PONTIFICIA UNIVERSIDAD CATOLICA DE CHILE

ESCUELA DE INGENIERIA

EX-POST ANALYSIS OF ENGINEERED TSUNAMI MITIGATION WORKS IN THE CITY OF DICHATO, CHILE

MAXIMILIANO ANDRÉS OPORTUS FOSTER

Thesis submitted to the Office of Research and Graduate Studies in partial fulfillment of the requirements for the Degree of Master of Science in Engineering

Advisor:
RODRIGO CIENFUEGOS

Santiago de Chile, (March, 2017)

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RESUMEN

Debido a la notoria y desafortunada actividad sísmica en Chile, los estudios relacionados con terremotos y tsunamis se han vuelto una prioridad en el interés de desarrollar medidas de mitigación efectivas y aumentar la resiliencia del país. Las medidas de mitigación son claves para lograr esto, y por lo tanto esta investigación adopta una metodología para la evaluación del daño por tsunami para evaluar el beneficio directo de las obras de ingeniería implementadas por el gobierno chileno como “medidas de mitigación de tsunami” en la localidad de Dichato luego de las secuelas del tsunami de Chile del año 2010. Elaboramos un análisis ex-post de la potencial reducción de daño producida por estas obras y analizamos cuáles habrían sido las consecuencias en el entorno constructivo si estas hubieran estado construidas para el tsunami del 2010. Utilizamos modelos de simulación de tsunami de alta resolución para evaluar la mitigación de un evento tsunamigénico, que actúa como input para evaluar el beneficio por daño evitado en contraste con los costos de las medidas de mitigación. Los resultados obtenidos muestran una reducción en el área de inundación y un retraso en los tiempos de arribo de las primeras olas de tsunami más pequeñas, pero una reducción de daño despreciable comparada con las olas más grandes. En conclusión, estas obras no habrían sido efectivas contra el tsunami producido por el terremoto de Chile del 2010, pero pueden ser útiles para mitigar oleajes por tormenta o tsunamis de mucha menor escala. Nuestros resultados destacan la importancia de la comunicación del riesgo por parte de los actores gubernamentales para evitar generar una percepción falsa de seguridad pública, particularmente cuando este tipo de estructuras se plantean como una respuesta política a un evento destructivo reciente.

Palabras clave: tsunami, medidas de mitigación, análisis de costo-beneficio

ABSTRACT

Due to Chile's notorious and frequent seismic activity, earthquake and tsunami related studies have become a priority in the interest of developing effective counter measures to mitigate their impacts and to contribute to improve the country's resilience. Mitigation measures are key to accomplish these objectives, so this investigation adopts a tsunami damage assessment framework to evaluate the direct benefits of the engineered works such as the ones implemented by the Chilean government as "tsunami mitigation measures" in the town of Dichato in the aftermath of the 2010 Chile tsunami. We perform an ex-post analysis of the potential damage reduction produced by these works analyzing what would have been the consequences on the built environment if they were in place for the tsunami of 2010. We use state-of-the art tsunami simulation models at high-resolution to assess the mitigation of a tsunamigenic event, which serves as input to evaluate the benefit from averted damage against the costs of the mitigation measures. The results obtained show a reduction in the flooded area and a delay in the arrival times for the first smaller tsunami waves, but a negligible damage reduction when confronted to the biggest waves. In conclusion, these works would not have been effective against the tsunami generated by the 2010 Chile earthquake, but might be useful to mitigate storm waves or tsunamis of much smaller scales. Our results highlight the importance of risk communication from government actors to avoid false secure public perceptions particularly when this type of mitigation works are decided as a political answer to a recent destructive event.

Keywords: tsunami, mitigation measures, cost-benefit analysis.

1 INTODUCTION

Chile is a highly seismic country, mainly due to the subduction process of the Nazca plate underneath the South American plate (Araya, 2007; Centro Sismológico Nacional, 2013; Fritz et al., 2011; Lomnitz, 1970); this characteristic, together with the vast coast line along the whole length of the country, sets propitious conditions for the generation of tsunamis from mega thrust earthquakes. Three destructive tsunamigenic events, namely the Maule 8.8 Mw earthquake in 2010 (Fritz et al., 2011), the Pisagua 8.2 Mw earthquake in 2014 (Catalán et al., 2015) and the Coquimbo 8.3 Mw earthquake in 2015 (Aránguiz et al., 2016) have hit Chile over the last 7 years.

The 2010 event, in particular, caused a huge impact in central and southern Chile, where economical, structural and human losses were of a big scale (Fritz et al., 2011; Gobierno Regional del Bío-Bío, 2010). Among the most damaged coastal towns is Dichato, a relatively small settlement that suffered the destruction of property near the beach and estuary (Japan Science and Technology Agency (JST), 2010; Martínez, Rojas, Villagra, Aránguiz, & Sáez-Carrillo, 2016). After the event, the government proposed a mitigation project that included engineered works in an attempt to reduce the impact of a future tsunami. The setting of this new scenario provides the opportunity to compare it to the base (original) scenario to study the actual effect of the mitigation works.

Therefore, the objective of this investigation is to develop and implement a methodology that estimates the direct damage from a tsunami, and apply it to a specific event considering mitigation works in contrast to the investment costs. The level of tsunami damage reduction from engineered measures on a coastal urban area can be evaluated comparing the impacts of this tsunami in different scenarios, with and without their presence. The methodology considers the concepts of exposure and vulnerability in the frame of tsunami risk, and applies them against a single historic event.

The significant impacts associated with recent tsunamigenic events worldwide have motivated several research studies in tsunami prone zones (Adriano, Hayashi, Gokon, Mas, & Koshimura, 2016; Adriano, Mas, Koshimura, Estrada, & Jimenez, 2014; Aránguiz et al., 2016; Arcas & Titov, 2006; Catalán et al., 2015; Goda, Li, Mori, & Yasuda, 2015; González et al., 2009; Fumihiko Imamura et al., 2012; Martínez et al., 2016; Melgar & Bock, 2013; Montenegro-Romero & Peña-Cortés, 2010; Nandasena, Sasaki, & Tanaka, 2012; Ozer Sozdinler, Yalciner, Zaytsev, Suppasri, & Imamura, 2015; Park & Cox, 2016; Santa María, Hube, Rivera, Yepes-Estrada, & Valcárcel, 2016; Anawat Suppasri et al., 2013). An approach is to consider exposure and vulnerability as key concepts in such studies. In (Santa María et al., 2016) they develop an exposure model for residential structures in Chile through the process of gathering the amount, construction material and location of buildings, classifying them according to the type of building, and assigning them a replacement cost. In (Martínez et al., 2016) they analyze the vulnerability in Dichato considering physical, socio-economic and educational dimensions for their variables, in pre- and post-disaster conditions. It is determined that vulnerability is now insufficiently reduced in the town, despite the new mitigation works.

Mitigation studies have been carried out as well, as is the case in (Nandasena et al., 2012). In that research, they perform an evaluation of the effectiveness of certain tsunami mitigation works against the Great East Japan Tsunami in 2011. They considered a vegetated dune, a coastal forest and a seawall and tested them using numerical modelling of the event. They were able to determine how they interacted with the inundation's moment and flow velocity.

From the same Great East Japan Tsunami, two other studies evaluate the effect of breakwaters in the coast of affected areas using tsunami modelling. In (Adriano et al., 2016), they conclude that the breakwater present in Onagawa reduces the tsunami impact by means of a 2 meter decrease in inundation depth, although it was completely destroyed by the flow. Such results were obtained with the use of a hypothetical bathymetry where the breakwater was not included. In a similar research presented in (Ozer Sozdinler et al., 2015), they studied the performance of a breakwater in Kamaishi by working with three scenarios: with, without, and with a damaged breakwater. They found out that the measure produces lower water levels in the protected zone. Furthermore, a damaged breakwater provides a certain protection in a smaller degree. However, the presence of the breakwater generates higher velocities in the direction of the incoming wave.

In this investigation, we perform a cost-benefit approach of the mitigation works, from the damage assessment and ex-post analysis. To perform this, we characterize an event, the exposure level, and the vulnerability of the built environment, against the 2010 tsunami. Next we quantify the direct impacts with and without the two engineered counter measures that are now in place. This methodology allows for the results to be directly evaluated in monetary terms, and better understand the tsunami impact reduction that these works provide.

The document is organized as follows: Section **Error! Reference source not found.** shows a brief overview of the important definitions and clarifications being considered, and Section 3 shows a characterization of the case being studied including a description of the tsunamigenic event and the area of impact. Section 4 extends on the methodology to be applied. Sections 5 and 6 present the results and corresponding discussion, and Section 7 refers to the concluding remarks of this study.

2 DEFINITIONS

2.1 Risk, hazard, exposure and vulnerability

In the present work, the definition of risk considered is composed by three factors: i) hazard, ii) exposure, and iii) vulnerability (González et al., 2009; Venegas San Martín, 2012; Weichselgartner, 2001). Hazard is described by the physical intensity measures that reflect the ability of a certain geophysical phenomenon to inflict harm (González et al., 2009). In the risk analysis framework it is necessary to assess all the possible events that may occur in the area of interest (Cutter, Mitchell, & Scott, 2000). Notwithstanding the general aspects of hazard definition, the information available and the orientation given to the study determines whether it is treated with a probabilistic or deterministic approach, or a combination of both (Mitsoudis et al., 2012).

