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Estimating the probability of relative isolation (PORI) of road network nodes under seismic hazards

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ABSTRACT

Strong earthquakes cause structural damage to structures adjacent to roads that may generate debris. Scattered debris thus has the potential to restrict emergency response vehicles from reaching areas of a road network after a seismic event. This research models a road network in terms of nodes (intersections) and links (roads). In this paper, the probability of blockage of a link conditioned on the peak ground acceleration (pga) is assumed. Subsequently, the probability of relative isolation (PORI) for each node was then obtained to ascertain the reachability of any node using Monte Carlo Simulation (MCS). Thus, the reliability of a road network that is capable of allowing emergency response vehicles to go to each section of the network can be determined. To illustrate the methodology, a road network for Intramuros, Manila, was chosen as a sample system. Values ranging from 0.3 to 0.5 were assumed and assigned to each link and represent the probability of road blockage or the probability that the road will be inaccessible to emergency vehicles. Using MATLAB and MCS, the PORI of every node was determined. A breadth-first search graph traversal algorithm was performed for each simulation to check if a node is reachable from a source node from where the emergency response will originate. The source nodes were assigned to be the nodes nearest to a hospital in the network. The source nodes are located near the northern and southern extremities of the road network; the results show that the values for PORI are highest at the outermost nodes of the road network and gradually decrease when moving toward the central nodes.

1. INTRODUCTION

Urban road networks are a critical lifeline vital to a city's continued capacity to

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function. It is essential in the aftermath of a major earthquake because it is the main way emergency response vehicles traverse a city. This includes vehicles such as ambulances, fire trucks, and rescue vehicles that must reach affected areas quickly to carry out their designated role as primary emergency responders. However, strong earthquakes cause structural damage to vertical structures, which have the potential to generate debris because of damaged structural elements. Damaged structures adjacent to roads may cause debris to partially or fully cover the road, inhibiting it from being accessible to vehicular traffic. In a heavily urbanized area, the density of buildings and their vulnerability to damage pose a risk to the continued capacity of roads to accommodate vehicles. This is due to the debris that will be generated by adjacent buildings, which will render some roads inaccessible. In a road network, there is potential for some areas of the city to be isolated relative to structures where emergency responders will originate. These are commonly hospitals where ambulances are stationed. Areas with a high chance of being cut off from hospitals will have difficulties receiving immediate post-seismic response. This challenges a city's disaster preparedness, response, and hazard mitigation.

Bruneau et al. presented the quantification of seismic resilience (2003). Resilience is defined as the ability of social units to mitigate hazards, limit the effects of disasters, and perform recovery activities while minimizing disruption. In other words, resilience is the ability to limit a disaster's impact on a community's daily operations. There are four dimensions of resilience, which are known as the 4Rs: robustness, redundancy, resourcefulness, and rapidity. In the context of this paper, the most relevant property of resilience is redundancy. Redundancy pertains to additional substitutable elements which can perform critical functions in the event of failure or disruption. In the event of a disaster, there is a probability that a system or unit will fail to function. Redundancy points to the availability of an alternative way or means so that the service will continue functioning and performing its designated task. Along with resourcefulness, redundancy is how a system's resilience can be improved.

The function of an urban road network is to connect the different areas of a city with each other. In the event of an earthquake, some roads will become impassable due to debris from adjacent buildings. A good network should have sufficient alternative routes so no area will become isolated in case of a road failure, especially for first responders. This relates to redundancy for road networks where alternative paths should be available so that when a road becomes blocked, there are other routes to take for first responders to reach areas needing immediate attention. In order to ascertain the redundancy of a city, it is advantageous to quantify and visualize which areas of the city have a higher probability of isolation.

