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EARTHQUAKE DAMAGE ASSESSMENT FOR IQUIQUE: CASE STUDY FOR IMPLEMENTATION OF HAZUS-MH IN CHILE.

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Abstract

Risk evaluation and loss analysis is key in foreseeing the impact of disasters caused by natural hazards, and may contribute effectively in improving resilience in a community through the pre-evaluation of preparedness and mitigation actions. The pilot study considered herein is the city of Iquique, located in north Chile where a large megathrust earthquake and tsunami is expected to eventually cover the south of Peru and north of Chile. Although the region was recently hit by an M_w 8.2 earthquake April 1st 2014, damage caused was only moderate. Geophysical evidence suggests that there is still a potential for a much larger event in the region. Therefore, a thorough risk assessment is key to anticipate its possible physical, social, and economic consequences. Consequently, HAZUS-MH was used to simulate a set of earthquake hazard scenarios generated from estimates of plate interlocking and the residual slip potential remaining from the April 1st 2014 rupture fault mechanism. Successful application of the HAZUS-MH methodology relies on the construction of a comprehensive exposure model that takes into account regional features and a good characterization of the physical vulnerabilities. For Iquique we have used a large body of public and local data to develop a detailed inventory of physical and social assets including an aggregated building count, demographics, essential facilities, infrastructure, and lifelines. To characterize the response of the built environment to seismic demand, HAZUS fragility curves and downtime models were applied, and outputs were calibrated using the observed damage after the April 1st 2014 earthquake. Using such calibration, a deterministic seismic risk assessment for the collection of generated scenarios and their expected impacts on all physical assets, population, and essential facilities were estimated. This analysis sets a basis for the simulation and evaluation of different physical and social mitigation measures for the city in the future.

Keywords: Risk; damage; deterministic; HAZUS; Iquique.

1. Introduction: Earthquake Damage Assessment for Deterministic Scenarios.

Seismic risk evaluation and loss assessments enable communities to estimate the impact of earthquakes in people, buildings, services and infrastructure, and hence identify the most effective mitigation policies and actions to decrease the potential for future adverse social and economic consequences. These analyses can be approached using a probabilistic framework, which characterizes the frequency of occurrence of all possible ground motions, or from a deterministic perspective, where specific scenarios are defined by location, magnitude and synthetic ground motions [1]. Both methodologies complement each other in risk mitigation and emergency planning, although more emphasis may be given to one or the other depending on the kind of decision to be made, the seismic environment, and the scope of the project. In particular, deterministic scenarios are well suited to check for worst-case events and identify the estimated maximum foreseeable losses, and plan for emergency management, response and recovery actions in the short and long term. This approach is specially relevant for high seismic regions located at active plate margins, where large earthquakes have short return periods relative to other less seismic regions [1, 2].

The need for disaster scenarios to support decision-making in planning and preparedness has motivated development of large-scale cooperative projects to examine the implications of major earthquakes in areas of high seismic hazard like California (e.g. ShakeOut and HayWired scenarios, [3, 4]), the Cascadia region (e.g. [5, 6]) and Turkey (e.g. [7]). Such studies typically comprise the design of a plausible earthquake that considers available geophysical knowledge on the tectonic setting and historic seismic activity for the area of interest, and assumes a certain fault rupture model that is then used to determine the expected ground shaking in the surrounding region. These ground motion estimates are subsequently used as input for engineering-based loss assessment methodologies that estimate the physical damage on the built environment, the impact on population measured in terms of mortality, morbidity and disruption of social systems, and the total direct and indirect economic consequences for the simulated event. The results thus obtained enable different users to anticipate critical weaknesses *before* a catastrophic event occurs, identify and prioritize actions that could mitigate losses, and train emergency response and recovery exercises, among several other possibilities.

This research develops a deterministic earthquake risk model for the city of Iquique (Chile), by applying the HAZUS loss-estimation methodology formulated by the U.S. Federal Emergency Management Agency (FEMA) and the National Institute of Building Sciences (NIBS), with the aim of producing estimates of human and economic consequences of earthquakes, hurricanes and floods [8]. Although the methodology was originally developed to help U.S. studies, its use has been extended in recent years to other earthquake prone international communities, and case studies for global implementation have been at least developed recently in Canada (e.g. [9, 10, 11]), Venezuela [12], Israel [13] and Egypt [14]. Our goal here is to demonstrate how geophysics-based modelling of seismic scenarios and standardized models for estimation of earthquake losses may be integrated and adapted to a national context, and eventually scaled so as to provide a comprehensive framework for multi-hazard risk assessment in Chile.

The HAZUS methodology integrates a quantitative representation of the solid earth hazard considered with (i) a detailed inventory and characterization of the social and physical assets exposed to losses (i.e., an *exposure model*), (ii) a set of analytical engineering models and parameters to estimate in probability terms the structural and non-structural damage to each component of the built environment, and (iii) the consequential social and economic impact. This paper is organized so that in Section 2 we start with a general description of the geographical study region, i.e. Iquique, and the strategic and geophysical justification to select it as the pilot case for HAZUS implementation in Chile. In Section 3, we focus on the characterization of the seismic hazard of northern Chile, and Iquique in particular, and in Section 4 we describe in detail the construction of a complete exposure model for the city. Section 5 discusses some specific assumptions and parameters of the HAZUS damage assessment methodology and their pertinence to the Chilean engineering and construction practices, and in Section 6 the results of deterministic seismic risk assessment for a previous event is used as calibration benchmark. Finally, Section 7 summarizes the conclusions for the proposed earthquake scenarios.