On the other hand, the exposure should consider an inventory of all the elements at risk, that is, communities and physical infrastructure that may be found facing a hazard (Pelling, Maskrey, Ruiz, & Hall, 2004). In the framework of tsunamis risk analysis, these elements are located in an area subjected to flooding (Penning-Rowsell et al., 2005).

Lastly, vulnerability is a complex concept that has many variants. Weichselgartner 2001 defines three different types of vulnerability. First, there is the pre-existing condition where vulnerability is evaluated as the situation preceding a physical or technological hazard, and the focus relies on the distribution of a certain condition, the occupancy of the area of interest and the degree of loss. The other two types of vulnerabilities are the response and the place, where the first is defined as the society's ability to cope with the disaster, and is marked by a social point of view. The latter refers to a combination of the first two types of vulnerabilities, with an emphasis on the geographical domain (Weichselgartner, 2001). This approach is the one that best applies to this particular investigation, as vulnerability will be characterized according to the scenario previous to the tsunami of 2010.

Linking these three factors, hazard, exposure, and vulnerability, should provide an assessment of the current risk level, and give the opportunity of quantifying potential risk and/or damage reductions through mitigation measures (e.g. urban planning and relocation, engineered counter measures, educational programs, etc.).

Although the general approach of this work comes from the concept of risk explained earlier, the study is carried out from a single event that belongs to the wide range of tsunami hazards. That is, we use a deterministic approach for the tsunami damage assessment, instead of a probabilistic one (Park, Cox, & Barbosa, 2017). Therefore, though exposure and vulnerability are being considered, their interaction to a single event represented by the earthquake and tsunami of 2010 yields the methodology and results presented here.

2.2 Benefit from averted damage

If there is a damage reduction through mitigation works, this reduction can be quantified in a cost-benefit analysis between the investment of the mitigation works and the benefits they produce against a tsunami. Therefore, comes the necessity to estimate the benefit as a value represented by the averted damage. This estimation may be obtained from the expression in equation (1) (Ministerio de Desarrollo Social, 2013), where B stands for benefit of the project, $P(i)$ is the probability of occurrence of the event i, C_{NP} refers to the costs with no project in event i, and C_{WP} are the costs with project in event i. Since the benefit here is obtained from the study of a single event, the consideration of the probability of its occurrence is beyond the scope of the investigation. Therefore, equation (1) is adapted as explained in Section 4.3.2.

$$B = \int_0^\infty P(i) * \left[C_{SP}(i) - C_{cp}(i)\right] di \tag{1}$$

2.3 Fragility functions

Fragility functions have now been widely used in a number of studies (Adriano et al., 2014; Favier, Bertrand, Eckert, & Naaim, 2014; Koshimura, Oie, et al., 2009; Koshimura, Namegaya, & Yanagisawa, 2009; Mas et al., 2012; Anawat Suppasri et al., 2012; Urra Espinoza, 2015). A tsunami fragility function or fragility curve constitutes a direct relation between a hydrodynamic feature of tsunami inundation flow and the damage probability of a structure (Koshimura, Oie, et al., 2009); they are usually built empirically using different data sources (Koshimura, Namegaya, et al., 2009). It is important to notice the level of refinement in the data used to build fragility curves, such as material type and number of stories, may affect the outcomes of the investigations (Goda et al., 2015). Fragility functions are essential for the methodology being proposed in this paper as a means to estimate tsunami damage, and the characteristics of the ones used here are described in Section 4.3.1.

3 CASE STUDY

Dichato is altogether a site of interest for this work because of its fast urban growth (Montenegro-Romero & Peña-Cortés, 2010). To represent the exposure in the area of interest, only physical losses to the households in the town of Dichato are considered, though more detail will be given in Sections 4.2.1 and 4.3.1. The reason why other physical or social assets are not considered here, is because of the difficulty in quantifying their vulnerability, especially when it comes to social vulnerability (Cutter, Boruff, & Shirley, 2003).

3.1 Description of Dichato

Dichato is located at the south end of Coliumo Bay, almost 40 kilometers north of Concepción (see Figure 1) with over three thousand inhabitants according to the last official census in 2002 (Instituto Nacional de Estadísticas). The town is composed of around 2 thousand homes, the majority of which are either made of wood or masonry (Servicio de Impuestos Internos). Its 2.4 kilometers long beach presents itself as a frequented attraction during the summer, with a population of roughly five thousand during January and February (Japan Science and Technology Agency (JST), 2010; Venegas San Martín, 2012). Coliumo Bay is described as quiet, with cold and still waters very suitable for the practice of aquatic sports. These qualities favor tourism, but also because of its horseshoe shape it may induce resonance and refracting effects when faced to a tsunami threat (Gobierno Regional del Bío-Bío, 2010).

The economic activities that were predominant before the disaster included fishing and tourism, which in turn contributed the most to a high exposure to tsunami hazards. It is relevant that the area did not have any kind of hazard flooding maps before the occurrence of the 2010 tsunami (Venegas San Martín, 2012).

3.2 The 2010 earthquake and tsunami

At 3:34 in the morning of the 27th of February of 2010, a violent earthquake shook the central region of Chile. The epicenter was located off the Chilean coast, about 105 kilometers north-east from the city of Concepción (Japan Science and Technology Agency (JST), 2010) with a reported 8.8 Mw magnitude (Japan Science and Technology Agency (JST), 2010; Mas et al., 2012; Robertson, Chock, & Morla, 2012). A wide-range tsunami was generated due to a rupture in the subduction interface between the Nazca and the South American plates (Quezada et al., 2010) with observed free surface disturbances at more than 150 locations in the Pacific basin, including the coast of Japan (Japan Science and Technology Agency (JST), 2010; Robertson et al., 2012).

In Chile, 521 people died during the event. The tsunami itself claimed 124 victims and 46 missing, mainly in the coastal regions of Maule and Biobío (Fritz et al., 2011; Nahuelpan López & Varas Insunza, 2010). After the event, an approximate of 370,000 homes were damaged and the economic loss escalated to almost USD 30 billion, which is roughly 18% of Chile's gross domestic product (Gobierno Regional del Bío-Bío, 2010).

Inland, measurements reported inundation depths as high as 12 meters (Robertson et al., 2012), and in some places the water managed to penetrate over a kilometer inland (Martínez et al., 2016). The maximum registered run-up peaked at 29 meters in Constitución, with the first wave arriving within 30 minutes of the earthquake in most locations. Many campgrounds near the beaches were flooded, with the Mocha and Orrego Islands' being the most memorable due to their particularly catastrophic outcomes (Fritz et al., 2011).

Dichato was one of the most affected locations. The inundation depths were estimated by post tsunami surveys to be around 8 meters, and water penetrated as far as 1.3 kilometers (Martínez et al., 2016). Though most people were able to evacuate, there were 66 fatalities, mostly tourists and elders who underestimated the magnitude of the phenomenon (Japan Science and Technology Agency (JST), 2010; Mas et al., 2012). More than 1,200 families reported damage to their properties (Japan Science and Technology Agency (JST), 2010), and approximately 80% of the built structures were washed away (Gobierno Regional del Bío-Bío, 2010), evidencing the high degree of destruction from the tsunami (Martínez et al., 2016; Venegas San Martín, 2012).

Damage was also induced by floating debris, including loose boats that collided against many structures. The typical wooden houses were incapable to uphold the large inundation depths and velocities. There were also 7 collapsed bridges, compromising the accessibility and connectivity to higher grounds and to nearby Pingueral (Gobierno Regional del Bío-Bío, 2010).

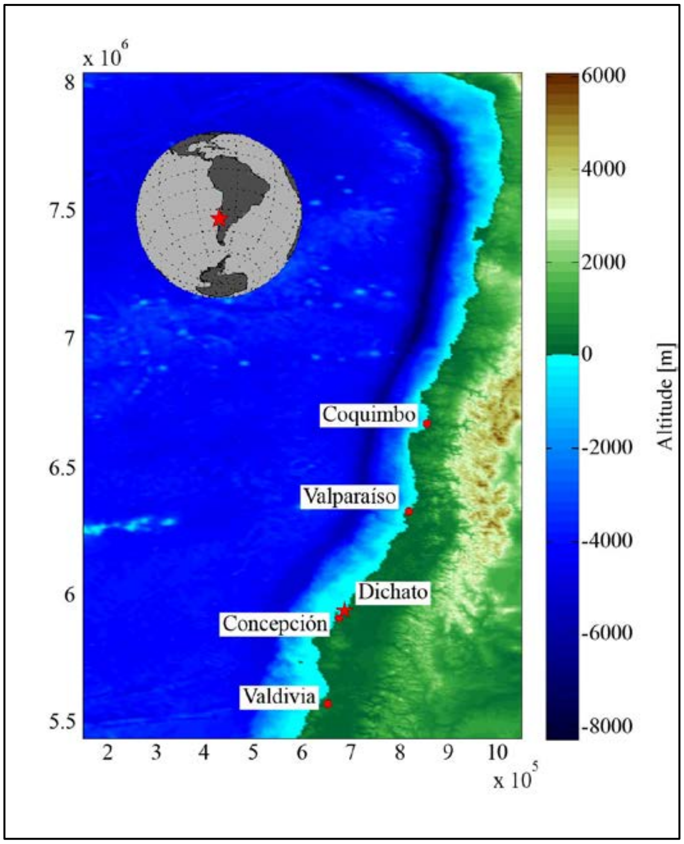

Figure 1 : Dichato's location in UTM 18S coordinates.

