14th International Conference on Applications of Statistics and Probability in Civil Engineering, ICASP14
Dublin, Ireland, July 9-13, 2023

Vulnerability Assessment of Infrastructure Networks Following Earthquakes: The Fundamental Step to Assess Network Resilience and Functional Recovery

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ABSTRACT: There is a need for infrastructure networks to restore their function or return to service more quickly following a disruptive event. Developing a framework to facilitate this process and enhance a network's resilience and functional recovery first requires identifying the network's most critical and vulnerable components that need rapid recovery. This paper provides a framework to evaluate the most vulnerable area of infrastructure networks by assessing the seismic hazard through integrating Complex Network Theory into a scenario-based seismic loss assessment. The results of this paper highlight the Bay Area Rapid Transit (BART) network components that are most affected by severe earthquakes based on a selected earthquake scenario. This paper is part of a larger project using a probabilistic regional seismic analysis, which expands the application of the assessment beyond single earthquake scenarios.

1. INTRODUCTION

The United States Geological Survey (USGS) estimates that nearly 143 million people live and work in areas prone to earthquakes. Hence, a significant portion of buildings and critical infrastructure systems (e.g., Transportation networks) are exposed to varying levels of earthquake hazards (Jaiswal et al. 2015). The widespread damage from earthquakes could trigger major and long-term disruptions in critical infrastructure systems (CIS) depending on the magnitude and size of the event, resulting in significant community, social, and economic impacts. The massive monetary recovery costs—in addition to the social toll—are alarming due to the increase in both the frequency of disruptive events and the growing population and density exposed to these events. The recovery process may take a considerable amount of time. Lengthy recovery processes alone pose multiple challenges in providing essential services to communities, such as a lack of access to jobs and schools. Thus, there is a need for infrastructure systems to restore their function or return to service more quickly following a disruptive event. This is where the concept of functional recovery emerges. Functional recovery as defined in the NIST-FEMA report is a performance state less than full pre-earthquake functionality, yet sufficient for the temporary provision of lifeline services. Thereby enabling the continuation of key community functions that depend on their services. Thus, there is a need to implement a functional recovery concept in the design and planning stages of infrastructure networks with appropriate metrics to increase infrastructure network resilience and decrease the functional recovery time, reducing long-term effects on the community. This effort alone requires first identifying the most vulnerable components of the network subjected to the earthquake, which need rapid recovery to restore the basic function of CIS.

CIS are interdependent and intertwined systems perceived as the engine of a nation's economy. According to the Department of Homeland security (DHS, 2018), the term critical infrastructure system refers to any infrastructure system considered vital to society. DHS (2018) classifies 16 critical infrastructure sectors; notable among them are communications, energy and power systems, healthcare and public health, transportation systems, and water and wastewater systems.

For years, modeling CIS to enhance their resilience has been a primary target of contemporary research in the field of infrastructure systems. According to a Presidential Policy Directive (PPD 21) (Presidential Policy Directive (PPD) 2013) on Critical Infrastructure Security and Resilience, "the term resilience means the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions." Resilience is the expected state as the recovery process unfolds and addresses all activities through recovery. Infrastructure systems are often modeled as networks, nodal points, or a combination of the two in terms of their distribution mechanisms and geometries (Pollalis et al., 2012). When an infrastructure system is categorized as a network, network components- basically several nodes connected by links- and patterns of connections among nodes- are responsible for distribution or collection purposes. Enhancing the resilience of CIS and decreasing their recovery time is essential for improving the performance and serviceability of CIS.

This paper presents a framework to assess the robustness and vulnerability of Urban rail transit networks. Robustness is defined as the ability of system components to sustain external shocks without significant performance degradation (Tierney & Bruneau 2007; Ayyub 2015), and vulnerability is defined as an internal risk factor of system components that are exposed to external shocks (Paul 2014).

In this study, we illustrate the application of the proposed framework using the San Francisco Bay Area Rapid Transit system (BART), hereafter referred to as BART network. We model BART as a network in which stations are represent by nodes and segments in between (i.e., tunnels, above grounds, bridges, etc.) indicate links.

