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Hospital System Response to Earthquakes in the COVID-19 Pandemic

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ABSTRACT

Compound events such as an earthquake and the COVID-19 pandemic can have disastrous consequences on the healthcare system, leading to overwhelmed hospitals and untreated critical patients. Recent studies have demonstrated a growing need for analytical models to capture hospital system response due to compound events. The healthcare system functionality of Lima, Peru, is used as a case study to analyze the relative capacity and demand of ICUs following a severe earthquake during the pandemic. This paper uses the results to discuss how an analytical model for organizing the system-level response can be developed by combining previously developed regional earthquake hazard and hospital network models.

Compound Effects of Earthquake and Pandemic

The prolonged nature of the COVID-19 pandemic has led to its coincidence with rare natural disasters. For instance, the M5.3 Zagreb earthquake in Croatia in March 2020, the M7.0 Samos-Izmir earthquake in the Aegean Sea in October 2020, and the M7.2 Haiti earthquake in August 2021 are examples of compound events, which exacerbated the impact of the disease (Kijewski-Correa et al. 2020; Quigley et al. 2020). The compound impact of an earthquake and a pandemic can lead to a disaster worse than the sum, particularly for already exhausted and overwhelmed hospital systems.

Earthquakes can cause an increase in the spread of the disease in an epidemic. After the 2010 Haiti Earthquake, a cholera outbreak resulted in additional 109,015 hospitalizations and 3,889 deaths (Date et al. 2011; Walton and Ivers 2011). For highly transmissible diseases such as COVID-19, the disruption of social distancing and safety measures and the destruction of structures can lead to an increase in cases and hospitalizations (Goldbaum 2020). Using earthquake simulations and COVID-19 infection scenarios, Silva and Paul (2020) showed that the spread of the virus can increase drastically without the rapid adoption of containment measures. The geospatial correlation of regional seismic risk and high virus transmissibility revealed that key urban areas are particularly vulnerable to compound crises, especially urban areas along the Pacific Coast in

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Compound events of natural hazard events and pandemics can overwhelm healthcare systems and lead to increased deaths. Hassan and Mahmoud (2021) found that the combined effect of wildfires and pandemics leads to exceedingly long waiting times for patients, especially with short relative time between the two events. By optimizing resource allocation using a temporary hospital with additional supplies, patient outcomes improved dramatically. Yet, emergency managers still need to plan for potentially destroyed healthcare facilities and disrupted hospital access (Dargin et al. 2021).

In non-pandemic times, patients usually are proportionally distributed between critical hospital systems, such as inpatient care, emergency room (ER), intensive care units (ICU), and operating rooms (OR). COVID-19 critical patients admitted to the hospitals require ICUs with mechanical ventilators, hospital beds, and oxygen supplies. Severely injured trauma patients from earthquakes (e.g., head injuries) require ORs, ICUs, and beds (Ceferino et al. 2018a; Yi and Paul, 2010). If the earthquake occurs during a COVID-19 surge with high hospitalization rates, the consequences could be disastrous as the increased demand for beds, medical personnel and equipment could largely exceed the post-disaster capacity. Thus, there is a growing need for analytical models that capture the spatial-temporal interaction of earthquakes and healthcare systems during pandemics to prepare plans that guide an effective response to future compound events. This paper conducts a risk assessment of hospital systems for Lima, Peru, for a compound pandemic-earthquake scenario and discusses approaches to model the system response.

Assessing Healthcare System Functionality following Earthquakes during the Pandemic

Pandemic in Lima

The functionality of medical resources for COVID-19 patients is assessed following an earthquake scenario during the pandemic in Lima. We focused on ICUs with mechanical ventilators as they provide lifesaving support for seriously ill patients (Iyengar et al. 2020). During the pandemic, mechanical ventilator shortages increased COVID-19 mortality in multiple countries, including Peru (Elhadi et al. 2020; Guérin et al. 2020; Mejía et al. 2020). Thus, earthquakes that disrupt or limit ventilators' functionality have the potential to increase mortality rapidly.

Lima has been one of the hardest-hit cities by the pandemic. Two waves resulted in ~920k confirmed COVID-19 cases and ~91k fatalities until October 2021 (Plataforma Nacional de Datos Abiertos 2021a, 2021b). Increased demand for critical medical resources, such as beds and ICUs with mechanical ventilators, followed both waves (Figure 1). In response, the city's health care system rapidly increased its ventilator capacity from ~100 in April 2020 to ~1500 in May 2021. Despite this, the ventilator demand vastly exceeded the capacity in both waves.

Even though by 08/15/2021 Lima was exiting the second wave, ventilator usage was still high, keeping the hospital system close to full capacity in many regions. For example, the Peruvian Ministry of Health (MINSA) and the Social Security (Essalud), the main healthcare providers, were at 81% capacity The spatial distribution of used and total mechanical ventilators is shown in Figure 1, where certain hospitals are close to 100% capacity. As of 10/29/2021, the ventilator demand has decreased below 60% capacity, and full-vaccination rates have rapidly grown to above 57% (Plataforma Nacional de Datos Abiertos 2021c, 2021d, 2021e). However, the risk of a third wave increasing demand beyond capacity is still a likely scenario. Cities have exhibited COVID-19's Delta-variant-triggered waves that have overloaded the hospital system to a crisis level, even after reaching vaccination rates above 50%, e.g., in Texas, Florida, or Alabama (Smart 2021).