Several studies were conducted to obtain the seismic redundancy of networks. Tan et al. developed a framework for obtaining the relative isolation probability of a vertex (2022). This included the introduction of the concept of relative isolation of a vertex and its potential for application, particularly in civil engineering, such as road and water distribution networks. The probability of relative isolation (PORI) is a concept from a branch of discrete mathematics called graph theory that involves the study of graphs (networks) with interconnected nodes (vertices) and edges (links). Real-life systems can be analyzed as graphs, such as water distribution networks, road networks, supply-chain networks, communication networks, etc. The graph traversal algorithm, which was initially proposed, was a frontier-based search and used the C++ programming language. Meanwhile, Tan and Ikeda introduced a more efficient algorithm utilising a breadth-first search algorithm (2024). de Jesus and Garciano was the first to present the utilization of the concept of PORI of a vertex in the quantification of redundancy (2024). It utilized the probability of relative isolation of a vertex by Tan et al. and used it to investigate the water distribution network of Surigao City. Additionally, Fernandez was able to obtain the redundancy index for a road network in Surigao City as part of the operationalization of the seismic resilience index (2023). This was based on the frontier-based search algorithm by Tan et al. and the quantification of de Jesus and Garciano for the redundancy index using the PORI. This was also performed considering only one source node.

This study outlines a proposed method for estimating the probability of relative isolation (PORI) of the nodes in a road network. Then, it will illustrate it through a case study of the road network of Intramuros, Manila. The study's novelty is that it is the first to consider multiple source nodes in obtaining the PORI for road segments given a seismic hazard. It is also the first to utilize the more efficient breadth-first search graph traversal algorithm. It presents an alternative and more efficient program using MATLAB to obtain the PORI. This is the first study to utilize this algorithm to obtain the PORI in the context of a seismic hazard affecting a road network.

2. METHODOLOGY

For better analysis of the initial capacity of the road segments within Intramuros, a corresponding road network was constructed, denoting the links, or road paths, that converge at nodes representing the road intersections. 116 links and 70 nodes were mapped to model the key areas of the study area, wherein 2 of the 70 nodes were designated as source nodes representing the origins for emergency response, specifically hospitals, to simulate accessibility during seismic events such as earthquakes. For ease of construction and visualization, geographic information system (GIS) software was used, with Quantum Geographic Information System (QGIS) being the particular software in combination with topographic data obtained from OpenStreetMap, a map detailing geographic data.

Moreover, after developing the road network, the links and nodes were assigned individual Link IDs and Road IDs for better identification and were catalogued using spreadsheets such as Microsoft Excel or Google Sheets, taking note of the Link ID and the IDs of the nodes that the corresponding link connects.

MATLAB was chosen as the programming language due to its higher level of abstraction, ease of use, and built-in functionality, as the language is commonly used for educational purposes, sacrificing efficiency without a decrease in accuracy. The program loads the road network, runs Monte Carlo simulations to count the number of times a node is isolated, and displays all valuable information in the form of graphs and tables. Its process intricacies follow the flow shown in Figure 2.1.