2. A Case Study for HAZUS Implementation in Chile: Iquique.

Geophysical studies based on the analysis of historical and recent seismicity are useful in the identification of regions of increased hazard, and are able to provide qualitative descriptions of the location and rupture mechanisms of plausible future earthquakes. The subduction zone along the coastal margin in north Chile last ruptured in a ~M_W 8.8 megathrust event in 1877 [15] and since has been identified as a major seismic gap with strong coupling over a 500km-long segment [16], which is anticipatory of a large earthquake. The area ruptured April 1st 2014 generating a M_W 8.2 earthquake that affected the coast of the Tarapacá region [17,18]. However, subsequent assessment of its seismo-tectonics indicates that this was not the expected sizable event, and that there is still a megathrust earthquake potential in the north of Chile and south Perú [19]. This geophysical evidence of elevated seismic hazard necessarily requires for intensive risk awareness, preparation and mitigation efforts, which can be more efficiently directed if there is a robust assessment of the physical, social, functional and economic impacts of plausible event scenarios on the affected communities.

Located at the core of the north Chile seismic gap, the coastal city of Iquique (20°13’00” S, 70° 10’ 00” W) is the capital and largest urban center in the region of Tarapacá, with an estimated population close to 184.000 [20]. It hosts roughly 60% of the total regional population, it is commercially very active and Chile’s 5th most important port [21], it has and an international airport and a tax-free zone, which makes it a hub for most commercial, industrial and touristic activities conducted inland. The city is also a main source of employment for the mining region, and provides supplies and social services to surrounding communities, including the neighboring Alto Hospicio area with a population close to 94.000 [22]. Iquique has a strategic importance in north Chile and its hazardous tectonic setting naturally motivates its selection as case study for the development of a deterministic seismic risk evaluation that benefits from the most recently availability of scientific knowledge. This analysis should consider plausible earthquake scenarios for the region, and provide an estimate of the potential impacts and location mostly affected.

3. Seismic Hazard Characterization for Iquique.

The aim goal of this research is to perform a comprehensive assessment of the potential physical, social and economic losses for a collection of synthetic but plausible scenarios that could affect the city of Iquique given the current state-of-the-art geophysical knowledge on the region and its current potential for a megathrust earthquake. This section describes how these scenarios were defined, and how they could be translated into potential hazard maps suited HAZUS use, by considering appropriate ground motion prediction equations (GMPEs) and local soil conditions. Moreover, the potential for ground failure due to liquefaction and land sliding was also considered.

3.1 Definition of deterministic earthquake scenarios.

The set of seismic scenarios considered have been developed by researchers at the National Research Center for Integrated Natural Disaster Management (CIGIDEN*) with expertise in the solid-earth processes and subsequent natural hazards, who have performed a combined analysis of trench parallel gravity anomaly — believed to predict seismogenic behavior in subduction zones [22]— and interseismic coupling modeled from inversion of geodetic measurements [23, 24, 25] in the seismic gap region extending from south Perú to Antofagasta (Chile, 17° S – 24°S). These data are used to build a normalized coupling index that allows identification of five asperities. As a results, ten possible earthquakes were proposed by considering the simultaneous rupture of one, two or three of the asperities, thus rendering moment magnitudes between M_W 8.42 and M_W 8.95 [23]. In this paper, we emphasize the two extreme cases, so as to raise awareness on a lower bound of damage expected for Iquique, and the eventual consequences for a most damaging larger magnitude event.

The first realization (scenario 01) corresponds to the relatively more favorable case where the rupture involves a single asperity located in front of the southern Peruvian coast (~ 17°S), causing a M_w 8.42 earthquake with epicenter nearly 50 km offshore the Peruvian-Chilean border. In the worst predicted scenario (scenario 10), three asperities identified between Ilo (Perú) and Antofagasta (Chile) rupture simultaneously, triggering a M_w 8.95 shock with epicenter located roughly 102 km S-W of Iquique. In Table 1 we summarize the main

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geophysical parameters of the proposed earthquakes, and in Fig. 1 we present the predicted slip distributions. The hypocenters for each scenario are hypothetically situated so as to coincide with the location of the maximum slip.

Additionally, and only for validation purposes, we simulate the M_w 8.2 earthquake occurred April 1st 2014 with epicenter located approximately 94 km NW the coast of Iquique, hereafter referred to as the "Pisagua 2014" scenario. In this way, we expect to compare and validate the results of our hazard characterization and damage assessment with the actual ground motions and damage cadasters observed during that event.

Table 1 – Geophysical parameters for the set of deterministic earthquake scenarios simulated in HAZUS.

Scenario	Magnitude (Mw)	Maximum Slip (m)	Epicenter	Depth (km)
01	8.42	6.9	(-19.042°, -71.750°)	12.1
10	8.95	8.6	(-23.917°,-70.769°)	24.9
Pisagua 2014	8.20*	4.0**	(-19.610°,-70.769°)*	25.0*

* Source: USGS [26]. **From slip distribution model based on InSAR+GPS data [27].

