12th National Conference on Earthquake Engineering
Salt Lake City, Utah
27 June - 1 July 2022

Hosted by the Earthquake Engineering Research Institute

A Novel People-Centered Approach to Modeling and Decision Making on Future Earthquake Risk

G. Cremen[1], C. Galasso[2,3], and J. McCloskey[4]

ABSTRACT

Numerous approaches to earthquake risk modeling and quantification have already been proposed in the literature and/or are well established in practice. However, most of these procedures are designed to focus on risk in the context of current static exposure and vulnerability, and are therefore limited in their ability to support decisions related to the future, as yet partially unbuilt, urban landscape. This paper outlines an end-to-end risk modeling framework that explicitly addresses this specific challenge. The framework is designed to consider the earthquake risks of tomorrow's urban environment, using a simulation-based approach to rigorously capture the uncertainties inherent in future projections of exposure as well as physical and social vulnerability. The framework also advances the state-of-practice in future disaster risk modeling by additionally: (1) providing a harmonized methodology for integrating physical and social impacts of disasters that facilitates flexible characterization of risk metrics beyond physical damage/asset losses; and (2) incorporating a participatory, people-centered approach to risk-informed decision making. It can be used to support decision making on policies related to future urban planning and design, accounting for various stakeholder perspectives on risk.

Introduction

This study proposes a comprehensive end-to-end simulation-based, people-centered framework for quantifying and decision making on future earthquake risk. The framework is designed to overcome some critical limitations of existing earthquake risk-modeling approaches. These include a predominant focus on static earthquake risk in the context of the present day and a failure of forward-looking tools to consider the effect of sociodemographic changes, which are an important part of community resilience planning [1] that enable disproportionate consequences of disasters on vulnerable groups to be accounted for [e.g., 2]. The proposed framework incorporates a harmonious integration of physical and social impact quantification that: (1) explicitly accounts for uncertainties in the future projections of underlying variables (e.g., asset location and structural or nonstructural features, building fragility, age and income profile of inhabitants); and (2)

[1] Lecturer (Assistant Professor), Department of Civil, Environmental and Geomatic Engineering, University College London, UK (email: g.cremen@ucl.ac.uk)

[2] Professor, Department of Civil, Environmental and Geomatic Engineering, University College London, UK (email: c.galasso@ucl.ac.uk)

[3] Associate Professor, Centro di Formazione e Ricerca per la Mitigazione del Rischio Sismico (ROSE), Scuola Universitaria Superiore, Italy (email: carmine.galasso@iusspavia.it)

[4] Professor, School of Geosciences, University of Edinburgh, UK (email: John.McCloskey@ed.ac.uk)

Cremen G, Galasso C, McCloskey, J. A novel people-centered approach to modeling and decision making on future earthquake risk. *Proceedings of the 12th National Conference in Earthquake Engineering*, Earthquake Engineering Research Institute, Salt Lake City, UT. 2022.

facilitates a flexible approach to risk measurement beyond conventional asset losses. The framework can be used as part of an effective support environment for urban development decision making. Here, the term 'environment' indicates the potential for iterative engagement with stakeholders to evolve optimized low-risk solutions within externally imposed constraints. Hence, the proposed framework incorporates a participatory approach to risk understanding and quantification that can account for diverse stakeholder priorities towards different dimensions of risk [3].

Proposed Framework

The proposed framework is presented in Fig. 1. It is composed of four main calculation stages (or modules): (1) Seismic Hazard Module; (2) Engineering Impact Module; (3) Social Impact Module; and (4) Decision Module. For a specific temporal instant in the future, each *i*th iteration of the framework evaluates the risk associated with a set of "hard'" (i.e., directly related to the physics of the built environment, such as urban design and building code improvement) and/or "soft" (e.g., social safety nets, post-disaster financing or insurance) policies to be implemented, with the ultimate aim of identifying the policy option leading to the minimum risk outcome. In this context, risk refers to the collective values of collaboratively selected risk metrics that are weighted in line with the priorities of stakeholders (e.g., administrative authorities responsible for future urban development and related policy implementation and/or relevant community representatives). Monte Carlo simulation is used to capture uncertainties in the calculations, such that random variables included as part of Modules (1) to (3) are sampled N_s times at the specific temporal instant of interest, to produce the risk-metric values that act as input to Module (4) in each iteration. During the first iteration, the framework provides flexibility to modify the considered risk metrics through a participatory process, which may require additional data collection and calculations in Modules (2) and (3). Each component of the framework is now briefly explained.

