

Combining Seismic Risk Analysis and Network Modeling to Assess Hospital Service Accessibility in the Bay Area, California

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ABSTRACT: Earthquakes can damage hospitals' infrastructure and disrupt critical healthcare functions. For example, the Northridge Earthquake in California damaged 11 acute hospitals, and eight had to be evacuated. These disruptions affect short and long-term accessibility to healthcare across large regions through cascading effects. In this paper, we propose a framework to combine risk analysis and network science methods to evaluate the post-earthquake functionality of hospital systems. We demonstrate the framework's applicability to the hospital system in the Bay Area, California, after a hypothetical M 7.2 earthquake on the Hayward Fault. First, we use risk analysis to estimate the post-earthquake capacities in 82 acute care hospitals in terms of the number of functional beds. Next, we combine this analysis with a graph representation of the healthcare network composed of the hospital and transportation system. We link the vulnerabilities of the hospitals to the graph's edge capacities and evaluate healthcare accessibility. We demonstrate that this approach can point to the hospitals with the most risk of losing hospital functionality and receiving patients from regions without medical services. Finally, we suggest future studies evaluate multiple scenarios and quantify the uncertainties in post-earthquake accessibility to healthcare services.

1. INTRODUCTION

Earthquakes can cause massive disruptions to hospital systems by damaging their infrastructure (Hariri-Ardebili et al., 2022). For example, the M 7.6 1999 Turkey disrupted ten major hospitals in

Izmit, triggering the relocation of most of their patients and reducing community access to healthcare services (Myrtle et al., 2005). Disrupted hospitals can have tremendous consequences during emergency response as critically injured people may

not find timely medical treatment in the first days following the disaster (Ceferino et al., 2018a,b, 2020a,c). Damage to hospitals can even have long-term effects on public health as people will experience longer waiting times for emergency departments for months or years, while hospitals are rebuilt and recover pre-disaster capacities (Alisjahbana et al., 2022).

In the United States, the M 6.7 Northridge Earthquake revealed critical vulnerabilities in the healthcare infrastructure. The earthquake caused substantial damage to 11 hospital facilities in California, making many buildings unusable (Cheevers and Abrahamson, 1994). Eight acute care hospitals in Los Angeles County were evacuated (9% in the county) (Schultz et al., 2003), an unacceptable state that led to the California Senate Bill 1953, which requires massive investments to reduce hospital vulnerabilities (Meade and Kulick, 2007).

Understanding the impacts of vulnerabilities on the accessibility of communities to healthcare services requires a convergent approach at the intersection of risk analysis and network modeling. Risk analysis can point at the hospital systems' components that are more likely to be damaged, but by itself, it cannot elucidate how the damage has cascading effects on access to healthcare services. This gap hinders our ability to inform emergency responders on what communities are more likely to lose access to healthcare or what hospitals will end up absorbing unforeseen demands from hospitals nearby that are likely to fail after earthquakes. In this paper, we present a methodology to combine risk analysis and network modeling to capture these cascading effects. Using data from the Bay Area, we exemplify the proposed modeling coupling to assess hospital and transportation systems after earthquakes focusing on hospital beds and the distribution of patients.

2. EXPOSURE DATA

We compiled data for 76 acute hospitals with 426 buildings in the Bay Area (California Health and Human Services, 2023; Department of Health Care Access and Information, 2013) (Figure 1). The compiled information includes buildings' locations, structural typologies, year of construction, num-

ber of stories, and vulnerability ratings. The structural vulnerability ratings are denominated Structural Performance Categories (SPC) and range from 1 to 5, with 1 assigned to buildings that pose a significant risk of collapse and 5 to the ones capable of providing services following strong earthquake shaking (Department of Health Care Access and Information, 2023). Similarly, the non-structural vulnerabilities, denominated Non-structural Performance Categories (NPC), range from 1 to 5, with 1 for buildings with equipment and systems that do not meet bracing and anchorage requirements and 5 for the ones that meet these requirements and have sufficient supplies to support 72 hours of emergency operations.

