Training and Communication for Earthquake Risk Assessment

TREQ Project

# Executive summary

June 2022


**Global Earthquake Model (GEM) Foundation**

www.globalquakemodel.org

Description of results and achievements during the TREQ project

# TREQ Executive Summary

Technical report produced in the context of the TREQ project

Version 1.0 – June, 2022

Global Earthquake Model Foundation

**Collaborators**

The authors would like to thank the Municipal offices of the cities of Quito, Cali and Santiago de los Caballeros, for their invaluable contribution to the project. In addition, the authors would like to thank the local partners for their support and contributions. They include, but are not limited to:

| | |
|---|---|
| Ecuador | - Municipio del Distrito Metropolitano de Quito, Secretaría de Seguridad.<br>- Empresa Pública Metropolitana de Agua Potable y Saneamiento de Quito (EPMAPS)<br>- Pontificia Universidad Católica del Ecuador (PUCE)<br>- Universidad de las Fuerzas Armadas (ESPE) |
| Colombia | - Servicio Geológico Colombiano (SGC)<br>- Secretaría de Gestión del Riesgo de Emergencias y Desastres, Alcaldía de Santiago de Cali.<br>- Departamento Administrativo de Planeación, Alcaldía de Santiago de Cali.<br>- Unidad Nacional de Gestión de Riesgo de Desastres (UNGRD)<br>- Área Metropolitana del Valle de Aburrá (AMVA), Medellin<br>- Universidad EAFIT, Medellin |
| Dominican Republic | - Servicio Geológico Nacional (SGN)<br>- Dirección Municipal de Ordenamiento Territorial de Santiago de los Caballeros<br>- Oficina Nacional de Evaluación Sísmica y Vulnerabilidad (ONESVIE)<br>- Universidad Autónoma de Santo Domingo (UASD) |
| Latin America | - Universidad de Costa Rica (UCR), San José, Costa Rica<br>- Universidad Autónoma de Baja California (UABC), Baja California, Mexico<br>- Universidad de El Salvador (UES), San Salvador, El Salvador<br>- United States Geological Survey (USGS |

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The TREQ Project was designed to demonstrate how earthquake hazard and risk assessment can inform decision makers in the development of risk reduction policies, as well as how earthquake risk can be properly communicated to stakeholders and the public in general. Specifically, the project aimed to develop capacity for urban earthquake risk assessment in Latin America, Quito (Ecuador), Cali (Colombia), and Santiago de los Caballeros (Dominican Republic), while the second part aimed to produce training, educational and communication materials to enhance the understanding of earthquake risk worldwide. This program targeted a wide spectrum of stakeholders, categorized into four main groups: governance (decision-makers/public authorities), industry (practitioners and professionals), academia (researchers and professors), and the community.

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# EXECUTIVE SUMMARY

The **Training and Communication for Earthquake Risk Assessment (TREQ) Project** was designed to demonstrate how earthquake hazard and risk assessment can inform decision makers in the development of risk reduction policies, as well as how earthquake risk can be properly communicated to stakeholders and the public in general. The project was organized into two main parts. The first one aimed to develop capacity for urban earthquake hazard and risk assessment in Latin America, Quito (Ecuador), Cali (Colombia), and Santiago de los Caballeros (Dominican Republic); while the second part was to develop training, educational and communication material to enhance the understanding of earthquake risk worldwide. The program was tailored for a wide spectrum of stakeholders, categorized into four main groups: governance (decision-makers/public authorities), industry (practitioners and professionals), academia (researchers and professors), and the community.

This report offers an overview of the work carried out during the 20 months of project activities. The outcomes include 23 deliverables, 15 technical reports, 15 videos on technical training using the OpenQuake-engine (in English and Spanish), 7 videos with material to disseminate the models and results of urban risk assessment in the TREQ cities, and 2 videos for communicating earthquake risk to the general public. The models and results for urban hazard and risk assessment of each city are publicly available in the repository https://github.com/gem/treq-riesgo-urbano, which was designed in Spanish in order to increase the impact and usefulness for the local audience. A dedicated website for OpenQuake online training (https://training.openquake.org/) was developed as a strategy to mitigate the restrictions imposed by the COVID-19 pandemic, and that at the same time helped to increase the outreach of the training activities.

The website of the project, https://www.globalquakemodel.org/project/treq, hosts the outcomes and material produced during the program. Table 1 presents the list of deliverables.

## Part 1 - Seismic Hazard and Risk Assessment at Urban Scale

Seismic hazard and risk assessments at the urban scale were completed for the three TREQ cities: Quito (Ecuador), Cali (Colombia), and Santiago de los Caballeros (Dominican Republic). State-of-art models were developed for each city in close collaboration with local partners. The activities completed to achieve this goal include: a detailed revision of existing national and regional hazard models; the development of a framework for the definition of specific site-response analysis that accounts for local characteristics of the soils and their corresponding behaviour under earthquake loads; urban seismic hazard analysis; building-by-building exposure models that can be utilized in risk assessment for multiple perils (e.g., earthquakes, floods, volcanoes, landslides, pandemics, etc.); formulation of potential earthquake scenarios that could impact the city as well as historical past scenarios and their consequences in the current-state city environment; urban seismic risk assessment; and the development of seismic risk profiles to communicate seismic risk to stake-holders and the general public. Urban risk assessment results and selection of earthquake scenarios are key components of the study. They support the risk management offices by improving earthquake risk awareness and preparedness, as well as emergency response and mitigation strategies. In addition, two urban

applications were carried out: scenario risk assessment of earthquake-induced secondary effects in Cali (landslides and liquefaction), and volcanic risk scenarios for three volcanoes in Quito.

*Table 1. TREQ deliverables.*

| | | |
|---|---|---|
| **Urban risk assessment in Latin America and the Caribbean** | | |
| **Component 2: Seismic Hazard Assessment** | | **Language** |
| D2.2.1 | PSHA models and datasets for urban hazard assessment. | English |
| D2.2.2 | Probabilistic seismic hazard model for the Dominican Republic. | English and Spanish |
| D2.2.3 | Seismic hazard results (rock and soil conditions). | English |
| D2.2.4 | Seismic hazard analysis at the urban scale. | English |
| **Component 3: Seismic Risk Assessment** | | **Language** |
| D2.3.1 | Building classes in Quito, Cali and Santiago de los Caballeros. | Spanish |
| D2.3.2 | Geo-referenced exposure database of population and buildings in the TREQ city. | - |
| D2.3.3 | Database of fragility and vulnerability functions for each building class present in the exposure model. | - |
| D2.3.4 | Maps and risk metrics generated for each city. | - |
| D2.3.5 | Executive summary Urban seismic risk assessment for the cities of Quito, Cali and Santiago de los Caballeros. | English |
| **Component 4: City Scenarios** | | **Language** |
| D2.4.1 | Database with ruptures selected for scenario analysis. | - |
| D2.4.2 | Scenario hazard assessment for the representative earthquakes in Quito, Cali and Santiago de los Caballeros. | English |
| **Component 5: Urban applications** | | **Language** |
| D2.5.2 | Earthquake-induced landslides and liquefaction in Cali. | English |
| **City reports** | | **Language** |
| D2.6.1 | Seismic Risk Assessment for the Metropolitan District of Quito. | Spanish |
| D2.6.2 | Seismic Risk Assessment for Santiago de Cali. | Spanish |
| D2.6.3 | Seismic Risk Assessment for Santiago de los Caballeros. | Spanish |
| | | |
| **Training and communicating earthquake risk** | | |
| **Component 1: Improving global capacity for seismic hazard and risk assessment** | | **Language** |
| D3.1.1a | Manual to perform seismic hazard analysis. | English |
| D3.1.2 | Video tutorials on seismic hazard and risk analysis. | English and Spanish |
| D3.1.3 | Website for OpenQuake online training. | English and Spanish |
| D3.1.4 | OpenQuake manual in an online format. | English |
| **Component 2: Raising earthquake risk awareness to the general public** | | **Language** |
| D3.2.1 | Educational material to raise seismic risk awareness. Application for the Metropolitan Area of Aburra Valley (AMVA). | Spanish |
| D3.2.2 | Guidelines for teachers for the development of an introductory course on seismic risk. | Spanish |
| **Component 3: Communicating earthquake risk to the general public** | | **Language** |
| D3.3.1 | Urban risk mitigation and response profiles for the TREQ cities. | English and Spanish |
| D3.3.2 | Video to communicate earthquake risk to the general public. | English and Spanish |

As a consequence of these studies, each city now has models and analysis results that reflect the potential impact that earthquakes pose in a probabilistic and deterministic manner. City profiles have been prepared for long-term planning activities (where all possible events are considered) and multiple earthquake scenarios are contemplated (deterministic events). Figure 5 shows an example of a city profile for mitigation purposes in Quito. The models and results for urban hazard and risk assessment are publicly available in the repository https://github.com/gem/treq-riesgo-urbano.