1. **Seismic Hazard Module:** This module contains calculations related to the earthquake hazard of interest. This hazard could be expressed in the form of a scenario earthquake, with a prescribed rupture (i.e., magnitude, location, etc.) that produces either deterministic or uncertain ground-motion fields across target locations. The hazard could also be represented probabilistically, accounting for uncertainty in the rupture features within a specified time frame [e.g., 4]. However, time-based seismic hazard assessments are more likely to appeal to the insurance sector rather than public policy makers [5]. The scenario approach (as opposed to probabilistic seismic hazard analysis) is particularly beneficial for communicating risk to a policy maker or to communities, who may not have an intuitive sense of probability and the dynamic discounting of financial assets [5]. Since ground-motion variability can dominate the uncertainty associated with scenario-based seismic risk calculations [e.g., 6], adopting a fully deterministic earthquake scenario is useful for obtaining a more comprehensive understanding of risk changes that are specifically related to the different policies of interest. The outputs of this module are ground-motion field estimates across a number of locations of interest (i.e., close to where assets/infrastructure at risk are located).
2. **Engineering Impact Module:** This module conducts calculations for assessing earthquake-induced physical damage (structural and nonstructural) to the future built environment (including buildings and critical infrastructure). The outputs of this module are damage and/or direct asset loss estimates (e.g., repair cost, casualties, asset downtime), including collective impacts associated with interconnected infrastructure. The exact spatial and physical configuration of the built environment (denoted as "Conditional Urban Plan" in Fig. 1) can depend on projections of future population and land-use [7] as well as the potentially time-dependent vulnerability of engineering assets [e.g., 8]. Any proposed hard policies (such as structural or nonstructural improvements, building-code upgrades, and critical infrastructure relocation) will also influence the details of the future built environment.
3. **Social Impact Module:** This module is used to enrich the asset loss estimates of the **Engineering Impact Module** on the basis of socio-economic and/or demographic projections. For example, **Engineering Impact Module** calculations of damage to commercial buildings could be combined in the **Social Impact Module** with data on the industrial flow of goods, to determine earthquake-induced impacts on the

productivity of different economic sectors [6]. This module also facilitates the disaggregation of asset losses in terms of socio-economic/demographic factors such as income level, age, or gender, which could be derived from census data or household surveys (among other sources). For instance, road network downtime outputs of the **Engineering Impact Module** can be attributed spatially to different socio-economic groupings, to determine accessibility losses across specific wealth classes [9]. The introduction of soft policies (related to disaster insurance or enhanced post-event liquidity access, for instance) can influence the coping capacity or response of different social systems to the hazard of interest, and can therefore alter the data examined in this module. The outputs of this module are used to construct risk metrics for decision making. These metrics could include, for instance, the expected proportion of various socio-demographic groups that are displaced because of damage to nodes of their social network (e.g., workplaces, schools, houses) as well as the extent to which those with low income disproportionately experience losses related to residential damage.

