Training and Communication for Earthquake Risk Assessment

TREQ Project

Earthquake-induced liquefaction and landslides in Cali, Colombia

Deliverable 2.5.2 – Version 1.0.0

Global Earthquake Model (GEM) Foundation

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Description of the methods, analysis and results for earthquake induced secondary perils for Cali, Colombia

Earthquake-induced liquefaction and landslides in Cali, Colombia

Deliverable D2.5.2

Technical report produced in the context of the TREQ project

Version 1.0.0 – June, 2022

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The TREQ Project is 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 aims 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 will produce training, educational and communication materials that will enhance the understanding of earthquake risk worldwide. This program targets 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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CONTENTS

1 EXECUTIVE SUMMARY

Earthquake-induced landslides and liquefaction are important secondary earthquake perils that can cause substantial damage to the built environment in addition to direct damage caused by seismic ground shaking. In spite of their impacts, they are not regularly included in probabilistic seismic hazard and risk analysis (PSHRA), in part because they have not been incorporated in most PSHRA frameworks such as GEM's OpenQuake Engine. As part of the TREQ project, existing landslide and liquefaction models were implemented within the OpenQuake Engine, and have been made available for both probabilistic and deterministic (scenario) analyses. In this study we present the methodological approach we used to implement these models using the city of Cali as the case study. Regarding coseismic landslides, found that the probability of coseismic landslides within the city limits of Cali is extremely small, although it is likely higher in the adjacent mountain regions. For liquefaction analysis, we tested the models on seismic scenarios selected by the USGS through a hazard disaggregation process. The risk metrics obtained suggest that, in the case of liquefaction, the models make an appropriate prediction of the spatial distribution of damage and loss. However,in terms of the absolute number of damaged structures, estimates for both, landslide and liquefaction risk, are inconsistent with the level of damage and loss obtained from the ground shaking. Hence, we concluded that the existing methodologies do not perform satisfactorily in urban risk applications.

2 INTRODUCTION

Coseismic landslides and liquefaction are common and impactful aspects of the response of the Earth's surface to seismic shaking. Coseismic landslides occur on steep slopes, when Earth materials are dislodged and mobilized downslope during an earthquake. This may cause a de-stabilization of the foundation of buildings or other infrastructure situated on the source area of the landslide, or damage to infrastructure in the runout zone of the landslide, as debris collides or covers the infrastructure. Liquefaction occurs on flat, wet soils when seismic ground motions cause water pressure in the pores of the soil to be temporarily elevated, which greatly reduces the load-bearing capacity of the materials, leading to the translation or settling of the soil and infrastructure built upon it.

2.1 Study area

Cali, Colombia is a city of over 2 million citizens in western Colombia. Geographically, the city is bounded on the west side by the high and steep mountains of the Cordillera Occidental. To the east is the Cauca River, a very large river draining much of central-western Colombia. The city is located on a low-gradient alluvial plane and cone emanating from small river drainages in the Cordillera Occidental, and on floodplains of the Cauca River. Cali is located about 100 km east of the Pacific subduction zone, where the Nazca oceanic tectonic plate dives under South America.

2.2 Scenario selection

For the analysis of earthquake induced landslides in Cali, we chose a scenario earthquake rather than a fully probabilistic analysis to better understand the functionality of the new secondary peril modules in the OpenQuake Engine and calculate the risk for plausible damaging events that could impact the city.

The scenario selection process has been performed by identifying relevant historical events whose magnitude, faulting style and rupture geometry are known. This task is the result of collaboration between GEM, the United States Geological Survey, and the risk management office in Cali (Calderon A. et al. 2021) .The catalogue of the selected scenarios is presented in *Table 1*, where six subduction and two crustal events have been listed ranging from magnitude 6.1M_w to 8.8 M_w earthquakes. The list includes the magnitude and depth, USGS Shake map idetification code[1] of each event, while their epicentre locations are given in Figure 1.

Table 1. List of selected historical scenarios for damage and risk assessment

	Cali earthquake scenarios				
	Fault style	**Mw**	**Depth (km)**	**ShakeMap ID**	**Description**
1	Oblique (strike - slip with a reverse component)	6.1	17	usp00091q3	1999 EQ
2	Normal	6.4	73.5	usp0006skc	1995 EQ
3	Strike-slip	6.8	12.1	usp0006dv8	1994 EQ
4	Oblique (strike - slip with a reverse component)	7.2	21.3	usp0004zbt	Twin EQ - 1991
5	Shallow thrust	7.2	15	usp000d8gx	Twin EQ - 2004
6	Subduction	8.8	20	official19060131153610_30	Nazca Subduction

[1] Access the USGS ShakeMap for an event by adding the corresponding *ShakeMap_ID* In the following link: https://earthquake.usgs.gov/earthquakes/eventpage/ShakeMap_ID/