For the Dominican Republic, a national seismic hazard model was developed in collaboration with the National Geological Survey (SGN). Multiple online sessions were conducted to interact with local scientists and to develop a strong partnership.

The results for each city demonstrate the importance of incorporating detailed information and local knowledge for the assessment of earthquake hazard and risk. Sensitivity analysis indicates that the estimated impact - for example, the expected economic losses or the number of collapsed buildings at different return periods - at a given site can vary by an order of magnitude. The resulting risk metrics are conditioned to the quality and accuracy of the input models, and therefore it is essential to adequately characterize the seismic hazard, the local soil response, the building inventory and its occupants, and the likely response of the structures under seismic action.

## Part 2 - Training and Communicating Earthquake Risk

This part of the program was designed to improve the understanding and awareness of earthquake hazard and risk, and to help bridge the gap between the information produced in detailed hazard and risk assessment studies and its communication to a wide variety of stakeholders (which range from local experts with the remit to assess seismic risk to decision-makers responsible for the implementation of risk reduction measures). Activities were devoted to developing training, educational and communication material designed for specific audiences and their associated needs. Due to the restrictions and impact of the COVID-19 pandemic, this part of the project was adjusted given the impossibility to carry out onsite activities.

An online course was designed that covers the basic concepts of earthquake hazard and risk assessment. The course is presented in four modules that cover:

- ***Module I:*** Introduction to OpenQuake and open-source tools for earthquake hazard and risk assessment.
- ***Module II:*** Earthquake Scenarios.
- ***Module III:*** Probabilistic Seismic Hazard Assessment (PSHA).
- ***Module IV:*** Probabilistic Event-Based Risk Assessment.

A dedicated website, https://www.training.openquake.org/, available in English and Spanish allows participants around the globe to engage in OpenQuake training activities for earthquake hazard and risk assessment. An additional module for volcanic risk scenarios completes the training material for a technical audience. Each module has material to support the learning process, such as slides, video tutorials, and questionnaires. More than 600 participants from 64 countries registered for the online sessions. A total of 32 online sessions (8 courses with 4 sessions of 3 hours each), plus a volcanic session completed the 99 hours of free online training. The videos available on the GEM YouTube channel reported more than 3,000 unique users, 13,300 views and more than 756 hours of watch time. The online courses had attendees from the public sector (risk management officers and officers), representatives from academia (professors, researchers and students), and representatives from the private sector.

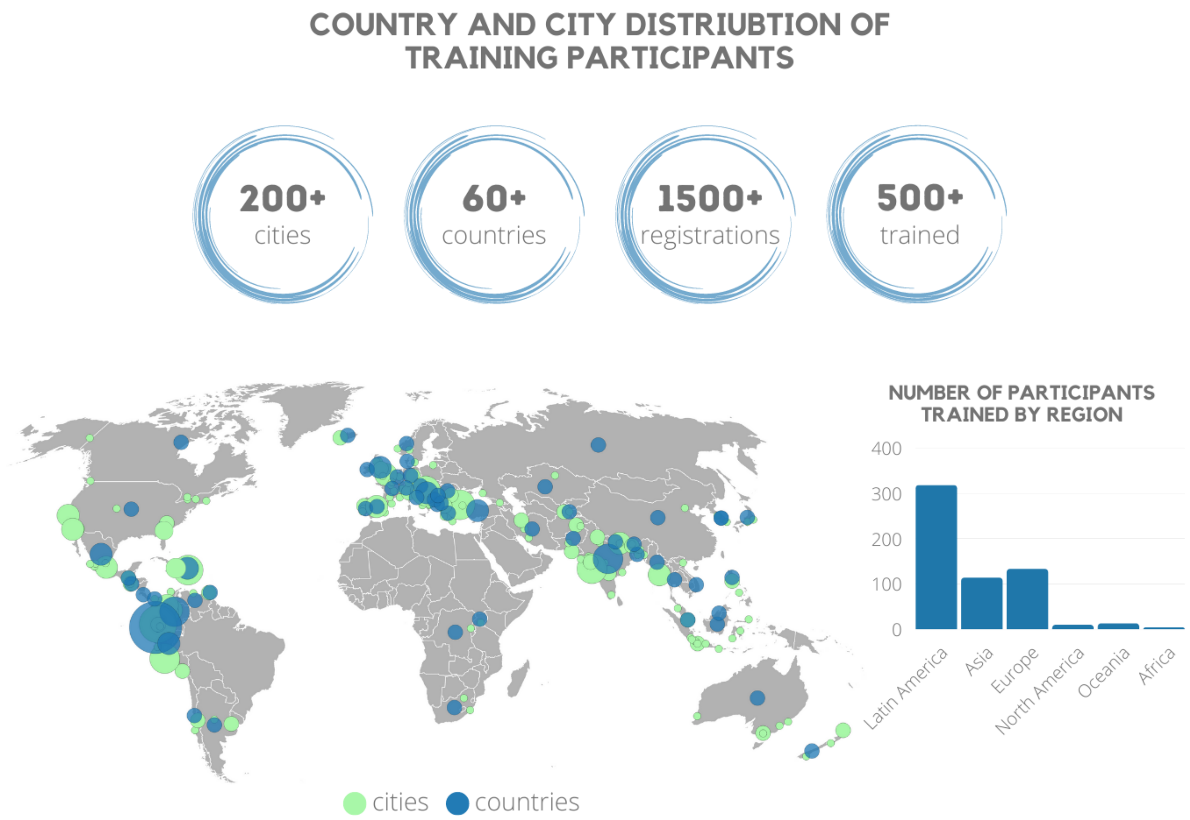


*Figure 1. Participation in the online training activities for earthquake hazard and risk assessment.*

For a technical audience, a *Probabilistic Seismic Hazard Analysis (PSHA) Training Manual* that presents basic examples to build the different components of a probabilistic hazard model using the OpenQuake suite of tools was developed. The manual and its 12 example notebooks demonstrate key concepts used in PSHA. The manual is available on the OpenQuake training website under the "Educational" tab. Also considering a technical audience, a web-based version of the OpenQuake manual was created, https://docs.openquake.org/oq-engine/manual/, which will increase its visibility, user-friendliness, and will better serve the community interested in assessing earthquake hazard and risk.

A "training the trainers'' activity was also considered in the program. Five university professors from Latin America developed, in collaboration with GEM, guidelines for the implementation of an undergraduate university course for teaching seismic hazard and risk assessment. It includes a detailed description of the course development phases, curricular priorities, content, and instructional design. They proposed the implementation of this course with two main purposes: i) to complement the training of students in careers that cover engineering, earth sciences and risk management in Latin America; ii) to serve as a guide for the establishment of the course tools in other regions of the world, with a similar level of exposure to seismic hazards and challenges in terms of high-level education. Currently, five universities in Latin America (EAFIT - Colombia, UABC - Mexico, UES- El Salvador, UCR - Costa Rica, and PUCE - Ecuador) have included the teaching of seismic hazard and risk assessment using the OpenQuake engine in their undergraduate and graduate programs.

