Decision support system for community earthquake drills and evacuation

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Abstract: Decision making to mitigate the effects of natural hazards, such as earthquakes, has always been a challenging subject. This is particularly the case in periods of increased seismicity (e.g. in a foreshock or aftershock period of a major earthquake) when the population is anxious and would like advice but when the chance of potentially damaging earthquake ground motions in the coming days remains low. In this study, a decision-making method based on multiple criteria is combined with cost-benefit analyses to create a hybrid decision-making framework to help decide amongst potential loss mitigation actions. The proposed framework is demonstrated for a hypothetical case study. The results show that the proposed approach is flexible enough to adapt to new problems, end-users and stakeholders. Additionally, it is revealed that reasonable mitigation actions are viable and financially beneficial during periods of increased seismic hazard in order to reduce the potential consequences of earthquakes.

Keywords: Operational earthquake forecasting, mitigation action, time-dependent seismic hazard, earthquake emergency management plan, TOPSIS.

1. Introduction

A disaster is a social situation characterised by non-routine, life-threatening physical destruction (Quarantelli 1998). Disasters can be classified as: natural, for those caused by geophysical, hydrological, meteorological, biological, extra-terrestrial, or climatological hazards; anthropogenic (technological); or technological triggered by a natural disaster (Natech) (Guha-Sapir et al. 2016). Until recently, droughts and floods killed most people worldwide, but deaths from these events are now generally low. The deadliest disasters today (apart from disease pandemics) tend to be triggered by earthquakes (e.g. Haiti 2010, Tohoku 2011) (Ritchie 2014).

Disaster/emergency management is the body of policy and administrative decisions, the operational activities, the actors, and technologies that pertain to the various stages and levels of a disaster (Lettieri et al. 2009). Due to the immense losses caused by natural hazards, effective disaster management is vital. Because of the changing nature of disasters and the uncertainty in managing them, disaster management is studied across many disciplines. Disaster management involves strategic interactions among various decision-makers, including different levels of government, private companies and non-profit organisations, making Operational Earthquake Forecasting (OEF) an exciting approach in this field (Goltz 2015). OEF is an emerging concept that aims to provide short-term forecasts of earthquakes to increase alertness and readiness among decision-makers and to initiate civil protection actions (Jordan et al. 2011; Field and Milner 2018).

Procedures for short-term forecasts through time-dependent seismic hazard assessment have been applied in various studies over the past decade, particularly in periods of increased seismicity such as following a large earthquake (Convertito and Zollo 2011;

Peruzza et al. 2017). Despite acknowledged weaknesses (Jordan et al. 2011; Wang 2015; Wang and Rogers 2014), OEF is the best available approach to forecast future earthquakes. The short-term probability of a severe earthquake is low (often less than one per cent daily) even in a heightened hazard situation, which presents a formidable challenge when making decisions based on OEF (Woo and Marzocchi 2014). Therefore, no comprehensive framework for OEF decision-making is yet available in the technical literature, although using cost-benefit analyses has been proposed (e.g. Douglas and Azarbakht, 2021). The purpose of this article is to propose another approach for decision making in the context of OEF.

Decisions to undertake mitigation actions based on OEF depend on the balance between costs and benefits, which are specific to the risk at hand (Field et al. 2016). Because these decisions are contingent on a host of economic, political, and psychological considerations that lie beyond the science of hazard analysis, scientific information about future earthquake activity should be developed independently of any specific risk assessment or mitigation effort (Field et al. 2016). Moreover, all validated OEF information should be made available to all potential end-users in an appropriate well-formatted and timely manner. These hazard-risk separation and transparency principles imply that seismologists should provide potential end-users with complete, probabilistic forecasts, including their epistemic uncertainties (Jordan et al. 2014). The OEF systems should be policy-neutral. In other words, OEF systems should not withhold information until some activity level or probability threshold is exceeded, or until a "significant" mainshock has occurred. Otherwise, doing so would not only imply that we know how to define these things for all potential users, but would also effectively put scientists in the inappropriate role of making policy decisions (Field et al. 2016). In summary, OEF systems should be used to inform potential decision-makers at all levels, not as a holistic decision-making tool itself.