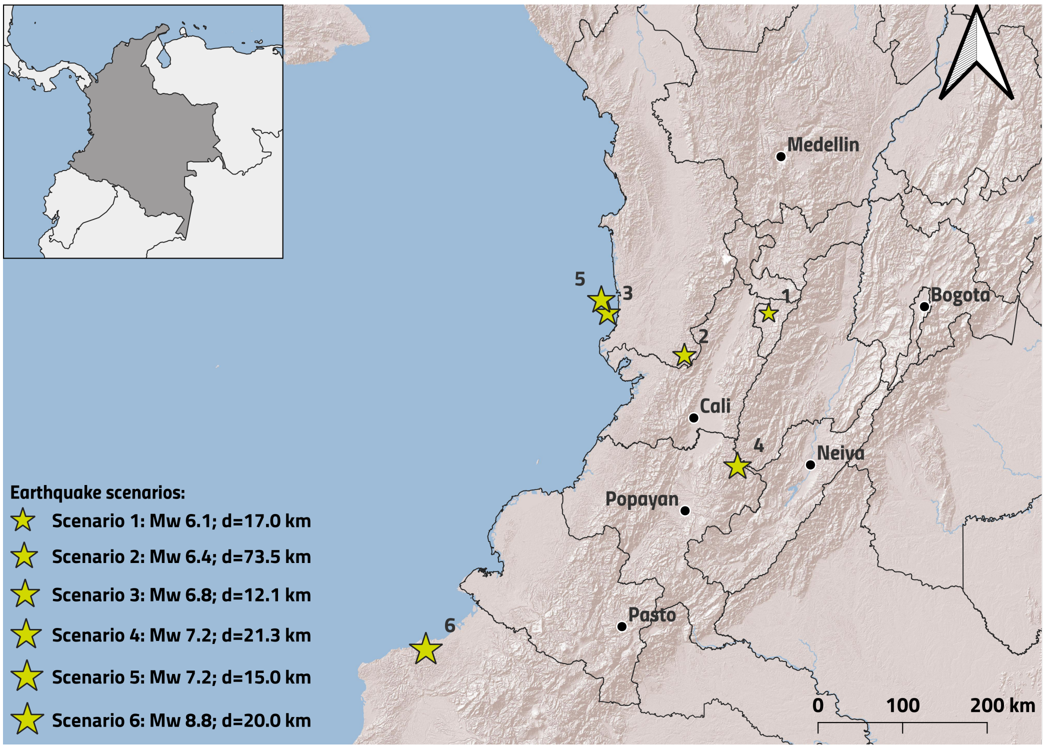

Figure 1. Epicentre location of selected earthquake scenarios

2.3 Gorund motion models and uncertainty in the ground shaking

The aleatory uncertainty in the ground shaking is taken into account by the generation of thousand of ground motion fields for each intensity measure type considered in the analysis. The epistemic uncertainty was accounted for by considering three different ground motion prediction equations (GMPE) with the corresponding weights indicated in Table 2. We used Goda and Atkinson's 2009 (Goda and Atkinson 2009) model to account for the cross-correlation of the ground motion fields.

Table 2. Ground Motion Models used for the earthquake scenario

Model	Tectonic environment	Variability	Weight
Abrahamson et al. 2015	Subduction interface	intra-event, inter-event	0.437
Zhao et al. 2006	Subduction interface	intra-event, inter-event	0.348
Montalva et al. 2016	Subduction interface	intra-event, inter-event	0.215

2.4 Building inventory and occupants

The Cali exposure dataset includes 2.1 million occupants, over 348,000 buildings classified into 6,000 different classes with a total estimated exposed economic value over 55 billion USD (Calderon A. et al. 2021). The exposed economic value aggregated at neighbourhood level is presented in Figure 3.

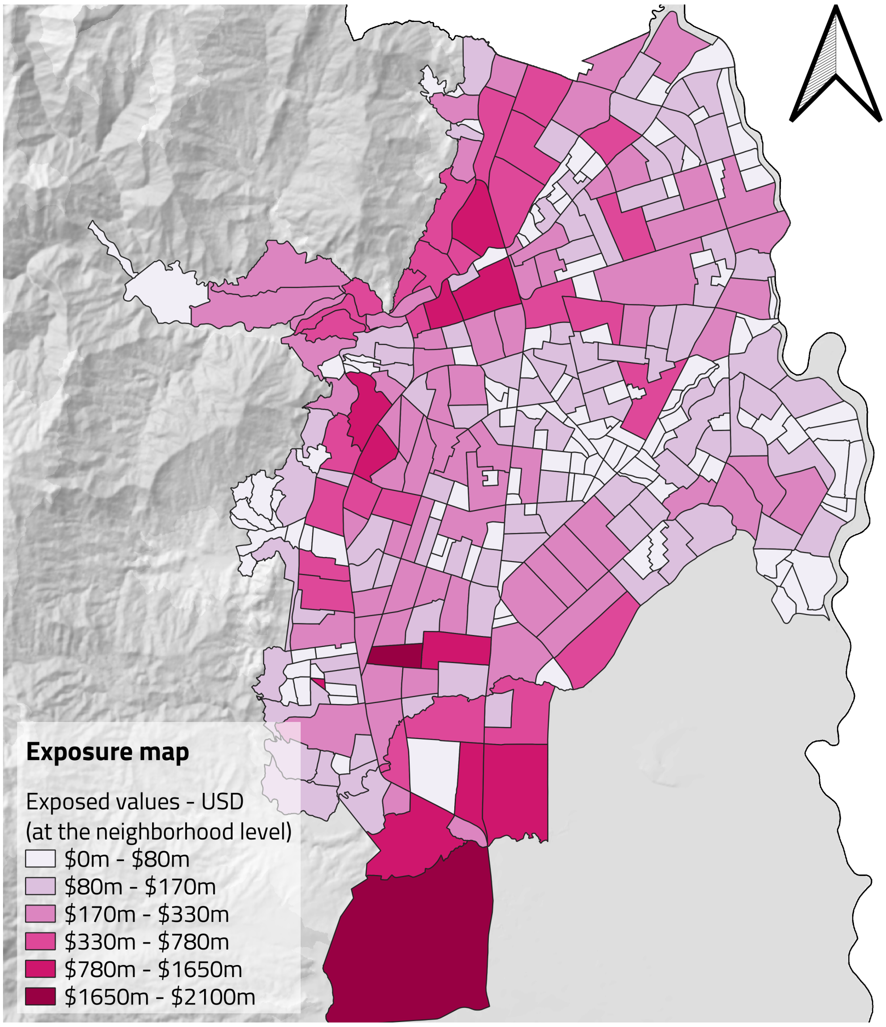

Figure 2. Exposed economic value for the city of Cali, aggregated at the neighbourhood level.

In regional damage and risk assessment, we generally clasify buildings according to their structural system, building materials, height, and expected seismic performance. These characteristics are sufficient for damage and loss estimations due to earthquake-induced ground shaking.