To assess the seismic performance of the network, we integrate regional seismic loss analysis with Complex Network Theory (CNT). Using scenario-based regional seismic loss analysis, we estimate the damage and loss (in terms of recovery time) for each component in the network using the Hazus loss assessment framework (FEMA 2020). We then use the outcomes from seismic damage estimation and employ CNT to model and assess the vulnerability and robustness of the BART network. Complex network theory (CNT) is a powerful tool that allows modeling of all interconnected entities, resources, and processes in the network. The method of CNT has been widely used in modeling urban critical infrastructure networks such as water distribution networks (Simone et al. 2018), grid networks (Albert et al. 2014; Wang and Rong 2009; Winkler et al. 2010, Ezzeldin and -EI-Dakhakhni, 2019), and transportation networks (Wu et al. 2007, Zhang et al. 2010, Saadat et al. 2019, Saadat et al. 2020). Analyzing the topology of the network is the key purpose of CNT. Topological characteristic indicators assist in assessing desired network attributes such as global network efficiency. Global network efficiency indicates how efficiently network entities are connected and is the basis of calculating the vulnerability and robustness of the network. The vulnerability assessment helps us to identify the area in the network that affect the network connectivity the most under a severe earthquake.

2. TECHNICAL APPROACH

This paper aims to increase the resilience of urban rail transit networks and reduce long-term effects on community recovery by assessing the vulnerability and robustness of rail transit networks when they are subjected to seismic hazards. Vulnerability and robustness assessments are the basis of enhancing the network resilience and minimizing the recovery time of urban rail transit networks in the design and planning stages. The proposed technical approach consists of two general frameworks: (1) a framework to quantify the seismic damage and loss of the network components and (2) a framework to assess the vulnerability and robustness of the network; both frameworks are described in the subsequent sections.

2.1. Framework to quantify the seismic damage and loss of the network components

Prior to assessing the performance of the network, the analyst needs first to collect the location and seismic performance characteristics of each component within the network. The seismic performance of each component is characterized by a seismic fragility curve, which defines the probability of exceeding a certain level of damage for a given hazard intensity, such as ground motion intensity; seismic fragility curves are typically modeled using a lognormal distribution. Network component fragility curves can be defined by either directly assessing seismic performance using performance-based methods or by using predefined seismic fragility curves such as those contained within the Hazus loss assessment framework (FEMA 2020).

After the network components are characterized, the regional seismic hazard is defined either using a scenario earthquake, defined by a specific magnitude-distance combination, or a probabilistic regional seismic hazard assessment. In the probabilistic approach, ground motions shake maps are simulated for each rupture scenario; integrating the regional loss outcomes with the recurrence rate from each rupture scenario allows the analyst to describe regional performance metrics probabilistically.

To quantify component damage for each rupture scenario, the seismic fragility curve is integrated with the ground motion intensity data from the shake map for each component within the network. Component damage is then extended to additional component-level consequences using consequence functions. Consequence functions define social and economic outcomes of component damage, such as cost of repair, component repair time, or potential casualties. While custom consequence functions can be developed for each network component, the predefined consequence functions from Hazus are typically used. The damage and loss outcomes of each component from the seismic assessment are then used as inputs into the network analysis. Figure 1 demonstrates this framework.

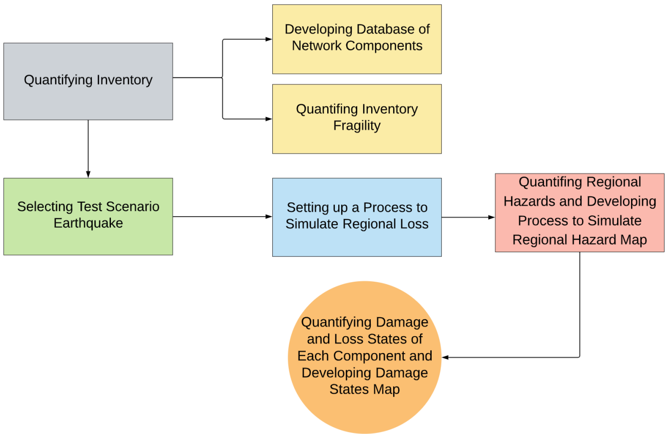

Figure 1-Framework for quantifying the seismic damage and loss of the network components.

