NOTE 2b

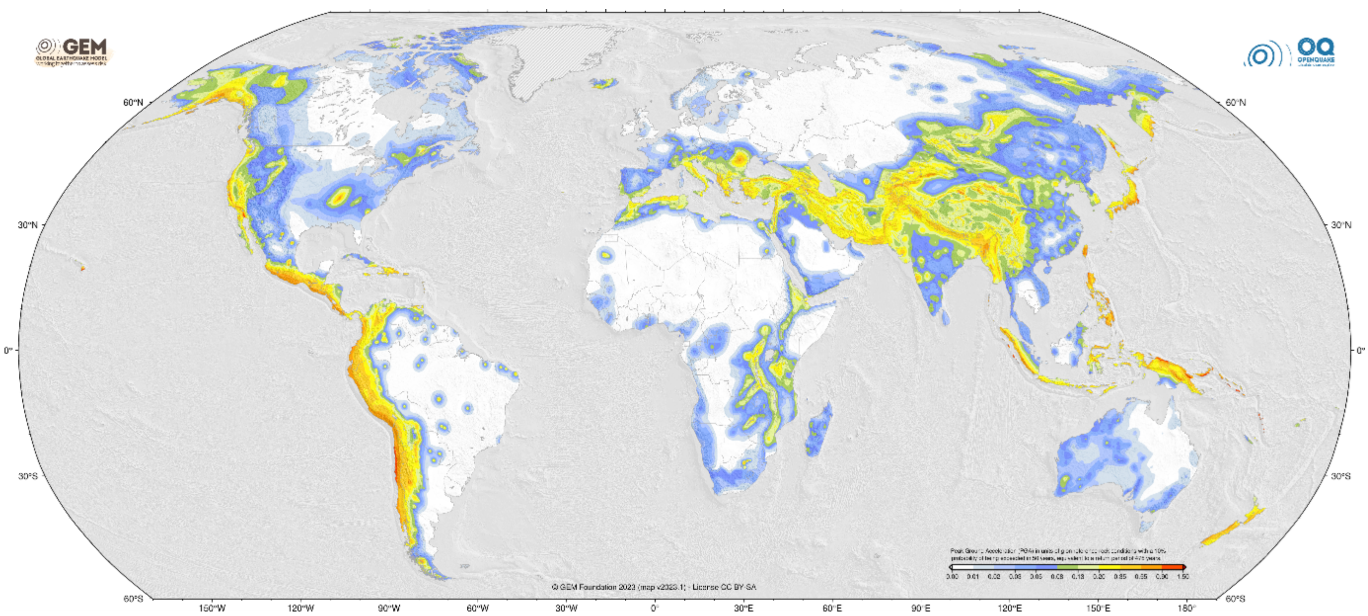
Earthquake Risk Modeling

Earthquakes are among the most catastrophic hazards. They can have large-scale impacts on entire regions and cities, occur with little to no warning, and are often associated with significant casualties and physical damage to the built environment. Earthquakes can also trigger cascading hazards, such as aftershocks, tsunami, landslides, and liquefaction.

Earthquakes can occur anywhere, but the vast majority of earthquakes (and the most severe) are of geological origin, resulting from the deformation and collision of continents (tectonic plates). They therefore tend to occur in the vicinity of plate boundaries, along tectonic fault lines (Figure 1). Other types of earthquakes can be triggered by volcanic activity or even man-made activity (such as mining, collapse of hydrological dams, or major explosions). Man-made earthquakes are generally much less severe than geological earthquakes. This note focuses on geological earthquakes only.

Unlike floods or windstorms, earthquakes tend to have long recurrence intervals in any given location, ranging from several decades to several thousand years. As a result, historical data are often scare and sporadic, and recent experience is a poor indicator of earthquake risk. To understand the likelihood and severity of earthquakes, the physical phenomena and their associated impacts must be modeled.

Figure 1: Seismic hazard map (475-year return period)



Source: Global Earthquake Model, "Global Seismic Hazard Map," 2023, https://www.globalquakemodel.org/product/global-seismic-hazard-map.

Note: Ground shaking from least to most severe is indicated by blue, yellow, orange, and red coloring.

Earthquake Modeling Approach

Developed in the 1980s, earthquake risk models were among the first to combine modules on hazard, exposure, vulnerability, and loss (see Note 2 on catastrophe risk modeling for more details); these are now commonly used in the risk financing industry.