When assessing damage and losses due to secondary perils, understanding the foundation system of the buildings is essential. A foundation system is the part of the building structure that is in contact with the ground and transfers the loads of the building structure into the ground. The type of foundation system is generally classified according to depth and whether it has lateral load-resisting capacity.

The city of Cali does not have openly available the information about the foundation system at city level. Therefore, for the present analysis we assumed that buildings with more than three stories are supported by deep foundations, while buildings with one, two or three stories rest on shallow foundation. Furhtermore, irrespective of the number of stories, we assumed that building built before 1960 have shallow foundations. Figure 3 displays the number of building supported by shallow and deep foundations aggreggated at neighbourhood level. We observed that the vast majority (i.e., approximately 97 %) of the structures are supported by shallow foundations.

2.5 Fragility analysis

Damage and loss estimation methodologies generally classify buildings according to the lateral load resisting system, building materials, and height, the features sufficient for the estimations due to ground shaking. On the other side, when assessing the damage of the exposed assets due to ground failure, a critical feature that must be considered is the foundation type of the buildings. Furthermore, the damage definition differs from what has been used traditionally in damage/loss estimation since a building can be tagged as 'uninhabitable' by the liquefaction-induced effects without actually suffering any structural damage to the lateral load resisting system.

We used Hazus (NIBS 2003) approach to estimate damage and loss due to vertical settlement and lateral spreading. According to this approach, buildings are assumed to be either undamaged or severely damaged due to ground failure, whichh implies that the buidling damage is characterized by one combined extensive/complete limit state. The likelihood of slight and moderate damage is considered to be low, therefore it is a reasonable assumption that these limit states are captured in the estimation of slight and moderate damage states due to ground shaking.

The fragility curves conditioned on permanent ground deformation (PGD) are modelled with cumulative lognormal distribution with a standard deviation of 1.2, and median value of 0.254 m for settlements, and 1.524 m for lateral spreading. These curves are available for buildings on shallow foundation. For structures supported by deep foundation, the probability of complete damage is reduced by a factor of 10 for settlement-induced damage, and by a factor of 2 for lateral spreading-induced damage (NIBS, 2003). These models indicate that deep foundations improve the building performance by a limited amount in case of ground lateral spreading. Figure 4 shows the fragility curves used in this study.

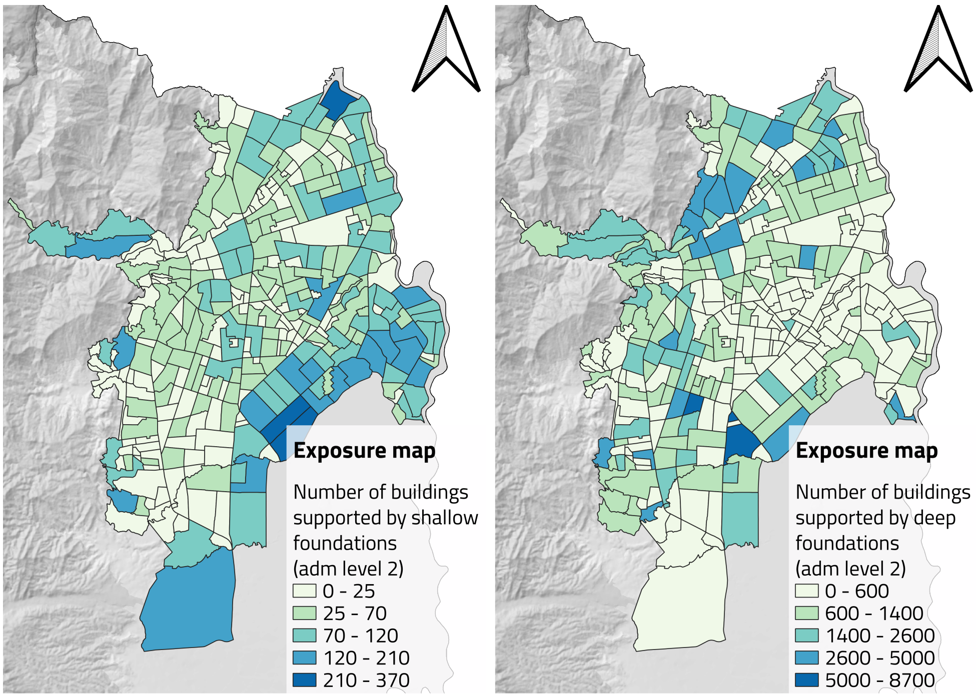

Figure 3. (left) Distribution of the buildings supported by shallow foundations, (right) Distribution of buildings supported by deep foundations

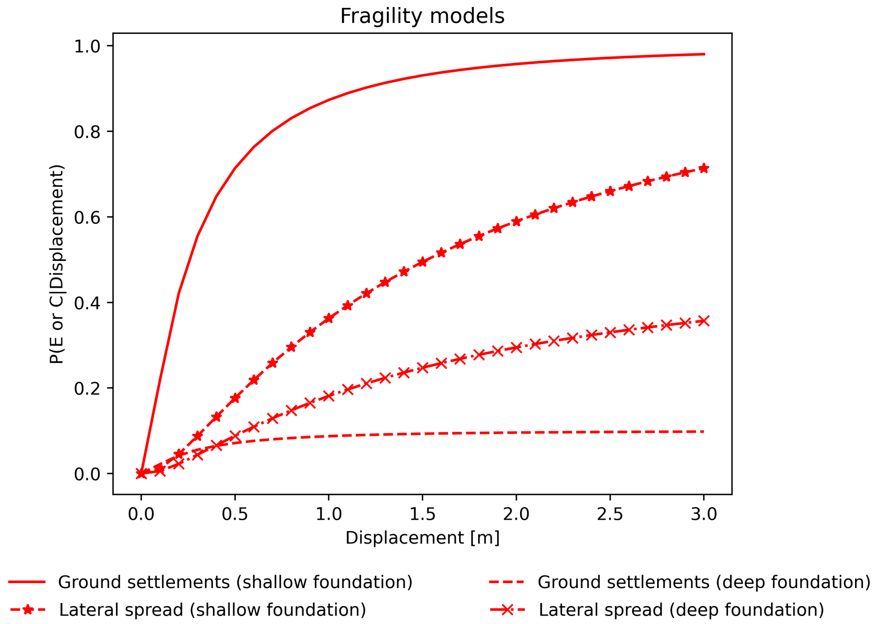

Figure 4. Hazus fragility models for two different intensity measures: ground settlements and lateral spreading.