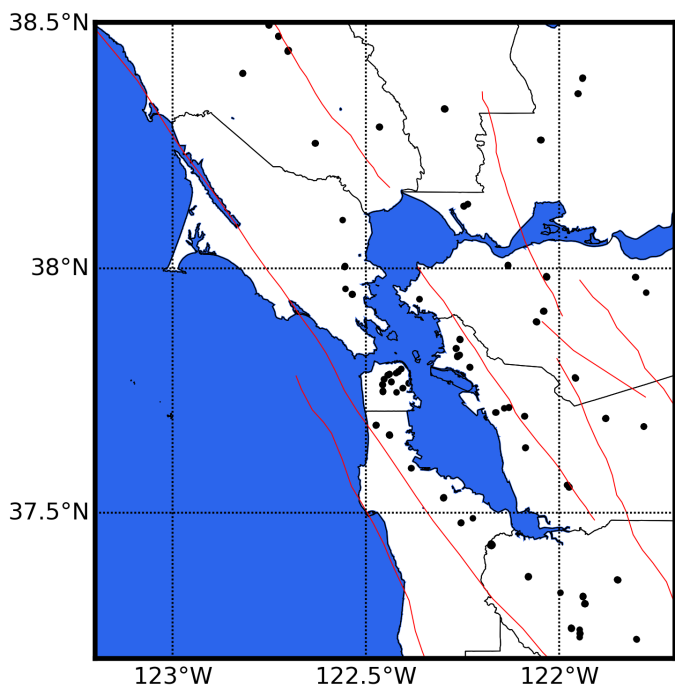


Figure 1: Spatial distribution of 426 buildings belonging to 81 acute care hospitals in the Bay Area. Major Bay Area Faults are also shown in red to highlight the high seismic hazards in the region.

The data shows that 19% of hospital buildings were built before 1973, when California passed the Alfred E. Alquist Hospital Facilities Seismic Safety Act requiring more stringent design for hospitals (Preston et al., 2019). Moreover, 59% of the buildings were built before 1994 when the Alquist Act was amended to establish both structural and non-structural vulnerability categories.

The average number of stories is 2.4 with a standard deviation of 2.2. Most buildings have 1- and 2-stories, 53% and 17%, respectively, highlighting a prevalence of structures with short periods of vibration (low-story buildings). The maximum number of stories is 15.

The building portfolio has various structural types. The structural type defines the structural system, e.g., steel braced frames. A few buildings report more than one structural type since structural systems can be mixed, or different for orthogonal directions. In this paper, we focused only on the primary structural type, which is reported for all buildings (Figure 2). However, an extension of this work can consider a combination of multiple structural types. The structural types are grouped in categories defined by HAZUS (Federal Emergency Management Agency (FEMA), 2020). Most hospital buildings are steel moment frames, followed by concrete shear walls, and steel braced frames, with 38%, 21%, and 17%, respectively.

Also, the building portfolio exhibits different seismic vulnerabilities (Figure 3). 24% hospital buildings have SPC between 1 and 2, and 42% hospital buildings have NPC between 1 and 2, revealing that non-structural vulnerabilities are more prevalent than structural vulnerabilities in the Bay Area. We also find a Pearson coefficient of 0.58 between the SPC and NPC ratings, indicating a moderate positive correlation between the structural and non-structural vulnerabilities.

3. REGIONAL RISK MODEL

We combined the exposure model with hazard and vulnerability models, utilizing the SimCenter R2D tool to perform computations (Deierlein and Zsarnóczy, 2021).

3.1. Hazard Model

We studied an M 7.2 earthquake scenario on the Hayward Fault since this scenario has been used to inform resilience policy-making in the Bay Area (Detweiler and Wein, 2017). We generated cross-correlated shaking simulations to evaluate the earthquake impact on the hospital portfolio (Figure 4).