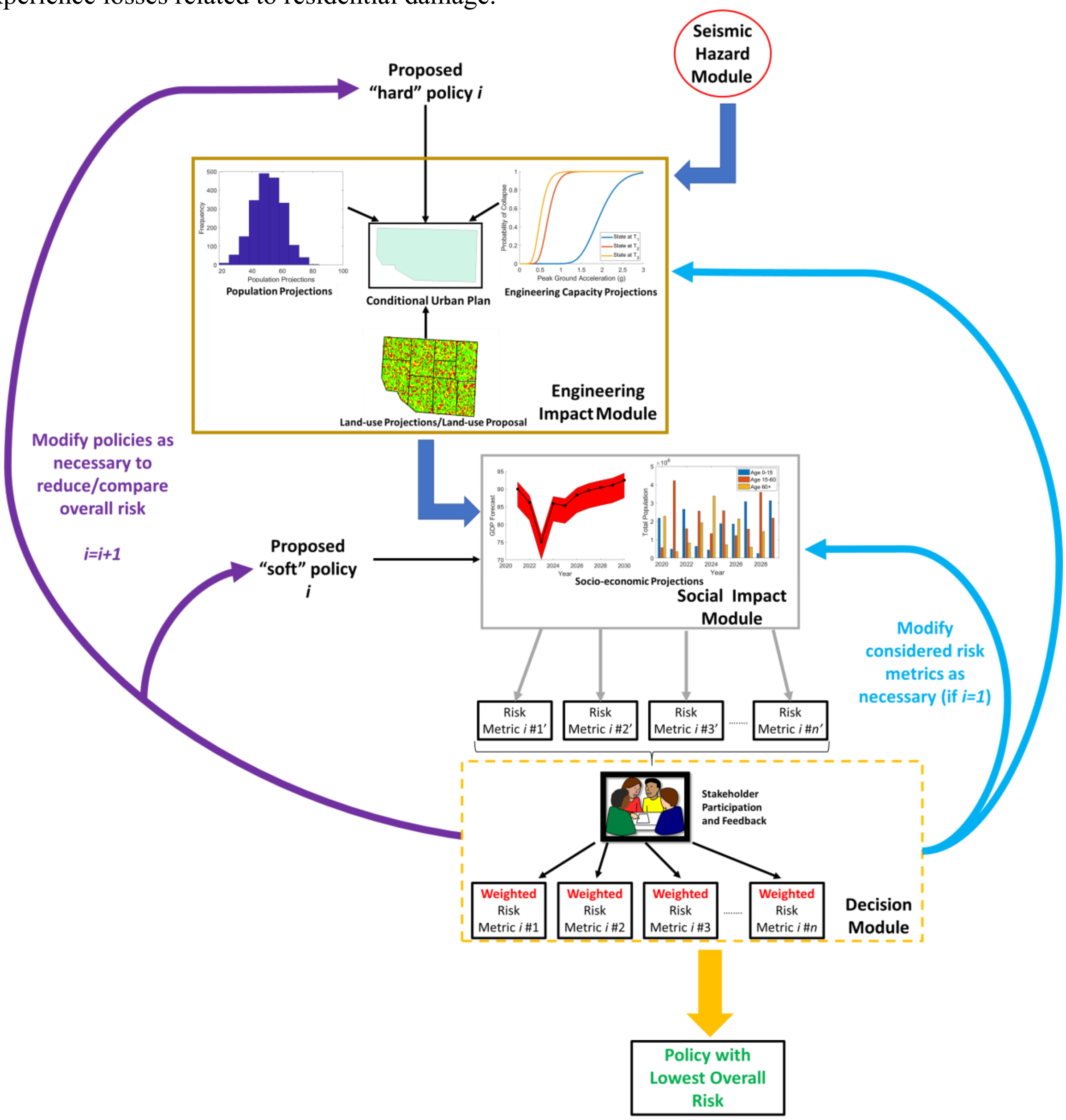

Figure 1. Proposed simulation-based framework for modeling and decision making on future earthquake risk, through a people-centered approach.

4. **Decision Module:** This module leverages stakeholder feedback in a participatory process to determine: (1) the n_{final} ultimate risk metrics to be considered based on outputs of the **Social Impact Module**. This step is necessary for the first framework iteration only, when $n_{initial}$ metrics initially proposed by the modeler are modified and finalized according to stakeholder perspectives; and (2) the weights to be placed on each finalized risk metric, in line with decision-maker risk priorities. Values for (2) can be obtained according to the analytic hierarchy process [10], for instance. This procedure involves the stakeholders comparing the relative importance of pairs of risk metrics on a scale from 1/9 to 9, where 1 indicates both metrics are equally significant, 5 implies that risk metric #1 is strongly important over risk metric #2, 9 indicates that risk metric #1 is significantly more important than risk metric #2, and reciprocal values imply inverse opinions. Weights w_j for each metric are equivalent to the principal right eigenvector of a $n_{final} \times n_{final}$ matrix that summarizes the quantitative results of the comparison.
5. **Policy with Lowest Overall Risk:** This calculation uses the outputs of the **Decision Module** across all n_{policy} examined policies in a decision-making algorithm, to determine the overall risk associated with each policy. TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) [11] is one such decision-making approach that could be used in this module. This multi-criteria decision making methodology would deem the best policy to be that with the highest S_i value according to:

$$S_i = \frac{y_i^-}{y_i^- + y_i^+} \tag{1}$$

where $y_i^- = \sqrt{\sum_{j=1}^{n_{final}} (v_j^- - r_{ij}w_j)^2}$, $y_i^+ = \sqrt{\sum_{j=1}^{n_{final}} (v_j^+ - r_{ij}w_j)^2}$, $r_{ij} = \frac{x_{ij}}{\sum_{k=1}^{n_{policy}} {x_{kj}}^2}$, x_{ij} is the magnitude of the jth risk metric for the ith policy, v_j^+ and v_j^- respectively denote the most ideal (i.e., minimum) and most non-ideal (i.e., maximum) values of $r_{ij}w_j$ across all examined policies, and all other variables are as previously defined. Thus, the optimum policy can change depending on stakeholder's priorities towards different risk types. This feature of the proposed framework reflects the critical importance of a collaborative risk assessment process that integrates stakeholder participation, capacity, and feedback [3].