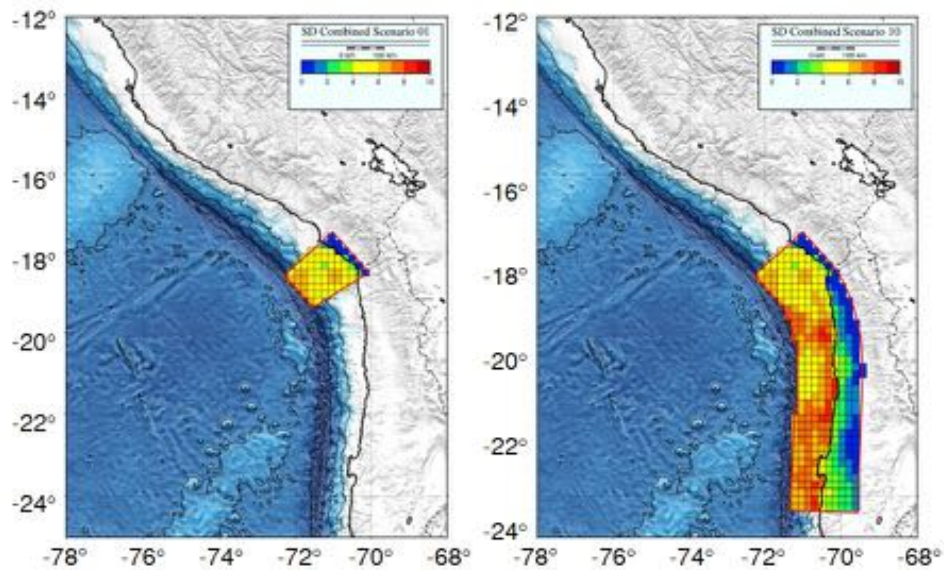


Fig. 1: Predicted slip distributions for the two deterministic earthquake scenarios proposed for north Chile.

3.2 Generation of seismic hazard maps.

In HAZUS, the calculation of direct physical damages for deterministic scenarios requires the seismic hazard to be characterized in terms of standard ground motion parameters used by engineers to estimate earthquake impact on structures, i.e. peak ground acceleration (PGA), spectral acceleration for periods of 0.3 and 1.0 seconds (PSA03 and PSA10), and peak ground velocity (PGV). Therefore, to predict PGA and spectral accelerations generated by each deterministic earthquake scenario throughout the city of Iquique, we use the suite of GMPEs for subduction zone earthquakes given in Abrahamson et al. [28], which are based on a global dataset of empirical strong-motion data with 292 events. These GMPEs were tested with satisfactory results in case of the Maule 2010 M_W 8.8 earthquake. For PGV, the GMPEs proposed by Kanno et al. [29] were used, which were derived from strong ground motion records collected during Japanese subduction earthquakes between 1963 and 2003. These GMPEs are applied to estimate PGA, PSA03, PSA10 and PGV at rock sites and then corrected following National Earthquake Hazards Reduction Program (NEHRP) provisions [30] to account for amplification effects due to local soil conditions. Such provisions define a standardized site geology classification scheme based on the average shear wave velocity in the upper 30 meters (V_{S30}) and recommend amplification factors for each site class. Values of V_{S30} for Iquique are obtained from the seismic micro-zonation proposed for Iquique by Becerra et al. [31], based on geophysical surveys, boreholes and the geological background of each area. Results show that Iquique's geology is rather heterogeneous. As shown in Fig. 2a, the urban area is divided into nine zones of similar dynamic behavior with a predominance of rock sites in the downtown area of Iquique, and dense soil conditions towards the north- and south-east limits of the city and in the port area, which are more likely to experience ground motion amplifications compared to rock. In Table 2 we list the NEHRP site classes and amplification factors assigned to each zone in Iquique, and show as an example the PGA estimates for the three earthquake scenarios described in Table 1. Similar results are generated for spectral accelerations at 0.3 and 1.0 seconds, and for PGV.

Predicted values for the Pisagua scenario are compared with available records from the April 1st earthquake, which include three records in zones I-A (PGA=0.27g and PGA=0.30g, respectively), and one in zone I-B (PGA=0.60g). Results are also satisfactorily compared before site amplification with the USGS ShakeMap [32], which considers only rock sites, with good results. This limited comparison suggests that our results are somewhat reliable for rock sites (e.g., I-A), but may underestimate the amplification of softer site conditions.

Table 2 – Seismic micro-zonation of Iquique [26] and PGA estimates for deterministic earthquake scenarios simulated in HAZUS.

	Seismic Micro-zonation for Iquique								
V_{S30} (m/s)	I-A 872±183	I-B 768±166	II-A 577±86	III-A 461±50	III-B 612±35	IV-A 403±38	IV-B 379±48	V-A 762±205	V-B 393±78
NEHRP site class	B	B	C	C	C	C	D	C	D
PGA/PSA03 amplification	1	1	1.2	1.2	1.2	1.2	1.6	1.2	1.6
PSA10/PGV amplification	1	1	1.6	1.6	1.6	1.6	2.0	1.6	2.0
Scenario	**PGA (g)**								
01	0.097	0.096	0.111	0.118	0.118	0.113	0.152	0.121	0.159
10	0.384	0.381	0.452	0.460	0.458	0.455	0.606	0.467	0.622
Pisagua	0.259	0.256	0.294	0.310	0.312	0.300	0.404	0.318	0.424