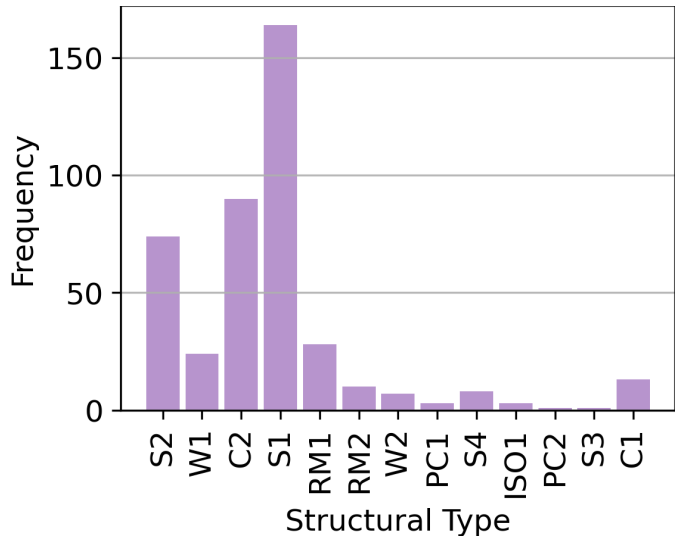


Figure 2: Histogram of structural types. W1: Wood, Light Frame, W2: Commercial and Industrial, C1: Concrete Moment Frame, C2: Concrete Shear Walls, S1: Steel Moment Frame, S2: Steel Braced Frame, S3: Steel Light Frame, S4: Steel Frame with Cast-in-Place Concrete Shear Walls, RM1: Reinforced Masonry Bearing Walls with Wood or Metal Deck Diaphragm, RM2: Reinforced Masonry Bearing Walls with Precast Concrete Diaphragms, PC1: Precast Concrete Tilt-Up Walls, PC2: Pre-cast Concrete Frames with Concrete Shear Walls, ISO1: Triple Concave Friction Pendulum Isolators.

We simulated Peak Ground Accelerations (PGA) at each building site, which were used to estimate structural damage in the entire building portfolio. In addition, for each site, we simulated spectral acceleration at the period of vibration of each structural type as a proxy for Peak Floor Accelerations (PFA) averaged over the building height. We used this proxy to evaluate non-structural damage on acceleration-sensitive components aggregated over the entire buildings since the resolution of the NPC rating is at the building level. Further studies can enhance the resolution of this analysis if higher-resolution information for non-structural components is available, e.g., on each floor. We did not conduct an assessment on drift-sensitive non-structural components since acceleration-sensitive components often fail first, e.g., ceilings and shelves, or are more critical for hospital service, e.g., x-ray equipment.

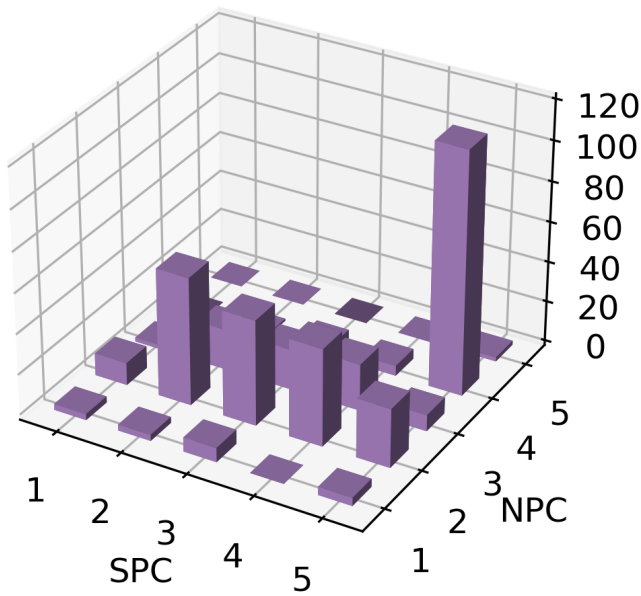


Figure 3: Joint Histogram of Structural and Non-structural Seismic Performance Ratings (SPC and NPC).