2.2. Framework to assess the vulnerability and robustness of the network

The framework to assess the rail transit network's vulnerability and robustness uses the output of the seismic loss assessment as input to form the weighted network and selects the CNT method as the primary method of use to calculate the network components' vulnerability and robustness. Figure 2 shows a framework using the CNT method incorporating the outcome of seismic loss assessment for evaluating network vulnerability and robustness.

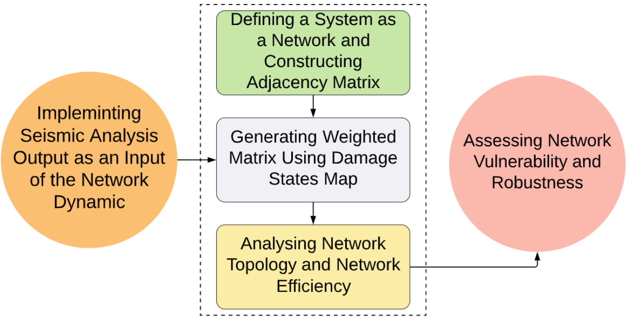

Figure 2- Framework for assessing the seismic vulnerability and risk

The steps that we follow are:

- Defining BART as a network by specifying the network components and pattern of connectivity within that network. This step is fundamental for analyzing the network topology;
- Using seismic loss assessment results to create the weighted matrix as the dominant indicator herein to define the dynamics of the network. In fact, the link weights are the damage states we obtained from the seismic loss assessment, which form the dominant network dynamic base of the objective of this paper. This step is the integration point of seismic loss assessment and network analysis;
- Analyzing network topology along with dynamics of the network as primary steps for any further assessment. This step results in computing network characteristic indicators and global network efficiency; and
- Assessing network vulnerability and robustness, which are based on adverse changes in global network efficiency as a result of an earthquake, and residual network efficiency remaining following an earthquake in the network, respectively.

To understand how CNT applies here, we need to know the basics of network analysis. A network is a large system consisting of many similar parts that are connected together to allow movement or communication between or along the parts, or between the parts and a control center (Cambridge dictionary, 1995). Such a network consists of nodes, links, and a pattern of connection among those nodes and links (Newman, 2010). To study the structure of a network and how its components work together, there are extensive integrated techniques, mathematical tools, and computational programs available that might well be useful. Among those, CNT is a useful method for modeling critical infrastructures networks such as urban rail transit networks. The mathematical network representation in the CNT method is a vector G specified as follows:

$$G= [S, E] \tag{1}$$

where G indicates a network, S is the number of all nodes, and E is the number of all links. Nodes are identified by unique integers in S, such as:

$$S= [S_i|i=1,2,3,\dots \text{n}] \tag{2}$$

Links are signified by e_{ij} in E. In other words, e_{ij} denotes the link that connects node i to node j and is indicated as:

$$E= [e_{ij}|i, j=1,2,3,\ldots \text{n}] \tag{3}$$

Each link can be expressed also as $e_{ij} =(i,j)$. Such an arrangement provides a link list for the network.

A topological representation of a network in addition to the number and location of nodes and links, is the pattern of connection among them. The pattern or state of connection for each network is demonstrated by the adjacency matrix. The adjacency matrix indicated as A_{ij} expresses the relation of any two nodes, and matrix elements a_{ij} are ∞ if nodes i and j are not connected directly, or 1 if there is a direct link between nodes i and j, or *0* if there *is* a connection of a node to itself.

Constructing the precise adjacency matrix is of importance for any further network analysis, and the network characteristics are usually built upon such a matrix. One of the most important characteristics of each network is its geodesic path or shortest path, i.e., d_{ij}. The geodesic path is the minimum number of links that are needed to be passed from node S_i to node S_j.

For weighted networks in which each link carries weight or strength, creating the weighted matrix is also required. Matrix elements w_{ij} are the weight of the direct link between two nodes. The matrix element is zero when there is no direct link between two nodes.