3 Coseismic Landslides

3.1 Coseismic landslide models

A wide range of phenomena falls under the category of coseismic landslides. We implemented a modified Newmark sliding-block model developed by (Jibson et al. 2000). This physics-based model represents the down-slope motion of a coherent block of earth materials. It is the most well-studied and commonly-implemented landslide model, both because of the simplicity of the model and the ubiquity of this type of earthquake-induced landslide. The model is based on a force-balance approach, comparing the gravitational and seismic accelerations encouraging sliding to the frictional resistance of sliding. The model predicts the probability of the landslide occurring, and the distance of displacement. Aside from the physical parameters of the site characterization (rock density, etc.), the model includes some unitless numerical tuning coefficients calibrated to Southern California by Jibson et al. (2000). The implementation of the model in OpenQuake allows for different values from different calibrations, but no data were available for the Cali region that could enable a local calibration.

3.2 Coseismic landslide analysis in Cali

3.2.1 Site characterization

Site calibration for the landslide analysis requires topographic (slope), geographic and geotechnical data. The topographic data was from a 30 m Shuttle Radar Topography Mission (SRTM) digital elevation model. The slope map was generated from the DEM in QGIS using standard techniques. Geological and geotechnical parameters include the rock or soil cohesion, coefficient of friction, water saturation level, and dry density. These values were assigned to each stratigraphic unit in the geologic map based on standard values for each rock type, and assigned to each analysis point by the rock unit that the point inhabits (Figure 5).

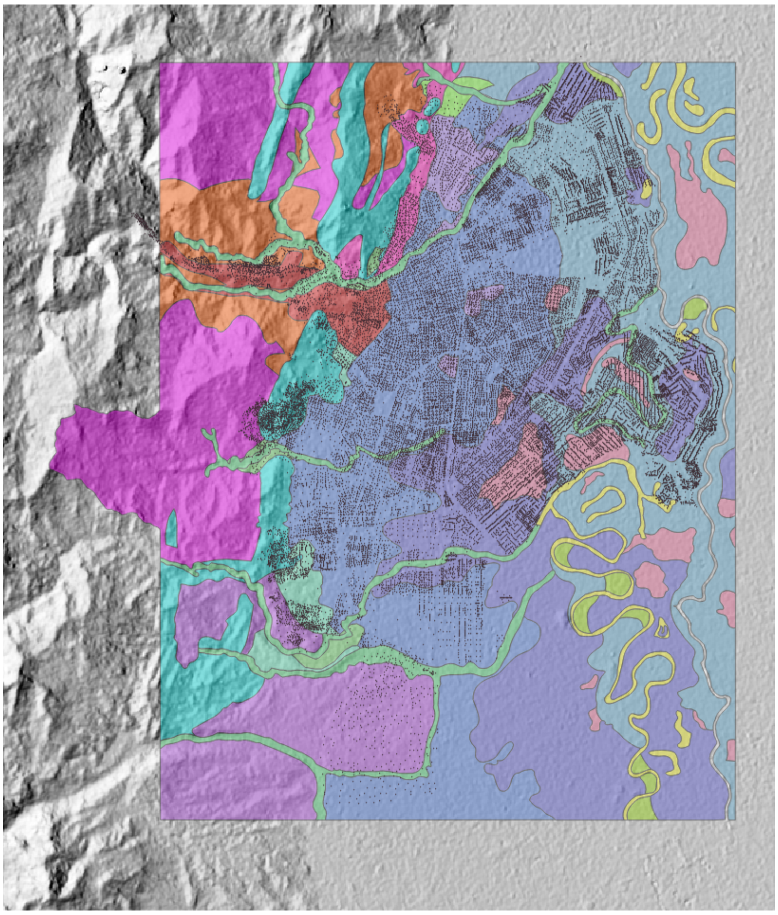

Figure 5. Geologic map of Cali, Colombia overlain on a hillshade based on a 30 m DEM. The sites for analysis are shown as tiny black dots.

3.2.2 Hazard analysis and results

The first step in the hazard analysis is to calculate the strength of coseismic ground motions at each point in the city required to induce landslides; this must be done before a scenario or probabilistic analysis using calculated ground motions is performed.

The results of the initial coseismic landslide hazard analysis indicate that the city of Cali has a very low probability of landslides within its borders, in large part due to the very flat terrain within the city limits, despite the relatively weak geological materials the city is built on. Almost the entirety of the city would require ground motions of over 5 *g*, extreme values well above what may be expected in even the strongest earthquakes that Cali could be subjected to (Figure *6*). A few locations in the far west of the city, into the mountains, may require merely very high levels of ground shaking (around 1-2 *g*). However, we note that our analysis was limited to sites within the City of Cali, where building information is available (which is necessary for risk analysis). Informal or exurban settlements outside of the city to the west, in the mountains, are likely to have much higher probabilities of coseismic landslides because of the steep terrain.