3.3 Mitigation works and relocation

Mitigation consists of any action or effort to partially or completely reduce the risk of a hazard capable of affecting people and/or property (Godschalk, 2003). In the case of tsunamis, hard mitigation measures may consist in coastal constructions built to diminish the impact of the flood. Other type of measures include evacuation planning, shelters, education, urban planning and land use. The latter is often referred as soft mitigation measures (Goda et al., 2015; Khew et al., 2015; Anawat Suppasri et al., 2013) ,e.g. in the case of Dichato there are five relocated neighborhoods where affected families were placed after the 2010 event, and only commerce-related buildings are allowed along the beach avenue since then. This avenue also includes a mitigation park, which construction started in 2015 (Martínez et al., 2016).

Figure 2: a) Wall and (b) channel built in Dichato after the 2010 event. Picture taken during an in-situ campaign.

Due to the tsunami impact, the government financed a mitigation project in order to provide protection for the town and its people against future tsunamis that modified 29% of the exposed area. According to the Dirección de Obras Portuarias (DOP), this mitigation work project was supposed to be finished by the end of 2014. It consists of a sea wall along the coastline and a channeling of the Dichato Estuary at its mouth, as shown in Figure 2. With the information provided by the DOP and reference prices from a catalogue (Portal Ondac Construcción) the construction costs of the wall and channel were estimated to be around 6.8 million US dollars (Details of this estimation in Annex A). A simple schematic of the wall and channel's main building materials are displayed in Figure 3.

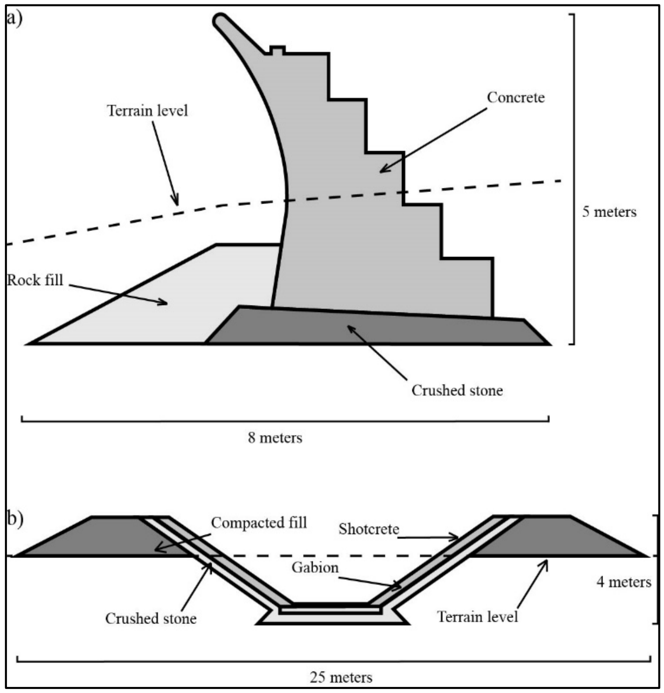

Figure 3: Basic representation of (a) wall and (b) channel with their main building materials. The dimensions are a reference for an average cross section of both the wall and channel.

4 METHODOLOGY

The methodology proposed in here considers the three relevant components for damage assessment being considered, which are the tsunami event, exposure and vulnerability. The event is estimated by tsunami simulations, the exposure is constructed from building inventories and the vulnerability is estimated with the fragility curves.

4.1 Tsunami modeling

We employ the open source code GeoClaw to perform the tsunami assessment. Geoclaw solves the nonlinear shallow water equations using finite volume methods and adaptive mesh refinement. The code has been used to model several historical tsunamis using bathymetric and topographic data (Arcos & LeVeque, 2015; MacInnes, Gusman, LeVeque, & Tanioka, 2013; Melgar & Bock, 2013). The tsunami in 2010 hit the coast during low tide, so that tide level is considered for the simulation. Great tsunamis in Chile have been known to last several hours (Catalán et al., 2015), including the event in 2010 (Venegas San Martín, 2012), therefore it is relevant to perform the tsunami modeling for an extended period of time. The time lapse considered for this simulation was 8 hours. It should be noted in addition that a Manning coefficient of 0.2 was considered, as it proved to produce the results closest to *in situ* measurements (see Section 5.1).

4.1.1 Fault model

Rupture mechanisms are estimated by inversion models, and are later translated into the initial conditions necessary for a tsunami modelling (Melgar & Bock, 2013; Shuto, 1991). More precisely, inverted slip distributions for an earthquake allows to determine the deformation of the seafloor. These inversions can be carried out from different earthquake sources, based on seismic waveforms, tsunami waveforms, and geodetic data giving rise to different tsunami source models for each event. Therefore, it may be prudent to test more than one earthquake-source model before choosing the one to be applied (MacInnes et al., 2013).

In 1985 Okada proposed a formulation to acquire an initial condition of tsunami from a source model (Okada, 1985), that has been widely used since then (Aránguiz et al., 2016; Catalán et al., 2015; Fritz et al., 2011; Fumihiko Imamura et al., 2012; Park & Cox, 2016; A.

Suppasri, Koshimura, & Imamura, 2011; Urra Espinoza, 2015). In this study the source models proposed by Delouis et al. 2010 (Delouis, Nocquet, & Vallée, 2010) and by Pollitz et al. 2011 (Pollitz et al., 2011) were tested, mainly because of the results of previous simulations in another experiment. Through a process of validation visited in a following section, the Delouis' model was determined to be the most appropriate. Figure 4 shows the initial condition as a displacement of the ocean's surface caused by the fault model.

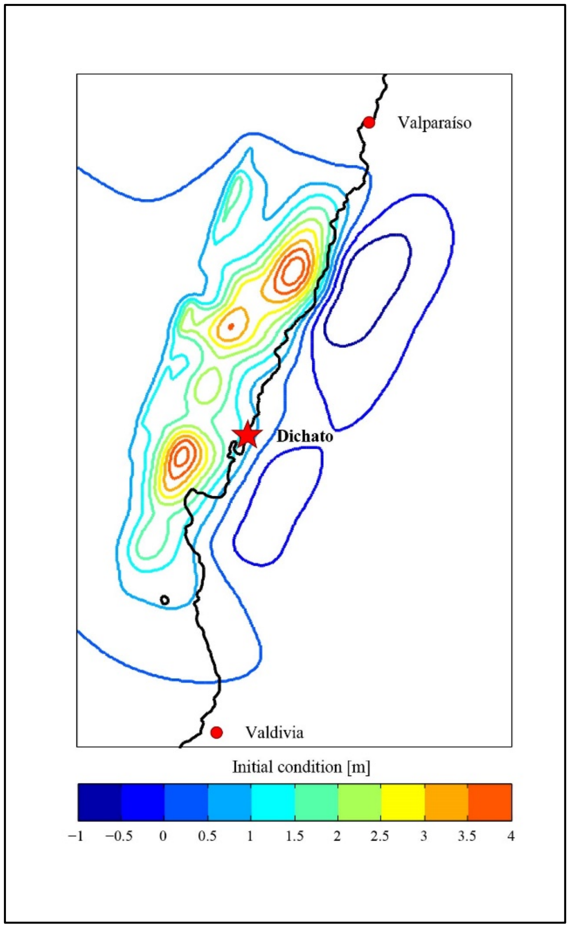

Figure 4: Initial condition proposed by Delouis et al. (2010) (Delouis et al., 2010).

4.1.2 Bathymetry and topography

The propagation of a tsunami takes place across the bathymetry and topography of the site being considered, and thus it requires an accomplished representation of the place that can be introduced to the modelling as bathymetric and topographic data. The usual format includes a z coordinate relative to a certain reference at a set of points on a rectangular grid (Berger, George, LeVeque, & Mandli, 2011).

In case of an urban settlement, the topography may or may not include information of the buildings, which in turn can produce an effect in the flow's behavior during the inundation (Fumihiko Imamura et al., 2012; A. Suppasri et al., 2011). Supposedly, a building-composed topography would include the interactions between the flow and the structures, while a no-building assumption may present inundation further inland. In the case of a situation like the latter, the applicability of a topographic model relies on the roughness parameter that is included to compensate for the lack of buildings (Fumihiko Imamura et al., 2012).

