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Earthquake iso-nuisance and iso-damage maps for the risk management of induced seismicity: Initial concepts

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Summary

The earthquake iso-nuisance and iso-damage maps show the spatial distribution of earthquake magnitude required to reach a specific level of nuisance and damage, considering human exposure and surficial geological conditions. As a first approach, the estimations of nuisance and damage rely on Vs30 modeling for the seismic site amplification and population density for the human exposure variable. Earthquake iso-nuisance and iso-damage maps can provide valuable assistance in effectively managing current and future cases of induced seismicity. They provide an overview of the impact of a wide range of earthquake scenarios. They can function as the base to guide the development of red-light thresholds for different industrial activities once the appropriate trailing seismicity factor is defined for a given activity. This study is the first of a two-part presentation series; in this part, we describe the initial concepts and methodology required to develop earthquake iso-nuisance and iso-damage. The second part is dedicated to the maps generated in Alberta using this methodology.

Theory and Method

The Iso-nuisance and Iso-damage maps show the spatial distribution of magnitudes required to reach a nuisance and damage threshold, respectively. In this analysis, we closely follow the methodology described by Schultz et al. (2021a, 2021c) to generate iso-nuisance and iso-damage maps:

- **Define Impact and earthquake node grids**. The impact grids contain information about population density and Vs30 (time-averaged shear wave velocity of the upper 30 m). Vs30 is used as a proxy value to estimate site amplification. The earthquake nodes define the locations of synthetic earthquakes.
- **Generate synthetic earthquakes**. For each earthquake node, a range of synthetic earthquakes is defined (magnitudes and depths) for a single realization. Multiple realizations are simulated following the Monte Carlo method to generate a range of earthquake impact scenarios.
- **Generate synthetic ground motion catalogs**. Given the distance and magnitude of the earthquake, we use Ground Motion Prediction Equations (GMPEs) to estimate the corresponding Peak Ground Acceleration (PGA) and Peak Ground Velocity (PGV) at each impact cell. The GMPEs are calibrated according to the site amplification (Vs30). We Include perturbation (aleatory uncertainty) for the ground motions, the Vs30, and population data.
- **Calculate Nuisance and Damage**. The probability of nuisance and damage for a simulated earthquake is estimated using Nuisance and Fragility (damage) functions (E.g., nuisance functions from Schultz et al., (2021b) and FEMA (2015). In other words, for a

given ground motion value in an impact cell, we estimate the probability of nuisance and damage per household.

- **Generate Nuisance and Damage curves**. From population density and the probabilities of nuisance/fragility per impact cell, we estimate the total number of households affected per simulated earthquake. Plots of the number of households affected vs. the earthquake magnitude are known as the nuisance and damage plots. Because of the multiple realizations (diverse realizations given by the perturbations and variabilities in the setting), there will be a distribution of households affected for each magnitude. The median of the distributions represents the 50% probability of households affected, and we will refer to it as the median curve for nuisance and damage plots. Nuisance and damage curves are calculated for each earthquake node.
- **Generate iso-nuisance, iso-damage and combination maps**. Given nuisance and damage tolerance thresholds, iso-nuisance and iso-damage maps are created. One example of nuisance tolerance threshold would be a 50% probability of causing nuisance to 30,000 households. For a given earthquake node, its median nuisance curve is used to determine the earthquake magnitude that causes nuisance at the threshold level. This determination is performed using the same nuisance threshold for all nodes and the results are presented as an iso-nuisance map. An iso-damage map is created in a similar fashion using a damage tolerance threshold. Finally, a combination map results from choosing the lowest magnitude value from the iso-nuisance and iso-damage maps at each earthquake node location.