Finally, for the general public and decision-makers, a two-hour session (workshop) called *'Am I at risk if an earthquake occurs?'* was designed. During the session, the community is engaged in an open dialogue with the facilitators and counterparts. Key questions that are often misunderstood in our society, such as "Can earthquakes happen near my city? How strong can they be? Is my country prepared to face an emergency caused by a high-intensity earthquake?" are discussed among participants. This dialogue closes the gap in the main understanding of risk in the community by effectively communicating seismic risk and raising awareness of its impacts. The session is divided into 8 activities, with defined goals, methodology and allocated time. The development of this activity was the result of a collaborative effort between the GEM Foundation, the administration of the Aburra Valley Metropolitan Area (AMVA) and its Early Warning System project for Medellin and the Aburra Valley (SIATA), and the EAFIT University. The supporting material for the session includes a personalized video for the Aburra Valley that explains the basic concepts of seismic hazard and risk, using striking images and animations along with a simple and clear message. The video is available on the YouTube platform for the Medellin local authorities (AMVA), https://youtu.be/U1QWqsCSPNw, and a guideline document for organizations interested in raising awareness in the community is available in the TREQ website. Didactic material to explain seismic risk serves as a support for people in charge of communicating this threat to different groups in society. The target audience for the session ranges from students in different grades to the general community, including staff involved in disaster risk planning, reduction and mitigation activities.

# PART 1 - SEISMIC HAZARD AND RISK ASSESSMENT AT URBAN SCALE

Hazard and risk assessment at the urban level was carried out, in close collaboration with local and national stakeholders, for the three selected cities of the project: Quito (Ecuador), Cali (Colombia), and Santiago de los Caballeros (Dominican Republic).

The results show the importance of hazard, site response, exposure and vulnerability models that capture the details and dynamics of the city. These input models are fundamental for the identification of the main drivers of risk in Quito, Cali and Santiago de los Caballeros. Local site characterization can exacerbate (e.g. in Quito) or reduce (e.g. Cali) the seismic risk estimates when combined with the different building classes present in the different seismic zones of the cities. Furthermore, local models reduce the uncertainty associated with the use of low-resolution proxy datasets and other assumptions commonly present in national and regional scale models. Sensitivity analysis indicated that the quantification of the impact, in terms of the expected economic losses, human fatalities or the number of collapsed buildings at different return periods, can be modified by one or more orders of magnitude. The resulting risk metrics are conditioned to the quality and accuracy of the input models, and therefore it is essential to adequately characterize the seismic hazard, the local soil response, the building inventory and its occupants, and the likely response of the structures under seismic action. The use of site response models based on regional scale proxy datasets resulted in an underestimation of seismic risk in more than 80% of the exposed assets and occupants in the city of Quito. In contrast, detailed information about the soil and exposed assets in Cali helped to better identify zones of lower risk. The deamplification of ground shaking intensity in areas with predominant mid-rise and high-rise construction resulted in better estimates of economic and human loss statistics in neighbourhoods that concentrate most of the economic value of the cities. Using this information, more accurate city risk profiles were produced for the risk management offices, which will be used to inform risk management policies.

Five components were contemplated in the first part of the project:

- **Component 1:** Capacity building and Outreach
- **Component 2:** Seismic Hazard Assessment
- **Component 3:** Seismic Risk Assessment
- **Component 4:** City Scenarios
- **Component 5:** Urban Applications

The models and results for urban hazard and risk assessment of each city are publicly available in the repository https://github.com/gem/treq-riesgo-urbano, which was designed in Spanish in order to increase the impact and usefulness for the local audience. In addition, a report in Spanish was generated summarizing all the components involved in the urban seismic hazard and risk assessment for each city:

- **"D2.6.1 Seismic Risk Assessment for the Metropolitan District of Quito"**
- **"D2.6.2 Seismic Risk Assessment for Santiago de Cali"**
- **"D2.6.3 Seismic Risk Assessment for Santiago de los Caballeros"**

Global Earthquake Model

## Component 1: Capacity building and Outreach

The urban hazard and risk assessment activities were developed in close collaboration with the local and national stakeholders. Due to the ongoing Covid19 pandemic, the planned visits and workshops in the cities were shifted to zoom calls and webinars. With the local partners and collaborators, the TREQ team maintained fluid communication. Working groups with representatives from the municipal offices, academia and the geological surveys were created for the development of the models and the review of the results in each city. The working groups met on a regular basis (bi-weekly or monthly) during the model development phase to discuss the status of the models and their results. Around 40 virtual meetings (~ 100 hours), with almost 60 individuals from different working groups, facilitated the sharing of data, knowledge, methodologies, scripts and results. The local partners and GEM scientists mutually learnt from diverse backgrounds and experiences. The TREQ project facilitated a space for thorough discussion and growing skills in the hazard and risk assessment fields in the city and the region. The list of collaborators is included in the ReadMe files available in the repository of each city.

## Component 2: Seismic Hazard Assessment

This component focused on assessing earthquake shaking hazard at an urban scale. The most recent seismic hazard models available at a national level for Colombia and Ecuador were used. For the Dominican Republic, a national probabilistic hazard model was developed in collaboration with the National Geological Survey (SGN) and the Autonomous University (UASD). The selected national models were used for the definition of the reference ground motion hazard on bedrock for the three selected cities, and for the selection of possible earthquake scenarios to be used for risk analysis. At a local scale, information required for completing an urban seismic hazard assessment was collected, to improve the estimates of ground shaking hazard using more refined information and more specific methodologies.

As a result of this component, since the OpenQuake version 3.11 it is possible to incorporate soil response models in the OpenQuake engine hazard calculator.

### *2.1 Compilation of existing models and data*

The report "***D2.2.1 PSHA models and datasets***" presents in detail the collected information and findings. For Cali, Colombia, the national model proposed by the Colombian Geological Survey (SGC) was selected and tested. The model was improved by adding a new fault underlying the city (i.e. Cauca-Cali-Patia fault), consistent with the seismic zonations used in the microzonation study for Santiago de Cali (Ingeominas-Dagma, 2005), and the Colombian building code. For Quito, Ecuador, the model of Beauval et al. (2018) was used.

### *2.2 Probabilistic seismic hazard model for the Dominican Republic*

The report "***D2.2.2 Probabilistic seismic hazard model for the Dominican Republic***" describes the PSHA input model developed for the Dominican Republic, and it presents: i) the primary data sources and their preparation; ii) the methodology used to develop the seismic source characterization and to select ground-motion models; iii) the hazard results computed; and iv) how the results compare to former models used to compute seismic hazard for the country. The seismic source characterization is based on the homogenized catalogue and active faults databases compiled in collaboration with the UASD and SGN, as well as geological, geophysical, tectonic, seismological, and geodetic information from open databases and the literature. The source modelling approach is similar to the one used to build the CCARA[1] PSHA model and other recent GEM models, but with the incorporation of more recently developed methodologies. In particular, the crustal component of the seismic source model uses faults as systems rather than independent seismogenic structures, and several epistemic uncertainties are accounted for. Figure 2 shows the mean peak ground acceleration (PGA) on rock computed for the full island of Hispaniola for a 10% and 2% probability of exceedance (POE) in a 50-year period.

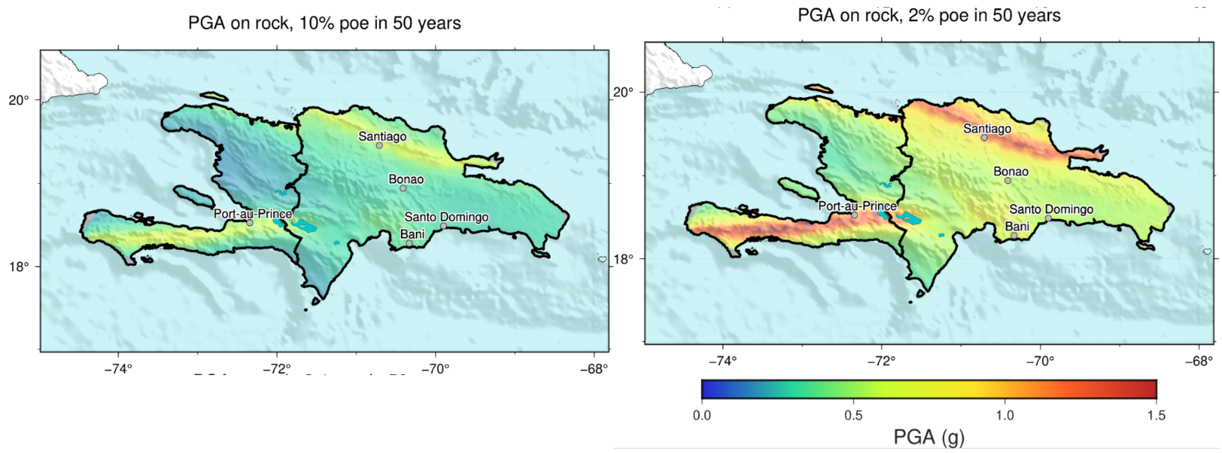


*Figure 2. Mean peak ground acceleration (PGA) on rock with a 10% probability of exceedance in 50 years computed using the seismic hazard model for the Dominican Republic.*

### *2.3 Site response analysis and urban earthquake hazard assessment*

A PSHA analysis for the three urban centres explicitly accounting for the local soil response in each city is available in the report **"D.2.24 Seismic hazard analysis at the urban scale".** The two requirements for this analysis were (1) hazard estimates on reference bedrock for each city and (2) soil response models that quantify the amplification (or deamplification) of ground shaking due to the shallow soil layers.

