Seismic Risk Assessment in Northern Chile - Lessons from a reconnaissance visit before the next mega-earthquake in Peru-Chile

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SUMMARY
In the northernmost part of Chile, a mega-earthquake and tsunami events have been expected for the last 20 years. A seismic gap has been developed since 1877, when a mega-earthquake and tsunami destroyed the existing infrastructure in most coastal cities of Northern Chile. Seismologists suggest that magnitude and mechanism be similar to the ones observed after the last 8.8-magnitude El Maule earthquake on February 27 of 2010. To better understand the potential effects of this expected earthquake/tsunami, the authors conducted site visits in the most populated cities in the northernmost regions of Chile. The aim was to determine what the risk level in these communities is and how local authorities develops their emergency response plans based on the lessons from recent large subduction earthquakes. The paper presents a summary of the observations and information gathered during the visits.

Keywords: subduction earthquakes, tsunami, seismic risk, emergency plans

1. INTRODUCTION

On May 10th 1877, a magnitude Ms = 8.3 earthquake affected mayor coastal cities in Northern Chile and Southern Peru. This earthquake and tsunami occurred after 9 years of another Ms=8.5 earthquake in Southern Peru. Fig. 1a shows the estimated rupture area of both earthquakes. Both earthquakes were followed by tsunamis flooding and destroying mostly the lower parts of Tacna, Arica and Iquique (Comte and Pardo 1991). Historical evidence suggests that these two earthquakes occur in intervals of 100 years, which has motivated the high level of alarm in the population and the activation of emergency plans during the last two decades.

The 8.8-magnitud El Maule earthquake in 2010 in Chile revealed a number of issues, such as communication problems between different first responders, lack of alarm or warning instruments, and a long delay in the activation of emergency plans. Several lessons have been learnt in Chile since then. The government and its agencies and other public-private institutions in Chile have worked toward an updated master emergency plan after major seismic events.

To understand the organization of public and private institutions in the event of earthquake-tsunamis and how lessons can be readily implemented in other seismic hazard regions, a research team from the University of British Columbia along with researchers in Chile visited most important cities in Northern Chile (Fig 1b), such as Arica, Iquique and Antofagasta during the last week of August in 2011. Arica, Iquique and Antofagasta are the cities with major risk to future earthquakes and tsunamis and also the three most populated cities in Northern Chile – populations being around 185k, 215k and 360k with densities of 35h/km2, 79h/km2 and 120h/km2, respectively. This paper summarizes observations and relevant information gathered from meetings with local officials and during quick visual screenings of the cities.

2. EMERGENCY MANAGEMENT AND ORGANIZATION IN CHILE

Chile has a National Emergency Plan since 1977, which has been updated and improved to become in 2002 the National Civil Protection Plan, NCPP (Gobierno de Chile 2002). The NCPP is a strategic multi-sector master plan that defines methodologies and the organization structure to prevent, mitigate and address emergencies or disasters in Chile. The NCPP can be put into action by different public/private institutions, government agencies, volunteering groups and organized local communities under the coordination of the National Emergency Bureau of the Ministry of Interior of Chile, ONEMI (for the Spanish version of Oficina Nacional de Emergencia del Ministerio del Interior)

