Decision support system for earthquake risk mitigation for hospitals and health facilities

Sarvenaz Amini Haji Bashi – University of Grenoble Alpes, Grenoble, France, e-mail: Sarvenaz.Amini-Haji-Bashi@etu.univ-grenoble-alpes.fr

Alireza Azarbakht - Department of Civil and Environmental Engineering, University of Strathclyde, Glasgow, UK, e-mail: alireza.azarbakht@strath.ac.uk & School of Engineering, University of Greenwich, Medway Campus, Chatham, Kent ME4 4TB, UK, email: a.azarbakht@greenwich.ac.uk

John Douglas - Department of Civil and Environmental Engineering, University of Strathclyde, Glasgow, UK, e-mail: john.douglas@strath.ac.uk

Abstract: Although the time of catastrophic earthquakes is not predictable, some mitigation actions can be taken to enhance preparedness against such events. Hospitals and other healthcare facilities are expected to remain operational during and after moderate to severe earthquakes. Taking mitigation measures in hospitals that are located in earthquake-prone regions is a wise decision that can lead to less damage in case of large earthquakes. Prioritizing these measures is of great importance from the economical point of view. This study employs a recent decision-making approach based on multiple criteria and cost-benefit analyses to help prioritize feasible mitigation actions for a hypothetical healthcare facility.

Keywords: Operational earthquake forecasting, mitigation action, earthquake emergency management plan, Sina Athar medical centre

1. Introduction

Earthquakes cause a worldwide average of 40,000 deaths and far more injuries every year. Between 1996 and 2015, 750,000 deaths were attributable to earthquakes, according to the Centre for Research on the Epidemiology of Disasters[1] ; more deaths than all other natural disasters combined. Research by well-respected seismologists (e.g. Bilham, 2009) suggests that a single earthquake striking a heavily populated city (e.g. Tehran in Iran) could cause over one million deaths.

Operational Earthquake Forecasting (OEF) is a method that can provide authorities with short-term earthquake predictions to help them take short-term mitigation actions (Jordan et al. 2011; Field and Milner 2018). These actions include reinforcing earthquake drills and having a survival kit available. In the last decade, several studies have developed short-term earthquake forecasts and time-dependent seismic hazard assessment, especially in periods of increased seismicity, e.g. following a large earthquake (Convertito and Zollo 2011; Peruzza et al. 2017; Douglas and Azarbakht 2021). However, making decisions that rely on OEF is challenging as the probability of severe earthquakes is often less than one per cent daily (Woo and Marzocchi 2014). The decision-making process has been facilitated by a cost-benefit analysis proposed by Douglas and Azarbakht (2021) as well as a hybrid approach (Azarbakht et al. 2021) combining cost-benefit analysis and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). The current study presents a new application of the decision-making approach proposed by Azarbakht et al. (2021) for the case of hospitals and health facilities in the context of OEF.

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[1] https://www.cred.be/

Hospitals have been reported to lose up to 50% of their capacity at the time and aftermath of earthquakes in some countries, such as the 2003 Algerian earthquake and the 2005 South Asia earthquake, which severely affected Pakistan (WHO, 2008-2009). Hospitals need to be operational during and after moderate and devastating earthquakes (Ceferino et al. 2020). It is worth mentioning that designing resilient health facility structures and considering mitigation actions during the construction phase will add no more than 4% to the building's cost (WHO, 2009).

A brief description of the employed methodology is presented in the following section. Consequently, a hypothetical hospital is introduced and a set of mitigation actions are proposed. The mitigation actions are compared using the cost-benefit analysis and TOPSIS algorithms and, finally, some conclusions are drawn.