Conclusions

This paper has outlined an end-to-end simulation-based framework for people-centered modeling on risks associated with future earthquakes, which addresses some significant gaps associated with state-of-practice approaches to future seismic risk assessment. The framework may be leveraged to support decision making on urban planning or design as well as related policies, accounting for varied stakeholder perspectives and priorities around the concept of risk as well as the multitude of uncertainties inherent in future projections of urban landscapes. We anticipate that the framework has the potential to play a leading role in preparing societies for future challenges related to earthquake hazards, directly addressing a need outlined in both the Sendai Framework for Disaster Risk Reduction [12] and the United Nations Sustainable Development Goal 11 [13]. While this specific paper focuses on earthquake risk, the proposed framework can be easily extended to other (or multiple) natural hazards with some ad-hoc modifications. For instance, future risks from river and flash flood hazard in urban/rural environments could be modelled by switching the positions of the Hazard and Engineering Impact Modules. This alteration would be necessary to account for the hazard's dependence on environmental change resulting from socioeconomic development; the expansion of impermeable surfaces (e.g., concrete or paved surfaces replacing natural ground cover) decreases infiltration and increases runoff during precipitation events.

Acknowledgements

All authors acknowledge funding from UKRI GCRF under grant NE/S009000/1, Tomorrow's Cities Hub.

References

1. Sutley E, van de Lindt JW, Peek L. Community-level framework for seismic resilience. I: Coupling socioeconomic characteristics and engineering building systems. *Natural Hazards Review* 2017; **18** (3): 04016014.

2. Verschuur J, Koks EE, Haque A, Hall J. Prioritising resilience policies to reduce welfare losses from natural disasters: A case study for coastal Bangladesh. *Global Environmental Change* 2020; **65**: 102179.

3. Galasso C, McCloskey J, Pelling M, Hope M, Bean C, Cremen G, Guragain R, Hancilar U, Menoscal J, Mwelu K, Phillips J. Editorial: Risk-based, pro-poor urban design and planning for tomorrow's cities. *International Journal of Disaster Risk Reduction* 2021; **58**: 102158.

4. Iacoletti S, Cremen G, Galasso C. Advancements in multi-rupture time-dependent seismic hazard modeling, including fault interaction. *Earth-Science Reviews* 2021; **220**: 103650.

5. Bonstrom H, Corotis R, Porter K. Overcoming public and political challenges for natural hazard risk investment decisions. *Journal of Integrated Disaster Risk Management* 2012; **2**(1): 26-48.

6. Markhvida M, Walsh B, Hallegatte S, Baker J. Quantification of disaster impacts through household well-being losses. *Nature Sustainability* 2020; **3**: 538-547.

7. Seto KC, Guneralp B, Hutyra LR. Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. *Proceedings of the National Academy of Sciences* 2012; **109**(40): 16083-16088.

8. Lallemant D, Burton H, Bullock Z, Kiremidjian A. A framework and case study for earthquake vulnerability assessment of incrementally expanding buildings. *Earthquake Spectra* 2017; **33**(4): 1369-1384.

9. Miller M, Baker J. Coupling mode-destination accessibility with seismic risk assessment to identify at-risk communities. *Reliability Engineering and System Safety* 2016; **147**: 60-71.

10. Saaty TL. *The Analytic Hierarchy Process: Planning, Priority Setting, and Resource Allocation and Strength of Materials*. McGraw-Hill International Book Co.: New York, 1980.

11. Yoon KP, Hwang C-L. *Multiple Attribute Decision Making: An Introduction*. Sage Publications: California, 1995.

12. UNISDR. *Sendai Framework for Disaster Risk Reduction 2015-30*. United Nations International Strategy for Disaster Reduction: Geneva, 2015.

13. Klopp JM, Petretta DL. The urban sustainable development goal: Indicators, complexity and the politics of measuring cities. *Cities* 2017; **63**: 92-97.