The hazard module includes:

a) An estimation the likelihood and severity of an earthquake, including location, magnitude, and annual probability. This includes an inventory of all known seismic faults and an estimate of the associated earthquake frequency (recurrence) along these faults. Instrumental records over the past century are too short to provide a realistic estimation of the frequency of earthquakes (in this respect earthquakes differ from tropical cyclones and floods). Calculation of earthquake recurrence is therefore informed by geological evidence using satellite imagery, dating techniques, and GPS systems. For completeness, instrumental earthquake records are included in the model, and are used to derive potential stochastic events using statistical and physics-based principles.

b) The quantification of ground shaking severity at each asset location. Ground shaking is estimated as a function of the location of each asset with respect to the epicenter and as a function of earthquake magnitude. Local ground conditions (e.g., soft soil, hard rock) and topography are also considered, as they can have an amplification effect on ground shaking. Common ground-shaking metrics are peak ground acceleration and Modified Mercalli Intensity (MMI).

Some hazard modules also include secondary effects such as tsunami (wave height at the short line, inland inundation); these can also be modeled using hydrologic models (e.g., wave propagation).

The ***exposure*** module uses detailed inventories of built assets and population. The exposure module consists of a detailed inventory of assets, including location details (e.g., latitude and longitude, street address), replacement cost, and asset characteristics (e.g., construction type, year built, number of stories, bracing system, soft stories).

Finally, the ***vulnerability*** module uses available knowledge of earthquake-related physical damage to various types of buildings and infrastructure. Damage to each asset is estimated based on ground-shaking intensity, historical observations of earthquake damage, or numerical simulation of buildings based on their construction characteristics.

The combination of these modules enables the probabilistic estimation of losses, either total (ground-up) losses, or retained and transferred losses when financial conditions are applied (e.g., limits, deductibles).[1]

[1]See for example W. D. Smith et al., "Earthquake Risk Assessment for Insurance Purposes," 2004, https://db.nzsee.org.nz/2004/Paper24.pdf.

Implications for Disaster Risk Financing and Insurance

The modeling of possible earthquake scenarios using the approach above enables the development of a loss curve (risk profile) to estimate likely losses as a function of annual probability for individual assets or a whole portfolio (e.g., buildings, people, infrastructure). Such modeling is crucial to inform the development of a disaster risk financing strategy (see Note 1).

Additionally, risk modeling is used to design earthquake insurance policies and determine their pricing. Examples of indemnity insurance schemes directly informed by earthquake risk models include the Turkish Catastrophe Insurance Pool (TCIP) and the residential insurance cover offered in New Zealand by the Natural Hazard Commission (formerly the Earthquake Commission). Earthquake modeling may also be used to design parametric triggers for risk financing instruments (see Box 1 for the application of modeling to parametric insurance in the Pacific).

Box 1.
Earthquake risk modeling and its application for parametric insurance in the Pacific region

Located on the Ring of Fire, many Pacific island countries are highly vulnerable to earthquake risk, including (but not limited to) Vanuatu, Papua New Guinea, Tonga, Samoa, and Fiji. Since most islands are geographically small, single earthquakes can severely impact entire countries or regions and harm the entire national economy. To better understand earthquake risk in the region and inform risk financing decisions, the World Bank funded the Pacific Catastrophe Risk Assessment and Financing Initiative (PCRAFI). This initiative collected exposure data, created inventories of built assets and population, and compiled country-specific information on hazards and risks (in the Pacific Risk Information System, PACRIS).

In 2011, using the modeling approach described above, the initiative developed a stochastic risk model to estimate probable losses associated with earthquakes (reconstruction costs, emergency losses) and to create earthquake risk profiles for each country. In 2024, the World Bank worked with the Pacific Catastrophe Risk Insurance Company (PCRIC)—the regional risk pool—and private sector experts to develop risk profiles of people impacted, using updated hazard and risk information.

The PCRIC used this information to design parametric insurance products for earthquakes that provide rapid payouts to sovereign governments in the aftermath of disasters. These payouts are triggered within 10 to 20 days after each event and support relief efforts.

For all products, PCRIC used the modeled risk profiles to estimate average annual losses and price the products. The modeled losses were compared with historical losses to minimize basis risk (i.e., the risk that payouts are inadequate or are not triggered when countries experience damage).