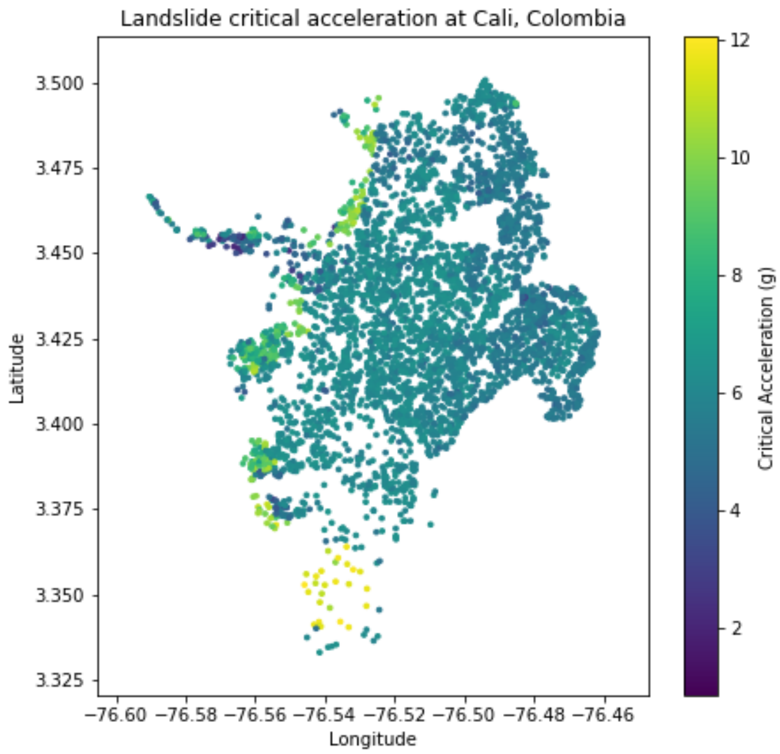

Figure 6. Critical Acceleration, or the minimum ground acceleration necessary to induce landsliding, in the City of Cali, Colombia.

3.2.3 Risk results

Despite the very low probabilities of triggering landslides in the majority of the urban area, several tests we performed with the existing fragility models for this peril resulted in a large number of buildings suffering significant damage. None of the scenarios yielded results that are credible in terms of the spatial distribution of the damage or consistent with the damaged obtained fom the groundshaking intensity of the events. In most cases, damage results exceeded the estimates of from direct groundshaking. As the probability of landslides across the city suggests the hazard approach is sound and consistent with the topography of the city, we concluded that the model is not approapiate for urban risk assessment until better fragility models for landslides become available.

4 LIQUEFACTION

4.1 Liquefaction models

Two published liquefaction models were implemented in the OpenQuake Engine; these are the only two general-purpose (i.e., not limited to particular environments) liquefaction models available that do not require subsurface information that can only be obtained from drilling. One model is part of the *HAZUS* suite of tools from the U.S. Federal Emergency Management Agency (NIBS 2003) .The other is an academic geospatial model developed by Zhu et al. (2015).

The *HAZUS* liquefaction model (NIBS 2003) requires a site characterization that places each site into one of six landslide susceptibility classes based on geotechnical characteristics of the site; these classes range from 'not susceptible' to 'very high susceptibility'. The model is calibrated to 1980s liquefaction data, mostly from the U.S. and Japan. The model predicts probabilities of liquefaction as well as the horizontal and vertical displacements. However, the displacement predictions (especially for the vertical component) are extremely crude. The calibration range of the magnitude of ground shaking is somewhat limited, in that moderate to large accelerations could produce very high horizontal displacements. For the vertical component of displacement, the magnitudes of displacement (settling) are fixed based on the liquefaction susceptibility of the site; this is a constant with no variability, so every earthquake that produces liquefaction will cause the same amount of vertical settling at each point in that susceptibility category. This is a very limited and approximate approach, therefore the model and the respective results must be interpreted with caution. However, it is the only known liquefaction model that predicts displacements, which are necessary to calculate building damage.

The geospatial (Zhu et al. 2015) model calculates the probabilities of liquefaction given a small number of parameters derived from remote sensing data through logistic regression. The method is fast and calibrated to a variety of sites globally in a range of environments and in principle, should be widely applicable. However, one parameter of concern is a value called the *Compound Topographic Index* or CTI, which is based on the area of the hydrologic basin upstream of any site, and is used as a proxy for soil saturation (a major determinant of liquefaction potential). The CTI is meant to be used on moderate hillslopes rather than floodplains (where most of the liquefaction risk occurs) and is unbounded, meaning that values can increase indefinitely, whereas soil saturation cannot.

4.2 Liquefaction analysis in Cali

4.2.1 Site characterization

Sites were characterized for liquefaction potential with means appropriate for each model. The *HAZUS* model (NIBS 2003) requires that each site be classified into a liquefaction susceptibility category, based on geotechnical characteristics of the site. This was done by assigning each stratigraphic unit a liquefaction susceptibility based on its characteristics and then classifying the sites based on which stratigraphic unit they are sited on. An additional parameter used beyond the site classification is the water table depth at that site (which was interpolated based on sparse drill logs throughout Cali).

The Zhu model uses two parameters derived from remote sensing data for the site characterization. The first is the CTI. Values for the CTI were taken from a dataset produced by the USGS, which is the source used in the original calibration. The second parameter is the Vs30 value, which was derived from the topographic slope using the methods by Allen and Wald (2007).

4.2.2 Hazard results

Liquefaction probabilities were calculated using both sets of methods, and then the displacements were calculated with the *HAZUS* (NIBS 2003) techniques.

The *HAZUS* (NIBS 2003) liquefaction probabilities have a fixed upper bound at about 0.3 (Figure 7). Sites closer to the river, where the site classification is generally 'very high', show the highest probabilities. Sites to the west, on the alluvial cone, show very low (or zero) probabilities of liquefaction in the scenario earthquake.