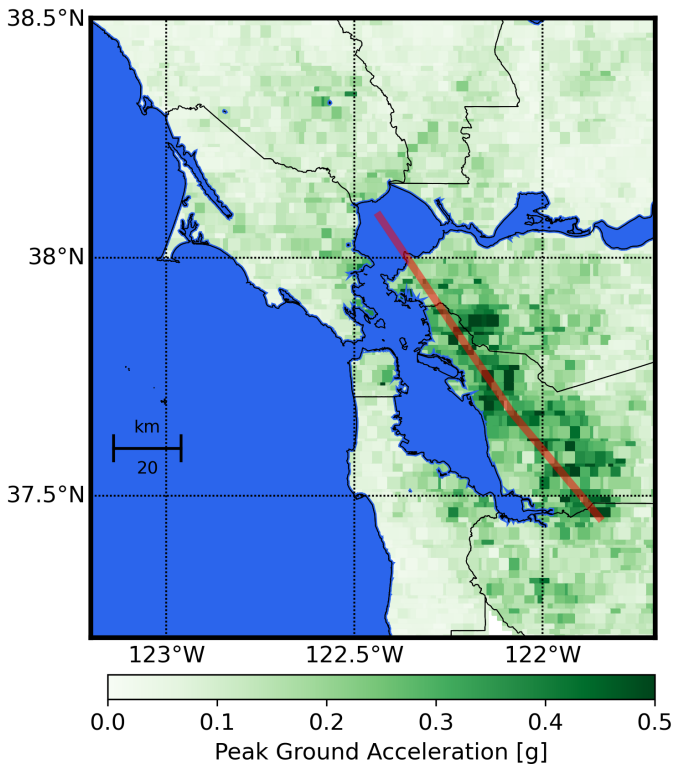


Figure 4: M 7.2 Earthquake Scenario on the Hayward Fault. One simulation of Peak Ground Acceleration (PGA) across the Bay Area. The Rupture geometry is indicated in red.

Thus, we co-simulated PGA and spectral acceleration at multiple periods of vibration. We utilized an existing ground motion model (Abrahamson et al., 2014) coupled with spatial correlation (Markhvida et al., 2018) and cross-correlation models (Jayaram and Baker, 2009) between ground motion residuals. Figure 4 shows a realization of PGA in the Bay Area.

3.2. Vulnerability Model

We utilized building-level fragility functions to determine damage in structural and non-structural building components. We used and adapted structural fragility functions developed in HAZUS (Federal Emergency Management Agency (FEMA), 2020) to create fragility functions for each SPC rating for each structural type. Using the definitions of SPC ratings (Department of Health Care Access and Information, 2023), we mapped SPC 1, 2, and 3 to pre-code, moderate-code, and high-code fragility functions for regular buildings from HAZUS (Federal Emergency Management Agency (FEMA), 2020). SPC 4 and SCP 5 ratings were mapped to enhanced fragility functions by increasing the median PGAs of high-code fragility functions to reach different damage states at 25% and 50% higher PGAs. These adjustments were made to represent that hospitals designed to meet the Alquist Act (SPC 5) according to the ASCE7-16 building code are designed to withstand 50% higher seismic loads than regular buildings, i.e., an importance factor of 1.5 (American Society of Civil Engineers, 2017). Figure 5 shows an example of the fragility functions indicating the probability of equaling or exceeding a structural damage state of moderate for a single structural type.

We followed a similar approach for the fragility functions of buildings' non-structural components. Thus, we mapped NPC 1, 2, and 3 to pre-code, moderate-code, and high-code fragility functions for acceleration-sensitive non-structural components in HAZUS (Federal Emergency Management Agency (FEMA), 2020). Next, for NPC 4 and 5, we adjusted the fragility functions of high-code fragility functions by increasing the median PGA to reach different damage states by 25% and 50%, respectively. Unlike structural components,

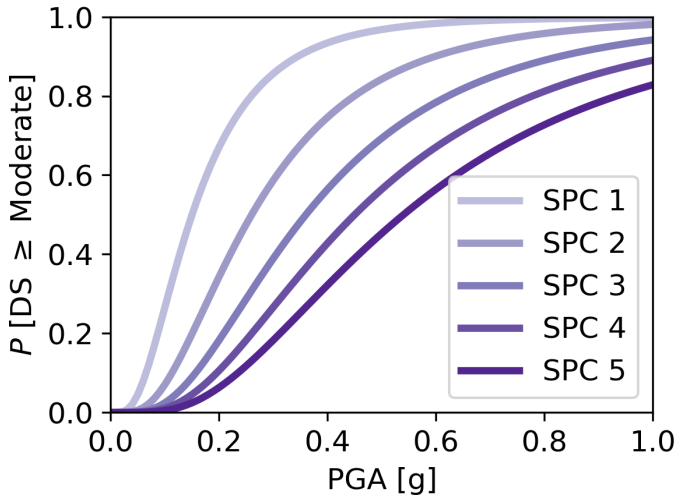


Figure 5: Fragility functions for different SPC ratings for concrete shear wall buildings (C2).

