 2008, explores the possible synergies between environmental issues and security as well as policies connected with planning, design and engineering of the built environment.

Chang, 2010, provides a framework for assessing empirical patterns in urban disaster recovery through the use of statistical indicators. Applying the framework to the 1995 Kobe earthquake, Chang concludes that it took Kobe 10 years to reach the pre-disaster population levels, 10 years to reach 89% of pre-disaster per capita income levels, 5 years to reach 90%

pre-disaster business levels and that 90% container trans-shipment business has been irretrievably lost by the Kobe port.

Rose, 2004, has proposed Computable General Equilibrium analysis as a framework for analyzing economic resilience to disasters. The framework is applied to the water supply system in Portland (US) and its resilience under simulated disruptions is studied.

3.2 Transportation Infrastructure/Network Resilience

Transportation is a critical part of today's global economy. Hence a robust and resilient transportation infrastructure is an essential element for a resilient global supply chain. Resilient supply chains and resilient organizations have been a field of active study during the past decade. Christopher and Peck, 2004, argue that as supply chains become more complex due to global sourcing and the "lean" trend, the risk of supply chain disruptions and their consequences have increased. Hence the challenge for today's business is to manage and mitigate that risk by creating more resilient supply chains.

Not only communities and networks, but enterprises should also be resilient to disasters if they are to survive the post disaster phase. Sheffi and Rice, 2005, argue that an organization's ability to recover quickly from disruption can be improved by building flexibility and redundancy into its supply chain. Klibi et al., 2010, have made a critical review of the supply chain network optimization models and discuss the major disruptive events threatening the supply chain network. In this context, they review the current definitions of robustness, responsiveness and resilience. An integrated perspective of supply chain resilience is provided Ponomarov and Holcomb, 2009, through an extensive cross discipline review of literature.

In times of disasters, it's not just enough to have good transportation infrastructure but it should be efficient, equitable and resilient. This is the conclusion arrived at by Litman, 2006, after studying the impact of hurricanes Katrina and Rita in the US. Litman observes that "Katrina's evacuation plan functioned relatively well for motorists but failed to serve people who depend on public transit. Rita's evacuation plan failed because of excessive reliance on automobiles, resulting in traffic congestion and fuel shortages." The impact of disasters on transportation networks and their importance in pre and post disaster evacuation has been studied by Amdal and Swigart, 2010. They used the Greater New Orleans region as a case study to assess the resiliency of individual transportation systems pre and post Katrina. Scanlon, 2003, examines the role of transportation systems for rapid and mass evacuation in times of crises. He examines the public transport system in particular and how it fares in the face of disasters.

Gordon et al., 1998 modelled the transport related business interruption impact of the 1994 Northridge earthquake. They estimated the total business related losses to be more than \$6.5 billion, of which transport related interruptions amounted to more than \$1.5 billion or more than 27%. Chang, 2009, shows that the performance and recovery of transportation systems seem to play a major role in post-disaster long term impacts. She uses the recovery process after the Kobe earthquake to support her arguments.

Zhang et al., 2007, have used TransCAD software to model intermodal network and generate transportation data for calculating measures of resilience in a framework proposed by them using Performance Index (PI) and Levels of Service (LoS) of highway networks and

intermodal terminals before and after disaster. Derrible and Kennedy, 2010, have applied network theory to study the robustness and complexity of metro rail networks by analyzing 33 metro systems in the world. Their analysis provides insights into the robustness of the metro networks which can be used to study the system resilience in times of extreme stress like a terrorist attack. Morlok and Chang, 2004, try to build flexibility into their transportation system models. They develop two approaches to measure transportation system capacity flexibility - the Fixed Traffic pattern Approach (MAXCAP) and the Adjusted Traffic pattern Approach (ADDVOL). They apply these measures to rail freight transportation systems to prove its efficacy in quantifying transportation system flexibility.

Murray-Tuite, 2006, defines ten properties of a resilient transportation system - redundancy, diversity, efficiency, autonomous components, strength, adaptability, collaboration, mobility, safety, and the ability to recover quickly. Noting that no widely accepted measurement of resilience is available for transportation systems, Murray-Tuite examines the influence of the system optimal and user equilibrium traffic assignments on the last four of the ten dimensions defined and provides multiple metrics for the four examined components. Murray-Tuite's paper builds on the earlier work by Godschalk, 2003, on Urban Hazard Mitigation, where Godschalk defines eight properties of disaster resilient systems, namely redundancy, diversity, efficiency, autonomous, strength, interdependence, adaptability and collaborative. Godschalk's paper reviews hazard mitigation practice, defines a resilient city, considers the relationship between resilience and terrorism, and discusses why resilience is important and how to apply its principles to physical and social elements of cities.

A methodological approach employing link based capacity disruption values for identifying and ranking the most critical links in a transportation network is proposed by Sullivan, et al., 2010. They also introduce a scalable system wide performance measure – Network Trip Robustness (NTR) – that can be used to compare networks of different sizes, topologies and connectivity levels. In a report prepared by RAND Corporation for American Association of State and Highway Transportation Officials Standing Committee on Planning, Ortiz et al., 2009, have analyzed transportation system resilience from a state and metropolitan planning perspective.

Vulnerability and Reliability of transportation networks arising from diverse causes is analysed by Jenelius et al., 2005, from an economics perspective. They measure such reliability and vulnerability based on the increase in the generalized travel cost when links are closed due to a disruptive event. Ip and Wang, 2011, define resilience of a transportation network as the number of reliable passageways between any pair of nodes. They argue that this definition represents the ability to recover transportation function once transportation links are partially shut down due to unforeseen events. They introduce a new concept termed friability, which they define as the reduction in network resilience caused by the removal of nodes or edges. They see friability as the quantifiable measure of the influence of a disaster on a network.