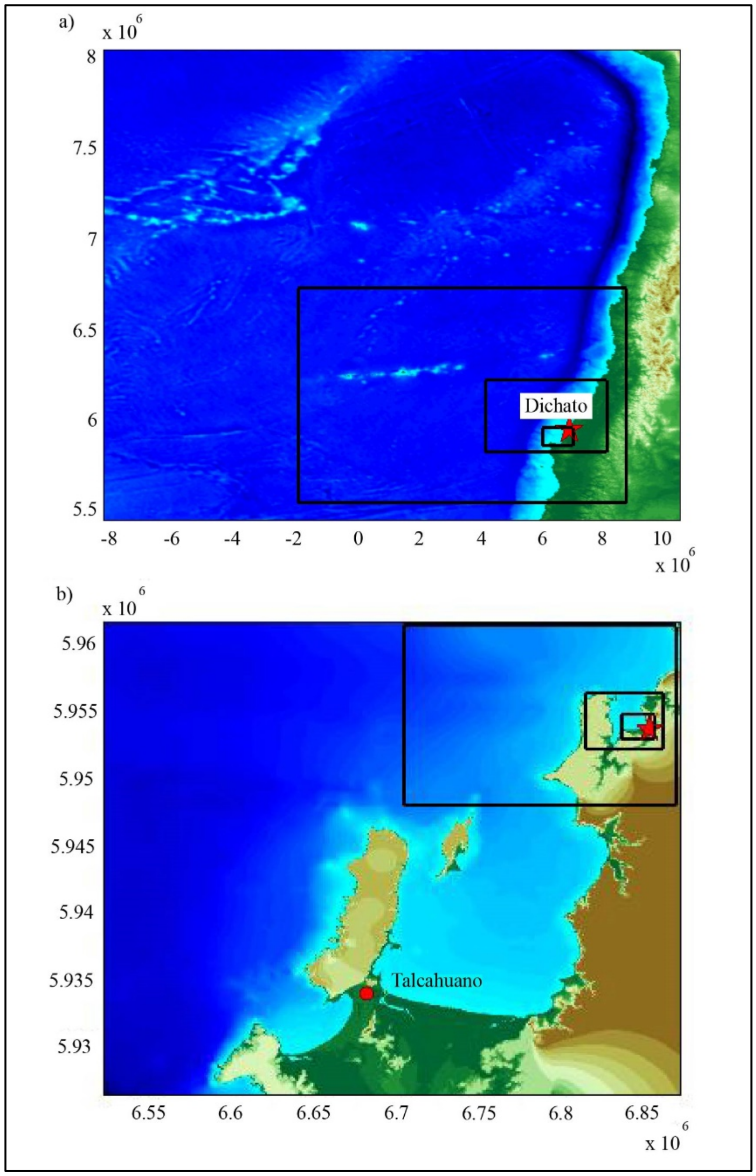

Figure 5: The 8 grids used for the tsunami modelling are displayed above, with (a) showing the 4 bigger grids, and (b) showing the remaining 4 smaller ones Bathymetric and topographic data from GEBCO (General Bathymetric Chart of the Oceans) and the Hydrographic and Oceanographic Service of the Chilean Navy (SHOA) as sources.

On the other hand, an effort should be made to use high bathymetric resolution, as most simulations on low-resolution bathymetry underestimate the tsunami (MacInnes et al., 2013). In summary, the resolution of both bathymetry and topography determines the quality of the results, and at the same time a high-resolution input demands lots of computational resources, so the use of nested grids is usually a good option.

For this particular case, the information available did not permit a topography with building information, therefore the roughness was included through the manning coefficient, and the spatial grid defined was composed by eight rectangular nested grids, each one three times higher in resolution than the previous one (see Figure 5). The smallest computational grid encloses the Dichato bay, it is composed from data from the year 2009, and has a resolution of two meters (see Figure 6). The reference level used for the bathymetry and topography was the mean sea level.

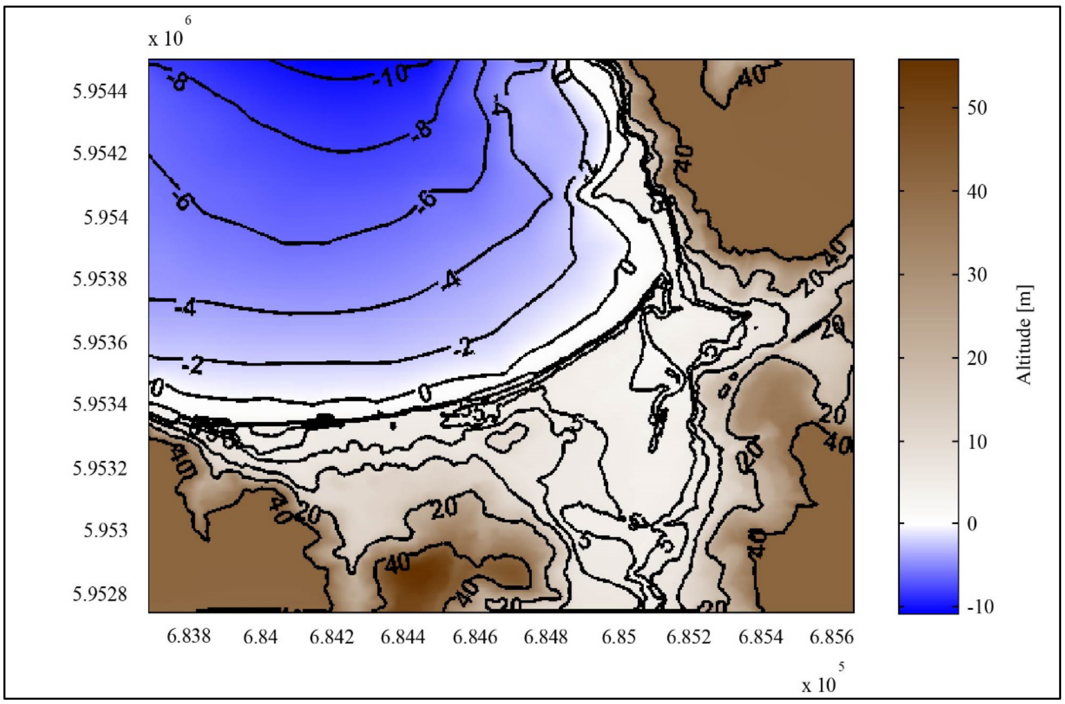

Figure 6: Detail of bathymetry and topography of Dichato with a resolution of 2 meters.

To incorporate the mitigation measures in the tsunami modeling, an in-situ campaign was carried out to get new topographic data using differential GPS. Most of the measurements were taken in and around the sea wall and channel, and special care was considered to ensure that the most important details of the final counter measures settings were included. The construction of the topography for the tsunami simulation was an aggregation of the new data acquired in the campaign and the 2009 topography and bathymetry available for this area, with a horizontal resolution of two meters. The difference between the new digital elevation model (DEM) and the previous one can be appreciated in Figure 7.

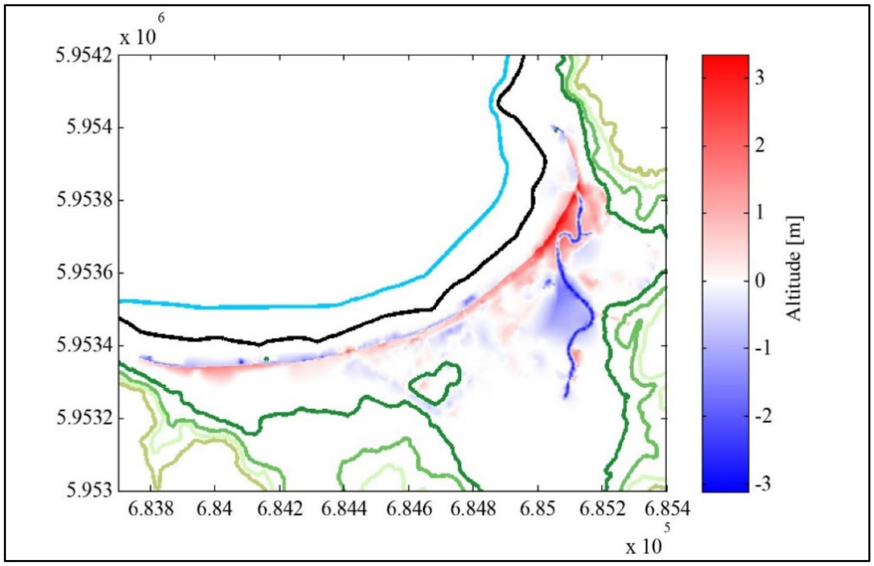

Figure 7: Differences between updated and old topography data. In blue is the terrain that was depressed after the update, and in red when it was elevated.

4.2 Proxys for damage assessment

4.2.1 Definition of vulnerable units

The definition of the vulnerable units that are used took into consideration the available information of households and their location in relation with the exposed area. As a consequence, the units represent exclusively physical vulnerability, because other aspects such as socioeconomic or educational vulnerability are beyond the scope of this work.

The characteristics of houses and buildings' materiality, price values and year of construction were assessed from a database provided by the *Servicio de Impuestos Internos* (SII). A field survey was conducted in an effort to geospatially locate every household in town, though because of in situ complications such as a poorly applied numbering system of the houses, and the presence of some unnamed streets, the sample was reduced to 451 households, representing 24% of the existing houses.