we defined the same fragility functions for all structural types considering that all hospitals have similar non-structural components, e.g., equipment for acute care. However, the input PFA for each hospital building is different and depends on the structural type since we use spectral acceleration as a proxy, as stated earlier. Figure 6 shows the fragility functions indicating the probability of equaling or exceeding a damage state of moderate for different NPC ratings.

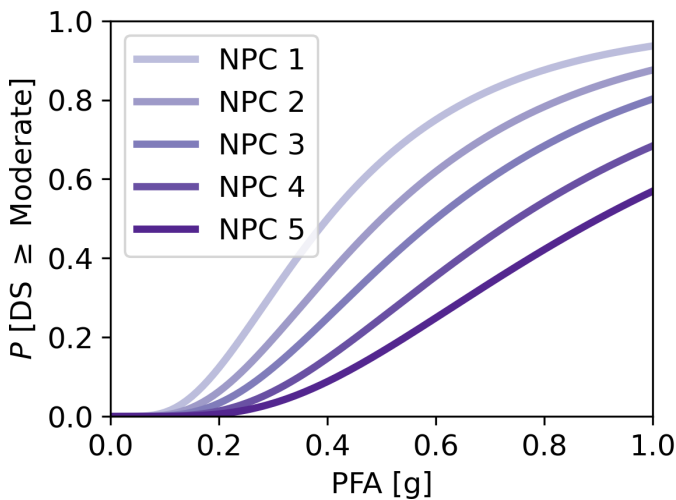


Figure 6: Fragility functions for different NPC ratings.

3.3. Building and Hospital Functionality

Hospitals require usable (i.e., occupiable) structures and working non-structural components to

function after disasters. Thus, we defined the event F of having a functional building as the intersection between the event S and N of having the structural and non-structural components below critical damage levels, respectively, i.e., $F = S \cap N$ (Fig. 7). With this model, we estimated the functionality of each hospital building using moderate damage as the threshold for both structural and non-structural components (e.g., Figures 5 and 6).

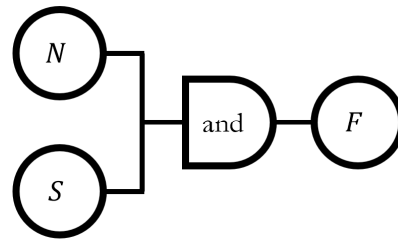


Figure 7: Fault tree model for hospital functionality. S : Structural, NS : Non-structural, F : Functionality.

Next, we determined the number of functional beds after the earthquake as the product of the percentage of the functional area after the earthquake times the number of beds before the disaster. At each hospital, the functional area is determined as

$$\text{Functional Area} = \sum_i F_i A_i$$

where F_i is the random variable of functionality for building i and A_i its built area.

3.4. Spatial distribution of Functional Beds

We used the risk framework outlined previously to quantify the distribution of functional beds after the M 7.2 earthquake scenario. Figure 8 shows one realization of hospitals' functionality associated with the PGA simulation in Figure 4. As stated before, each hospital campus is composed of different buildings; thus, the resulting distribution of functional beds at the hospital level is a function of the vulnerability across several buildings. As expected, the simulation shows that the most impacted hospitals are near the earthquake rupture line, with several losing complete functionality. Multiple simulations could be obtained with this framework to capture the corresponding uncertainties associated with extreme earthquakes.