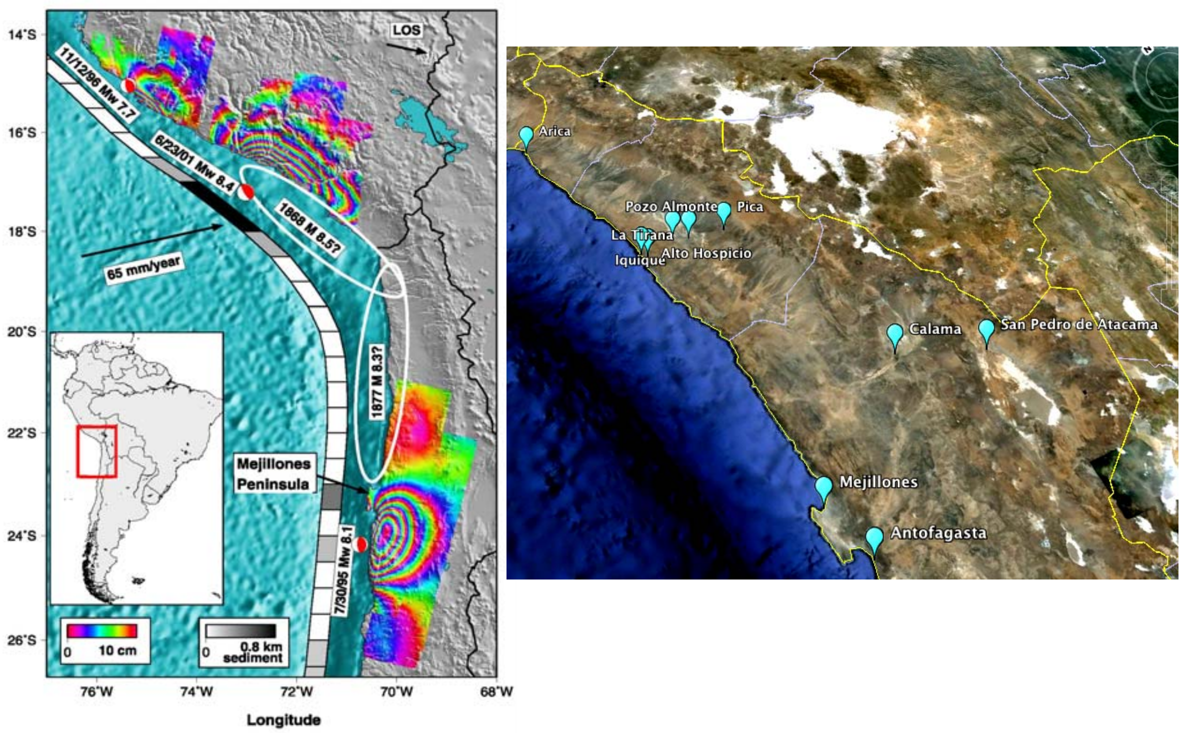

Figure 1. (a) Last major subduction earthquakes in Southern Peru and Northern Chile (reproduced from Pritchard and Simons 2006) and (b) places visited in Northern Chile

ONEMI serves as a logistic entity and gives continuous support to different institutions on both prevention and response at different geo-political levels in Chile, such as National, Regional, Provincial and Municipal (Fig. 2). Prevention activities are coordinated by the Civil Protection Committee which is mainly comprised of professional organizations, private institutions, local industry groups, local government agencies and any other organized entity willing to participate, improve or develop mitigation/ preparation plans. The response, including also the rehabilitation process, is the actual activity during and after the event coordinated by the Emergency Management Committee, EMC (COE in Fig. 2), which is mainly comprised of national or local government authorities, the military forces and the police.

3. LESSONS LEARNT FROM THE 2010 EL MAULE EARTHQUAKE IN CHILE

Civil engineering infrastructure in Chile after the 8.8-magnitude El Maule earthquake in 2010 has a relatively good performance considering the high level of shaking and the close distance of a large population to the rupture area. Most structural damage was observed in low-rise informal construction buildings (e.g. 1 or 2-storey unreinforced masonry buildings). However, this earthquake also revealed many flaws and deficiencies in the design and construction of other different types of buildings in Chile.

A couple of months after the earthquake, the government of Chile introduced two temporary laws, DS 60 (2011) and DS 61 (2011), to quickly address the reconstruction process in Chile based on the recent experience and more updated seismic design standards. Currently, researchers and structural engineers are working together to modify the seismic design and construction standards, the NCh433 (2009) and the NCh430 (2008), of new buildings in Chile addressing the flaws and issues observed after the earthquake in 2010.