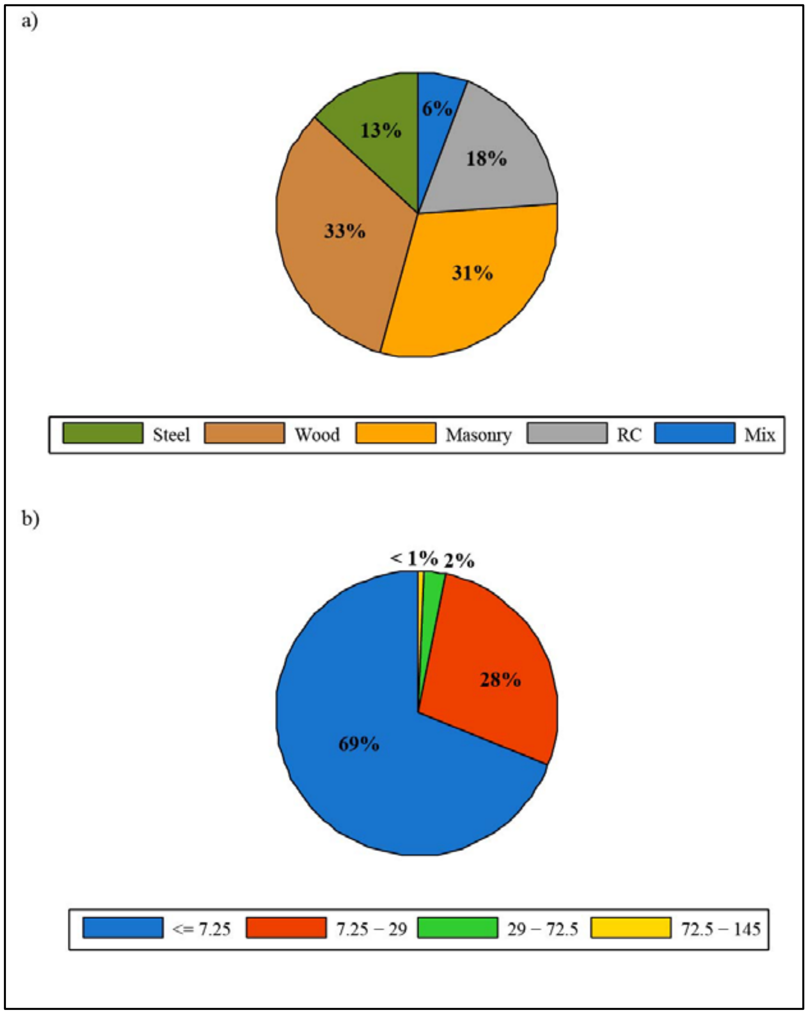

Figure 8: Inventory of (a) exposed households in Dichato and (b) estimated costs (b) (Servicio de Impuestos Internos).

It was determined that most houses were made from wood and masonry, while the rest were either made from concrete, steel frames or other less common materials. On the other hand, the majority of homes where valued in approximately 7 thousand US dollars (Servicio de Impuestos Internos) (See Figure 8).

A decision was made to use a spatial aggregation of data to conceive spatial units of a size comparable to the urban blocks in Dichato (Merz, Kreibich, Schwarze, & Thieken, 2010). Therefore, defined polygons are proposed in an attempt to follow the urban pattern of the blocks in the town, and at the same time to distribute the unevenly scattered data in a more homogeneous way. Thus, each polygon contains an unequal number of households inside, but their distribution across the area is regular. As a result, every polygon contains information of materiality distribution - depending on the amount and material of the buildings inside it - , total price as a sum of each household's valuation and the year of construction, so as to consider only the buildings that were built before the 2010 event. Figure 9 shows the output of this procedure.

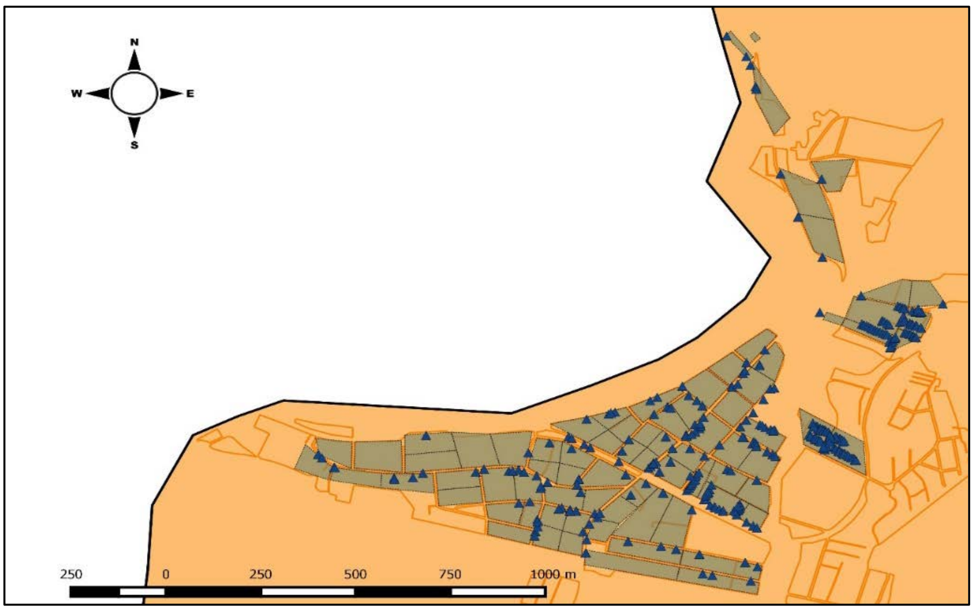

Figure 9: Sample of households and polygons as the defined vulnerable units in Dichato.

4.2.2 Tsunami intensity measures

There are certain parameters generally accepted as a reliable source of information about tsunami intensity. These tsunami intensity measures, or TIMs, include inundation depths, velocity, momentum and arrival times (Macabuag et al., 2016; Park & Cox, 2016).

Inundation depths seem an appropriate parameter to rely on as a simulation output (e.g. Koshimura et al. 2009a; Koshimura et al. 2009b; Delouis et al. 2010; Montenegro-Romero and Peña-Cortés 2010), and can be used to provide flood maps (Cançado, Brasil, Nascimento, & Guerra, 2008). Here, maximum inundation depths are considered as the key parameter used in the benefit quantification methodology, and together with the fragility curves selected for the households can provide a proxy for direct damage estimation.

Nevertheless, other potentially important parameters can be considered. Flow velocities, for instance, have also been studied and utilized for the development of fragility curves for structural damage in buildings (De Risi, Goda, Yasuda, & Mori, 2017; Mas et al., 2012; Park & Cox, 2016), as it may contribute with information about the interactions between the flow and the topography that otherwise cannot be attained (Arcos & LeVeque, 2015; Anawat Suppasri et al., 2012). In addition, both maximum inundation depth and velocity have been mentioned to be applicable for the estimation of building damage due to tsunamis (Park & Cox, 2016). Thus, maximum celerity and maximum energy – as an extension of the latter -, are also estimated from the simulation.

Finally, arrival times of inundation constitute a crucial matter, particularly when it comes to evacuation assessment e.g. in both the Pisagua Tsunami in 2014 and the Coquimbo Tsunami in 2015 the arrival time of the first wave was under 15 minutes in the locations closest to the source (Aránguiz et al., 2016; Catalán et al., 2015).

4.3 Damage estimation

The damage estimation pursued here are only from primary physical capital losses, which refer to damage of private infrastructure caused by the tsunami (Iwata, Ito, & Managi, 2014). Other forms of damage are not visited.

4.3.1 Direct damage and cost

Tsunami fragility is an essential tool to obtain direct and tangible damage of a building given a certain tsunami intensity. Direct damage is thus considered to be the result of the interaction of buildings with the flow and its hydrodynamic properties (Penning-Rowsell et al., 2005). This methodology contemplates a crossing of information between the inundation depths modeled or observed in each polygon and its materiality distribution, with the use of the fragility curves associated with damage level and type of material.

Fragility curves become an extremely useful tool for the purpose of this investigation, and as such they were chosen from a previous research involving the same four main construction materials that were observed in Dichato. In 2012, Suppasri et al. (Anawat Suppasri et al., 2012) performed an analysis of all available data delivered by the Ministry of Land, Infrastructure and Transportation of Japan (MLIT) regarding the 2011 Great East Japan tsunami impact zone. The result was called at the time “one of the most complete data set among tsunami events in history”. These authors developed fragility curves with six damage levels for wood, masonry, reinforced concrete and steel frames. These damage levels were defined as 1: minor damage, 2: moderate damage, 3: major damage, 4: complete damage, 5: collapse and 6: washed away (Anawat Suppasri et al., 2012). One additional fragility curve was built for the purpose of this investigation, as a mix of wooden and concrete fragility curves, as a certain type of building in Dichato is best represented as a concrete house in the first story (2 meters in height), and as a wooden house for the second story. For more detail on this see Annex B.1.

A house can end up with serious consequences after enduring a tsunami inundation, mainly because of six forces: the hydrostatic, the drag, the buoyancy and uplift, the impulsive forces debris impact, and damming (Palermo, Nistor, Saatcioglu, & Ghobarah, 2013). Now, the resulting damage for the purposes of this investigation is obtained solely from the use of fragility curves (Koshimura, Oie, et al., 2009; Koshimura, Namegaya, et al., 2009), and the specific phenomena involved in the process of damaging will not be inquired in further detail.

To estimate the direct damage in households, the inundation data inside a polygon is identified and averaged to obtain a representative inundation level for each vulnerable unit (Adriano et al., 2014), which is later the input to the unit's materiality distribution to produce – with the fragility curves - a probability of damage for each damage level.

Once the probability of direct damage for each damage level is estimated, the expected loss is quantified in monetary terms. To link each level of damage to a percentage of the total cost (C_t) of the household that it would be needed to repair it, in the ratio C_r/C_t, where the numerator stands for cost of repair (Mavrouli & Corominas, 2010; Penning-Rowsell et al., 2005). Table 1 shows the cost ratio associated with each level of damage, where there is an estimated cost of 20% of the total value of the household needed to repair a level 1 damage, and a cost of 120% the total value if the household was washed away. This allows for an easy application of a tangible damage upon an asset as a mean of damage estimation (Merz et al., 2010; Shreve & Kelman, 2014).

Table 1: Costs of repair associated with each level of damage.