For the first requirement, the report **"D2.2.3 Seismic hazard results (rock and soil conditions)"** presents the results for the seismic hazard on reference bedrock for the three selected cities, as well as the expected ground shaking on soil using simplified approaches to account for the local site response. In the simplified approach, the local site-response is accounted for by using ground motion prediction equations containing a so-called site-term generally relying on a single, simple parameter, i.e., the time-averaged velocity of shear waves in the uppermost 30 m (Vs30).

[1] CCARA: Caribbean and Central America Risk Assessment project, funded by USAID. Details of the PSHA model available at [https://hazard.openquake.org/gem/models/CCA/](https://hazard.openquake.org/gem/models/CCA/)

Second, the report **"D2.2.3 Seismic hazard results at urban scale"** presents in detail the data, methodology and results for the incorporation of local site effects into hazard estimates. In collaboration with local experts, we developed the soil response models for each city using available local geotechnical and geophysical data. The soil response was simulated using 1D equivalent linear analysis, where the soil response is treated as linear, but the dynamic properties of the soil (i.e., shear modulus and damping) are updated based on the strain level at each layer in order to capture the non-linear soil behaviour. The software pySRA[2] was used, and a large suite of input motions was generated from (and therefore fully compatible with) the underlying hazard model, which accounts for uncertainty in the input motions. The computed soil response models consist of a set of soil amplification factors (AF) and their uncertainty ($\sigma_{\ln AF}$), covering the respective urban centres.

Figure 3 shows an example for two sites. The AFs were defined for periods relevant for risk analysis (PGA – 2.0 s), as well as for a wide range of bedrock shaking intensity levels (0.05 – ~4 g), and can therefore be readily used for probabilistic hazard and risk analysis. Finally, hazard curves were computed at the surface by convolving the bedrock hazard with the AFs and $\sigma_{\ln AF}$ at a set of sites. The results demonstrate the importance of incorporating local soil response when the goal is to model hazard at the urban scale with a higher level of detail compared to more standard approaches using Vs30, which does not always provide an accurate measure of amplification.

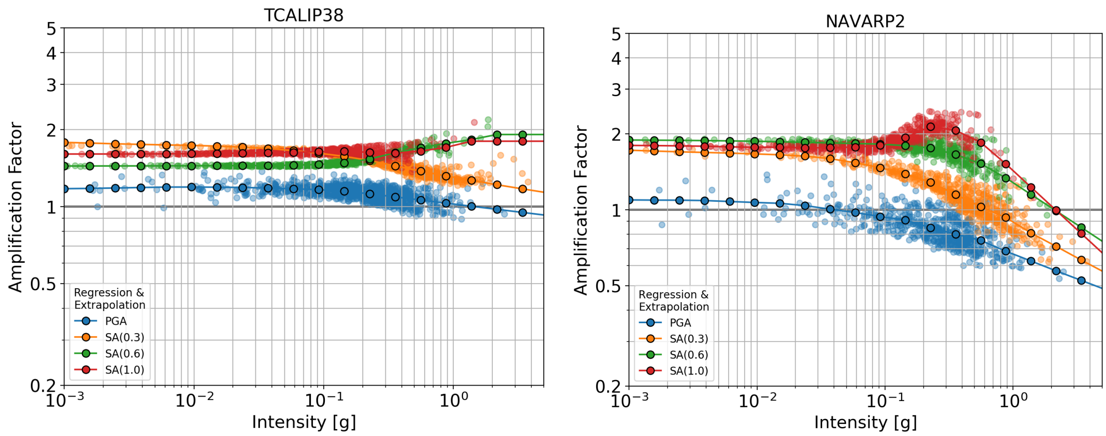


*Figure 3. Example of simulated AFs using the same input motions at two different sites, a) one stiffer, with Vs30=418m/s (left) and b) one softer, with Vs30=273 m/s (right).*

## Component 3: Seismic Risk Assessment

This seismic risk component at the urban level covers the development of highly detailed, uniform, open and transparent datasets for the urban building inventory (exposure model), the physical response of the infrastructure under seismic loads (vulnerability model), and the assessment of the impact from earthquakes, along with risk metrics required for the development of risk reduction plans.

[2] PySRA: Site response analyses implemented in Python. https://github.com/arkottke/pysra

As a result of this component, earthquake loss assessment models were developed in close collaboration with technical groups composed of researchers, city officials and risk managers of each of the TREQ cities. In addition, the event-based damage and consequence calculator[3] were implemented in the OpenQuake engine, in order to provide additional risk metrics that can inform policy and decision-makers. The report **"D.2.3.5 Executive summary Urban seismic risk assessment for the cities of Quito, Cali and Santiago de los Caballeros"** presents this component in detail.

### *3.1 Development of urban exposure model*

An exposure model is fundamental for the assessment of the impact due to natural hazards, as it comprises information concerning the geographical location, vulnerability characteristics and value of the assets exposed to the hazards. The man-made environment, its contents and occupants are all elements exposed to natural hazards and must be examined to correctly quantify their physical vulnerability and potential risk. The exposure information available for each city was improved in order to provide detailed models suitable for earthquake risk assessment at the urban scale. Among the main improvements to the datasets, we highlight the detailed spatial resolution of the assets, the robust characterization of the buildings, including all occupancy categories, and the updates regarding replacement cost. This was achieved through the collection of better information for the cities and the constant involvement of the local experts in each one of the development stages.

Figure 4 presents examples of the information included in the exposure models for the three cities. The building classes and construction practices in the cities are summarized in the report **"D2.3.1 Description of building classes identified in the TREQ cities"**. The deliverable **"D2.3.2 Geo-referenced exposure databases of buildings and population in the TREQ cities"** is available in the open repository https://github.com/gem/treq-riesgo-urbano, under the folder of each city and in the "Exposicion" folder.

### *3.2 Urban earthquake risk assessment*

The assessment of damage, economic losses and fatalities require a set of fragility and vulnerability models for the building classes found in the exposure. A fragility function represents the probability of exceeding a level of damage conditional on ground shaking intensity. These are used to make estimates of damage, like damage distribution statistics and maps of building collapse. On the other hand, a vulnerability function defines a probabilistic distribution of loss ratio (e.g., mean loss ratio and the corresponding coefficient of variation) conditional on the ground shaking intensity, which can be used to estimate losses, such as economic loss statistics and maps of human fatalities. The vulnerability models used in the study are included in the deliverable **"D2.3.3 Database of fragility and vulnerability functions"** which is available in the open repository https://github.com/gem/treq-riesgo-urbano, under the folder "Vulnerabilidad_GEM".

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[3] The OpenQuake event-based damage and consequence calculator uses a Monte Carlo simulation approach to probabilistic damage assessment in order to estimate the damage distribution for individual assets and aggregated damage distribution for a spatially distributed portfolio of assets within a specified time period.