Recent events have revealed the public's hunger during ongoing earthquake sequences for information from OEF. It is well known that information vacuums invite unfounded predictions and misinformation (Mileti and Peek 2000), such as the rumours on Twitter that "experts are holding back on a prediction to avoid panic" within hours of the 2010 El Mayor–Cucapah earthquake (Jordan and Jones 2010). The level of apparent certainty provided by amateur predictors can also be particularly attractive and therefore distracting (Marzocchi 2012). The infamous L'Aquila trial, in which seven Italian officials were charged with involuntary manslaughter, was at least partly a consequence of miscommunications about earthquake risk by the Italian Department of Civil Protection (Field et al. 2016). That agency convened its Grand Risk Commission before the L'Aquila earthquake to address ill-founded earthquake predictions that were worrying the public during the seismic sequence preceding the L'Aquila mainshock. Still, this Commission lacked the operational capabilities to accurately assess and report on the evolving seismic hazard (Marzocchi 2012). The best solution in such predicaments is to have an OEF system that produces authoritative scientific information (Jordan 2013; Jordan et al. 2011).

The probability from a time-dependent forecast, produced by short-term forecasting models, can be quite high (Probability Gains, PG>100) relative to the time-independent probability (e.g. Gulia et al., 2016). In these situations, the forecasting intervals are typically much shorter than the recurrence intervals of large earthquakes (days compared to hundreds of years), and the probability of potentially damaging earthquakes remains much less than unity (generally <1% per day). As a result, although the value of long-term forecasts for ensuring seismic safety is clear, the interpretation of short-term forecasts is problematic, because earthquake probabilities may vary over many orders of magnitude. Such forecasts cannot provide earthquake "predictions" associated with high probabilities.

Translating such low-probability forecasts into effective decision-making is a difficult challenge. Therefore, it is necessary to establish earthquake probability thresholds for different mitigation actions by means of, for example, a cost-benefit analysis (Douglas and Azarbakht 2021; Azarbakht et al. 2020) and also by taking psychological preparedness and resilience into account. In this context, a multi-criteria decision support system (DSS) is also helpful since cost-benefit analyses are only straightforward when one action is compared to the case of no action, and such analyses cannot account for end-user priorities that are not expressed in financial terms. Alert procedures should be standardised to facilitate decisions at different levels of government and among the public if necessary. Moreover, the principles of effective public communication established by social science research should be applied to delivering seismic hazard information (Jordan et al., 2011).

In the present study, we adapt a recent multi-criteria DSS, initially introduced by Cremen and Galasso (2021) for Earthquake Early Warning (EEW) systems, for use in an OEF framework. The method is briefly described in the following section; however, the reader is referred to the journal article (Azarbakht et al 2021) for more details. This method is then applied to a case study regarding earthquake drills and evacuation and finally some conclusions drawn.

2. Methodology

As mentioned in the previous section, decision making in 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 the Technique for Order of Preference by Similarity to Ideal Solution (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 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 the best action is “no action”. 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), the method is adapted here in the case of OEF in order to systematically compare possible OEF mitigation actions (Azarbakht et al 2021). The final output 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 below for a hypothetical example but the method can be applied to help guide other decisions in the context of OEF.

3. Earthquake drills and evacuation

Community earthquake drills aim at simulating the scenarios that might accompany a serious earthquake to improve disaster preparedness. This is an opportunity for the community residents to speak freely about scenarios that are too frightening and chaotic. The quality of the drill exercise is dependent on the skills of both planners and participants. Additionally, a large scale community-based earthquake drill has the power to change the political climate of support for such activities (Simpson 2002).