Earthquake Assessment

To assess the impact of an earthquake during the pandemic, a scenario-based analysis was conducted for three earthquake magnitudes of 7.0, 8.0, and 8.8, with their source on the subduction fault offshore Lima, Peru.

These scenarios are based on seismic hazard, vulnerability, and hospital functionality models developed previously (Ceferino et al. 2018b; Ceferino et al. 2020a and 2020b). This paper extends these studies by focusing on the functionality of mechanical ventilators for COVID-19 patients rather than on ORs. The hospital dataset, which consisted of 41 hospital campuses with +500 buildings (Santa Cruz et al., 2013), was extended to 46 to include new hospitals since 2013. Also, ventilator datasets from Plataforma Nacional de Datos Abiertos (2021c) and (2021d) were integrated into our existing hospital inventory dataset for the risk assessments. In total, we analyzed 703 ventilators distributed in MINSA and Essalud's hospitals in Lima (Figure 1).

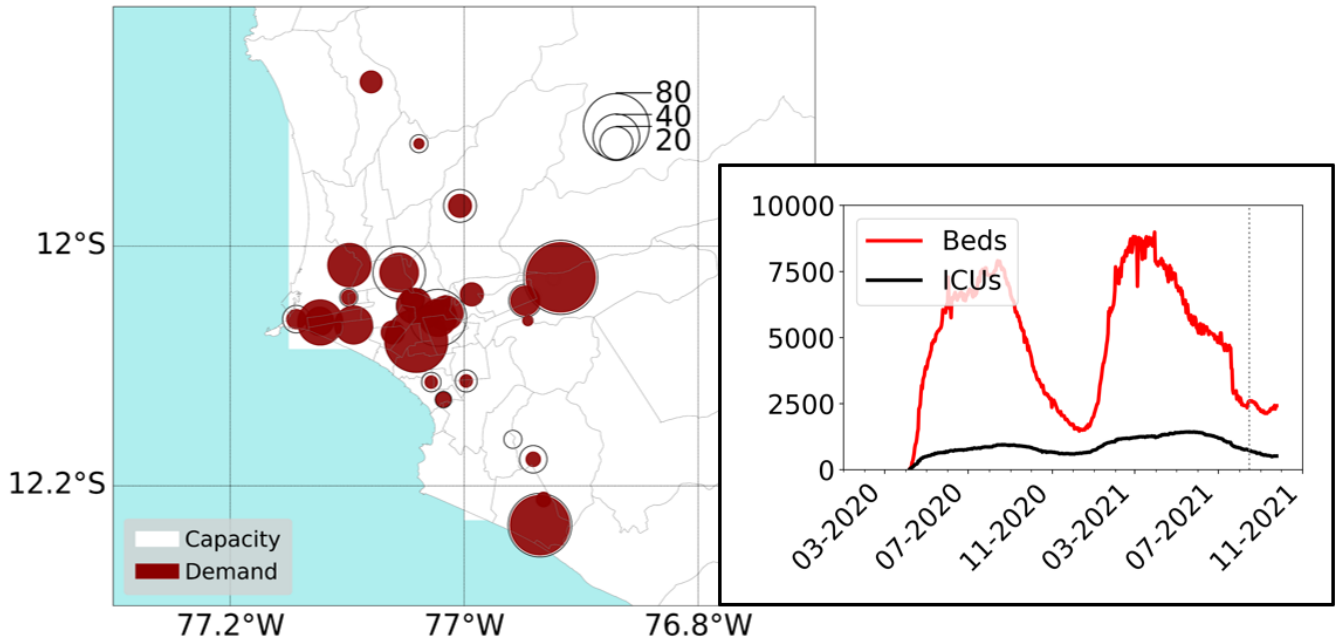

Figure 1. Demand and capacity of ICUs with mechanical ventilators in 46 hospitals in MINSA and Essalud's systems (as of 08/15/2021). The plot also shows the time-series of the bed and mechanical ventilator usage in ICUs through the two waves. A dotted line marks 08/15/2021 for reference.

Using 10,000 Monte Carlo simulations, our assessments output the probability distribution of functional ICUs per hospital. Figure 2 shows the spatial distribution of the average number of functional ICUs. The plot shows that higher magnitudes decrease the number of functional ICUs as more damage to the hospital infrastructure is expected. Figure 2 also shows the probability distribution of the aggregated number of ICUs, with mean values of 542, 403, and 260 for the scenarios with magnitudes of 7.0, 8.0, and 8.8, respectively.