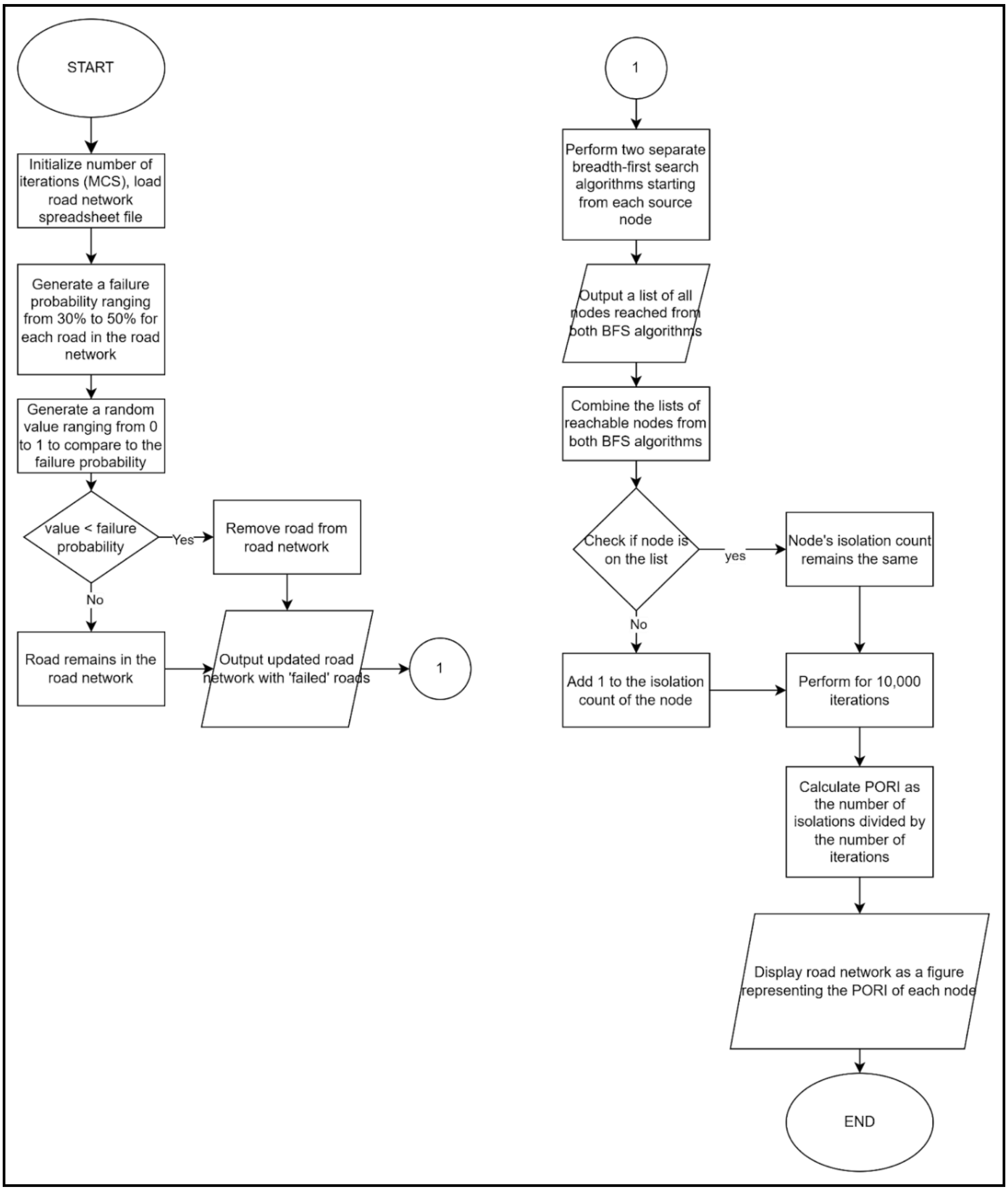

Fig 1 Flowchart of the Monte Carlo Simulation for Assessing the Probability of Relative Isolation

The program starts by loading an Excel file containing the road ID and the nodes (i and j) that the road connects. The information regarding the nodes was then split into two matrices to develop a graph connecting the two properly. An array to store the isolation count, the number of times a node is isolated, was also initialized. To simulate varying values of failure probabilities for the road, ranging from 30% to 50%, random values were generated inside a for loop for all roads. These values were assigned as the 'weight' of each link in the graph using the language's graph function. To determine whether a link fails or not in one iteration, a random value between 0 and 1 was generated for each link and compared to the failure probability generated earlier. If the random value is less than the failure probability, that road is removed from the road network, leading to an updated road network in one iteration.