Evacuation is the most difficult and disruptive decision that authorities could make prior to an earthquake or during an aftershock sequence. Evacuation as a mitigation action is likely rarely cost-effective (e.g. Van Stiphout et al. 2010). That is why we choose earthquake drills and evacuation as two contrasting mitigation actions to be compared with taking no action. The input variables for this situation is summarised in Table 1. As seen in Table 1, we have assumed that the population of the community is 100,000, that a severe earthquake will cause injuries to 2 per cent of the population and kill 0.4 per cent (Van Stiphout et al. 2010) in the absence of any mitigation actions. The annual cost of an earthquake drill is taken as $150,000, the cost of an injury equal to $10,000 per person, and the cost of a casualty as $1,000,000 per person. Finally, it is assumed that the earthquake drill will reduce the injuries and casualties by a factor of 5, and the evacuation will eliminate the entire risk of casualties and injuries. Evacuation will cost $500 per person per day. Hence, the total evacuation cost is the product of $500, the community population and the duration of the crisis. A comprehensive sensitivity calculations are also available in the original manuscript (Azarbakht et al 2021) for interested readers.

Table 1. Input parameters for earthquake drills and evaluation in a community example.

Type of parameter	Value
Crisis period	7 days
Community population	100,000
A severe earthquake scenario with 2 % injury and 0.4 % casualty (no action)	
Annual earthquake drill cost	$150,000
Injury cost	$10,000/person
Casualty cost	$1,000,000/person
Annual earthquake drill will reduce the injury and casualty by a factor of	5
Evacuation cost	$500 per person per day
Weightings of each criterion, [Wdirect_cost, Wdeath, Winjury]	[1/3 1/3 1/3]

The results are shown in Figure 1 and 2. As seen in Figure 1, an earthquake drill is recommended for all PGA thresholds and it is preferred over evacuation by a considerable distance. Additionally, the benefit-to-cost ratio for earthquake drills is always greater than unity; however, evacuation, at least within the assumed variables here, is not recommended financially. The level of financial feasibility is shown in Figure 2 where an earthquake drill is highly cost-beneficial up to 0.35g, clearly cost-beneficial between 0.4g and 0.5g, moderately cost-beneficial between 0.55g and 0.7g, and marginally cost-beneficial between 0.75g and 0.85g and not cost-beneficial beyond 0.9g.

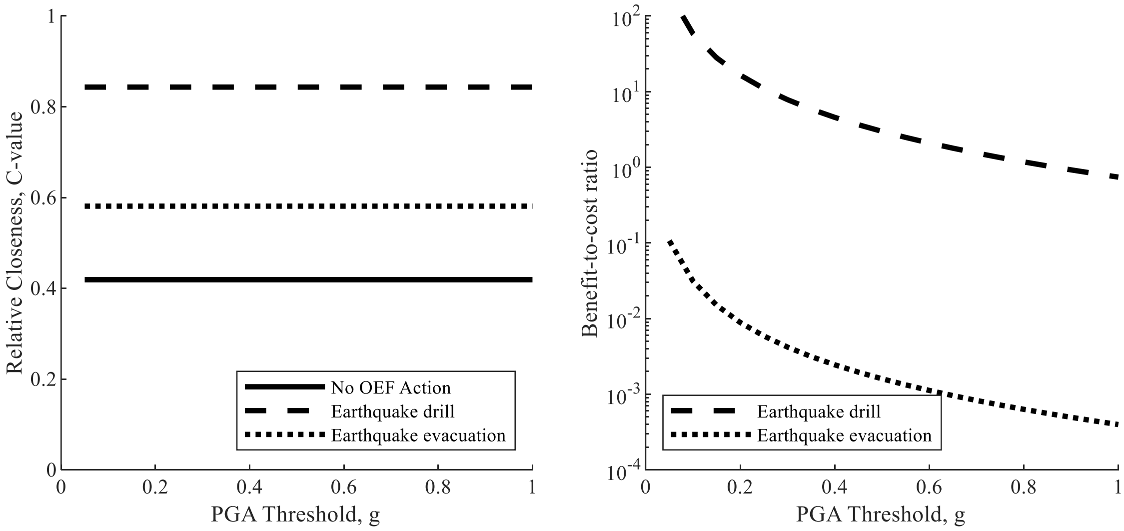

Figure 1. (left): C versus different PGA thresholds, (right): R versus PGA thresholds for different OEF actions for earthquake drills in a community example.