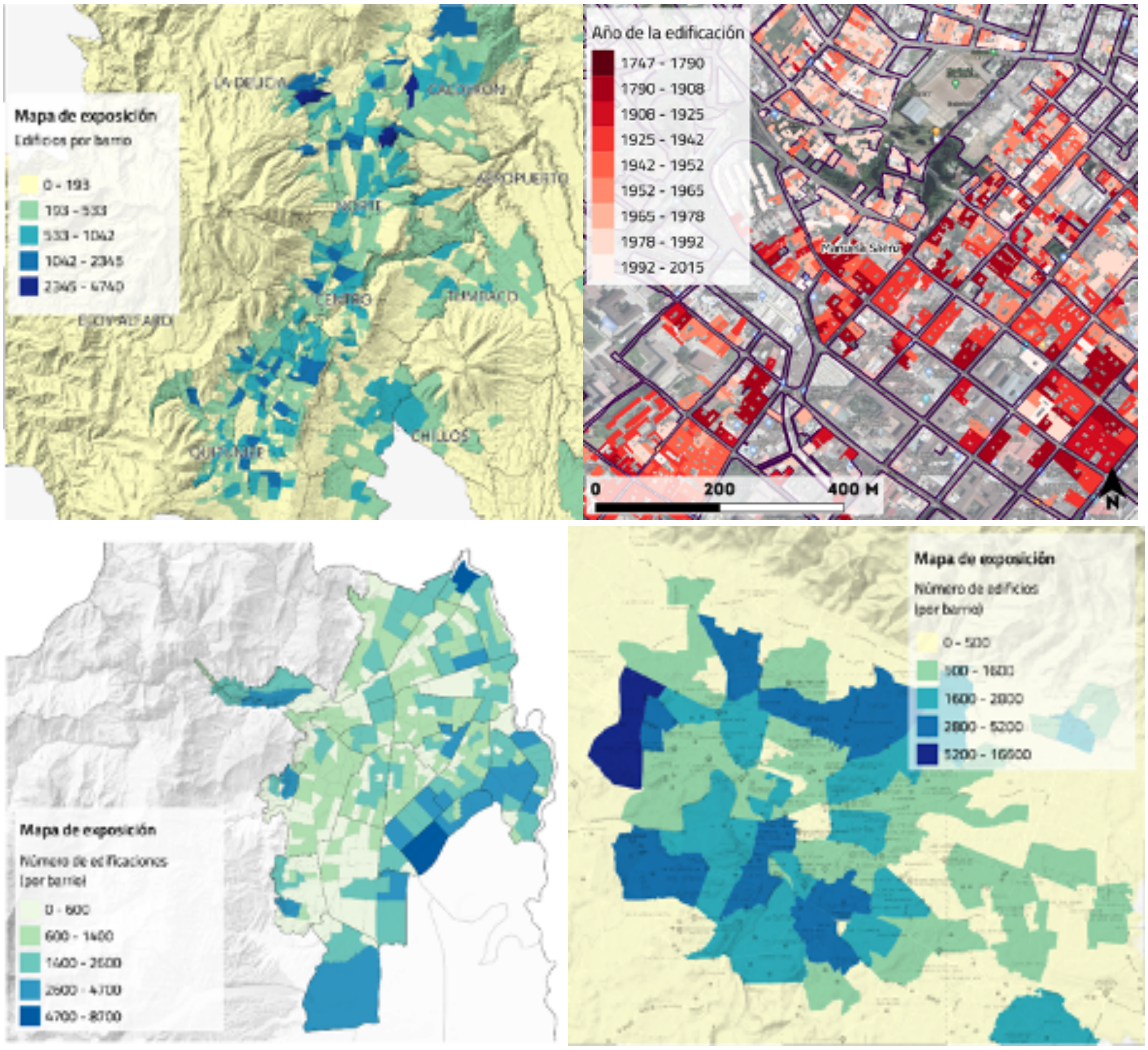


*Figure 4. Example of information available in the exposure models of the TREQ cities. The number of buildings per neighbourhood in Quito (top-left), Cali (bottom-left), and Santiago de los Caballeros (bottom right). Zoom for the historical centre of Quito (top-right) shows the year of construction for each building.*

By combining the probabilistic seismic hazard, exposure and vulnerability models it is possible to calculate probabilistic risk in each city. Several risk metrics critical for the development of risk reduction plans were included and customized for each city based on the local needs, such as average annual economic and human losses, probable maximum losses, and loss maps at different return periods. Figure 5 presents an example of the seismic risk profile for Quito. These results allow the identification of the areas in the cities where the potential for economic or human losses is highest, and thus where risk reduction activities should be prioritized. For additional maps and curves see the deliverable **"D2.3.4 Maps and risk metrics"**, available in the open repository [https://github.com/gem/treq-riesgo-urbano](https://github.com/gem/treq-riesgo-urbano) under the folder "Mapas".

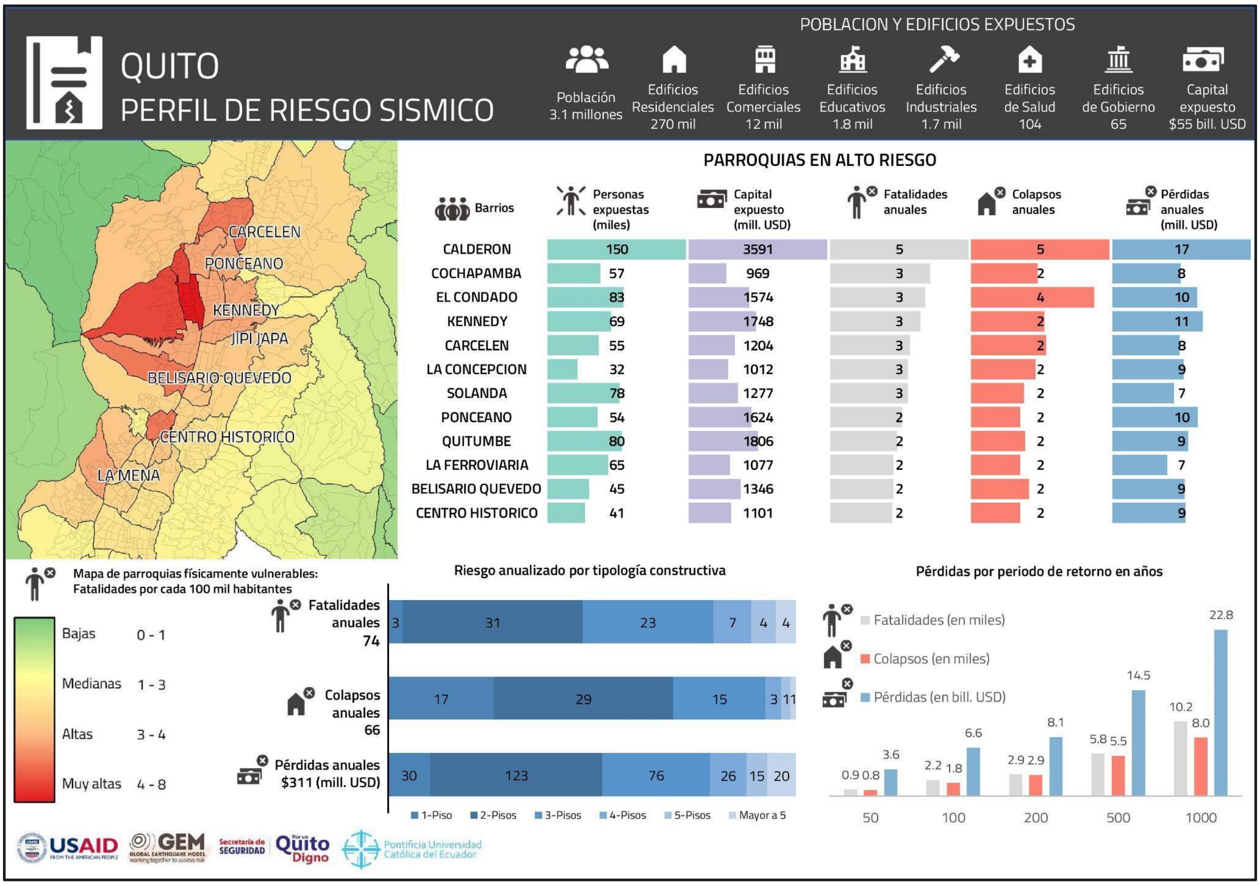


*Figure 5. Risk mitigation profile for the city of Quito. It presents a set of probabilistic risk metrics that take into account the potential impact of thousands of events that could affect the city.*

The urban risk assessment in the TREQ cities showed the importance of hazard, site response, exposure and vulnerability models that capture the details and dynamics of the city. These input models are fundamental for the identification of the main drivers of risk in Quito, Cali and Santiago de los Caballeros. Local site characterization can exacerbate (e.g., in Quito) or reduce (e.g., Cali) the seismic risk estimates when combined with the different building classes present in the different seismic zones of the cities. Furthermore, local models reduce the uncertainty associated with the use of low-resolution proxy datasets and other assumptions commonly present in national and regional scale models. Sensitivity analysis indicated that the quantification of the impact, in terms of the expected economic losses, human fatalities or the number of collapsed buildings at different return periods, can be modified by one or more orders of magnitude. The resulting risk metrics were conditioned to the quality and accuracy of the input models. Using this information, more accurate city risk profiles were produced for the risk management offices, which will be used later to inform risk management policies.

