RESILIENCE OF TRANSPORTATION INFRASTRUCTURE SYSTEMS TO CLIMATIC EXTREME EVENTS

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Abstract: A topology-based approach has been used to measure the resilience of a highway network to extreme events of a climatic nature. Because these systems are regionally distributed, their components undergo a wide range of hazard intensities, often dependent on their relative locations. This creates a conditional vulnerability situation inherently complex to analyze. The ability of an infrastructure system to withstand, adapt to and rapidly recover from extreme events is paramount to its ability to continuously serve users. The topological properties of a network can provide a good means to assess the resilience of the system. While the topic of resilience has been largely investigated after seismic events, studies regarding the resilience of infrastructure systems to extreme events of climatic sources such as: hurricanes, storm surges, and rising sea levels are less abundant. Furthermore, the effects of climate change are proven to increase the intensity of climatic events, worsening the effects of these stressors on infrastructure networks.

Keyword: Extreme events, vulnerability situation, climatic sources, hurricanes, storm, surges, infrastructure networks

I INTRODUCTION

Resilience is an indicator of the preparedness and adaptability of a civil infrastructure system; it is useful to a range of management teams such as policy makers, engineers and emergency service workers. Civil infrastructure systems, such as transportation networks, power transmission systems and water distribution networks, constitute the backbone of a functioning society and affect entire populations if disrupted. The importance of resilience in networks has grown parallel to the increasing traffic volumes traveling highways and roads, and the continued construction of urban and suburban areas, trends that will continue well into the future. Additionally, there is a lack of long-term investment to elongate, if not simply guarantee, the lifespan of current infrastructure systems. With more vehicles on the roads, and the increase of truck loads, the consequences and delays resulting from a seemingly minor accident or failure can propagate through the system over a wide radius; a developed area will suffer greater economic damage from an extreme event than a more rural region. Infrastructure resilience can be improved after assessing its current state, thereby reducing the vulnerability of civil infrastructure networks to disruptions and extreme events, allowing plans for possible failures, flexibility during probable disruptions, and post-event response and eventual repairs. These components correspond to the preparedness, absorptiveness, adaptation, and recovery of a resilient infrastructure system. This can be done by analyzing the resilience of the infrastructure system, allowing a holistic approach that takes into account several different aspects to improve the network's overall performance against disturbances.

II LITERATURE REVIEW

Turnquist and Vurgin, are (2015) encompassing these concepts, resilience of a transportation network is defined as the ability of the system to withstand, adapt to and rapidly recover from the consequences of disruptive events . Resilience of a transportation network is defined similarly as the ability to absorb minor disruptions and, after more extreme events, to return back to full serviceability in a short time.

Bruneau et al. (2014) outline four aspects of the resiliency concept: robustness, redundancy, resourcefulness and rapidity. Robustness is a measure of strength, describing how adept the system is at simply resisting the forces of disruption. The existence of alternative paths and options in a network is represented by a level of redundancy; in a transportation network this may refer to the range of combinations of roads and highways allowing a vehicle to travel between the same origin and destination. Post-event, the ability to efficiently direct resources and repairs reflects the system resourcefulness and the rapidity is the speed at which recovery is accomplished.

Perhaps derived from the ecological origins of resilience, Ortiz et al (2013) defines a specific measure of adaptability as adaptive capacity, which measures how efficiently a network can accommodate extra disturbances in flow. After the initial disruptive event has occurred, the system's ability to recover completely and in a reasonable time frame contributes to its resilience. Carlson et al focused on, (2014) the speed and completeness of recovery is mentioned in a number of texts, whether referring to a structure or economic market. In total, these compose four important "abilities" of a system which are used to measure resilience: ability to anticipate, to absorb, to adapt and to recover .Additionally, across disciplines, the idea of resilience almost always includes both pre-event and post-event tasks

. Rose et al. (2011) stated that several scientists and researchers have approached the topic of resilience from an economic standpoint, choosing to highlight the financial and business effects of an extreme event or disaster. This perspective is certainly relevant to our investigation of critical infrastructure resilience, as the economic losses may outweigh the physical losses to the system. In determining economic resilience, although it is perhaps more tangible and easier to quantify the physical asset loss immediately after an extreme event, this often only corresponds to a short-term economical consequence. A longer period of loss occurs with respect to business operations, both indirectly and directly Of course, in order to appropriately suggest strategies through which resilience and vulnerability of critical infrastructure can be improved, the economic factors and costs must be taken into account. In analyzing the economic resilience of a system, two different types of resilience are recognized: the inherent resilience, which occurs in normal situations, and the adaptive resilience, which occurs in situations of crisis. Adaptive resilience is separated because it is characterized by an ingenuity only elicited in an extreme event, such as conserving water after a devastating earthquake. These branches of resilience may be applied to a more engineered approach. Finally, excluding economic resilience will actually result in an underestimation of post-event measurements of loss. Considering the economic resilience is also significant to legislators and decision-makers because it allows an evaluation of mitigation strategies primarily concerned with the minimization of financial losses.