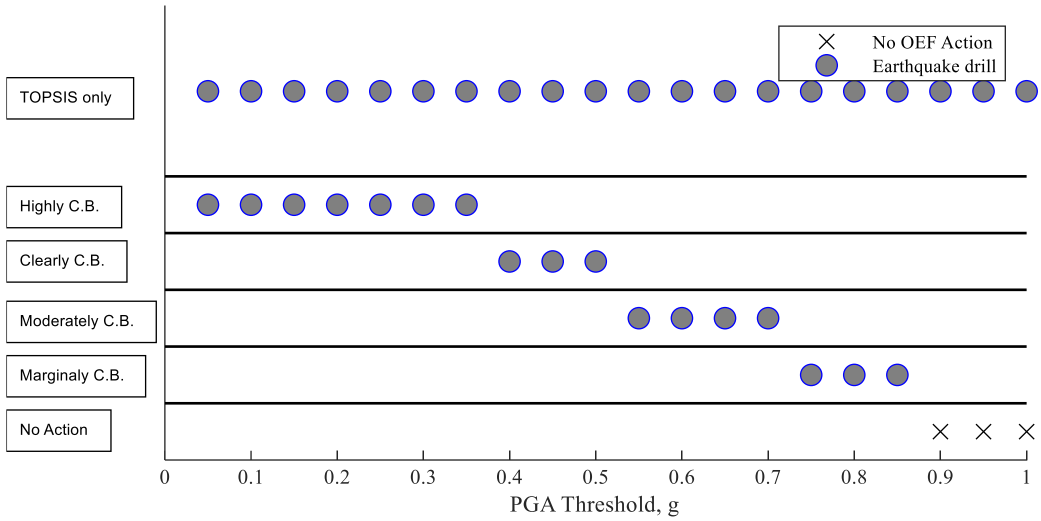

Figure 2 The final result of the TOPSIS only algorithm (top row) and the combination of TOPSIS and cost-benefit analysis for the community example.

4. Conclusions

This study has introduced a new approach to systematically investigate the effectiveness of mitigation actions during a period of heightened seismicity in the context of operational earthquake forecasting. A recently proposed decision support algorithm for early warning systems has been adapted to the problem of operational earthquake forecasting. This algorithm has been combined with a cost-benefit analysis to examine the financial benefits of the recommended actions. A hypothetical case was studied regarding earthquake drills and evacuation for a community. The results show that mitigation actions are beneficial if damage is caused by low shaking levels and when the actions are cheap enough and can mitigate a significant portion of the underlying risk. The employed approach has the potential to be adapted to various contexts. Tailoring the methodology for a specific end user is a vital next step.

Acknowledgements

This study was supported by the European Union's Horizon 2020 research and innovation programme under grant agreement No 821046, project TURNkey (Towards more Earthquake-resilient Urban Societies through a Multi-sensor-based Information System enabling Earthquake Forecasting, Early Warning and Rapid Response actions). We thank the partners of Workpackage 5 of TURNkey, and particularly Professor Carmine Galasso and Dr Gemma Cremen, and the project management team for their comments on these analyses.

References

Azarbakht, A., Rudman, A., & Douglas, J. (2021). A decision-making approach for operational earthquake forecasting. International Journal of Disaster Risk Reduction, 66, https://doi.org/10.1016/j.ijdrr.2021.102591.

Azarbakht, A., Ebrahimian, H., Jalayer, Fatemeh., & Douglas, J. (2021). Variations in hazard during earthquake sequences between 1995 and 2018 in western Greece as revealed by a Bayesian ETAS model. Geophysical Journal International, (under revision).

Azarbakht, A., Cremen, G., Darzi, A., Fayjaloun, R., Galasso, C., Gehl, P., Halldorsson, B., Iasio, C., Guerin Marthe, S., Negulescu, C., Zuccolo, E., and Douglas, J. (2020). Report on the limits and potential applications of current state-of-the-art OEF, EEW and RRE systems for European conditions. Deliverable 3.4 (part II), TURNkey project (https://earthquake-turnkey.eu/).

Caterino, N., Iervolino, I., Manfredi, G., & Cosenza, E. (2008). Multi-criteria decision making for seismic retrofitting of RC structures. Journal of Earthquake Engineering, 12(4), 555-583.