Adjacency and weighted matrices are the basis for calculating the global network efficiency. Global network efficiency is a measure of how well flow occurs between any two nodes (Latora and Marchiori, 2001) and is an indicator of node connectivity in the network. It is proportional to the reciprocal of the geodesic path (Saadat et al. 2019), and is correlated with the sum of weights assigned to links of all corresponding geodesic paths as follows:

$$E_G=\frac{1}{n(n\text{-}1)}\sum_{i\neq j}\frac{W_{ij}}{d_{ij}} \tag{4}$$

where n is the number of nodes,d_{ij} is the geodesic path, and W_{ij} is the sum of all w_{ij} on each geodesic path.

When a network is subjected to a disruptive event and one or more network components fail(s), the network efficiency is no longer the same as the initial network efficiency in the original state. The residual network efficiency after a failure (E_{Gi}) in the network indicates the network robustness, while network vulnerability is determined by calculating the changes in the network efficiency following a disruptive event and the original state. The network vulnerability of each component is quantified as:

$$V_i=\frac{E_G\text{-}E_{Gi}}{E_G} \tag{5}$$

The greatest V_i represents the network vulnerability.

3. CASE STUDY

Large earthquakes are more frequent in regions such as the Bay Area of San Francisco. According to the California earthquake authority (CEA, 2020), there is a 72% probability of an earthquake magnitude 6.7 or greater in the Bay Area of California in the next 30 years. Therefore, it is essential to protect CIS from seismic hazards in that region. One of the major CIS of the region is BART which is a heavy rapid transit that connects different counties and districts. The number of its existing components are 50 stations comprising 19 surface, 15 elevated, and 16 underground stations in addition to 49 links in 6 color-coded rapid lines of Red, Yellow, Green, Blue, Orange, and Beige covering131 miles. Figure 3 shows the Bart map in which most of the color-coded lines share the same tracks and stations. These share components are treated as a respective single link in the network study of the BART. To highlight outcomes from the proposed network vulnerability and robustness framework, we integrate CNT with a scenario earthquake loss assessment of the BART network.

Figure 3- BART map (Adopted Budget, Fiscal Year 2021)

4. ANALYSIS

To define the seismic hazard for our case study, we use a magnitude 7.2 earthquake scenario on the San Andreas fault. Along with other major faults in the region, the San Andreas fault is a significant source of seismic hazard for the region. We use the weighted average of the ground motion prediction equations defined in Abrahamson et al. (2014), Campbell & Bozorgnia (2014), and Chiou & Youngs (2014) to determine the intensity of ground shaking at each site. We simulate spatially correlated ground shaking maps from the lognormal probability distributions of ground motion intensity (spectral acceleration) at each site; the dispersion of the predicted spectral accelerations are divided into two components: inter-event (i.e., variability between different events) and intra-event dispersion (i.e., variability from site-to-site within an event). Spatial correlation of the intra-event variability is simulated with the model developed by Loth & Baker (2013), which considers site-to-site distance and building period. Period-to-period correlation of the inter-event variability is simulated with the relationship developed by Baker & Jayaram (2008). The resulting shake map is then used to quantify the damage and loss for each network component according to the Hazus fragility and consequence functions (FEMA 2020).

Damage states data resulting from the selected scenario in this study range from 0 to 4, showing the severity of the damage, where 0 means no damage and, 1, 2, 3, 4 are slight, moderate, severe, and complete damage, respectively. Technically, the damage states are fundamentally described as a probability of exceeding damage states 1-4 given the earthquake shaking.

The damage states data is used here to create the $n \times n$ weighted matrix for the BART network and integrate the seismic loss analysis with a network assessment. The $n \times n$ adjacency matrix is already generated using the network realization of the BART map demonstrated in Fig.5. Solid black circles *show* the ordinary stations in the network and the three attached clear circles represent transfer stations that enable passengers to exchange across metro lines.