Damage level	**Description**	**Cost of repair (C_r/C_t)**
1	Minor damage	0.2
2	Moderate damage	0.4
3	Major damage	0.6
4	Complete damage	0.8
5	Collapse	1.0
6	Washed away	1.2

Finally, the calculations to estimate the total costs from the loss after the tsunami for each scenario is represented in equation (2), where ds_i stands for damage state i, c_i for the corresponding cost ratio C_r/C_t for the damage state i, $P(ds_i)_j$ for the probability of damage for damage state i and material j. The variable p_j^k stands for the materiality percentage for material j in polygon k, calculated according to equation (3), where h_j^k stands for the number of households of material j in polygon k. The result of equation (2) is the expected total cost from loss in all polygons, from the sum of the product between the cost ratios and their probability of occurrence for every damage level and every type of material.

$$C = \sum_k \sum_j \left(\sum_i P(ds_i)_j * c_i \right) * p_j^k \qquad (2)$$

$$p_j^k = \frac{h_j^k}{\sum_j h_j^k} \qquad (3)$$

4.3.2 Benefit quantification

To assess the benefit from a certain mitigation measure, first it is necessary to precisely define the project being considered as a mitigation, then identify its impacts, determine which ones are economically relevant and evaluate them. In this case, the evaluation is conducted by means of the quantification of damaged as explained earlier in Section 4.3.1 (Shreve & Kelman, 2014).

Cost-benefit analysis is hereby applied to value mitigation measures, considering the scenario previously described. By means of estimating damage from a certain natural occurrence, we modify a method originally developed towards flood inundations, as it allows to obtain a benefit from the inundation damages that are averted by the application of measures (Iwata et al., 2014; Ministerio de Desarrollo Social, 2013; Penning-Rowsell et al., 2005).

However, as a result of working with a specific tsunami, the expression for the benefit from a probabilistic approach showed in equation (1) results as expressed in equation (4). Therefore, the benefit obtained by the comparison between the base scenario and the current scenario considering the engineered counter measures in place is simply the difference in costs from the damage estimated in both cases.

$$B = C_{NP} - C_{WP} \tag{4}$$

5 RESULTS

5.1 2010 tsunami impact base situation

First, a tsunami modeling exercise was carried out without mitigation works. To validate model settings, model results are compared to actual recorded data taken from in-situ surveys from five campaigns, resulting in a set of 37 measurements (Fritz et al., 2011; F. Imamura, Fujima, & Arikawa, 2010; Matsutomi, Harada, Ogasawara, & Kataoka, 2010; Mikami et al., 2011)

To estimate the model performance, Aida's Root Mean Square Error (RMSE) method is used (Aida, 1978), as done by (Koshimura, Oie, et al., 2009; Martínez et al., 2016; Shuto, 1991; A. Suppasri et al., 2011). Parameters K and κ presented in equations (5) and (6), respectively, where K_i stands for the ratio between observed and simulated values of inundation height.

$$\log K = \frac{1}{n}\sum_{i=1}^{n} \log K_i \qquad (5)$$

$$\log \kappa = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (\log K_i)^2 - (\log K)^2} \qquad (6)$$

In 2002, the Japan Society of Civil Engineers (JSCE) proposed and accepted range for K and κ as follows: $0.95 < K < 1.05$ and $\kappa < 1.45$ (Tsunami Evaluation Subcommittee & Nuclear Civil Engineering Committee, 2002). The Dichato simulation yields $K = 0.97$ and $\kappa = 1.38$, which is considered sufficient.

The tsunami simulation results were also qualitatively compared with the inundation results obtained by Mas et al. 2012 (Mas et al., 2012) (Figure 10.a). Relative sea levels during the event are compared with the information registered at Talcahuano inside the Bay of Concepcion, as seen in Figure 10.b and with data provided by a Deep-ocean Assessment and Reporting of Tsunamis (DART) Station of the coast of northern Chile and southern Peru (Figure 10.c).

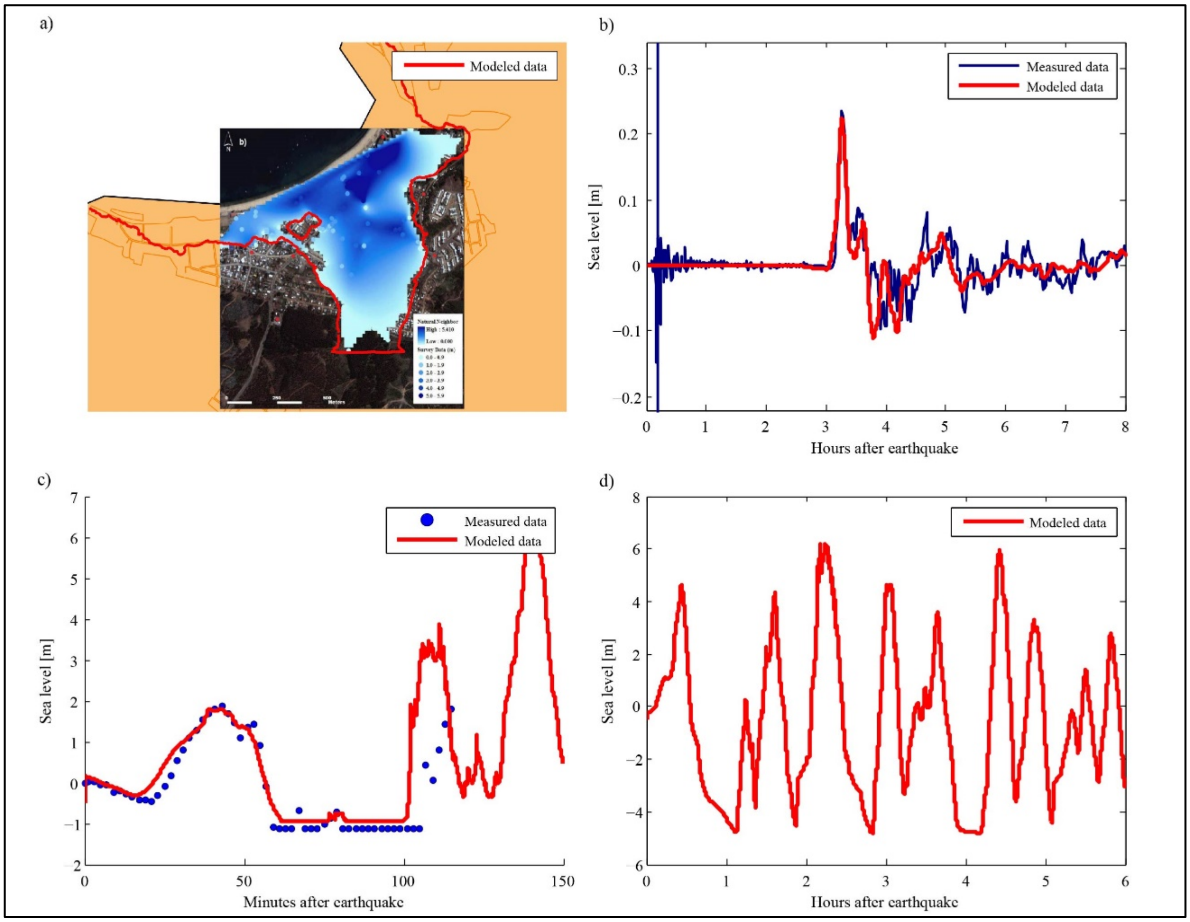

Figure 10: a) Qualitative validation of modeled data (in red) with measured data from a research by Mas et al. (2012). Numerical (red) and measured (blue) sea level in (b) DART buoy 32412 (National Data Buoy Center), (c) Talcahuano (Sea Level Stationing Monitoring Facility, Intergovernmental Oceanographic Commission) and (d) Dichato, but the latter without measured data.

Peak values of inundation depth, celerity and energy were plotted, together with the arrival times. Figure 11.a shows the maximum levels of inundation depths registered by the simulation. The highest inundation depth corresponded to nearly 10.8 meters. For the case of celerity values, the maximum registered in the area shown in Figure 11.b is 11.4 m/s. The maximum run up reached 16 meters.

Local energy values were calculated using Bernoulli's expression $H = h + \frac{v^2}{2g}$, where h stands for inundation depth, v for flow celerity, g for the gravitational acceleration, and H for hydraulic head, measured in meters. The results obtained for maximum head are shown in Figure 11.c. Figure 11.d displays the arrival times of the different groups of waves, up to the first 4 hours of simulation. It can be noted that the biggest wave arrives around two hours after the earthquake nucleation, while the second largest hit Dichato an hour earlier. The total costs estimated from the methodology explained in Section 4.3.1, considering this scenario scales up to 13 million US dollars.