In the same iteration, the connectivity of the non-source nodes to the source nodes is checked using breadth-first search algorithms. Having two source nodes in the road network, nodes 10 and 68, two separate algorithms run, starting from each source node. The algorithm, a fundamental algorithm in graph theory, traverses graphs of vertices and links in a systematic manner starting from a single node, in this case, the source node (Tan and Ikeda, 2024). Simply, the algorithm implements a first-in-first-out queueing system, noting the 'visited' vertices. Starting by visiting the source or starting vertex, the algorithm iteratively dequeues the vertex being visited and enqueues all of its unvisited and directly neighboring vertices. The algorithm ends once all vertices reachable from the source vertex have been reached. Since MATLAB has abstraction as one of its features, algorithms like the breadth-first search algorithm are simplified to increase the language's ease of use, unlike when using other languages, wherein manual development of the algorithm's code is required.

However, since MATLAB lacks the function for conducting a multi-source BFS algorithm, a variation of the algorithm wherein instead of starting with one vertex, multiple vertices are considered to be source nodes and the traversal is done simultaneously, two separate BFS traversals are done for each source node. Each traversal produces a matrix of all the nodes visited, depending on the starting node, and these are combined into one matrix containing the list of all the nodes visited from both source nodes. The program then checks if all the nodes are in this list, and if not, adds 1 to their respective isolation count. This repeats for 10,000 iterations, wherein to obtain the probability of relative isolation of a single node is taken as the quotient between its isolation count and the number of iterations.

3. CASE STUDY

To demonstrate the proposed methodology, a case study was conducted in Intramuros, Manila, a historically significant walled city at the heart of the Philippine capital. According to the 2020 Census of Population and Housing (Philippine Statistics Authority, 2021), Intramuros had a population of 6,103 residents within a land area of 1.183 square kilometers, resulting in a population density of approximately 5,159 persons per square kilometer. The annual population growth rate from 2015 to 2020 was recorded at 0.59%, indicating a relatively stable yet densely populated urban environment. These conditions suggest heightened vulnerability to natural hazards, particularly earthquakes, which can have severe consequences in compact and aging urban areas.

Beyond the demographic and spatial characteristics, Intramuros' historical significance further underscores the urgency of evaluating potential weaknesses in its infrastructure, particularly the road network. While some buildings have been reconstructed, a number of structures date back to the 16th century and have been preserved in their original form. This introduces the likelihood that some buildings are pre-code structures, constructed long before the adoption of modern building standards. As such, they may be more susceptible to collapse during seismic events, potentially blocking roadways and impeding emergency response.

Fig 2 San Agustin Church, one of the oldest structures in Intramuros, Manila (Photo by Parker, 2013)

Given the imperative to preserve these heritage structures, the goal is not to alter or replace them but to mitigate potential risks by identifying alternative routes and critical weak points in the road network. By analyzing the probability of relative isolation of each node within Intramuros, the study aims to improve emergency response planning and reduce the risk of casualties during disasters.

To represent the road network of Intramuros, a graph-based model consisting of nodes and links was developed. Nodes correspond to intersections, while links represent road segments. Major roads included in the network model are General Luna Street, Muralla Street, Real Street, Victoria Street, and Anda Street, among others. While a comprehensive inclusion of all road segments was ideal, certain segments were excluded due to practical constraints. These include roads that were too narrow for emergency vehicle access and those located on private property, which are not publicly accessible.