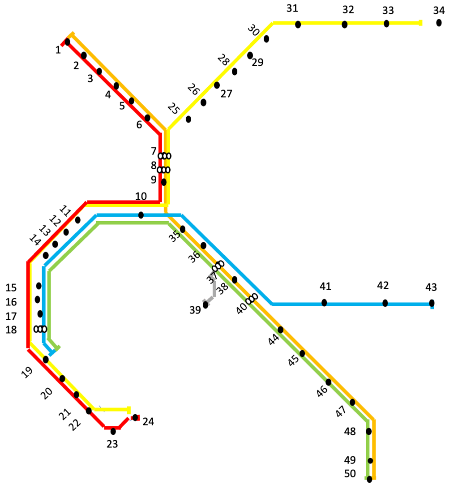

Figure 4- BART map network consisting of 50 nodes and 49 links

5. RESULTS

Using Eq. (4) and also running the Floyd algorithm (Floyd 1962), the global network efficiency is calculated and is equal to 0.1263. Global network efficiency is the basis for vulnerability assessment.

The network vulnerability is assessed considering two failure cases in the network as follows:

- The network is subjected to node failure; and
- The network is subjected to link failure.

In the case of a node failure, we assumed all nodes are removed one- at-a-time. After the removal of each node in the network, the network is reconfigured, therefore, regenerating the adjacency matrix was required. The size of the adjacency matrix in the network following the failure is $(n-1) \times (n-1)$. We calculated the global network efficiency for the new network reconfiguration and using Eq. (5) the vulnerability is assessed for each component. Table 1 demonstrates the five most critical stations in the network that failing them makes the network more vulnerable to severe earthquakes.

Table 1: Most critical stations in the network when experiencing the severe earthquake

Station ID	*Name of the station*	*Vulnerability Magnitude (%)*
40	*Bay Fair*	*58*
38	*San Leandro*	*50*
37	*Coliseum*	*49*
39	*Oakland International Airport(OAK)*	*39*
44	*Hayward*	*23*

The vulnerability analysis with link removal follows a similar process to the vulnerability assessment with node removal and examines the contribution of each link to the global network efficiency. The size of the adjacency matrix makes a difference between two cases of vulnerability evaluation here; the size of the adjacency matrix in the case of link removal remains unchanged; however, the matrix element for the link that is removed changes from 1 to ∞. Table 2 shows the most critical links in the network when experiencing a severe earthquake.

Table 2: Most critical links in the network when experiencing the severe earthquake

link ID	*Link's Two End Stations*	*Vulnerability Magnitude (%)*
(38,40)	*(San Leandro- Bay fair)*	*48*
(37,38)	*(Coliseum- San Leandro)*	*47*
(37,39)	*(Coliseum- OAK)*	*38*
(40,44)	*(Bay Fair- Hayward)*	*23*
(40,41)	*(Bay Fair- Castro Valley)*	*19*

6. CONCLUSION

As part of an ongoing NIST research initiative, this project aims to develop a robust computational framework to enhance the resilience of infrastructure networks when they are subjected to seismic hazards and minimize their post-earthquake recovery time. We will use this framework to assess network performance and ensure the network is able to regain acceptable levels of functionality, preserve post-earthquake operability, maintain integrity and stability, and restore services within an acceptable timeframe. The project employs different methods of scenario, and probabilistic regional hazard analysis, integrated with CNT to model and analyze the resilience and recovery of such networks after earthquakes. In this paper, we only focused on the scenario-based assessment and CNT method to evaluate the network vulnerability and identify the most critical components in the network as the early step of the framework and the basis of further resilience and recovery assessment. The scenario-based assessment provides us with the damage state of each component which helps to construct the weighted matrix. The adjacency matrix is generated from the connectivity pattern of the topological BART network. Evaluating global network efficiency follows by using such matrices and employing the modified Floyd algorithm. The basis for the vulnerability and robustness assessment lies with the variation in global network efficiency before and after the earthquake.

Results of the case study show that station and links in the central part of the network and near Oakland International airport are more vulnerable to severe earthquakes in terms of degrading the network connectivity. Outcomes of the proposed framework help analyze network vulnerability considering both individual component susceptibility to damage and the effect of component loss on overall network efficiency. The framework can be used to develop recommendations to protect the network's critical components during the planning, management, and further development of the network. Moreover, the network efficiency evaluation will help to develop metrics to quantify its overall network resilience and determine the time required to restore the network to a certain functionality target following a disruption which is the near future work of this study.

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