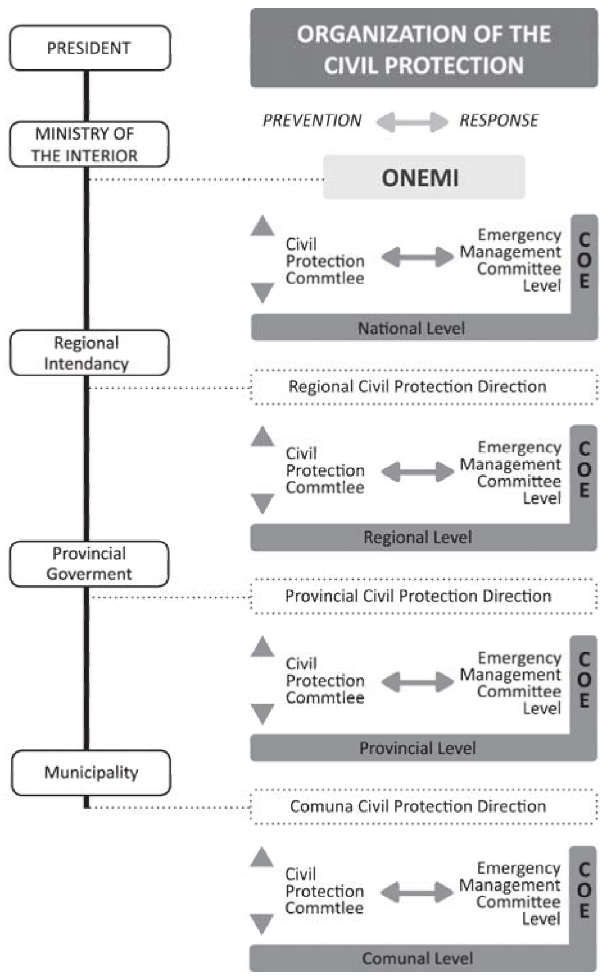

Figure 2. Organization of the preparedness and emergency management in Chile

In terms of the emergency management process during the event, local communities and reports identified a number of issues, such as uncoordinated efforts between the central government, the ONEMI and local authorities, lack of communication tools, poor interaction with international agencies, deficiencies on emergency plan implementation amongst many others. Most casualties were tsunami related in coastal cities/towns within the rupture area and currently being investigated with respect to their relationship with the flaws and issues identified during the emergency coordination process.

To avoid the same issues identified during the earthquake in 2010, ONEMI has reorganized its structure and is currently developing an Integral Emergency Information System, SIIE (Instituto Geografico Militar 2011) and an Early Warning System. Some preliminary information regarding the implementation of these systems was gathered from the meetings in Arica, Iquique and Antofagasta.

4. OBSERVATIONS AND INFORMATION GATHERED DURING VISITS

In Arica, Iquique and Antofagasta, the team met with the directors of the regional ONEMI offices. Rapid visual screenings of each city and nearby towns/cities were conducted, including the identification of building typologies, location of main residential areas, typical structural systems, and an overall understanding of the distribution of the population and its vulnerability during and after a major earthquake. In addition, micro-vibration measurements were recorded in several points of each visited city or town to have a rough estimate of the underlying soil.

4.1. ONEMI meetings

4.1.1. ONEMI-Arica

The Director of ONEMI-Arica, Franz Schmauk, described some earthquake/tsunami-related prevention/response activities in Arica. ONEMI-Arica has been involved in two simulations with the participation of different organizations and communities. The idea was to evacuate the most at-risk communities and to identify flaws and possible emergency scenarios due to a mega-earthquake/tsunami event in the city of Arica. A security line was defined by ONEMI-Arica based on information provided by the Hydro-Oceanographic Service of the Navy Army, SHOA. Positive outcomes were observed from these simulations, such as people reacting to the simulated event and moving quickly to safe zones above the security line.