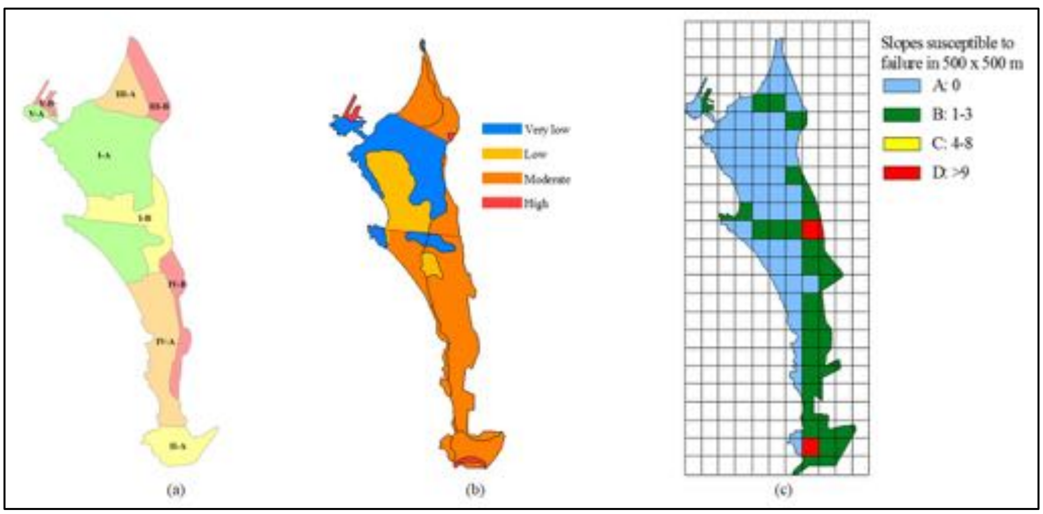


Fig. 2: Maps of the studied area in Iquique: (a) site classification, (b) liquefaction susceptibility; and (c) slope failure potential.

3.3 Liquefaction and landslide susceptibility.

In any seismic event, hazardous geotechnical phenomena like liquefaction and landslides, say caused by slope failures, may result in increased damage to structures due to permanent ground deformation (PGD). Therefore, such effects are therefore considered in the HAZUS loss assessment methodology in combination with ground shaking. Each of these types of ground failure is specified through a conventional geotechnical hazard map that defines areas of varying susceptibility ranging from very low to high. In Iquique, the method proposed by the Kanagawa prefectural government in Japan [33] was used, which defines geological and geomorphological criteria for identifying areas of high liquefaction potential, and formulates a method for zoning slope failure susceptibility according to seven factors: (1) maximum surface acceleration; (2) length of the contour of average elevation; (3) maximum difference in elevation; (4) rock hardness in a typical slope; (5) total length of faults; (6) total length of artificial cut or filled slopes; and (7) topography of typical slopes in each grid element. The liquefaction and landslide susceptibility maps developed according to this procedure for Iquique are shown in Fig. 2b and 2c.

4. Exposure Model for Iquique.

For any damage assessment methodology, the quality of the results is critically dependent on the input information regarding the elements at risk, say the degree of completeness of the inventory, and the detail and accuracy of the exposure model fed into the analysis. In the case of Iquique, a large body of public and local data was used to develop a detailed inventory of physical and social assets including aggregated building count, essential facilities, infrastructure, lifelines, and demographics.

4.1 Aggregated building count.

To model the general building stock for Iquique, a detailed property cadaster generated by the Chilean Internal Revenue Service (Servicio de Impuestos Internos, SII) was used. The data was updated January 2014 and obtained under Law N° 20.285 on transparent access to public information. The SII database registers for each property a code, address, block, lot and total appraisal, and detailed information on the destination, material, quality level, and built area for each construction within a property. These data are referenced to a digital map of the 1652 blocks into which Iquique is subdivided, which has been published online by the Ministry of Public Assets in a Spatial Data Infrastructure [34]. For completeness, this inventory is combined with information provided by the Ministry of Housing and Urbanism (Ministerio de Vivienda y Urbanismo, MINVU), which reports on the location, construction year and structural specifications of social housing units, which are tax exempt and hence not accounted for by the SII. Both datasets combined account for 33.386 buildings, with the geographical distribution presented in the color map of Fig. 3, which depicts the total number of buildings per block.

In HAZUS, buildings are classified according to their declared use in one of seven general occupancy categories —residential, commercial, industrial, agriculture, religious, education, and government— which are further subdivided into 28 specific occupancy classes [35]. For calculation of physical damage, the methodology defines 36 model building types based on construction material, structural systems and height range according to NEHRP guidelines [36]. This work considers only 14 of these building models that are more commonly found in Chile. Construction of the aggregated building stock is based on a census of the number of buildings or a certain occupancy class per block, and the corresponding distribution of building model types is estimated through application of a specific occupancy-to-model building type mapping scheme, which is defined at regional level. In this work, SII and MINVU information was used to derive a specific mapping scheme for the Iquique study region, which is summarized in Fig. 3 in terms of general occupancy categories and building types. We find that 88.4% of all buildings are residential, 10.2% have a commercial use, and only 0.7%, 0.4%, 0.2%, and 0.1% correspond educational, industrial, religious, and government purpose buildings, respectively. In particular, for residential houses, the predominant building type is reinforced masonry (59.4%), followed by wood (38.8%) and minor percentages of reinforced concrete and steel frames. Detailed distributions in terms of HAZUS building typologies were obtained for all specific occupancy classes as part of our region-specific mapping scheme.