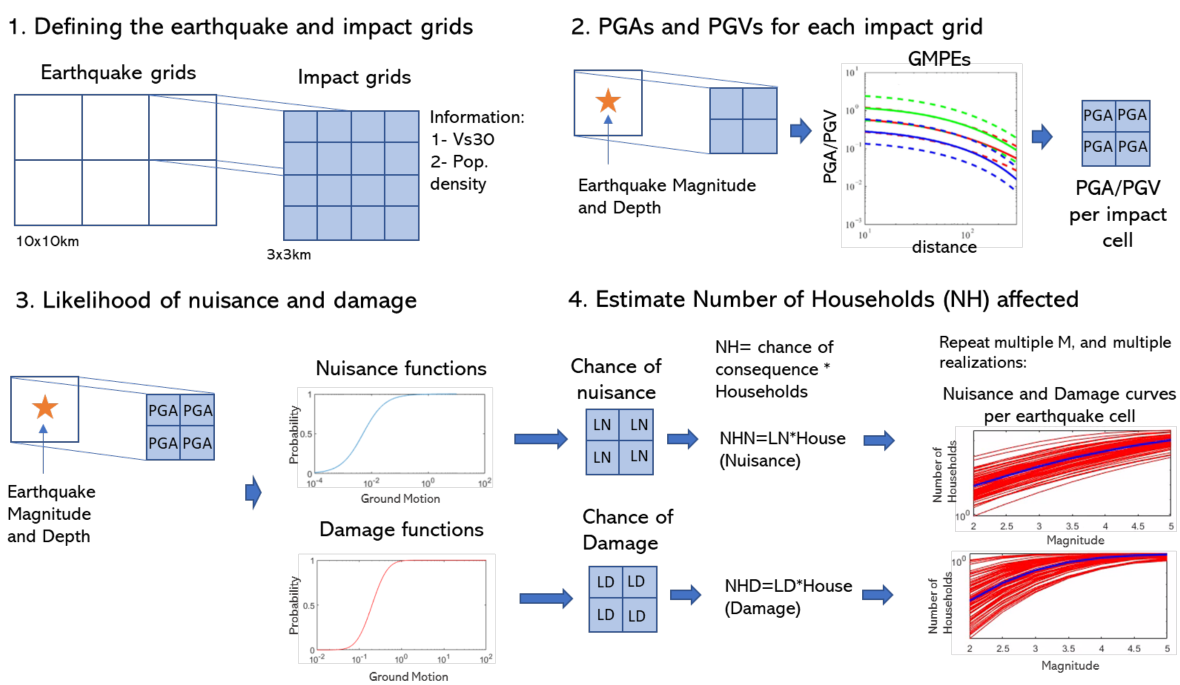

Figure 1. Sketch of the methodology used to generate Nuisance and Damage Curves.

Discussion

In traffic-light protocols for hydraulic fracturing-induced seismicity, the operator must cease operations immediately if a red light event occurs. For instance, in the area defined by Subsurface Order No. 2, the current red light for hydraulic fracturing activities in the Duvernay Fm. is M>4 (Alberta Energy Regulator, 2015). Schultz et al. (2021a) developed a risk-informed strategy for choosing red-light thresholds based on a combination of datasets to simulate spatially heterogeneous nuisance and damage impacts. As a factor in their simulation, they include a factor called "trailing seismicity," which accounts for the seismicity after a red-light event. However, in the setting shown above for iso-nuisance and iso-damage maps, we do not include the trailing seismicity factor required to generate "red-light" maps from the iso-nuisance and iso-damage estimations. Therefore, the iso-nuisance and iso-damage maps should not be used directly to guide traffic light protocols but as a map that shows the potential impact given an earthquake magnitude. To properly delineate maps applicable to traffic light protocols ("red-light" maps), a trailing seismicity factor should be included:

$$M_{red} = M_{limit} - dM_{trailing} \text{ , (1)}$$

Where M_{limit} refers to the magnitude indicated by the Iso-nuisance and Iso-damage maps at a particular tolerance level (E.g., 50% of causing nuisance to 30,000 households, and 50% probability of causing damage to 3 households). $dM_{trailing}$ refers to the factor associated with the trailing seismicity since it is possible that an event larger than the earthquake that triggers the red light occurs after stopping the operations. Finally, M_{red} refers to the red-light magnitude that corresponds to a particular tolerance level. The trailing seismicity factor, which is key in determining the appropriate red-light magnitude, ultimately depends on the tolerance to risk from post-operational seismicity. The same should be said about the magnitude M_{limit}, which ultimately depends on the levels of nuisance and damage tolerated. Furthermore, other factors beyond the population distribution might be considered, such as critical infrastructure, warranting a different tolerance level.

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