Omer et al., 2011 propose a Networked Infrastructure Resiliency Framework (NIRA) based on the road network connecting Manhattan. The resiliency is measured as the ratio of the travel time preceding a disruption to that following a disruption to the network. Travel time is used by Ukkusuri and Yushimito, 2009, to assess the criticality of highway transportation networks. The theoretical model developed by them in the paper is tested on Manhattan road network. Zimmerman and Siminoff, 2009, present a study of transportation density and infrastructure bottlenecks in and around New York City from security challenge angle.

Research is addressed at reducing the security threats in terms of transportation operations and expediting recovery from a serious security linked disruption to the transportation infrastructure. Taniguchi et al., 2010, stress on the need for urban transport logistics models to incorporate risks to make them more resilient to natural and man-made hazards. They review recently developed modeling techniques that can be applied to urban freight and supply chain networks.

Two measures commonly used to evaluate highway performance are the Volume-Capacity (V/C) Ratio which is used to evaluate congestion in specific highway segments and the Gamma Index, which is a network connectivity index relating the actual number of links to the maximum number of possible links. Scott, et al., 2005, argue that the V/C ratio is a localized performance metric whereas the Gamma Index accounts only for the network topology and neither measure is sufficient when used independently. They propose a Network Robustness Index (NRI) which is based on the capacities of individual highway segments, the routing options for the origin-destination pairs using a particular segment as well as the topology of the entire network.

Chang and Nojima, 2001, argue for a highway system wide performance assessment for evaluating post-disaster transportation network health. They claim that traditionally used measures of overall system wide performance like total travel time on the network in vehicle hours are not practical because in a post disaster situation availability of travel time or traffic flow data is very limited. They thus emphasize the need for summary system performance measures and propose three such measures – Total Length of Highway Open, Total Distance Based Accessibility and Aerial Distance Based Accessibility. They apply these measures to assess the performance of urban rail and highway transport system after the 1995 Kobe earthquake.

3.3 Port Resilience

World trade increasingly relies on longer supply chains with maritime transportation a vital part of the link. Ports are a critical intermodal link in international trade and much transportation activity which is vital to most nations' economy is linked to maritime ports. Hence having disaster resilience plans for ports and their transportation infrastructure is of critical importance.

Longer and more complex supply chains are more vulnerable to unforeseen threats and hazards. Berle et al., 2011, propose a structured Formal Vulnerability Assessment (FVA) methodology to assess maritime supply chain vulnerability. Martagan et al., 2010, have developed a simulation model for best re-routing strategies to minimize supply chain disruptions during crisis conditions. The model uses lead time or the total time a container spends in the system as the main performance measure. Similarly, Paul and Maloni, 2010, have developed a simulation model to help port networks to analyze disaster response scenarios. Regression based parametric metamodels are derived from the results of the simulation model to reflect changing port congestion conditions arising out of a disaster.

Nair et al., 2010, have proposed an intermodal resilience framework that could be applied at the intermodal component level. They claim that their framework is general and can be applied to any intermodal component like port and other logistics terminals, marshalling yards, etc. O'Reilly et al., 2004, describe the impact on flow of goods and materials through ports, as well as the economic impact on ports, under a telecommunications disruption

scenario. For this purpose they use Sandia National Laboratories' System Dynamics simulation models.

Maritime security concerns post 9/11 has driven much research in port and maritime disaster management. Helmick, 2008, argues that a systematic, coherent research agenda for enhancement of maritime security does not exist at present. The key determinants of current maritime security research priorities are reviewed and directions for future research in this area are suggested. To address the global maritime security concerns, the International Maritime Organization (IMO) implemented the International Ship and Port Security Facility (ISPS) Code. Goulielmos and Anastasakos, 2005, provide an overview of the new legal regime.

Mansouri, et al., 2009, have proposed a Risk Management based Decision Analysis Framework (RMDA) for resilience in Maritime Infrastructure and Transportation Systems (MITS). Their RMDA framework uses a Decision Tree Analysis (DTA) methodology for assessing the cost effectiveness of the strategies proposed for risk mitigation. Mansouri, et al., 2010, have applied the RMDA framework to the Port of Boston to analyze the decision process of some resilient strategies in port infrastructure systems.

The increasing vulnerability of ports to natural and man-linked disasters led the US Comptroller General to conduct a review to examine port disaster preparedness measures and to examine the federal role in helping ports plan and recover from disaster impacts. The Government Accountability Office's (GAO) report, 2007, was prepared based on a review of 17 US ports. The most visibly apparent challenge port authorities faced was dealing with damaged infrastructure and silting and debris clogging key waterways. Port authorities also faced difficulties restoring power, water and other utilities.

4. Conclusion

This review was primarily focused on the current literature on disaster resilience of road transportation infrastructure as well as port linked transportation structure. A limitation of the review is that it excludes literature on disaster resilience of rail and air transport infrastructure. Similarly, in marine transportation, we have limited ourselves to port linked activities and have excluded discussions on disasters on high seas like collisions, piracy, oil spills, etc. From the review it becomes evident that there is still no widely accepted measure for resilience of road transportation infrastructure. Measures for port disaster resilience and disaster resilience of port linked multimodal transportation systems are still scarcer. There is an overwhelming preponderance of research on US transportation and port infrastructure resilience. Such studies in other parts of the world, particularly in economically important countries like India, China, Brazil, Russia, etc are meager in comparison. There is thus a serious information gap for planners and administrators in such countries to make informed investment decisions. These areas require immediate attention of researchers.

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