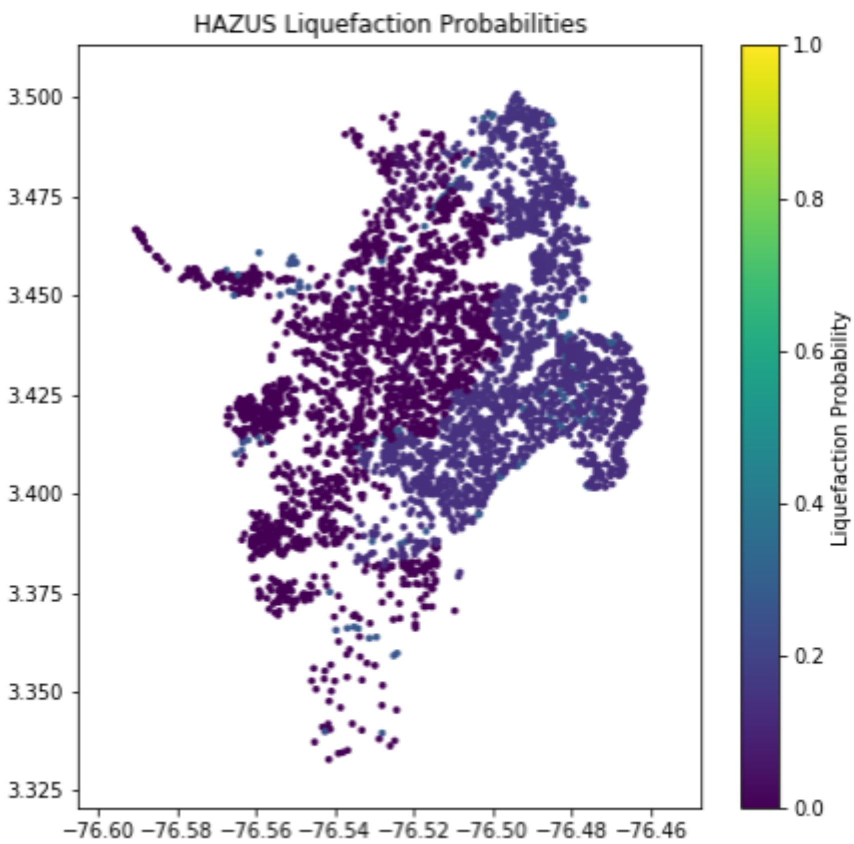

Figure 7. Liquefaction probabilities for the 1906 Mw 8.8 earthquake scenario, calculated using the HAZUS methods.

The (Zhu et al. 2015) liquefaction probabilities are much higher in the liquefaction-prone regions of eastern Cali (Figure 8). In these areas, where the CTI values are quite high and the Vs30 values are low, the probabilities of liquefaction occurrence are far greater than 0.5 and in some cases are > 0.9. These are surprisingly high probabilities and may need extensive validation to instill a sense of confidence in the results.

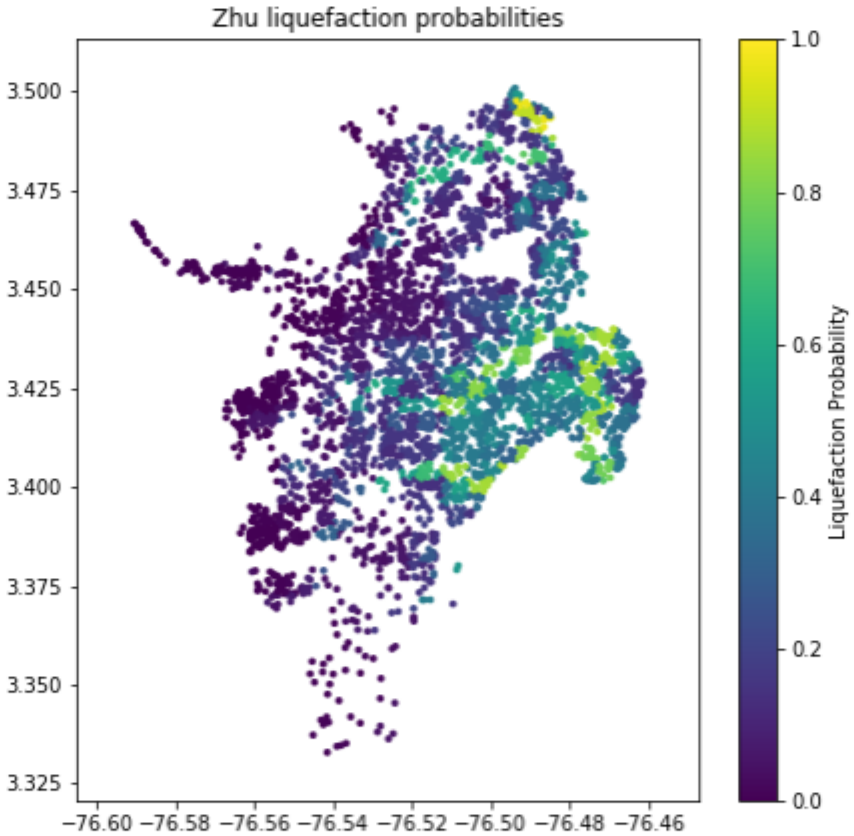

Figure 8. Liquefaction probabilities for 1906 Mw 8.8 earthquake scenario, calculated using the Zhu et al. (2015) methods.

The results of the two liquefaction models are incompatible, which suggests that one or both proposed model do provide credible results. Other than a general pattern of increasing liquefaction to the east, into the floodplain of the Cauca River (which is expected), the values do not show any numerical correlation (Figure 9). The ranges of the values are dramatically different, and sites with relatively high or low values from one set of model results do not show correspondingly high or low values from the other set of model results.