2. Methodology

As mentioned in the previous section, decision making in the context of OEF is still a challenging area of research since many considerations influence this problem, and the likelihood of false alarms is always high. Multi-criteria decision making using TOPSIS was initially proposed in general terms by Hwang and Yoon (1981) and implemented in the field of earthquake engineering by Caterino et al. (2008). Cremen and Galasso (2021) have recently adapted this framework to earthquake early warning (EEW). However, EEW only considers two possible actions (trigger or not trigger an alarm), whereas many mitigation actions could be triggered by OEF. It is also worth emphasising that OEF concerns a longer time frame (often days or weeks) instead of a few seconds in the case of EEW. In EEW, it is considered almost certain that an earthquake will occur in the next few seconds (probability near to unity), whereas for OEF, the chance of an earthquake actually occurring during the forecast period (e.g. next days or next week) is small, which means the risk of a ”false alarm” is much higher, making it more likely that “no action” is best. Actions will generally be far reaching and have a more significant impact in the context of OEF than for EEW as they will be in place for a long time and affect many people. Nevertheless, significant planning for low probability/high consequence events (such as earthquakes) may be made without being overly disruptive to social and economic activities. This is because many actions triggered by OEF are actions that are routinely performed. Actions such as drills and exercises, communicating on recommended evacuation routes in case of tsunamis and having a survival kit can be reinforced during periods of enhanced seismic hazard since public concern about a possible event in the short term is increased. Therefore, being inspired by the approach of Cremen and Galasso (2021), Azarbakht et al. (2021) adapted the method in the case of OEF and it is applied here to systematically compare possible OEF mitigation actions for health care facitilies.

The final output of TOPSIS is the ‘Closeness Value’, i.e. the similarity to the best possible solution. This could be used in future applications to determine which OEF mitigation actions are recommended, as the longer time frame for OEF compared with EEW allows for more thorough decision making. Besides, the TOPSIS results have been combined with a cost-benefit analysis (Douglas and Azarbakht 2021) to make a hybrid algorithm to also financially justify the selected actions. For more details, the reader is referred to the original manuscript (Azarbakht et al 2021). This method is demonstrated in the next section for a hypothetical hospital.

3. Mitigation Actions in a hypothetical hospital

Hospitals and healthcare facility infrastructures become inoperable mostly when non-structural elements (e.g. mechanical, electrical and communications equipment, shelving and water heating) are damaged (WHO, 2009; Achour et al. 2011). Retrofitting non-structural elements surprisingly costs only about 1% of the hospital's construction budget, nevertheless, it can safeguard up to 90% of its value (Guleria 2017). Proven measures comprise early warning systems, regular hospital safety assessments, protecting equipment and supplies, development and testing of emergency response plans, preparing staff to manage mass casualties and infection control measures (WHO, 2009). Using building techniques such as "base isolation technology" by which a building is isolated from the ground oscillation in earthquakes is considered to be another possible solution (WHO, 2009).

As mentioned earlier, a hospital's functions are mostly interrupted when non-structural components are damaged, e.g. toppling of unanchored helium and oxygen gas cylinders, which was frequently reported during past earthquakes (FEMA, 2012). Therefore, mitigation actions on medical equipment, lifelines and architectural elements could be a rational decision. To elaborate on this concept, inspiration from an explosion that happened at the *Sina Athar* Medical Centre in Tehran on June 30th 2020 (Tehran Times, 2020) is discussed here. An electrical short circuit initiated a wide-spread fire. Gas leaks and a spread of the fire to helium and oxygen cylinders stored in the basement caused a massive explosion. Based on the ISNA news agency, 43 people were in the building at the time of the explosion, 19 people were killed and 14 were injured (Tehran Times, 2020).

Although the *Sina Athar* medical centre disaster was due to an electrical safety issue, the same concept is a likely scenario after a moderate to severe earthquake in the case of unanchored cylinders in a hospital. It should be emphasized here that the above-mentioned explosion occurred as a result of the unsuitable preservation of about 30 gas cylinders. Therefore, anchorage of cylinders and building a new safe storage for the operation of cylinders are the two considered mitigation actions in the present study. These two mitigation actions will be later compared with a 'No Action' strategy. A hypothetical hospital is assumed here with a total area of 10,000 m^2 over five stories and housing 500 staff and patients. The cost of cylinder anchorage is assumed to be about \$100 for each cylinder. We also assume 100 cylinders to be used by the different hospital wards. Therefore, cylinder anchorage is a mitigation action with an estimated total cost of \$10,000. Building a new and safe place for cylinders' storage is the second assumed mitigation action. Hence, a 200 m^2 new storage space area is needed to appropriately manage the cylinders. Its cost has been estimated to be \$500 per m^2, resulting in a total cost of \$100,000.