Although there is a notorious interest in the population to participate in simulations and to receive earthquake/tsunami information, ONEMI-Arica does not have a clear post-earthquake plan. There is awareness, nevertheless, that the most critical point during and after a big earthquake event is the heavy transit of vehicles and people through the Peru-Chile border which is very close to the city. It was also noted that ONEMI-Arica and other government agencies have to deal with other important hazards in the city and the rest of the region, such as rain, chemical deposits in residential areas, and flooding due to the Bolivian Winter, making the earthquake/tsunami event a not the main priority for emergency planning in that region.

In Arica, there was no earthquake/tsunami warnings system in place, but ONEMI-Arica has direct communication with a local seismological service provided by the University of Tarapaca, UTA. This service has many instruments located across the region providing important information/data for researchers across the world. However, the network is obsolete and has poor maintenance due to the lack of funding and support from the government.

4.1.2. ONEMI-Iquique

The acting director of ONEMI-Iquique, Andrea Gonzalez, described similar general aspects to the ones in ONEMI-Arica regarding organization structure, equipment, emergency coordination and earthquake/tsunami simulations. ONEMI-Iquique, however, has to deal with a much larger population, an extensive tsunami risk area, with a much more developed infrastructure in the shore line and a very complex geographical situation. Iquique has an extended plain surface that makes evacuation of the population a rather complex task. Many tall buildings had to be tagged as vertical evacuation zones to provide more evacuation alternatives to people in case of tsunami.

Experience acquired from past simulations and events have helped ONEMI-Iquique to identify most critical emergency situations. Most common emergency for Iquique is the lack of access or exit routes from/to Iquique after and earthquake or tsunami. Unfortunately, Iquique has only two exit routes to other cities, airports or nearby towns. A real tsunami emergency occurred after of the 9.0-magnitud Sendai earthquake in 2011 when a chaotic evacuation blocked with cars one of the two access/exit routes. Many emergency cars could not assist during that emergency because they were trapped in the traffic congestion and the city was virtually isolated for hours. Alternative procedures have been studied by local authorities and ONEMI-Iquique after this incident and included in the master emergency plan for the city.

ONEMI-Iquique has already planed post-earthquake activities with the national army. Aid and relief support will be stored in the army's airport and supplied to a safe zone in Iquique through the air. A plan for the distribution of the aid has been also coordinated with local communities and organizations.

As well as Arica, Iquique doesn't have yet an early warning system implemented neither the support of a local seismological service or strong-ground motion network. The staff at ONEMI-Iquique is aware of the existence of private seismograph networks without public access. The tsunami early warning relies only on the SHOA's service or real-time information from international tsunami warning systems (e.g. NOAA).

In logistic terms and considering the importance of ONEMI, it was of great concern that the office where ONEMI-Iquique coordinates the emergencies is below the tsunami security line and that its electric generator is at the lower level of the building. At the time of the meeting, alternative zones within the city were being considered to built or rent a new regional ONEMI office.

4.1.3. ONEMI-Antofagasta

The meeting at ONEMI-Antofagasta was with its acting Director Mr. Mauricio Soriano and with Dr. Patricio Tapia, researcher and professor at Universidad Catolica del Norte. A brief summary of Antofagasta vulnerability due to tsunami/earthquakes and past simulations in the city and the region were described. Antofagasta was the first region to conduct a massive regional simulation with a high participation of the population. Antofagasta is also one of the few cities with a functioning early warning system with more than 30 sirens located throughout the shoreline and with an active communication system between the city and interior towns and municipalities.

According to Dr. Tapia, Antofagasta should not experienced extensive damage due to the event of an earthquake or tsunami. The situation during and after the last 8.1-magnitude Antofagasta earthquake in 1995 was used as the basis of the most likely outcome expected in Antofagasta for future large earthquake. However, the post-earthquake situation in terms of emergency coordination and assessment of damaged buildings is, as well as in Arica and Iquique, not clear from the local authorities.