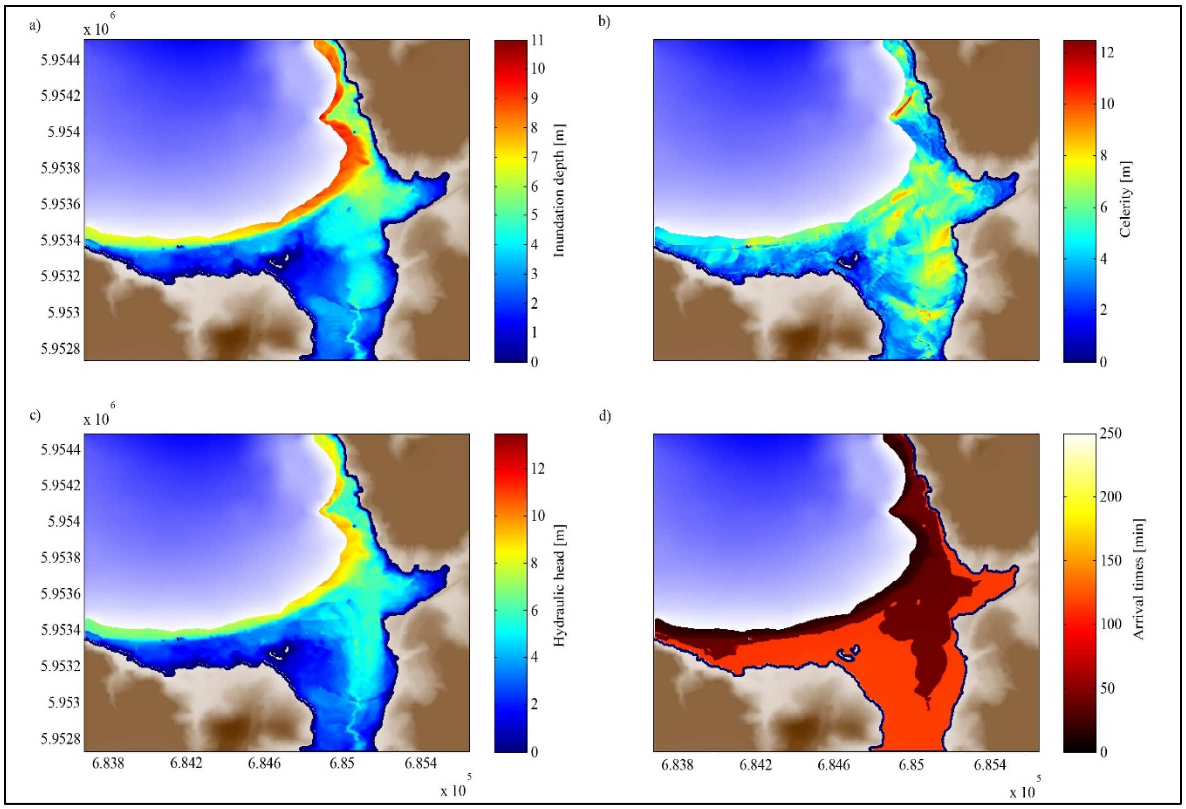

Figure 11: Results of the simulation on Dichato's base scenario. The maximum values of (a) inundation depth, (b) celerity, and (c) energy. d) Tsunami arrival times.

5.2 2010 tsunami impact considering the engineered counter measures in place

An additional simulation was carried out including the mitigation counter measures to compare against the base scenario. Figure 12 shows the difference between this new scenario and the base scenario. The values for inundation depths and run-ups in the scenario with mitigation works reached maximums of 10.6 meters and 16.1 meters, respectively, being very similar to the base scenario, though in the case of the maximum head, the values observed in the new scenario are lower compared to the base scenario. However, no significant mitigation of the tsunami intensity can be attributed to the engineered counter measures in place. Arrival times of tsunami waves in the new situation differ the most with the base scenario, as the inundation area of the second wave is reduced approximately 40% in the presence of the sea wall and channel. The time available to carry out an evacuation in that area is thus increased in approximately an hour. Nevertheless, for the biggest wave that reaches the area after 120 minutes, the engineered counter measures appear to be ineffective since the inundation area is almost equivalent to the one observed in the situation without mitigation works. The total costs estimated for the direct damage in this case are nearly 12.2 million US dollars.

A summary of these results are presented in Table 2. In view of these results, several appreciations must be noted. There is a benefit associated to an increase of the available time for evacuation as observed in Figure 13. This gain traduces the fact that the first two tsunami waves were smaller than the third one which was responsible for most of the damage in Dichato (Figure 12.d). The latter indicates that these mitigation measures might be efficient against more frequent and less destructive events, such as storm waves or surges or even minor tsunamis, but are not able to withstand a tsunami event such as the one that occurred in 2010.

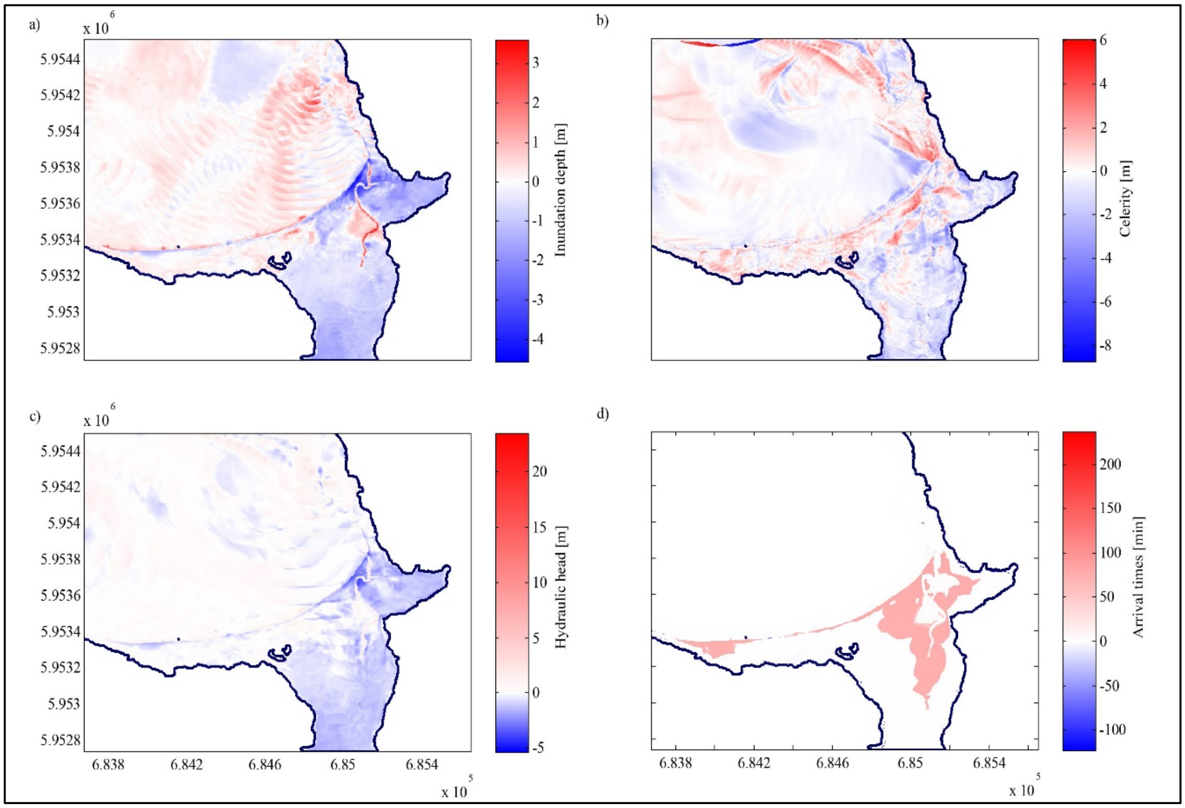

Figure 12: Results of the simulation on Dichato considering the mitigation measures, in contrast to the old scenario. Red regions correspond to higher values in the new scenario, and blue when values are lower. Difference of maximum (a) inundation depth, (b) celerity, and (c) energy. d) Arrival times for the new scenario.

Whereas, in terms of maximum values of inundation depth, there is a limited mitigation effects that the constructed works produce, which according to the methodology employed gives a very low benefit when confronted to a situation similar to the one that took place in 2010. Since the inundation depths are similar, the benefit obtained with the presence of the mitigation works are estimated to be only 755 thousand US dollars, a number that is 10 times less than the direct cost of the mitigation works, and way lower than the costs from tsunami damage in the new scenario as well, which escalate to 12.2 million US dollars.

Table 2: Summary of results from the old and new scenarios.

	Area [km^2]	**Damage costs [MM USD]**
Old scenario	13.4	13.0
New scenario	13.2	12.2
Benefit		0.8

6 DISCUSSION

6.1 Household materiality and impact forces

The performance of households against tsunami forces depends on their materiality (Anawat Suppasri et al., 2012). Thus, it is possible to reduce the damage by using more resistant materials, which in turn would of course be costlier. In order to analyze this aspect, we produce maps with the probability for buildings to suffer severe damage level (level 6) as a function of their materiality. Figure 13 shows the probability distribution of level 6 damage (i.e. ‘washed away’), for the five types of materials considered in the present work. An estimation of the average probability of level 6 damage for each material is summarized in Table 3. These results are illustrative of the important role that materiality and structural design could play in damage reduction once a successful evacuation is warranted. However, having more resistant buildings would be costlier and this is where a more complete and integrated risk and cost-benefit analysis would be useful to define the optimal combination of mitigation measures.