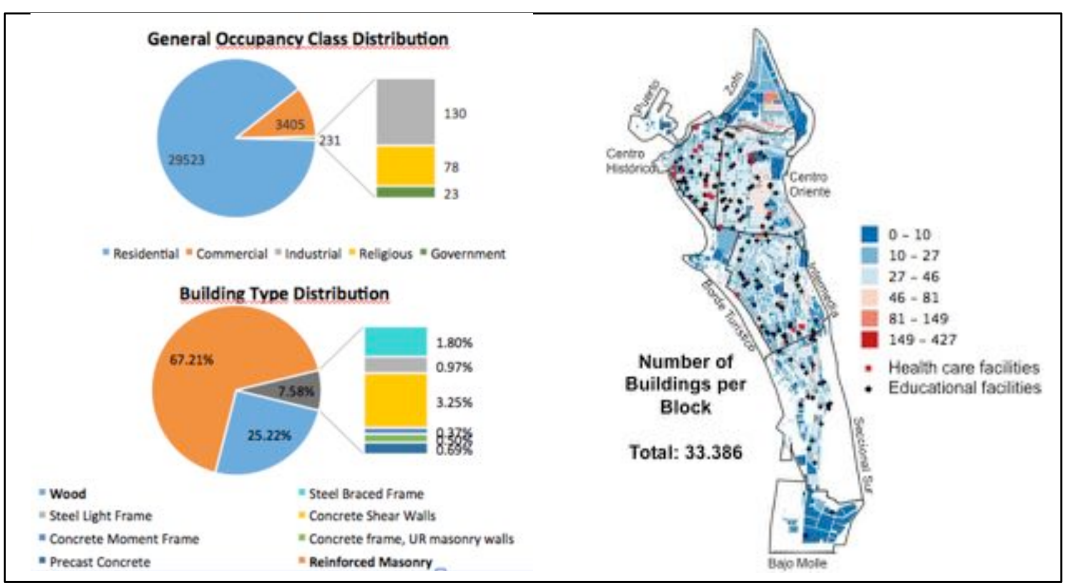


Fig.3: Aggregated building stock and mapping scheme for Iquique. Panels on the left show the general distribution of occupancy classes (top) and building types (bottom) for all buildings included in the exposure model. The color map presented on the right shows the block subdivision considered in setting the aggregated building inventory, and the resulting building count per block.

4.2 Essential facilities.

Special consideration is given in HAZUS to facilities that provide essential services to the community and whose functionality after an earthquake is thus critical from the perspective of emergency response and social recovery. These essential facilities include health care services, police stations, fire stations, emergency operation systems and schools. For these cases, an assessment of physical damage and downtime is carried out individually for each building, as opposed to the aggregated analysis considered for the general building stock.

Data on the structural properties, functions and capacity of essential facilities was compiled from relevant public data sources like the Ministry of Health (Ministerio de Salud, MINSAL), Ministry of Education (Ministerio de Educación, MINEDUC), Fire Brigade of Iquique, Carabineros de Chile and the Municipality of Iquique. Shown in Fig. 3 are the locations of the most relevant installations, which typically have structural properties similar to those of regular buildings of the same material and building system, although with higher design standards. Therefore, their probabilities of reaching different states of damage for a given hazard are calculated in identical manner as for building in the general stock, but it is done at individual level.

4.3 Lifelines and utilities.

Damage assessment for lifelines is based on the estimation of earthquake effects on the main components of ground, air and ship transportation systems. At this stage our analysis is focused on the urban area of Iquique, so lifelines considered are limited to the urban roadway network, port and airport facilities. An extended analysis considering damage to structures and transportation networks in surrounding areas will be conducted in the near future, so as to gain a broader and more complete understanding of earthquake direct and indirect effects at the regional level.

Required data for damage assessment of the roadway network includes the geographic location and structural classification of individual components (i.e. segments, bridges and tunnels). At the spatial scale of a city, the main element of interest are street segments, which were mapped using LIDAR data as part of a JICA/SATREPS Disaster Prevention and Mitigation Project developed in Iquique in collaboration with our University [37]. Data on port and airport facilities were obtained from the Ministry of Public Works (Ministerio de Obras Públicas, MOP) and the respective management companies (Iquique's Port Company and Iquique's Airport Concession Society). Finally, georeferenced information on potable water, waste water and electricity distribution networks and facilities was obtained from the supervising governmental organisms, i.e. the Superintendence of Sanitary Services (Superintendencia de Servicios Sanitarios, SISS) and Superintendence of Energy and Fuels (Superintendencia de Energía y Combustibles, SEC), respectively.

4.4 Demographics and population dynamics.

The population of Iquique was characterized using raw data from the Census 2012 database [38], which has been reported to suffer from methodological shortcomings and has an estimated national omission rate of 9.3% [39]. Nevertheless, this omission rate is still considerably lower than the 26.3% population growth estimated for the Tarapacá region since the last valid Census of 2002 [40], so the 2012 census, albeit incomplete, was considered since still represents the most up-to-date data of Iquique's demographics. These data are used to determine the total population, age and sex distribution at block level taking as a reference the same cartography used for construction of the aggregated building count, and shown in Fig. 3.

Demographic data is used for estimation of casualties due to earthquake-induced physical damage to structures, which can vary significantly depending on the time of occurrence of the seismic event according to the population's continuous flow and redistribution across the city. Census data accounts for permanent residents in each building, and therefore allows for a good estimate of expected casualties during a night-time earthquake. For assessment of daytime scenarios, we combine Census data with results from the Origin-Destination Survey (Encuesta Origen-Destino, EOD) carried out by the Ministry of Transportation and Telecommunications (MTT). The survey was conducted in 2010 in Iquique as part of a broader plan for urban transport modernization [41], and collects information on the number and purpose of trips made between predefined zones of Iquique, shown in Fig. 3, and its surroundings at four times of day (morning, noon and afternoon during rush hours, and non-rush hours). In this work, we use morning-rush hour (7:30-8:30 AM) data to estimate the expected population distribution for a daytime seismic scenario, hereby assuming that people move around the city and come in(out) from(to) nearby locations in the morning for their daily activities, and stay there at least until noon. We distinguish between daytime resident population and those relocating for work or educational motives; final demographics estimates for each zone are summarized in Table 3. These total figures are distributed among tracts in each zone according to the relative number of residential, commercial and educational buildings in each of them.

Table 3 – Census 2012 and daytime population distribution for Iquique.