The worst case tsunami scenario described by ONEMI-Antofagasta is Mejillones, a small fisherman town located in the shore line with a very extensive plain surface. Mejillones also has several sirens as part of the Antofagasta early warning system and clearly denoted evacuation routes and safe zones. Mejillones has also important ports for the region, including the main power distribution plant of Northern Chile. A damaging tsunami event in this zone could therefore affect the entire region.

4.2. Rapid visual screening

4.2.1. Arica

An overall distribution of the city was easily observed form the characteristic El Morro, a 130-m tall hill in the southern part of the city (Fig. 3a to b). There were many informal buildings made of wood, concrete or unreinforced masonry walls. It was also noticed an important number of new residential and commercial buildings under construction at not more than 300 meters of the shoreline (Fig. 3e, h). The main commercial activities of the city were also observed to occur very close to the shoreline with a great affluence of people during rush hours (Fig. 3i, j, k, l).

The south part of city has less development with only few low-rise buildings located in steep slope. Most residential buildings are located in the upper lands (east side) of the city (Fig. 3f, g). Unreinforced masonry buildings are the most typical structural systems observed in this area with evident unfinished last floors or roofs.

Figure 3. Pictures from visits to Arica: a) west side, b) downtown, c) mid-east, d) east side, e) new reinforced concrete shear wall buildings near the shoreline, f) typical residential 2-storey brick masonry shear wall buildings, g) typical residential 4-storey confined masonry shear wall building, h) new typology of residential reinforced concrete shear wall building near the shoreline, i) downtown district at less than 500 meters from the shoreline, j) north view of typical commercial streets in downtown Arica, k) south view of closest structures to shoreline, and l) streets at the shore line with the view of the characteristic 130-m tall hill El Morro.

4.2.2. Iquique

Iquique is one of the most touristic places in Northern Chile during summer time, which population considerably increases at that time of the year and eventually plays an important role on the emergency plans of the city. Iquique has a wider variety of buildings and infrastructure than Arica. More than 30 reinforced concrete shear-wall mid-rise buildings were distinguished at less than 200 meters from the shoreline (Fig. 4a to d). Several one to two-storey heritage wood buildings were observed in downtown Iquique (Fig. 4e, f). In the north part of the city and downtown, there are two ports with an important traffic of trucks and coastal touristic/commercial activity (Fig. 4i, j, k).

Figure 4. Pictures from site-visits in Iquique: a) North view of main beach (Cavancha) and buildings, b) south view of buildings in the shoreline, c) typical high-rise reinforced concrete shear wall buildings, d) first level of a 20-storey building next to main beach, e) main entrance from the coast to the historic downtown of Iquique, f) typical heritage wood buildings in downtown, g) south part of Iquique showing typical confined masonry shear wall residential buildings, h) mid and high-rise buildings in the south-west side, i) historical buildings near the ports, j) view of fishing boats and main port of Iquique, k) west north side with a view of the coast and nearby buildings, and l) view from a safe zone in the south side.

4.2.3. Antofagasta

Antofagasta is the densest city in northern Chile with consequently more development of tall buildings in the shoreline and of residential areas throughout the city (Fig 5a to d). There are mid-rise buildings across the entire shoreline, commercial shopping centers and an extended pedestrian seawall (Fig. 5e to i). The predominant structural system for most tall buildings is reinforced concrete shear walls and for low-rise residential buildings is unreinforced masonry shear walls (Fig 5j, k). As a difference with Iquique, most buildings and residential areas are at a much higher level from the sea. Many houses and low-rise buildings can be observed in the slopes of hills. Antofagasta is also the main region for mining operations in Northern Chile with a highly growing population.

Figure 5. Pictures from site-visits in Antofagasta: a) south-west side, b) west side (coastal), c) east side, d) view of the shoreline from residential south side, e) typical shoreline, f) typical construction of residential high-rise reinforced concrete shear wall building, g) panoramic south view of the coast line, h) panoramic view of downtown, i) typical reinforced concrete frame systems, j) low-rise reinforced concrete building in downtown, k) new residential reinforced concrete buildings, l) typical construction of low-rise buildings in residential areas in the north side.