## Component 4: City Scenarios

The United States Geological Survey (USGS) led the selection of seismic events that could impact the cities, in collaboration with GEM and the local groups. The list of events was defined in agreement with the needs of the risk management offices in Quito, Cali and Santiago de los Caballeros. The list is composed of two types of scenarios: 1) historical events and 2) events with the potential of producing damaging intensities in each city, selected based on hazard disaggregation (i.e., identification of the combination of distance, magnitude and seismogenic sources that contribute the most to the seismic hazard and loss at each urban centre). The historical scenarios are a collection of past and recent scenarios. Past events were selected by the risk management offices to understand the level of impact of past earthquake ruptures in today's-built environment. Recent events are meant to serve as benchmarks to test the loss assessment model components developed for each city. On the other hand, the scenarios based on hazard disaggregation were identified by the USGS using the PSHA model of each city. These are meant to test the cities' preparedness against plausible disaster scenarios.

Emergency response and preparedness profiles were generated for the possible events selected for each city. The impact to the city will depend on the selected scenario (the results can show weak to very strong consequences); for example, Figure 6 presents the results for a strong event in Cali. The social component involved in an emergency situation is not incorporated in the profile. The generated seismic scenarios support the creation of a common understanding of the impact that an earthquake can cause in a region. Stakeholders can visualise the most affected areas within the region of interest, the number of collapsed and damaged buildings, and their respective spatial distribution. Thus, earthquake scenarios allow the identification of weaknesses and strengths in the management system, and evaluation of the required measures for reducing the risk, and improving preparedness and recovery in future events.

The report **"D.2.5.2 Scenario hazard assessment for the representative earthquakes in Quito, Cali and Santiago de los Caballeros"** provides information about the selected events, and the deliverable **"D2.4.1 Database with ruptures selected for scenario analysis"** is available in the open repository https://github.com/gem/treq-riesgo-urbano under the folder of each city and the "Rupturas_Sismicas" folder.

## Component 5: Urban applications

Two urban applications were carried out using the generated urban hazard and risk models: volcanic risk scenarios in Quito, and earthquake-induced secondary perils (landslides and liquefaction) for scenario risk assessment in Cali.

The report **"D2.6.1 Seismic Risk Assessment for the Metropolitan District of Quito"** presents the details of the volcanic scenarios. Using the exposure model generated within TREQ in combination with six hazard footprints provided by the risk management office (Dirección Metropolitana de Gestión del Riesgo - DMGR) and generated by the Instituto Geofísico (IGPN), the OpenQuake engine was used to estimate the impact of these events as implemented during the CRAVE project. The scenarios correspond to previous eruptions from volcanoes in the province of Pichincha and exhibited different impacts depending on the hazard peril considered (e.g., lahars, ashfall, or pyroclastic density currents, among others). The most severe event modelled was the Atacazo Ninahuilca eruption, where a combination of ashfall and lahars resulted in significant destruction in the southern parishes of the city.

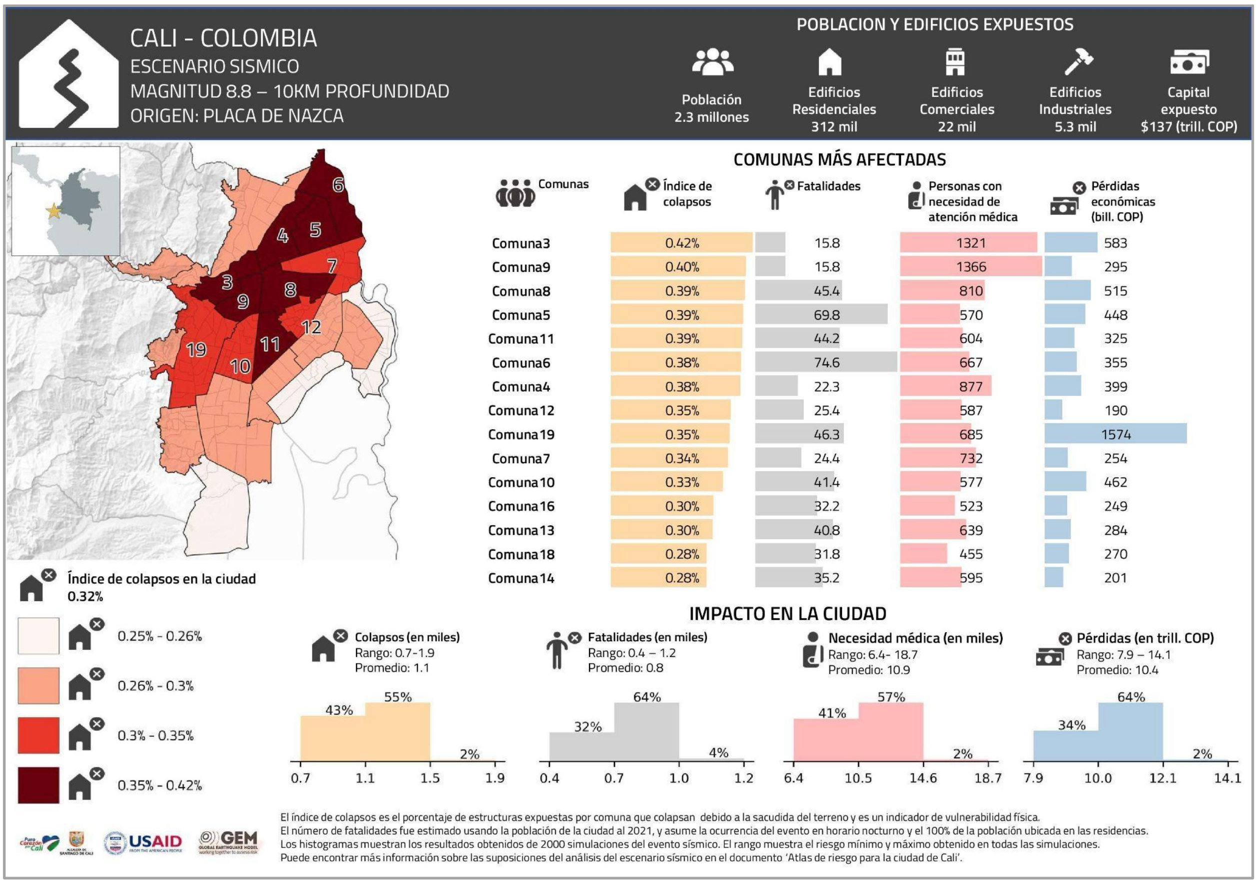


*Figure 6. Risk response profile, which presents the consequence metrics for Cali from a Mw 8.8 rupture occurring in the Nazca seduction zone.*

The report **" D2.5.2 Earthquake-induced landslides and liquefaction in Cali."** presents the secondary effects in the city due to the earthquake scenarios presented above. Different global methodologies to calculate probabilistic landslide and liquefaction hazard and risk were implemented into the OpenQuake engine. The implementation considered one coseismic landslide model, and two liquefaction models, with a flexible and general framework for the calculation, and therefore the tools can grow as the body of scientific methods develops. Since the preparation of the data and the characterization of the geotechnical parameters of each site in the analysis is a complex task, thorough documentation based on interactive *Jupyter* notebooks that illustrate workflows and custom-built tools to aid in this preparatory phase are available at https://gemsciencetools.github.io/oq-mbtk/contents/sep.html.