	Census 2012	Daytime resident	Daytime working	Daytime student	Total daytime
Bajo Molle	2392	303	809	2601	3735
Borde Turístico	5633	2149	1300	606	4079
Centro Histórico	19455	14847	11049	11831	37950
Centro Oriente	66266	42566	6689	6524	56109
Industrial Zofri	251	63	4855	0	4947
Intermedia	55964	38689	6488	12357	57874
Puerto	1339	-71	757	0	690
Seccional Sur	28740	14240	1236	5425	21025
TOTAL	**180040**	**112786**	**33183**	**39344**	**186409**

5. Fragility and Damage Assessment Methodology.

In order to calculate direct physical damages, HAZUS combines the seismic demand characterized in terms of PGA, spectral accelerations and PGV, as shown in Section 3, with the characterization of building seismic response. The latter is composed of structural capacity curves, and structural and non-structural fragility curves. Capacity curves represent the required lateral force required to deform laterally a building to a certain displacement, while fragility curves represent the probability of being in, or exceeding, a certain building damage state for a given demand parameter such as PGA or spectral displacement (S_d). The five damage states considered are *None, Slight, Moderate, Extensive*, and *Complete*. Their descriptions for all building types are found in the HAZUS manual [35].

In this study, capacity and fragility curves provided by HAZUS were used, even though more specific local information of Chilean construction practice is not accounted for in them. This is partially justified since Chilean seismic design provisions are based on equivalent to U.S. codes (e.g. ASCE-7 and ACI), which are used by HAZUS. Therefore, lacking a better representation of local capacity and fragility curves ready to be input into the program, the use of default curves from HAZUS is deemed as a reasonable approximation with some clear advantages: (1) these curves are based on thoroughly studied code provisions such as the Uniform Building Code (1976 and later) and NEHRP (1986 and later editions); (2) all of them are the result of applying a homogenous methodology; and (3) they are readily available to perform initial analyses on a geographical region where no more specific information is available.

6. Earthquake Damage Assessment for Seismic Scenarios in Iquique.

Combining the hazard maps generated in Section 3 and the comprehensive exposure model constructed for Iquique in Section 4, we examined the consistency between the results predicted by HAZUS with the results observed during the Pisagua 2014 scenario. Subsequently, a simulation is carried out to evaluate the damage caused by the two predictive earthquake scenarios considered in this case study. For the sake of brevity, we only report herein on damages to the aggregated building stock and essential facilities. Direct and indirect impact on lifelines, social systems, and economy will be addressed in a future publication.

6.1 Damage calibration during the Pisagua 2014 earthquake in Iquique.

Following the April 1st 2014 earthquake, different public entities assembled damage cadasters that were contrasted here with HAZUS predictions for the same event. First, the Municipality of Iquique's Direction of Public Works (Dirección de Obras Municipales, DOM) surveyed a total of 2712 residential units to assess their post-earthquake condition and need for repairs or demolition. This cadaster includes only buildings for which owners voluntarily reported earthquake effects, and classifies the damage state of each building as either *None*, *Partial* or *Complete*, including in most cases a brief description of the observed structural and non-structural damage. We note, however, that these reports are not typically homogeneous or complete, which hinders the correlation with the corresponding HAZUS discrete levels of physical damage, classified as *None*, *Slight*, *Moderate*, *Extensive* and *Complete*. Moreover, municipal damage reports contain no information on the material and structural properties of the inspected units, so we are unable to classify them in terms of specific building types.

Additional information is obtained from the official documents emitted by the Ministry of Interior Affairs and Public Safety [42] that reproduce information compiled by MINVU on the total number of social dwellings with minor and major damage. These reports refer to affected homes and families, so apartments are presumably counted individually, and not as a single building. The available information for Iquique's urban area is summarized in Table 4. The immediate conclusion is that there are rather significant disagreements among public data sources, most notably in the number of units with minor and complete damage. This has two plausible explanations. First, it is expected that the damage census provided by the Municipality of Iquique underestimates the number of buildings with slight or minor effects, because: (i) inspections are conducted only if demanded by homeowners, which is prone to happen when important repairs and government subsidies are required, and (ii) the data collection process conducted by the Municipality reportedly extends for over a year after the earthquake, so it is likely that minor damages have already been repaired before inspection. Secondly, the gap in the number of dwellings with major or complete damage is probably owed to the fact that MINVU reports building apartments individually, so demolition of a few social building compounds translate into a large number of damaged units (e.g., habitational complexes "Las Quintas" and "Las Dunas" considered to suffer total damage according to [37]). Finally, the degree of overlap among different data sources (e.g. MINVU and DOM) is not clear, which reveals and evident weakness in the system of data recollection.

6.2 HAZUS damage estimates for the Pisagua 2014 earthquake in Iquique.

Table 4 shows general estimates on direct physical damage obtained from HAZUS simulation of the Pisagua 2014 earthquake in Iquique, so as to compare with real data collected after the event. Although HAZUS number counts for damaged buildings are given separately for specific occupancy classes and building types, we present here the aggregated tally for residential structures, adopting the following criteria: *Slight* and *Moderate* HAZUS damage states are grouped in a single category that we assimilate to what is generally defined by public entities as *Minor* damage, *Extensive* damage is deemed analogue to definitions of *Major damage, repairable* or *Partial damage* according to DOM and MINVU respectively, and the *Complete damage* state is matched to MINVU's definition of *Major damage, non-repairable* condition. The assumed equivalences are based on a comparison between HAZUS detailed damage state descriptions for each construction type [35], and definitions given in MINVU's technical guidelines [43].