III METHODOLOGY

Resilience is dependent on the structure of the network, vulnerability, and adaptive capacity. Similar to adaptive capacity is network flexibility, which is the ability of a network to easily adapt and change while maintaining function in the event of a disturbance. Road and highway networks are relatively flexible compared to a network such as railway tracks, where the existence of alternative paths is not as abundant. The question that must be answered is how decision-makers and public departments can assess and improve infrastructure resilience. Critical components must first be identified; this can be done by ranking network components according to importance.

1. Fundamental concepts of graph theory

Knowledge of the most fundamental concepts of graph theory is necessary to investigate the topological parameters of a network. For this reason, an overview of essential terms and definitions in graph theory will be discussed. Graphs are composed of two types of elements--links (edges) and nodes (vertices) and can be uniquely defined by the set of links and nodes they contain. Networks and graphs are two different terms to describe the same concept, although networks are usually examples of graph systems that exist in reality. The connections and locations of nodes and links determine the majority of identifying properties of the graph. A network is a wide-inclusive term; it can include links and nodes of different types, weights and (for links) directions. Directed graphs can be cyclic, with closed loops, or acyclic, without closed loops. Hyper graphs are graphs with hyperlinks, or links that connect more than two nodes. Bipartite graphs contain two different types of nodes and, generally, links connect only nodes of the same type.

2. Random graphs

The development of the Erdos-Renyi random graph was a turning point in graph theory science. Undirected with a fixed number of nodes, the random graph is one of the fundamental graphs analyzed for simulations or properties. The existence of a specific node is dependent on a probability p. The degree distribution is binomial or, if the number of nodes n is large, follows a Poisson distribution. The study of random graphs often involves creating a random graph in stages of increasing p values. A specific graph property is tracked and the corresponding p value at its phase transition is the concern of research. It should be noted that there are different modified clustering coefficients in a random graph, where the clustering coefficient is equal to the probability that two nodes are adjacent, p. In most real networks, however, the clustering coefficient is much higher. Random graphs can be modified to be more realistic, which is often done to create a base model for a network, but these generalized random graphs lack the transitivity property. Incorporating transitivity into random graphs is difficult because of the presence of loops, which is another barrier in using them to model complex networks. At first, random graphs were used to study the science of complex networks because such networks had no clear organizing pattern and the links seemed to be randomly distributed.

3. Studies of complex networks

The dramatic increase in the size and complexity in networks which were desirable to analyze necessitated a change in traditional analytic methods. Graph theory, up until recently, was mainly concerned with the study of traditional networks, or networks where nodes all had similar levels of connectivity and degrees. Real networks, however, did not follow this pattern and, as exhibited by the Internet network, exhibited hubs nodes of extremely high connectivity and nodes with minimal connectivity. The difference in degree distributions between traditional and real networks is sometimes referred to as homogeneous and heterogeneous graphs, where homogeneous graphs have a uniform degree distribution and heterogeneous graphs have a power law degree distribution. Traditional graph theory has since grown to the study of complex networks to incorporate dynamic properties, irregular topology and to allow the comparison of networks from separate fields of study. Additionally, common methods of observing the graphics of a network quickly became useless to large, expansive networks. The analysis of complex networks necessitates a different set of properties and characteristics than those which describe traditional graphs. Accurately modeling network topology in complex networks is a challenge but has been shown, in several studies, to lead to more accurate determination of network properties. Network topology is vital to complex networks mainly because it determines dynamic properties, such as the network response to failure.

4. Resilience measurement using network properties

Resilience is characterized by a variety of factors which can be quantified by the parameters described in the previous section. Nodal and average degrees, which allow the determination of degree distribution, are crucial to the vulnerability of a network to nodal or link failure. The degree distribution across all nodes relates to the network robustness, or how well the network absorbs a shock without failure in service or functionality after an extreme event. By categorizing the degree distribution, specifically as homogeneous or heterogeneous, the level of damage after a catastrophic event can be estimated. Separately, the algorithm to calculate nodal degrees is often the first step in the calculations of other parameters, such as betweenness. The betweenness centrality measure underscores the importance of nodes relative to links in a network and becomes central to a discussion on network resilience. The removal of a node potentially affects several links, certainly all the links of which it is an end. The removal of a link, however, only affects the functionality of one link. Therefore, the failure of a network node is more harmful to network performance than the failure of a link. By ranking nodes based on betweenness centrality, the resilience of a network to extreme events can be quantified. Events that result in the failure of important nodes are clearly more devastating than those on nodes of lower importance