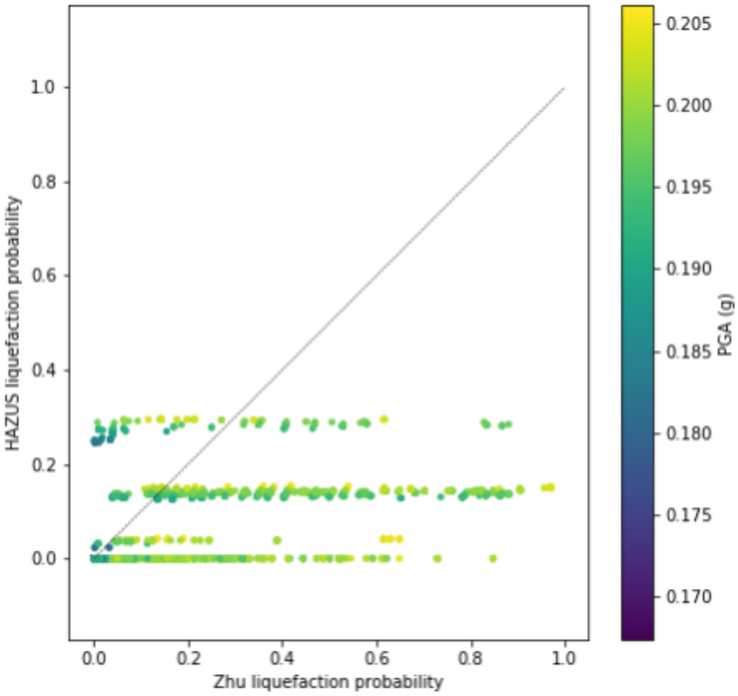

Figure 9. Scatterplot of liquefaction probabilities from the HAZUS methods (y axis) and Zhu et al. (2015) methods (x axis). The lack of correlation and substantially different ranges demonstrate the incompatibility of results that can be obtained using these approaches.

The horizontal displacements calculated using the *HAZUS* methods (NIBS 2003) are very sensitive to the peak ground accelerations generated from the earthquake. When PGA is calculated using only the median of the GMPEs, with no variation, displacements are modest (and perhaps realistic, although there is no data from a similar event in the region to compare to) (Figure 10). Displacements are essentially zero for the less susceptible sites in western Cali, at higher elevations, aside from some sites on small rivers and creeks. Displacements of 0.4-0.7 m are found in susceptible soils in the low-elevation floodplains of eastern Cali. Note that these displacements are conditional upon the occurrence of liquefaction at each site, which will be very different for different models, as noted above.

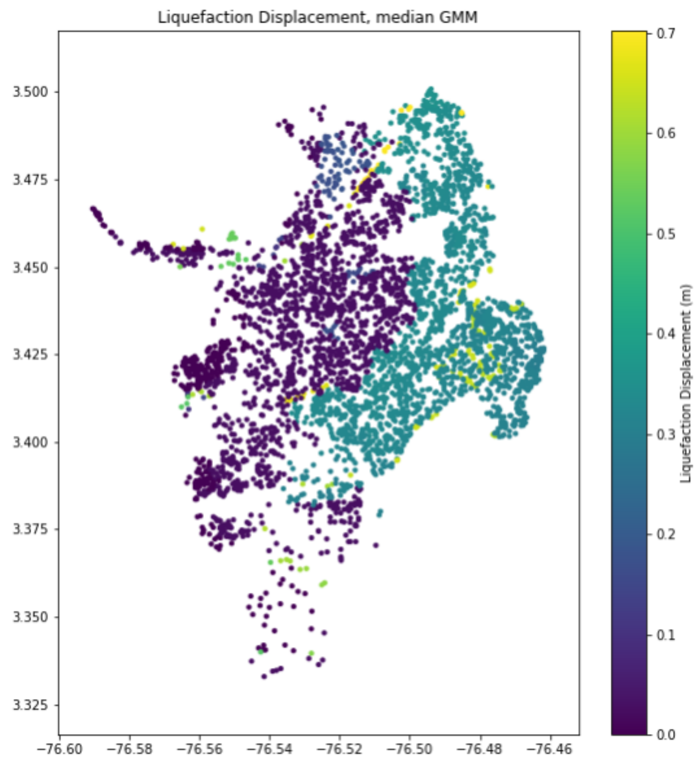

Figure 10: Displacement from liquefaction in Cali, conditional upon liquefaction occurrence, using the median ground motion with no uncertainty.

When aleatory variability in the GMPEs is included, the possible range of displacements increases dramatically (Figure 11). Many sites have displacements above 1 m, and the highest calculated displacements are close to 25 m. Such high horizontal displacements are not impossible in exceptional conditions, such as where a gentle topographic slope can lead to landslide-like mobilization of a liquefied groundmass, but it is 1-2 orders of magnitude higher than observations from earthquakes like the 2011 Christchurch earthquake, where PGA reached almost 2 g, and liquefaction was widespread. It is likely that the calibration of the displacement functions was performed with a dataset that included much smaller values of PGA, and values above 0.5 g were outside of the range of the data.

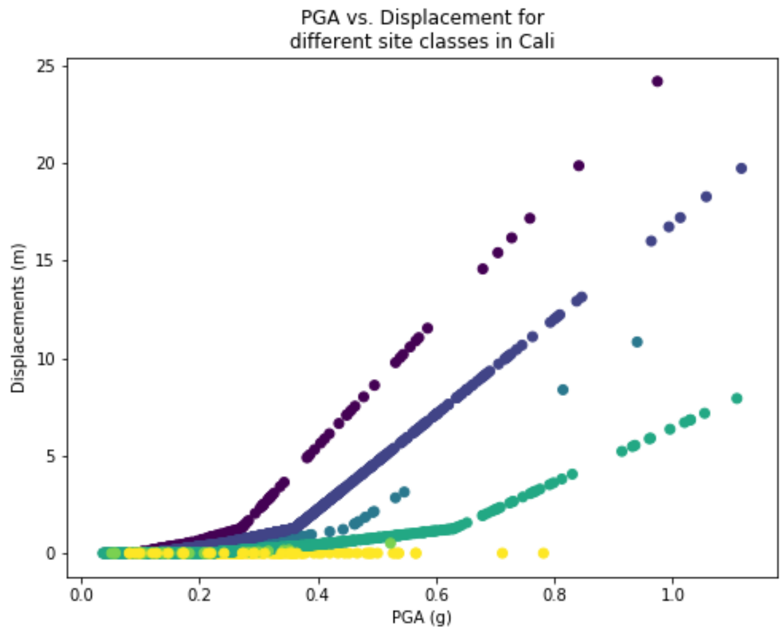

Figure 11: Displacements from liquefaction in Cali as a function of Peak Ground Acceleration, when aleatory variability is included in the ground motion model. The different colors represent displacement in each site class.