# PART 2 - TRAINING AND COMMUNICATING EARTHQUAKE RISK

This part of the program was designed to improve the understanding and awareness of earthquake hazard and risk, and to help bridge the gap between the information produced in detailed hazard and risk assessment studies and its communication to a wide variety of stakeholders (which range from local experts with the remit to assess seismic risk to decision-makers responsible for the implementation of risk reduction measures). Activities were devoted to developing training, educational and communication material designed for specific audiences and their associated needs. Due to the restrictions and impact of the COVID-19 pandemic, this part of the project was adjusted given the impossibility to carry out on-site activities.

Three components were contemplated in this part of the project:

- **Component 1:** Improving global capacity for seismic hazard and risk assessment
- **Component 2:** Raising earthquake risk awareness to the general public
- **Component 3:** Communicating earthquake risk to the general public

The training and communication material is available at the project website: https://www.globalquakemodel.org/project/treq

- OpenQuake training website: https://www.training.openquake.org/
- YouTube Channel: https://www.youtube.com/channel/UCfvGcHtZYk_kQ_mqz3AYQYQ

## Component 1: Improving global capacity for seismic hazard and risk assessment

### *1.1 Online training for earthquake hazard and risk assessment using the OpenQuake engine*

An online course that covers the basic concepts of earthquake hazard and risk assessment was designed. The course is presented in four modules that cover:

***Module I:*** Introduction to OpenQuake and open-source tools for earthquake hazard and risk assessment.

***Module II:*** Earthquake Scenarios.

***Module III:*** Probabilistic Seismic Hazard Assessment (PSHA).

***Module IV:*** Probabilistic Event-Based Risk Assessment.

A dedicated website, https://www.training.openquake.org/, available in English and Spanish, allows participants around the globe to engage in OpenQuake training activities for earthquake hazard and risk assessment (deliverable **"D3.1.3 Website for OpenQuake online training"**). An additional module for volcanic risk scenarios completes the training material for a technical audience. Each module has material to support the learning process, such as slides, video tutorials, and questionnaires. More than 600 participants from 64 countries registered for the online sessions. A total of 32 online sessions (8 courses with 4 sessions of 3 hours each), plus a volcanic session completed the 99 hours of free online training. The videos are available on the GEM YouTube channel (deliverable **"D3.1.2 Video tutorials on seismic hazard and risk analysis"**), where there have been more than 3,000 unique users, 13,300 views and more than 756 hours of watched time. The online courses had attendees from the public sector (risk management officers and officers), representatives from academia (professors, researchers and students), and representatives from the private sector. Figure 7 presents additional details on the attendance of the online training.

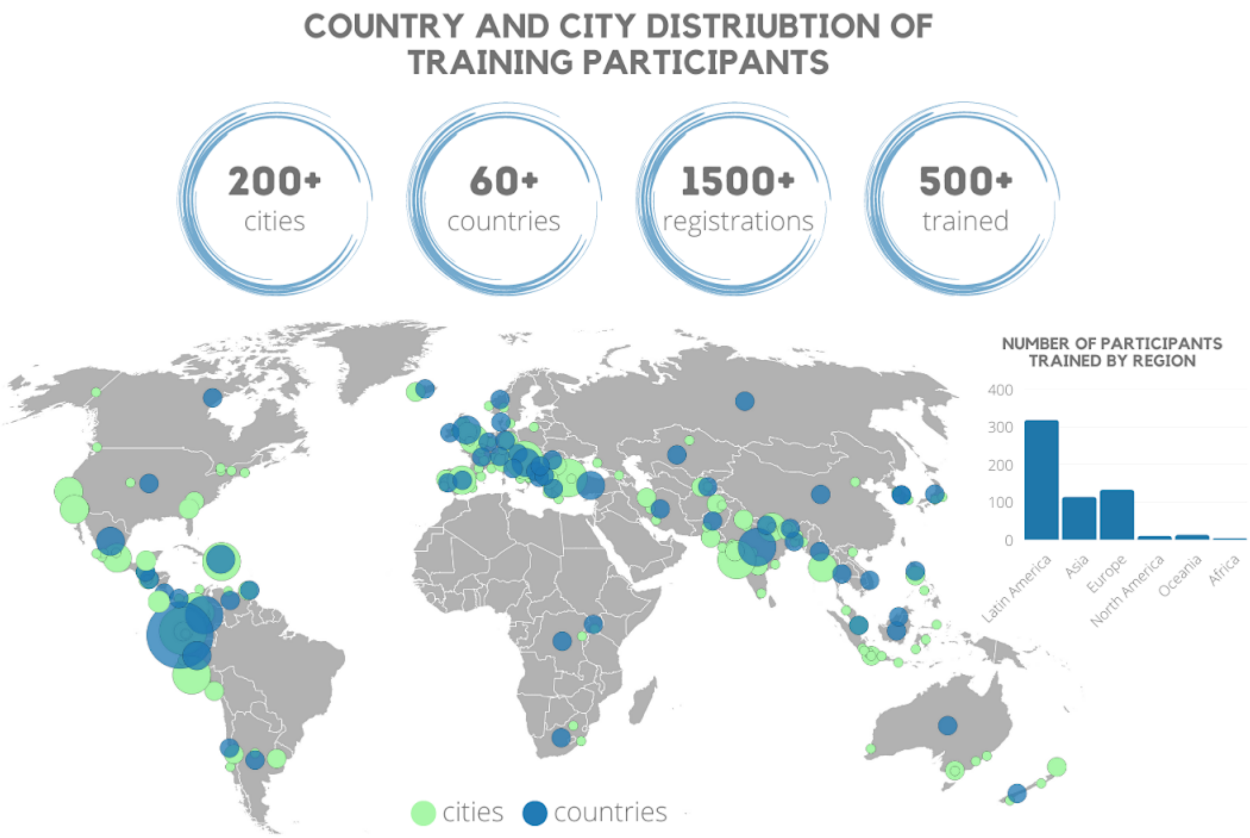


*Figure 7. Participation in the online training activities for earthquake hazard and risk assessment.*

After each online session, a feedback form was shared with participants to evaluate the impact and helped us to shape and improve the material, content and methodology of the activities. The excellent feedback confirms the value of the training activities, the contribution to the participants' skills and the quality of the activities. We collected more than 8000 votes from more than 500 trainees. Using the 'before and after' self-assessment method and a rating scale of 1 to 5 (1 - having no or little understanding and 5 - being confident to describe and give elements about the topic), participants indicated they have gained relatively high knowledge and skills in four earthquake hazard and risk topics covered by the online training (an average of 31% increase), see Figure 8. However, it must be noted that the increase is relative to the participants' personal assessment of their knowledge 'before' the training; i.e. a lower 'before' self-assessment rating could result in a higher percentage of points increase.

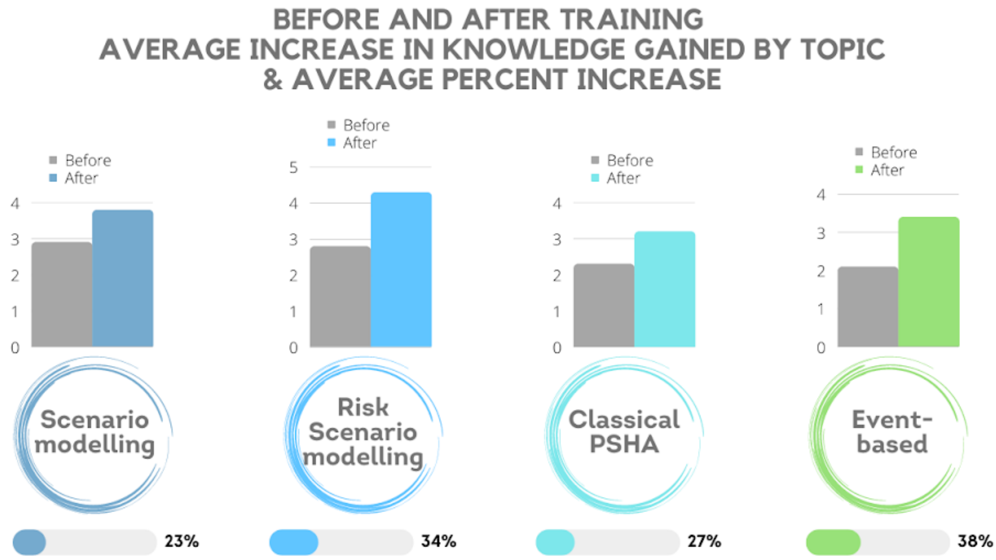


*Figure 8. The average increase in knowledge before and after training.*

### *1.2 Manual to perform seismic hazard analysis using the OpenQuake suite of tools*

The *GEM Foundation's Probabilistic Seismic Hazard Analysis (PSHA) Training Manual* and its 12 example notebooks demonstrate key concepts used in PSHA. The manual presents basic examples to build the different components of a probabilistic hazard model using the OpenQuake suite of tools. The deliverable ***"D3.1.1a Manual to perform seismic hazard analysis"*** is available on the OpenQuake training website.