Convertito, V., & Zollo, A. (2011) Assessment of pre-crisis and syn-crisis seismic hazard at Campi Flegrei and Mt. Vesuvius volcanoes, Campania, southern Italy, Bulletin of volcanology, 73(6), 767-783.

Cremen, G., & Galasso, C. (2021). A decision-making methodology for risk-informed earthquake early warning. Computer-Aided Civil and Infrastructure Engineering, 36(6), 747-761.

Douglas, J., & Azarbakht, A. (2021). Cost–benefit analyses to assess the potential of Operational Earthquake Forecasting prior to a mainshock in Europe. Natural Hazards, 105(1), 293-311.

Field, E.H., & Milner, K.R. (2018) Candidate products for operational earthquake forecasting illustrated using the HayWired planning scenario, including one very quick (and not-so-dirty) hazard-map option, Seismological Research Letters, 89(4), 1420-1434.

Field, E. H., Jordan, T. H., Jones, L. M., Michael, A. J., Blanpied, M. L., & Workshop Participants. (2016). The potential uses of operational earthquake forecasting. Seismological research letters, 87(2A), 313-322.

Goltz, J. D. (2015). A further note on operational earthquake forecasting: An emergency management perspective. Seismological research letters, 86(5), 1231-1233.

Guha-Sapir, D., et al. (2016) EM-DAT: international disaster database, Universit Catholique de Louvain Brussels Belgium.

Gulia, L., Tormann, T., Wiemer, S., Herrmann, M., & Seif, S. (2016). Short-term probabilistic earthquake risk assessment considering time-dependent b values. Geophysical Research Letters, 43(3), 1100-1108.

Hwang, C. L., & Yoon, K. (1981). Methods for multiple attribute decision making. In Multiple attribute decision making (pp. 58-191). Springer, Berlin, Heidelberg.

Jordan, T. H., Marzocchi, W., Michael, A. J., & Gerstenberger, M. C. (2014). Operational earthquake forecasting can enhance earthquake preparedness.

Jordan, T. H. (2013). Lessons of L'Aquila for operational earthquake forecasting, Seismological Research Letters 84 (1): 4–7.

Jordan, T.H., et al. (2011) Operational earthquake forecasting, State of knowledge and guidelines for utilisation. Annals of Geophysics, 54(4).

Jordan, T. H., & Jones, L. M. (2010). Operational earthquake forecasting: Some thoughts on why and how. Seismological Research Letters, 81(4), 571-574.

Lettieri, E., et al. (2009) Disaster management: findings from a systematic review, Disaster Prev Manag Int J 18:117–136.

Marzocchi, W. (2012). Putting science on trial. Physics World, 25(12), 17.

Mileti, D. S., & Peek, L. (2000). The social psychology of public response to warnings of a nuclear power plant accident. Journal of hazardous materials, 75(2-3), 181-194.

Peruzza, L., et al. (2017) PSHA after a strong earthquake: hints for the recovery, Annals of Geophysics.

Quarantelli, E. L. (Ed.). (1998). What is a disaster?: perspectives on the question. Psychology Press.

Ritchie, H., (2014) "Natural Disasters", Published online at OurWorldInData.org, Retrieved from: 'https://ourworldindata.org/natural-disasters' [Online Resource]

Simpson, D. M. (2002). Earthquake drills and simulations in community-based training and preparedness programmes. *Disasters*, *26*(1), 55-69.

Van Stiphout, T., Wiemer, S., & Marzocchi, W. (2010). Are short-term evacuations warranted? Case of the 2009 L'Aquila earthquake. Geophysical Research Letters, 37(6).

Wang, Z. (2015). Predicting or forecasting earthquakes and the resulting ground-motion hazards: A dilemma for earth scientists. Seismological research letters, 86(1), 1-5.

Wang, K., & Rogers, G. C. (2014). Earthquake preparedness should not fluctuate on a daily or weekly basis. Seismological research letters, 85(3), 569-571.

Woo, G., & Marzocchi, W. (2014). Operational earthquake forecasting and decision-making. In Early Warning for Geological Disasters (pp. 353-367). Springer, Berlin, Heidelberg.