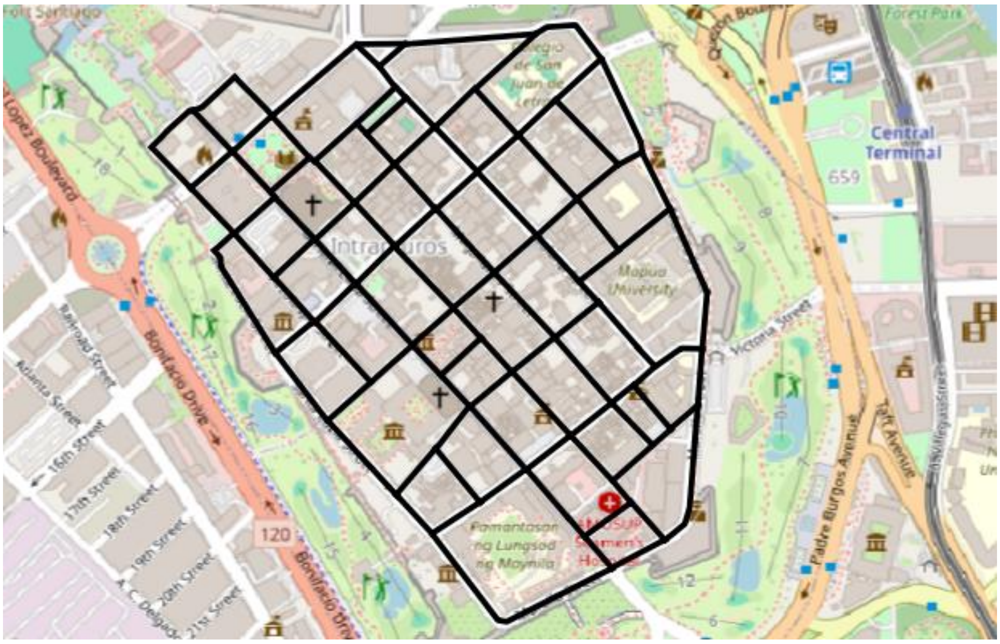

Fig 3 A Road Network of Intramuros, Manila

Among the intersections, several were designated as source nodes, which serve as key origins for emergency response operations. In this study, two hospitals were identified as primary source nodes: American Hospital and AMOSUP Seamen's Hospital Manila, corresponding to Nodes 10 and 68, respectively. These locations form the basis for assessing connectivity and accessibility during simulated earthquake scenarios using the proposed methodology.

4. RESULTS AND DISCUSSIONS

4.1. Results and Discussions

The Probability of Relative Isolation (PORI) analysis provides a detailed assessment of the potential disruption to the Intramuros road network under seismic hazard conditions. The PORI metric quantifies the likelihood that specific nodes within the network will be isolated from hospital access after an earthquake. This analysis aims to identify high-risk zones, evaluate the influence of network topology on isolation probabilities, and highlight critical nodes and links essential for emergency accessibility. The network comprises 70 nodes and 120 links, with two centrally located source nodes representing hospitals. Their positions and the structural fragility of network components underlie the calculated PORI values.

The PORI results show a distinct spatial trend: nodes closer to the source nodes typically exhibit lower PORI values, indicating stronger resilience against post-earthquake isolation. Central areas of the Intramuros network benefit from higher connectivity and shorter travel paths to hospitals, resulting in a higher accessibility rate during an emergency. Conversely, outer zones demonstrate elevated PORI values due to their distance from the source nodes and limited redundancy in their connections. The average PORI across the network was calculated at approximately 0.25, with values ranging from a low of 0.01 up to 0.50.

Nodes 3 and 62, both located near the source hospitals, displayed exceptionally low PORI values. These nodes are unlikely to be cut off in a post-earthquake scenario due to their proximity to the source hospitals. In contrast, nodes located at the fringes of the network exhibited the highest isolation probabilities. Node 5, Node 11, Node 31, and Node 56 represent high-priority targets for infrastructure reinforcement or the establishment of alternative emergency access routes.

The map of PORI values visually reinforces the analytical findings. Nodes with higher PORI values are shown in deep red and orange, signaling greater vulnerability. These zones are concentrated in the northeast and far west of the Intramuros area. In contrast, green and blue zones, mostly in the network's central core, suggest lower probabilities of isolation. The spatial distribution reveals that network geometry plays a substantial role in risk: areas with limited alternative paths and few redundant links face a significantly higher probability of post-earthquake disconnection.