On the loss side, a potential of causing 0.4 and 2 per cent death and injury due to this fire is also assumed (inspired by the discussion in Azarbakht et al. 2021). Considering 500 hospital inhabitants, 10 people will be injured and two people will be killed in the case of a severe earthquake and consequent fire. In addition, we assume the cost of an injury is equal to \$10,000 per person, and the cost of a casualty is \$1,000,000 per person (Azarbakht et al. 2021). The direct loss is assumed to be severe damage to at least one entire ward of the given hospital resulting in a loss of \$800,000. The downtime is also assumed to be three days that will be needed for fire extinguishing and recovery. \$100,000 loss for every downtime full day for the hospital is assumed. Besides, equal weights (0.25) are used here for four considered criteria: direct cost, death, injury and downtime. The disaster duration is assumed to be 7 days and the site and seismic hazard input are the same as in Azarbakht et al (2021).

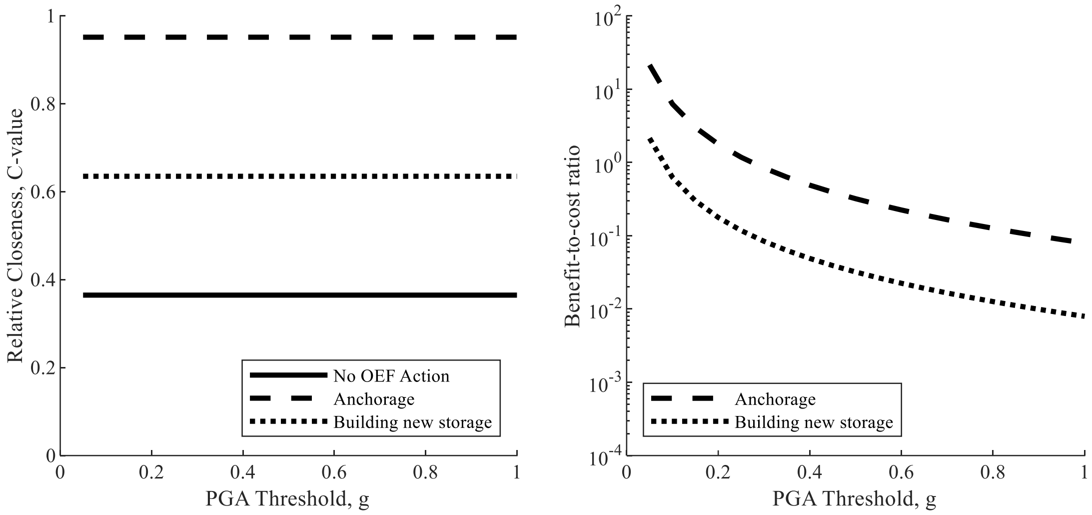

Figure 1. (left): C versus different PGA thresholds, (right): R versus PGA thresholds for different OEF actions for a hospital.

The results of the TOSIS algorithm is shown in Figure 1(left) which indicates that both mitigation actions are recommended and the 'No-Action' is never optimal. The 'Anchoring' mitigation action is always superior when compared to the 'Building new storage' mitigation action as it is more affordable. The cost-benefit results are also shown in Figure 1(right), confirming the 'Anchoring' mitigation action is feasible up to about 0.3g as the Threshold PGA. However, the 'Building new storage' mitigation action is less feasible (before 0.1g as the Threshold PGA). This is due to the very low probability of rare events with very high levels of PGAs. However, it is worth mentioning that Figure 1 is based on Probability Gain (PG) equal to 10, which means a heightened situation where the seismicity is 10 times the background long-term seismicity. It is worth noting that the feasible PGA Threshold will be equal to 0.85 g in the case of PG equal to 100, which indicates particularly heightened seismicity.

We have assumed an equal scheme for weighting the different criteria within the decision matrix and only three days of downtime. However, one can significantly increase the weight and duration of a potential downtime since hospitals need to be operational during and after severe earthquakes. Then, in this case, the given mitigation actions will be better justified even for very rare earthquakes.

4. Conclusions

In the framework of operational earthquake forecasting, this study has applied a new approach to systematically examine the efficiency of mitigation activities for healthcare facilities during a period of increased seismicity. The decision support approach has been modified from a newly presented method for early warning systems. To analyse the financial benefits of the advised activities, this algorithm was paired with a cost-benefit analysis. A hypothetical example involving ‘Anchoring cylinders’ and ‘Building a new storage’ for a hospital infrastructure was investigated. The findings suggest that mitigation efforts are effective when modest shaking levels cause damage and when the interventions are affordable and may offset a large proportion of the underlying risk. The method used can be modified to fit a variety of situations based on specific end-user preferences.

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