4.3. Measurements

Free field micro-vibration measurements where conducted when visiting northern Chile cities and interior towns. Table 4.1 shows a summary of the measurements taken during the visits with micro-tremor instruments, (details of instrumentation, measurement techniques and data processing are explained in Ventura et al. 2004). The characteristic frequencies were identified from recorded data, also included in the figures.

Table 4.1. Summary of sites with micro-vibration measurement and data

Region	Site Name	Latitude	Longitude	Predominant Frequency* (Hz)	Estimated Vs30 ** (m/s)
Arica - Parinacota	Isla del Alacran	18º 28' 23"	70º 19' 42"	0.85***	102
	Valle Azapa - Museo	18º 30' 58"	70º 10' 51"	0.9	108
	Hotel El Paso	18º 28' 23"	70º 18' 51"	0.7	84
Tarapaca	Salitrera Santa Laura	20º 14' 04"	69º 47' 26"	1.1	132
	Pica	20º 29' 07"	69º 19' 03"	0.6	72
	Alto Hospicio	20º 13' 07"	70º 07' 35"	0.8	96
	Hotel Holiday Inn - Iquique	20º 14' 23"	70º 08' 44"	0.7	84
Antofagasta	COVIEFI	23º 41' 22"	70º 24' 40"	1.1	132
	Casino Enjoy	23º 41' 13"	70º 24' 43"	1.2	144
	Seawall Antofagasta	23º 39' 40"	70º 24' 11"	0.9	108
	Hotel – Story 11	23º 39' 42"	70º 24' 12"	0.6***	72
	Calama - Plaza	23º 27' 43"	68º 55' 37"	0.5	60
	Calama-San Pedro Route	23º 43' 06"	68º 24' 27"	0.7***	84
	San Pedro - Plaza	23º 54' 39"	68º 12' 01"	0.7***	84
	La Portada	23º 30' 55"	70º 24' 05"	1	120
	Mejillones	23º 05' 60"	70º 27' 28"	0.75	90
	Mejillones – Safety Zone	23º 06' 20"	70º 26' 46"	2	240
	Port of Mejillones	23º 05' 25"	70º 24' 58"	1.4***	168
	Airport	23º 26' 57"	70º 26' 28"	0.63	75.6

* First peak identified in the frequency domain of the H/V ratio.
** Vs30 using 4 × 30m × Frequency.
*** Not clearly identified

Fundamental frequencies do not vary much amongst all the points measured, between 0.8Hz and 1.2Hz the dominant frequencies for most sites. These frequencies are equivalent to site periods between 0.8s to 1.30s which suggest that most cities are in soft soil with an average shear wave velocity in the upper 30 meters around 100m/s.

5. SUMMARY OF OBSERVATIONS

The trip to Northern Chile was part of a research initiative at the University of British Columbia to understand the emergency plans in Chile and the effects of the El Maule earthquake in 2010 in terms of lessons and improvement on earthquake preparedness and safety issues.
A clear understanding of local governments, private sector and the general public of the hazard and the risk that pose earthquakes and tsunamis to main cities in Northern Chile has been clearly observed from these visits.

The participation of the population in simulations and interest to improve safety issues for future events from local authorities were observed is very high and notorious. However, there are many issues still not clear in the overall emergency coordination plan such as the development and implementation of an early warning system and post-earthquake/recovery plans.

Information gathered during the meetings at the three ONEMI offices and throughout the site visits were of high importance for understanding the use of past experience on emergency coordination in a seismic region. The summarized information described in this paper could eventually help on the development of emergency plans in other communities in seismic areas with less experience from past earthquakes, such as the areas and cities located near the Cascadia subduction zone in southwestern Canada.

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