Two types of parametric earthquake products have been developed. The first product, implemented between 2016 and 2023, includes an event occurrence–based trigger called “modeled loss” and uses the PCRAFI model to estimate local impacts and calculate damages. Following an event, the epicenter location and the ground-shaking intensities reported by the

United States Geological Survey are matched with the closest hazard event existing in the model database in terms of epicenter and ground shaking. The hazard event is then superposed on the building exposure data, and damage is assessed as a function of hazard intensity (e.g., ground shaking) and building characteristics (e.g., construction type, year built, number of stories). A payout is provided if the resulting damage exceeds a threshold pre-agreed with the government. Such a modeled loss can be calculated rapidly—within a few days after an event has occurred—and is generally associated with relatively low basis risk compared to other types of parametric products (i.e., payouts are connected to modeled damage, so they tend to be provided when actual damage on the ground has occurred). However, it is highly reliant on the quality and robustness of the model.

PCRIC developed a second product in 2024 to address the need for more up-to-date data (because of population growth and urban development). This product uses more recent risk profiles. Instead of a modeled loss trigger, this new product uses a parametric index of people impacted, as this metric has a more direct connection to emergency losses and relief efforts than building damage. This index is based on ground shaking across administrative areas (e.g., districts or villages) and the number of people located in each area (using national census or WorldPop data) who are exposed to ground-shaking intensities greater than MMI VII. A payout is provided if the index exceeds a pre-agreed threshold.

FAQs

What are the key limitations of earthquake risk models?

Damage information remains scarce and sporadic for a number of assets and in particular for critical infrastructure networks. In many countries, such damage information is insufficient to calibrate and validate the model appropriately. Therefore, vulnerability assessments are generally associated with large uncertainties, and these should be taken into account by decision-makers.

In addition, many existing earthquake risk models tend to estimate the likelihood and severity of earthquake ground shaking only—that is, they do not include cascading effects or other hazards (such as aftershocks, tsunami, landslides, and liquefaction) that earthquakes may trigger. Although model adjustments might be applied to account for these cascading perils, research analyzing the compound impact of cascading hazards is still in its infancy.

What is possible if no local data can be obtained?

Global models such as the Global Earthquake Model (GEM) have been developed over the past decade and are the result of academic collaborations between countries. They allow for estimating earthquake losses to the built environment (residential, commercial, and industrial buildings) and to people at subnational level. These models can provide an initial representation of earthquake risk and potential losses. However, users should be aware that these models have not necessarily been validated locally for all countries.

How do I know if I can trust an earthquake risk model?

While earthquake risk models have high degrees of potential bias and uncertainty due to the complexity of the peril being modeled, they are still representations of the physical world and can therefore be tested at various levels to ensure they provide trustworthy risk metrics. The approach to such testing is similar to the approach used for other perils, in that the model needs to be calibrated and validated against historical data. This process that can be particularly complicated in emerging market and developing economies (EMDEs), where historical data are often limited.

Where data are available, the model needs to be validated both at an individual-component level (for example, by comparing modeled and historical data for ground-shaking severity, etc.) and at the output level (for example, by comparing population affected in historical events to population estimated by the model).

Are earthquakes associated with climate change?

Most earthquakes are of geological origin and are therefore not triggered by climate change. Over the long term, however, climate change and associated sea-level rise can have an impact on cascading hazards such as earthquake-triggered tsunami, as rising sea levels can increase tsunami inundation levels. Climate change can also increase the chance that an earthquake will trigger cascading hazards. For example, heavy rainfall can increase the likelihood that landslides will be triggered and can also increase liquefaction risk. In other words, compound risk can increase because of climate change.

Reading List

Grossi, P., and H. Kunreuther, eds. 2005. Catastrophe Modeling: A New Approach to Managing Risk. Springer.

Silva, Vitor, Helen Crowley, Kishor S. Jaiswal, Ana Beatriz Acevedo, Massimiliano Pittore, and Murray Journeay. 2018. "Developing a Global Earthquake Risk Model." https://www.researchgate.net/publication/326426092_Developing_a_Global_Earthquake_Risk_Model/link/5b4ce9050f7e9b240fe4f24c/download?_tp=eyJjb250ZXh0Ijp7ImZpcnN0UGFnZSI6InB1YmxpY2F0aW9uIiwicGFnZSI6InB1YmxpY2F0aW9uIn19.

Smith, W. D., A. B. King, and W. J. Cousins. 2004. "Earthquake Risk Assessment for Insurance Purposes." https://db.nzsee.org.nz/2004/Paper24.pdf.