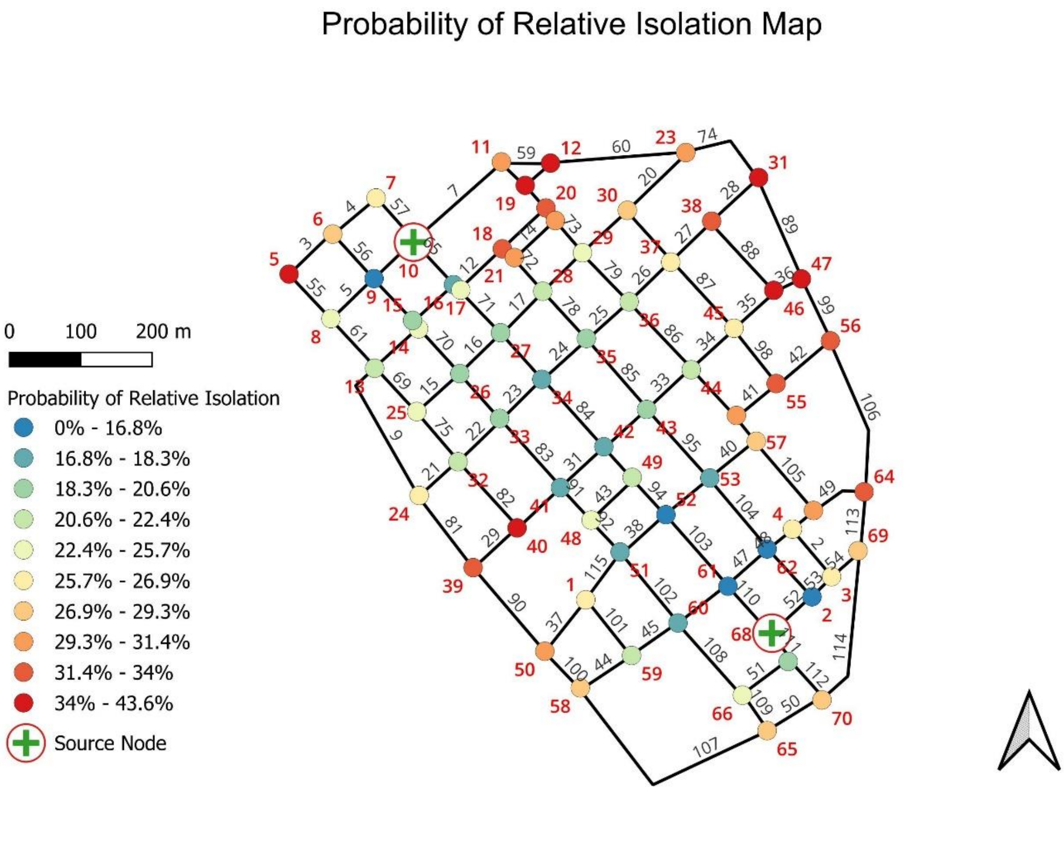

Fig. 4 Probability of Relative Isolation (PORI) Visualization of the Road Network

The centrally placed hospital nodes effectively serve the densely populated core of the network, maintaining low PORI values for many nearby nodes. However, this concentration leaves the outer regions with weaker coverage. In scenarios where one of the two hospitals is rendered nonfunctional, PORI values are expected to increase sharply, especially for nodes dependent on that single source. Conversely, adding strategically placed emergency facilities in the surrounding area could significantly reduce PORI values in underserved zones.

Although this study focuses on a generalized seismic hazard, stronger earthquake scenarios would likely heighten network vulnerabilities. Higher seismic intensity increases the probability of link failures throughout the network, leading to uniformly higher PORI values. While the relative vulnerability rankings of nodes may remain consistent, their absolute isolation probabilities would rise, stressing the importance of structural resilience and redundancy.

Critical nodes and links were identified not solely by their PORI values, but by their importance in maintaining connectivity between high-risk and low-risk zones. Nodes such as 1, 49, and 51 serve as vital connectors; their failure would sever multiple paths, isolating large network segments. Likewise, links like those connecting Nodes 1 to 4 or bridging remote sectors to the central area are critical. These chokepoints, if compromised, could paralyze emergency response operations. The lack of redundancy in these areas further heightens their strategic importance.