After analysing the feedback and needs for communication and training to assess earthquake hazard and risk, we gave priority to the improvement of the existing documentation on the OpenQuake engine, rather than creating a new risk manual (initially, deliverable D3.1.1b). As a result, a web-based version of the OpenQuake manual was created, https://docs.openquake.org/oq-engine/manual/ (deliverable **"D3.1.4 OpenQuake manual in an online format")**, which will increase its visibility, user-friendliness and will better serve the community interested in assessing earthquake hazard and risk.

## Component 2: Raising earthquake risk awareness to the general public

### *2.1 Educational material to raise seismic risk awareness*

A two-hour session (workshop) called "Am I at risk if an earthquake occurs?" was designed. During the session, the community is engaged in an open dialogue with the facilitators and counterparts. Key questions that are often misunderstood in our society, such as "Can earthquakes happen near my city? How strong can they be? Is my country prepared to face an emergency caused by a high-intensity earthquake?" are discussed among participants. This dialogue closes the gap in the main understanding of risk in the community by effectively communicating seismic risk and raising awareness of its impacts. The session is divided into 8 activities, with defined goals, methodology and allocated time.

The supporting material for the session includes the workshop guidelines, report **"D.3.2.1 Educational material to raise seismic risk awareness. Application for the Metropolitan Area of Aburra Valley (AMVA)"**, and a personalised video for the Aburra Valley (deliverable **"D3.3.2 Video to communicate earthquake risk to the general public")** that explains the basic concepts of seismic hazard and risk, using striking images and animations along with a simple and clear message. The video is available on the YouTube platform for the Medellin local authorities (AMVA), https://youtu.be/U1QWqsCSPNw. The video is available in Spanish and English. The session was designed as a guideline for organisations interested in raising awareness in the community. Didactic material to explain seismic risk serves as a support for people in charge of communicating this threat to different groups in society. The target audience for the session ranges from students in different grades to the general community, including staff involved in disaster risk planning, reduction and mitigation activities.

This activity was the result of a collaborative effort between the GEM Foundation, the administration of the Aburra Valley Metropolitan Area (AMVA) and its Early Warning System project for Medellin and the Aburra Valley (SIATA), and the EAFIT University.

### *2.2 Training the trainers: Guidelines for professors for the development of an introductory seismic hazard and risk course*

Within the framework of TREQ, five universities of civil engineering from the University of UES (El Salvador), UMG (Guatemala), UABC (Mexico), UCR (Costa Rica) and EAFIT (Colombia) developed, in collaboration with GEM, guidelines for the implementation of an undergraduate university course for the teaching of seismic hazard and risk assessment. It includes a detailed description of the course development phases, curricular priorities, content, and instructional design. They proposed the implementation of this course with two main purposes: i) to complement the training of students in careers that cover engineering, earth sciences and risk management in Latin America; and ii) to serve as a guide for the establishment of the course tools in other regions of the world, with a similar level of exposure to seismic hazards and challenges in terms of high-level education. Currently, the guides are in Spanish and cover the implementation of a comprehensive introductory course on seismic risk, formulated as 7 units, 32 topics and 24 activities. In addition, this initiative benefited from the collection of learning evidence and audio-visual tools developed during TREQ training workshops, which can be taught in universities with academic cycles of 4 to 6 months. This material was successfully implemented by the professors in four countries (Mexico, El Salvador, Costa Rica and Colombia), benefiting four academic institutions and more than 100 undergraduate students. The report **"D3.2.2 Guidelines for teachers for the development of an introductory course on seismic risk"** provides a summary of the course instructional design (DI) template. The design is structured by three guiding questions: What will the student learn in the course? How will the student learn it? And how will the teacher know that the student has learned it? The DI proposed contains the description, the activity plan of the course units and their respective objectives.

## Component 3: Communicating earthquake risk to the general public

### *3.1 Urban risk mitigation and response profiles for the TREQ cities*

Supported by the outcomes of the urban risk assessment component, earthquake risk profiles for the TREQ cities were developed for emergency preparedness and mitigation planning activities in the risk management offices, as well as to present the impact of possible events to the community. The purpose of the profiles is to communicate earthquake risk thoroughly, highlighting the potential physical impact (social, economic, and infrastructure) in each city and the risk drivers.

The deliverable "D3.3.1 Urban risk mitigation and response profiles for the TREQ cities" includes 34 profiles, which are available in the open repository https://github.com/gem/treq-riesgo-urbano under the folder of each city, under the “Riesgo” folder.

### *3.2 Seminars, meetings, online material and training*

Table 2 summarises the events carried out during the project. It includes activities related to events, training and conferences organised by or participated in by GEM staff and collaborators. More than 10,000 people benefited from events, videos on the YouTube channel and training website material. Moreover, the GEM staff held more than 40 meetings with the working groups in each city during the project.

*Table 2. Events, meetings and seminars during the TREQ project*

| Event | Description |
|---|---|
| TREQ events | **TREQ Kick-off workshop** in the Metropolitan District of Quito |
| | **TREQ Webinar**: Presentation of TREQ milestones in urban risk assessment and milestones to the communication to the general public. Online attendance plus unique views of YouTube videos. |
| | **Hybrid webinar** to present the national seismic hazard model for the Dominican Republic (in collaboration with SGN and ONESVIE). |
| | **Urban risk assessment in Quito**: Presentation of final results and transfer of TREQ models and products to the local collaborators and stakeholders |
| | **Urban risk assessment in Cali**: Presentation of final results and transfer of TREQ models and products to the local collaborators and stakeholders |
| | **Urban risk assessment in Santiago**: Presentation of final results and transfer of TREQ models and products to the local collaborators and stakeholders |
| Meetings | Meeting and visit to Guayaquil representatives and the national office for disaster risk reduction (SNGRE) |
| | Meetings in Tijuana and visit to the UABC University |
| | Meetings with the offices for disaster risk management of the city and other technical officials |
| | Presentation of TREQ activities to stakeholders in Santiago de los Caballeros and officials in Santo Domingo |
| | Presentation of risk assessment results for Quito to the Ecuadorian Normative on Construction (NEC) |
| Online dedicated training on seismic hazard and risk assessment using the OpenQuake engine | Launch of the online dedicated trainings for specific groups of stakeholders and institutions in the TREQ cities and Latin America |
| | Online dedicated training to participants beyond Latin America |
| | Online dedicated training to the global community |
| | Online training for volcanic scenarios risk assessment |
| Earthquake risk awareness sessions | 2 pilot sessions for seismic risk awareness in communities in Medellin and the Aburra Valley: Training the trainers and city managers |
| | Sessions to the community of the Aburra Valley facilitated by the municipality (AMVA and SIATA) and EAFIT university |
| Conferences and seminars | VOBP4 Workshop in Mexico City. Presentation of CRAVE project results to the volcano community. |
| | Presentation of TREQ milestones in the international seminar for risk assessment CERAM |
| | GAGE/SAGE 2021: Dissemination of TREQ urban risk assessment and training activities in the SAGE international panel |
| | Presentations in the X National Conference on Earthquake Engineering of Colombia. Two sessions related to TREQ activities: a plenary session about seismic risk and resilience, and a technical session presenting the exposure model for Cail. |
| | Cities on Volcanoes (COV11) conference |