These are significant capacity reductions in 23%, 43%, and 63%. For comparison, we show that the ICU demand for MINSA and Essalud as of 08/15/2021 is 556. Our probabilistic framework demonstrates that even the magnitude 7.0 can significantly increase the risk of overflowing the ICU capacity, e.g, there is a 63% probability that functional ICUs are below demand. Earthquake magnitudes of 8.0 and 8.8 would certainly overflow the system with probabilities greater than 97% (compared to the demands of 08/15/2021).

Discussion: Coordinating Hospital Response to Earthquakes during the COVID-19 Pandemic

Our results highlight the need for coordinating the effective use of medical resources during compound events. However, an analytical framework for modeling hospital system response due to compound effects is lacking, hindering our ability to quantify the impact of coordination and mitigation policies. Ceferino et al. (2020a) developed a framework for modeling the optimal use of healthcare resources following earthquakes.

The study showed a geospatial mismatch between earthquake injuries and post-event healthcare capacity, demonstrating the need for effective resource allocation to minimize patient wait times. This model can serve as the starting point for assessing compound effects of pandemics and earthquakes. Crucially, the framework should model ICUs with mechanical ventilators as a critical component of the hospital system. The framework should also model medical resources in high demand for both COVID and earthquake patients, such as hospital beds and personnel.

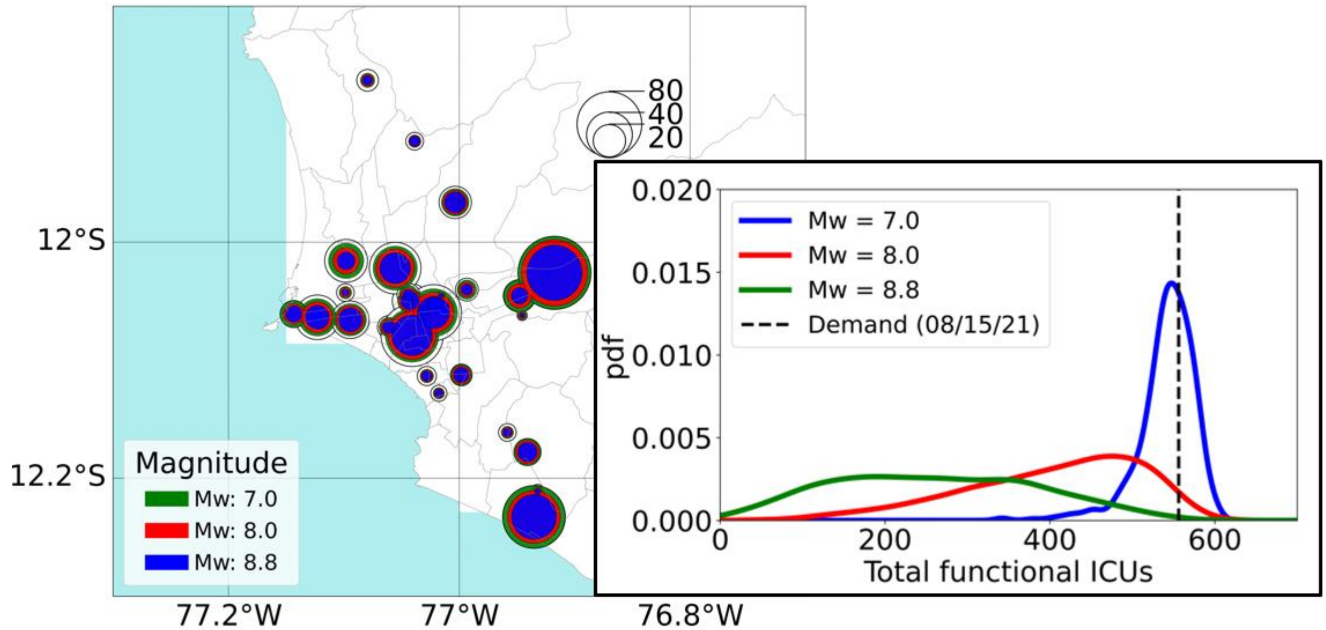

Figure. 2. Distribution of average functional ICUs with mechanical ventilators per hospital after the three earthquake scenarios. Circles in white show the total number of ICUs for reference. The plot also shows the probability distribution of the aggregated number of functional ICUs.

The severity of the earthquake and the rate of transmissibility of the virus at the time of the seismic event will affect the hospital system's response. Thus, the envisioned framework must investigate multiple earthquake magnitude scenarios occurring during different COVID scenarios (hospitalization waves), e.g., like in Ceferino et al. (2020a) and Hassan and Mahmoud (2021). The framework can then test the effectiveness of plans for emergency response for compound events to assess, for instance, bringing scarce resources such as ventilators from neighboring regions not affected by the seismic event. ICUs could also be divided into COVID and non-COVID patients to avoid the spread of the virus. Social distancing and vaccination rates' benefits for the hospital system can also be incorporated in the analysis by modeling their effects in cases and hospitalizations (Sun et al. 2020; Bubar et al. 2021).

Understanding how to mitigate the impacts of destructive earthquakes during the pandemic and optimizing an organized and distributed system response is paramount to limiting the casualties due to compound events.

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