Given these considerations, we it is apparent that HAZUS estimates of the impacts for the April 1st 2014 earthquake on residential constructions in Iquique provide a reasonable representation of the actual facts. An absolute quantitative comparison is impracticable due to ambiguities in the definitions of damage states, unclear definition of the sample of buildings included in each catalogue and the uncertainty regarding the evaluation criteria applied by different inspection teams. However, the results are consistent overall in terms of partial to complete damage, which are the most relevant from the perspective of affected population, induced casualties, shelter needs, and planning for reconstruction and recovery. The total number of buildings with minor damage appears to be considerably overestimated by HAZUS, but this may be attributed in large extent to the fact that minor damages (i.e. with no structural relevance and mostly cosmetic consequences) are more likely to be handled individually by homeowners and thus overlooked in official cadasters. On the other hand, HAZUS accounts for the full inventory of buildings that may be subject to even slight effects. In fact, if we compare counts of buildings with minor damage versus the total number of structures surveyed in each report and in the HAZUS exposure model (i.e. columns 5 and 2 in Table 4), we obtain ratios of 30%, 46% and 40% for DOM, MINVU and HAZUS reports, respectively. Additionally, as shown in Fig. 4, the spatial distribution of damage compiled by the Municipality an those predicted by HAZUS are also consistent, with a concentration of affected buildings to the east and south of Iquique, where soil amplification and liquefaction susceptibility are higher (see Fig. 2). In summary, all three evaluations of the impacts of the Pisagua 2014 earthquake are coherent within the constraints that arise from working with heterogeneous datasets. Hence, we can sensibly believe that use of hazard maps generated in Section 3 in combination with the HAZUS damage assessment methodology yield a realistic representation of the consequences that different earthquake scenarios may have in Iquique.

Table 4: Reported and Estimated Damage to Residential Buildings in Iquique after the Pisagua 2014 Earthquake.

Source	**Total surveyed units**	**Complete damage**	**Partial damage**	**Minor/no damage**
Municipality of Iquique	2712	80	1806	826
	Total surveyed units	**Major damage, non-repairable**	**Major damage, repairable**	**Minor damage**
MINVU	4766	908*	1656	2202
	Total surveyed units	**Complete damage**	**Extensive damage**	**Moderate/Slight damage**
HAZUS	33386	95	1660	13285

* Accounts for all damaged apartments in social building compounds, not independent buildings.

6.3 HAZUS Damage Estimates for Predictive Earthquake Scenarios in Iquique.

After successful validation of the proposed damage assessment methodology during the April 1st 2014 earthquake, we extend the city model to other plausible earthquake scenarios as defined in Section 1: a M_W 8.42 earthquake generated by rupture of a single asperity in south Perú (Scenario 01), and a worst-case M_W 8.95 event where three asperities in north Chile rupture simultaneously (Scenario 10). Shown in Fig. 5a is a summary of the results of all HAZUS simulations conducted in this research. Results are presented in terms of the number of buildings in the most relevant occupancy classes that are expected to suffer different damage levels. It is evident from this plot that the effects of the earthquake considered in Scenario 01 would be negligible as compared to the Pisagua event, with the vast majority of buildings in all occupancy classes being unaffected, and only a minor fraction experiencing slight or moderate damage. Essential facilities, lifelines and economic activities (commercial and industrial) would be similarly unaffected, and therefore the indirect social impacts negligible. This is explained by the distant location of the hypothetical epicenter, which translates into relatively weak ground shaking (i.e. low PGA) across Iquique albeit the magnitude being higher than the one in the 2014 event.

In contrast, the impacts of Scenario 10 would be significant for Iquique, with roughly 40% of residential dwellings experiencing complete damage, plus 27%, 20%, and 28% of commercial, educational and industrial facilities seriously damaged and eventually collapsed, respectively. As shown in Fig. 5b, essential facilities would also be severely affected. In this scenario, all education and health care buildings have more than 58% probability of complete damage after the earthquake, which translates into loss of functionality of a large fraction of critical social services. Moreover, 10% of all schools have a probability of complete damage >90%, which would leave roughly 6500 students almost certainly without access to education and other services provided by public schools like food and shelter in case of emergency. Beyond the direct physical damage and losses generated by such a large earthquake, the indirect social and economic effects are manifold, and warrant an integral, multidimensional analysis that will be addressed in future work.