4.2. Implications

4.2.1 PORI as a Measure of Isolation Risk

PORI values provide a direct and actionable estimate of access vulnerability. A PORI of 0.40 indicates a 40% chance that a node will be removed from hospital access after an earthquake. This metric allows planners to prioritize nodes for mitigation measures based on isolation likelihood, making it a powerful tool for post-disaster preparedness and emergency logistics planning.

4.2.2 Influence of Network Topology and Structure

Topological features of the road network significantly influence PORI outcomes. Nodes with higher degrees (more connecting links) typically show lower PORI due to route redundancy. Border nodes with few connections and located at the station of long branches face elevated isolation risks. Chokepoints, where a single link connects an entire sub-network, pose critical threats to connectivity if disrupted.

4.2.3 Role of Seismic Fragility and Hazard Models

The PORI analysis is closely tied to the fragility models assigned to road links and the assumed ground shaking distribution. Links with higher failure probabilities under seismic loads contribute significantly to node isolation. Therefore, the analysis is both spatial and probabilistic, rooted in structural performance under specific hazard intensities. Strengthening these vulnerable links would decrease their failure probabilities and the overall PORI values of dependent nodes.

4.2.4 Implications for Urban Planning and Risk Mitigation

The findings highlight the need for focused urban resilience strategies. High PORI zones in the northeast and far west demand retrofitting of roadways and the introduction of backup emergency stations. Ensuring the structural integrity of critical links and creating redundant paths in low-connectivity areas will greatly reduce the network's vulnerability. These measures should be prioritized in any future infrastructure development or disaster response strategy for Intramuros.

5. CONCLUSIONS

This study addressed the critical issue of road isolation in urban environments during seismic events by introducing a method to estimate the Probability of Relative Isolation (PORI) for nodes in a road network. It is focused on Intramuros, Manila, a historically dense and vulnerable district. The research aimed to identify which areas are at greatest risk of being cut off from emergency response services, particularly hospitals, following an earthquake.

To achieve this, the road network was modeled as a graph consisting of 70 nodes and 120 links. Monte Carlo simulations and a breadth-first search algorithm were applied to determine whether each node could maintain connectivity with two source nodes representing hospitals. The methodology, implemented in MATLAB, considered varying failure probabilities for links, simulating real-world uncertainty under seismic conditions.

The results demonstrated a clear trend that nodes located closer to the hospitals consistently exhibited lower PORI values, while those at the network periphery showed significantly higher probabilities of isolation. Additionally, some centered position nodes with moderate PORI values were identified as critical points that serve as connectors whose failure could significantly sever the network and isolate large sections. These findings reinforce the importance of both proximity to emergency resources and structural redundancy in maintaining post-earthquake accessibility.

The implications of this research are substantial for both urban planning and disaster preparedness. It provides a data-driven basis for prioritizing infrastructure retrofitting, optimizing the placement of emergency facilities, and enhancing network resilience. Furthermore, the study contributes to academic literature by applying a multi-source PORI estimation technique using an efficient breadth-first search algorithm, offering a replicable framework for other cities with similar vulnerability profiles.

Nevertheless, the study is limited by its use of a generalized seismic hazard model and simplified assumptions regarding building fragility and debris generation.

Future work should explore more detailed seismic risk modeling, incorporate updated structural data, and examine dynamic aspects of resilience, such as the time required to restore connectivity after disruption.

In conclusion, improving the resilience of urban road networks against seismic hazards requires a targeted approach. By identifying the most vulnerable and critical components of the network, planners and policymakers can take decisive steps to ensure that emergency response pathways remain functional when they are needed most. This work serves as a foundation for further development of risk-informed infrastructure strategies and contributes meaningfully to the pursuit of safer, more connected cities.

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