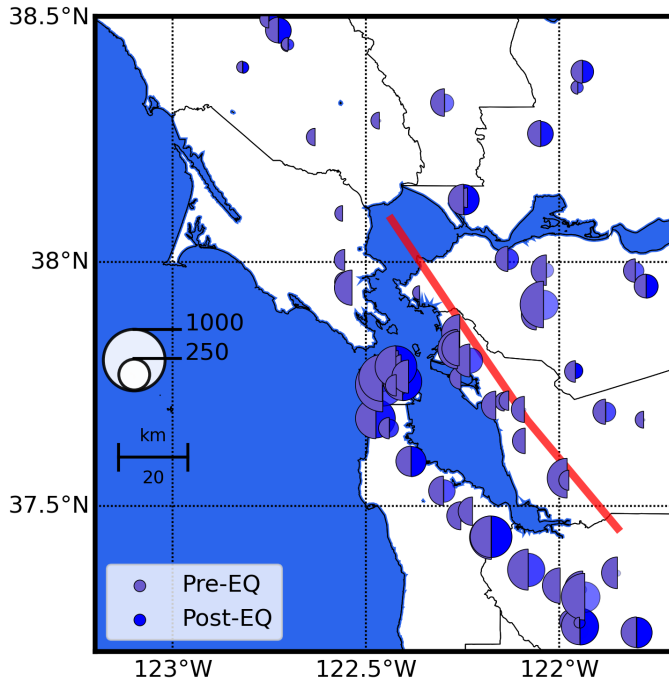


Figure 8: Pre and post-earthquake distribution of functional beds after the M 7.2 earthquake. Loss of capacity can be seen from the reduction in the circle size (right side) and its increased transparency (as a function of percentage loss).

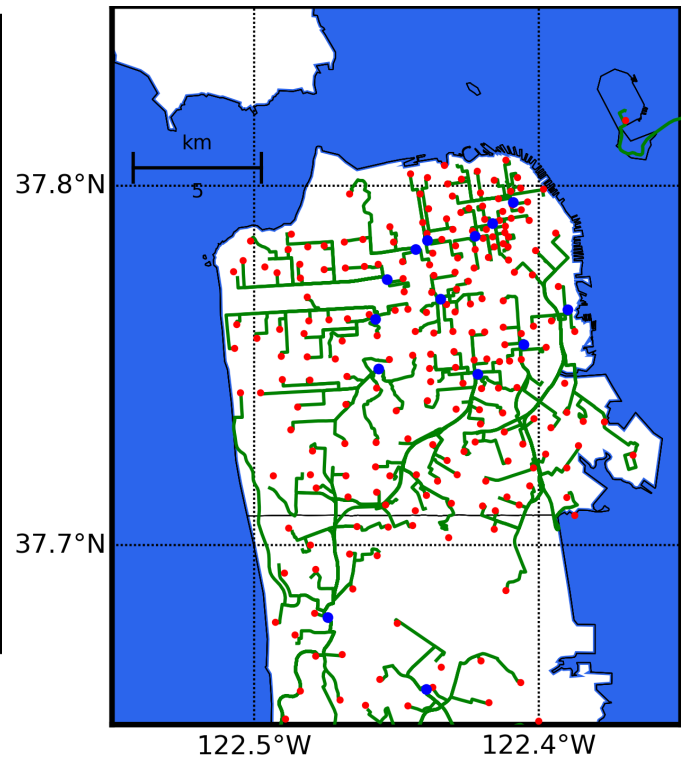


Figure 9: Origin (red) and destination (blue) nodes and shortest paths from each origins to the closest destination in pre-earthquake conditions.

4. POST-EARTHQUAKE HOSPITAL ACCESSIBILITY

Capturing healthcare accessibility at large scales requires network behavior modeling to evaluate cascading effects triggered by damaged infrastructure. We proposed using graph models to capture this behavior and evaluate accessibility to hospitals after earthquakes. We define a directed graph model $G(N, E)$ with N nodes and E edges. The nodes in the graph represent the origins and destinations of people seeking medical treatment in an affected hospital system. The edges in the graph represent the roads in the transportation system, whose information was obtained from the San Francisco Region Roadways (Association of Bay Area Governments, 2021). With this definition, we can model short-term recovery (Ceferino et al., 2020b), where patients will be mainly earthquake patients with trauma injuries, or long-term recovery (Alisjahbana et al., 2022), where patients need to go emergency departments after injuries from frequent accidents.