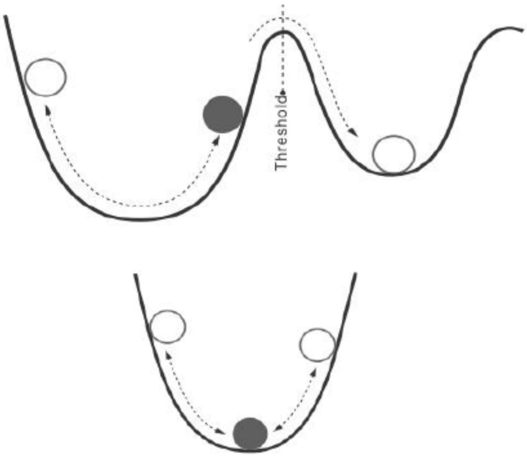

Figure 1 Ecological resilience (top) and engineering resilience (bottom) concepts

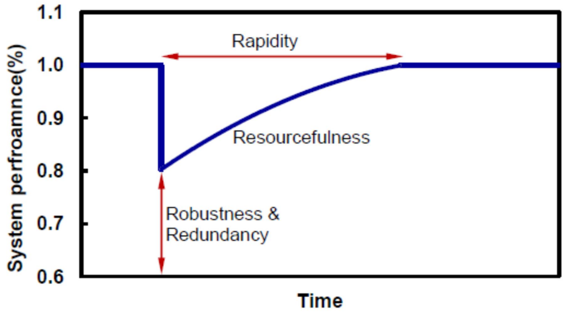

Figure 2 System performances as the quality of infrastructure varying with time

5. MUMBAI CITY AS A CASE STUDY

The highway network of Mumbai City was chosen as a case study for several reasons. Its location is situated on the coast, specifically the western coast of the India, and its highly developed, urban infrastructure renders the consequences of an extreme event devastating and costly. Aside from hurricane risk, the number of days of extreme precipitation in Mumbai City is also predicted to double under future climate scenarios. On a larger scale, the importance of Mumbai City to the economy of its region and the nation cannot be overstated. The potentially devastating consequences of climate change will not be confined to the relatively small set of counties analyzed By concentrating on vital urban centers, an investment is made not only for the individuals inside the city but for those connected to it. Of course, the inherent diversity present in such environments makes implementing and enforcing policy changes challenging for governing bodies. The risks pertinent to the Mumbai City metropolitan area are mainly hurricanes which involve the simultaneous occurrence of high winds, torrential rains, and large storm surges.

IV RESULTS

After selecting the highway network of the Mumbai City metropolitan area, for a range of reasons, as a case study for this research, the network behavior was studied as fractions of random nodes were removed from the network. During these simulations of random attacks, topological network properties were measured and plotted against the fraction of node removal to observe trends and make comparisons. To develop a more realistic node removal method SLOSH was used to simulate enveloped hurricane scenarios on the Mumbai City basin. These results were used to determine which nodes were flooded, then to find which nodes were removed from the network. In these scenarios, the specific surge heights at Priyadarshani Park were used to categorize the results into groups. Network properties were then measured in each scenario-based damaged network, which were plotted to observe the degradation of network connectivity and redundancy. Overall, these results provide important information which can be closely related to the resiliency of the Mumbai City network to both random and scenario-based removals.

V CONCLUSION

The results in this investigation can be replicated to evaluate and compare network resilience measures between different systems or after improvements and developments have been made to existing infrastructure. The large uncertainty associated with extreme climatic events forces transportation agencies to respond with over-engineered designs or in many cases, to not prepare at all because of the overwhelming and expensive nature of the potential hazards. Supplied with this type of data, however, decision-makers and legislators are better able to direct resources to the most vital locations, allowing a more reasonably budgeted response to climatic hazards. Transportation agencies can pinpoint the specific network components which are most critical to maintaining network flow. Instead of attempting a complete system overhaul, agencies can easily achieve prioritization of replacements and structural updates. The approach which references hurricane storm surge simulation results allows transportation agencies to identify not only the nodes which are most critical to network flow, but also those which are most vulnerable to a specific hazard. While a range of methods exist to measure the resilience of a network, the use of topological graph properties to track network response are shown to be useful in investigations of this transportation network. Examining the nodes most affected by the envelope simulation, planners can incorporate these vulnerabilities into long-term planning.

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