The displacement magnitudes calculated for horizontal displacements (lateral spreading) that are strongly dependent on PGA are in stark contrast to the values for vertical settling, which are independent of PGA, despite that both components are estimated using the functions from *HAZUS*.

4.2.3 Scenario damage results

We performed damage assessment for the chosen scenarios (see Section 2.2.1), and it can be seen that the most adverse effects for the city were estimated for 1906 M_w 8.8 Nazca earthquake with the epicentral distance of 400 km SW of Cali. We summarized the results in Table 3 and in Figure 12 we observed that neighborhouds in the east suffered more damages and losses which is in line with the higher liquefaction susceptibility of the region along Cauca river.

Table 3: Scenario damage results for the considered historic events

No	ShakeMap ID	Scenario damage calculation	
		Number of completely damaged buildings	Damage ratio [%]
1	usp00091q3	418	0.12
2	usp0006skc	100	0.03
3	usp0006dv8	738	0.21
4	usp0004zbt	247	0.07
5	usp000d8gx	142	0.04
6	official19060131153610_30	3728	1.07

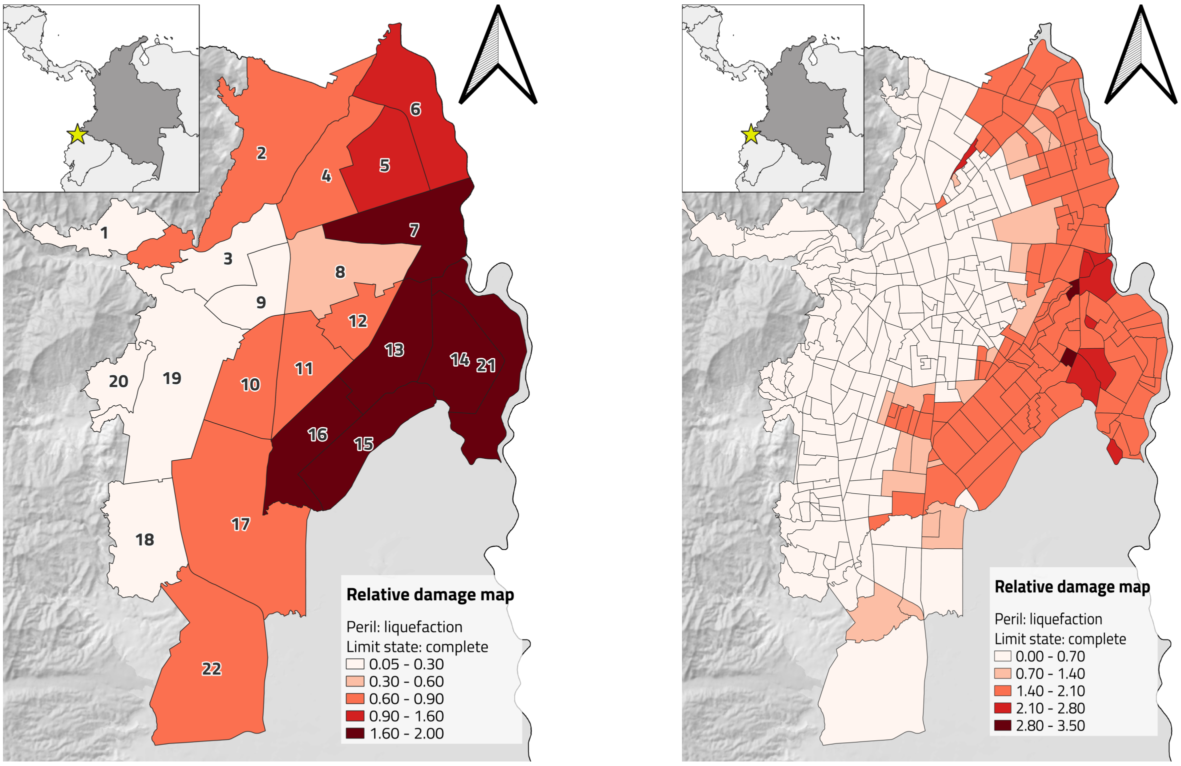

Figure 12: Expected damage ratio: (left) at the admin level 1; (right) at the admin level 2

5 Discussion and conclusions

For the first time, functionality to predict the hazard and risk from secondary seismic perils (coseismic landslides and liquefaction) has been incorporated in the OpenQuake Engine. This is a major milestone and can greatly enhance hazard and risk modeling for susceptible regions.

However, the low quality of the implemented models greatly reduces the utility of liquefaction modeling in OpenQuake. Great inconsistencies within and between the *HAZUS* and Zhu et al. (2015) models for liquefaction occurrence probability as well as displacement magnitudes are limiting the credibility of the results using these methods. Nonetheless, they are the only published methods that use data that can be collected remotely, in the absence of subsurface information only available through laborious on-site geotechnical site characterization.

It is possible that, with calibration, the liquefaction methods may be partially improved. However, there are substantial inconsistencies fundamental to the methods (for example, whether the strength of ground shaking has any controls on the magnitude of the liquefaction displacements) that hint that these models should be replaced by new approaches in the future.

The most substantial problem with improving the methods is the lack of available, high-quality landslide and liquefaction data that can be used to either calibrate existing models or develop new models. As remote sensing data and processing techniques (i.e., using machine learning) develop, it may be possible to semi-automate dataset development from recent or future earthquakes so that models may be improved or replaced.

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