The graph model is coupled to the risk model through the infrastructure components. The realizations (or probabilities) of hospital failure can be introduced to the graph by reducing node capacities (or eliminating destination nodes in case of full bed losses). Further, if the risk analysis includes bridges, edge capacities can be reduced or eliminated in the network model as in Kiremidjian et al. (2007), but bridge vulnerability falls outside this paper's scope.

While this coupling can be utilized to represent dynamic networks (Ceferino et al., 2020a), this paper focuses on a static representation to assess accessibility with computational efficiency. We solve for a shortest-path tree (Gallo and Pallottino, 1988) to evaluate the pre- and post-earthquake accessibility of different regions to acute care. We assumed that there are $\sim 20,000$ injured people after the earthquake, from the study in Detweiler and Wein (2017), and distributed them proportionally to the population. Future studies can refine these results using earthquake casualty models as in Ce-

ferino et al. (2018b,a). We created $\sim 1,600$ superblocks and lumped the patients there to reduce the number of origin nodes for computational feasibility. Figure 9 shows the origin and destination (hospitals) nodes for pre-earthquake conditions highlighting the shortest path to the closest hospital.

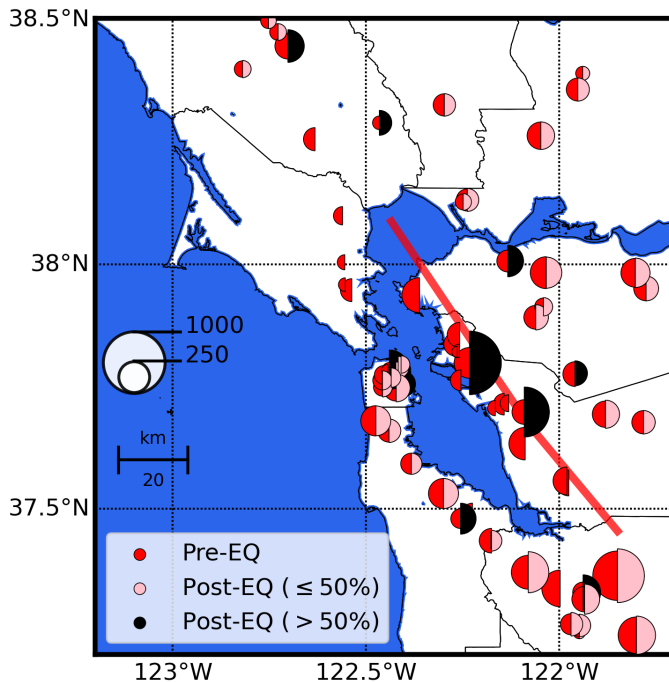


Figure 10: Patient volumes from pre- and post-earthquake conditions. Black highlights the largest changes ($> 50\%$)

For the post-earthquake conditions, we eliminated the nodes of those hospitals that lost all beds. Thus, we consider that partially operative hospitals can still receive patients. Next, we analyze the changes in the patient volumes to point out the hospitals that may have to absorb additional demands for healthcare due to people who find their closest hospital non-functional. Figure 10 shows one simulation of changes in patient arrivals, highlighting the cases where hospitals sustain heavy increases in their expected demands. While this example shows how to couple network and risk models for one simulation, it can be easily extended to multiple ones to study hospital systems' resilience across multi-California

5. CONCLUSIONS

We presented a methodology to couple regional seismic risk analysis with network methods to characterize the accessibility to medical centers after earthquakes. We showcased the applicability of the methodology through a case study in the Bay Area, California, after an M 7.2 earthquake scenario.

We first showed how hazard, vulnerability, and exposure models can be coupled to simulate the bed functionality in 76 acute care hospitals in the Bay Area. We also demonstrated that a graph model connecting neighborhoods with care hospitals through the transportation network can be built to evaluate different cascading effects. Using solutions from a shortest-path algorithm, this approach can point to the hospitals that will receive increased patient loads, as well as the communities that reduce their access to hospitals more drastically. This paper focused on demonstrating the applicability of this methodology using only one simulation, and future studies will evaluate the propagation of uncertainty from the risk model to the network model through multiple earthquake scenarios.

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