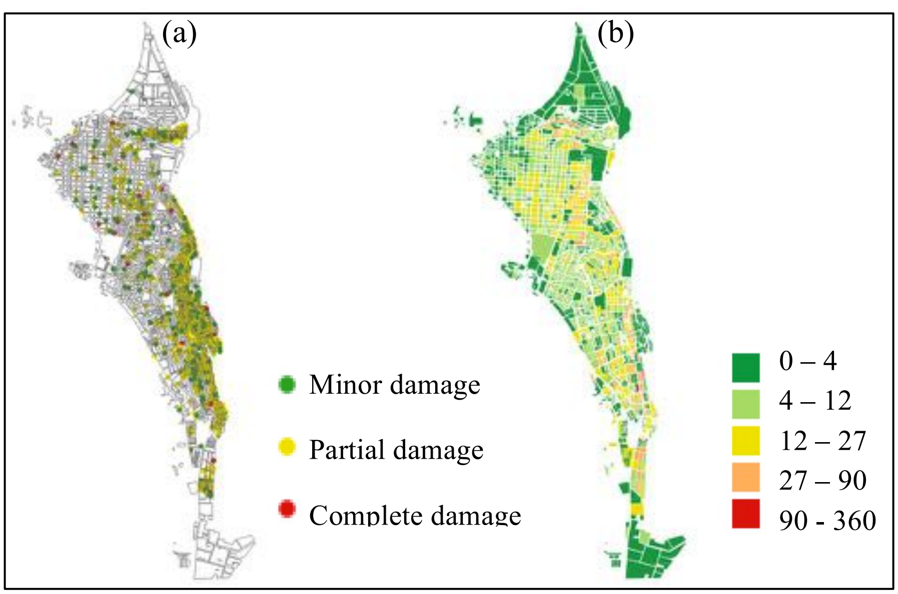
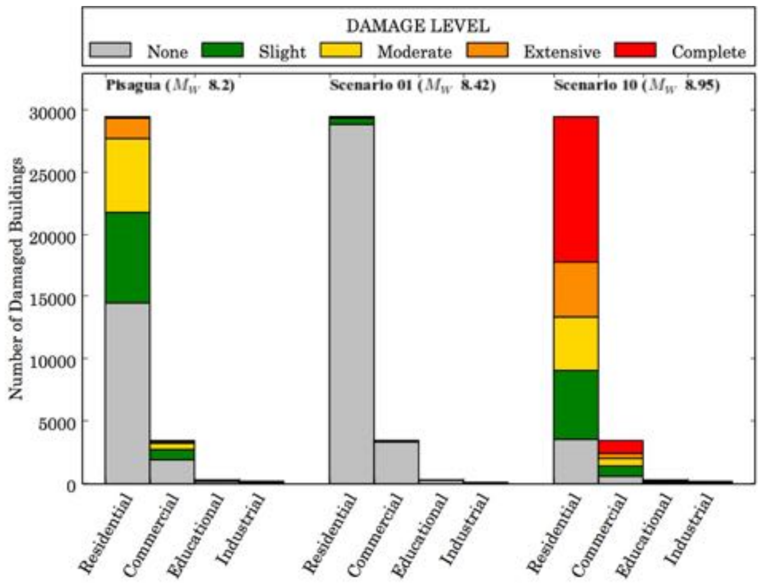
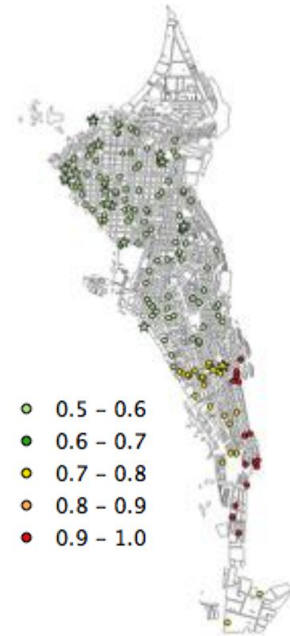


Fig. 4: Distribution of damaged buildings in Iquique after the Pisagua 2014 earthquake. Map (a) shows the location of residential structures with minor, partial or complete damage as reported by the Municipality of Iquique, and map (b) corresponds to HAZUS damage evaluation for the same scenario, represented by a color scale that indicates the total numer of damaged residential buildings per block.



(a)



(b)

Fig.5: Results of HAZUS simulations for the three earthquake scenarios considered in Iquique. (a) Damage to buildings in the aggregated inventory. For each event, the corresponding set of stacked bars represents the distribution of buildings with *None* to *Complete* damage in Residential, Commercial, Educational and Industrial occupancy classes, respectively. (b) Damage to essential facilities for Scenario 10. Circles and stars show the location of schools and health care buildings, respectively, and colors represent the probability that a certain building will reach the *Complete* damage state after the earthquake.

7. Conclusions.

It is concluded that ground motion intensities as predicted by GMPE's for subduction regions combined with reliable information on soil conditions, represent reasonable estimates of parameters like PGA, spectral accelerations and PGV. This conclusion is inferred from the limited number of seismic records available for Iquique and widely used ground-shaking models such as USGS ShakeMap. More spatially accurate results can nowadays be obtained from a combination of physics-based and stochastic models for generation of synthetic seismic records. This provides a sensible representation of both, the low- and high-frequency components of ground motion, including other factors such as site effects, directivity, radiation pattern and the distribution of slips within the faulting segment. Currently a robust methodology to reproduce low-frequency (i.e. < 1 GHz) time histories that are consistent with the observed co-seismic surface deformations [44] has been developed. Research is currently focused in the calibration of stochastic [45] and physics-based models [46, 47] to enable a complete representation of the high-frequency portion of these records.

The significant correlation between damage estimates using HAZUS and the observed damage in Iquique during the past event of April 1st 2014 enables us to conclude that this model can be used for future risk evaluation of the city under different earthquake scenarios. Indeed, all three evaluations of the impacts of the Pisagua 2014 earthquake are coherent in terms of numbers of buildings affected and also with the spatial distribution of the observed damage. Naturally, the quality of this evaluation needs to be addressed considering the important constraints imposed by the use of heterogeneous datasets. Consequently, the use of the hazard maps generated in Section 3 in combination with the HAZUS damage assessment methodology yields a useful model to evaluate the expected consequences of different earthquake scenarios in Iquique.

The two predictive seismic scenarios in the region lead to very different conclusions in terms of the expected consequences. The south Peru scenario results in a less demanding condition than the one imposed by the Pisagua earthquake in 2014, and can be discarded from the analysis. However, the scenario combining the three asperities that have not still been activated from the south of Peru down to the south of Iquique would lead to a very serious condition of damage in the city of Iquique with percentages of seriously damaged and collapsed structures in the range of 30%-40%. Although an estimate, this fact deserves special attention from local and central authorities to evaluate mitigation measures that could reduce this damage and the overall impact of this plausible scenario.

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