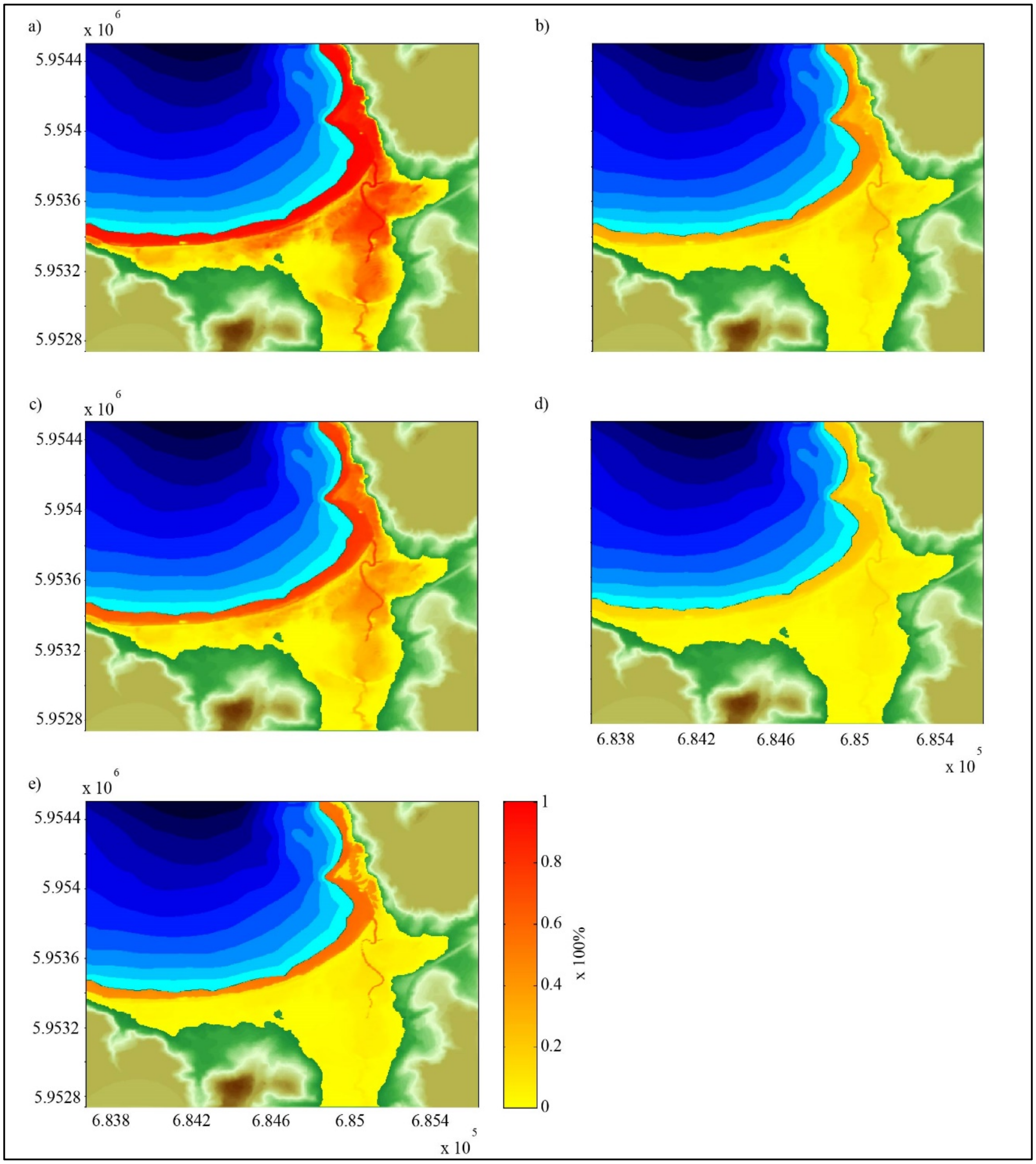

Figure 13: Probability distribution for damage of level 6 (washed away) according to building material: a) wood, (b) metal, (c) masonry, (d) reinforced concrete and (e) mix.

Although not incorporated in the present study, debris impact on structures could increase the damage (Goseberg, Stolle, Nistor, & Shibayama, 2016; Palermo et al., 2013; Robertson et al., 2012). Likewise, further inclusion of hydrodynamic interaction between buildings and the tsunami flow could contribute to obtain better estimations of actual situations (González et al., 2009), such as the effect of building orientation towards the sea and other buildings in the surrounding area (Anawat Suppasri et al., 2012). Similarly, other studies have defined the flow momentum as a more robust tsunami intensity measure (Macabuag et al., 2016).

Table 3: Average probability of level 6 damage from each material studied.

	Average probability of level 6 damage
Wood	0.43
Metal	0.12
Masonry	0.26
Reinforced concrete	0.07
Other	0.13

6.2 Wall height

Dichato's reconstruction project considered two main hard mitigation measures, but the outcome of a simulation repeating the 2010 tsunami showed that the level of mitigation it produces is not significant. The latter motivates us to evaluate alternatives for the wall height and to produce a sensitivity analysis on this parameter by loss quantification. The rationale behind this idea is that there must be certain wall height that should resist a major tsunamigenic event, or produce larger direct benefits than the costs of construction. Thus, we consider different wall heights from +0.5 meters up to +4 meters from its actual configuration, to assess potential mitigation effects and damage reductions so an optimal height could be determined (Favier, Eckert, Bertrand, & Naaim, 2014; Shimozono & Sato, 2016).

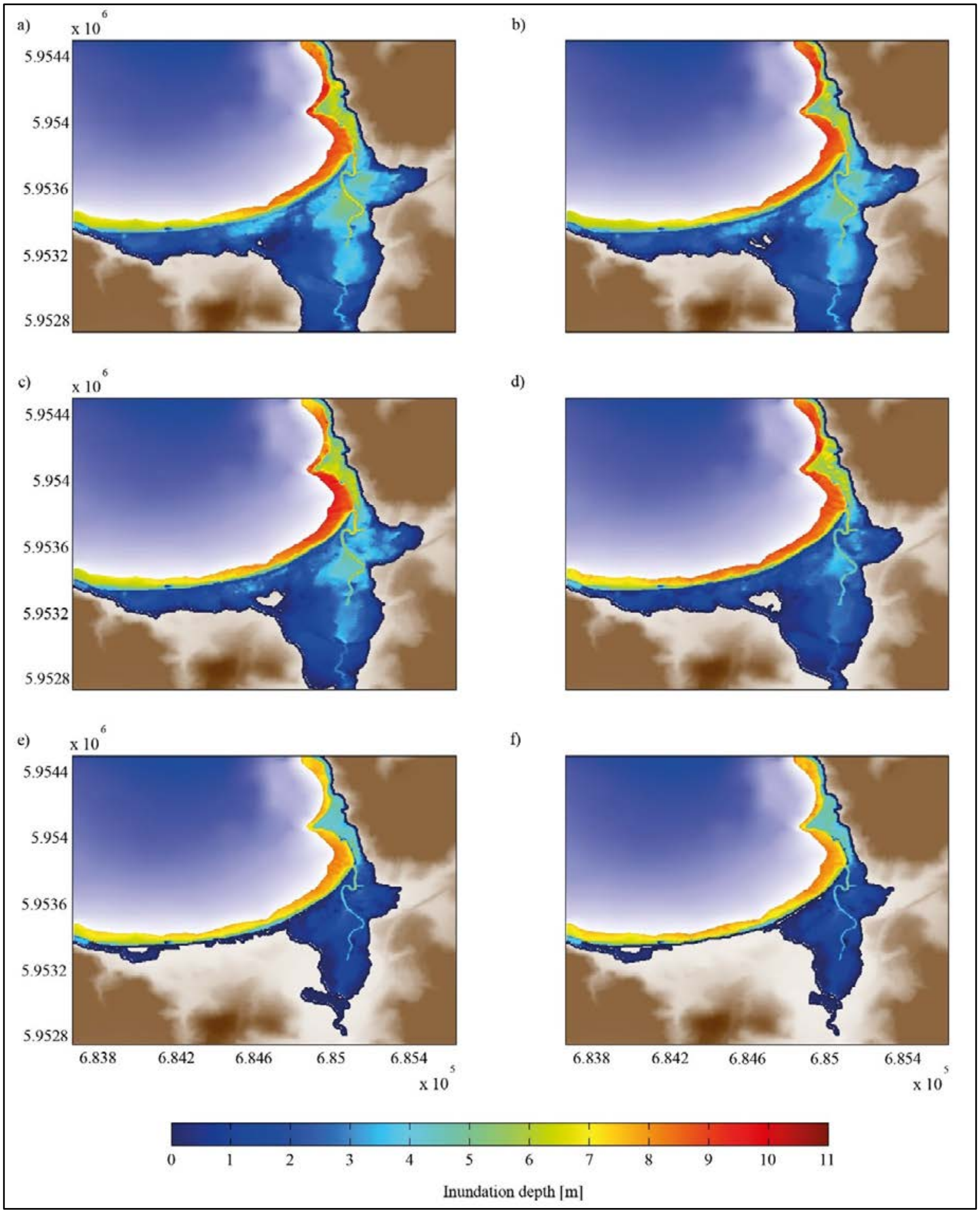

Figure 14: Results of the simulation on Dichato considering different wall heights. The maximum values of inundation depth for the (a) new scenario, (b) with a wall 0.5 meters taller, (c) 1 m taller, (d) 2 m, (e) 3 m and f) 4 m taller.

The described methodology was performed considering walls 0.5, 1.0, 2.0, 3.0, and 4.0 meters taller than the as-built wall, and the resulting inundation maps for the same 2010 event are shown in Figure 14. As expected, the inundated area gradually decreases as the wall height increases. Indeed, when the sea wall is 3 meters higher, the flooded area is greatly reduced (43.3% of area reduction and consequently 84.4% reduction in damage costs). When the benefits for each wall level are calculated, as shown in Figure 15.a, substantial cost reductions are obtained with a wall height of 5 meters, i.e. 3 meters taller than the one that is now in place. Increasing the wall height improves the cost-benefit ratio reaching the optimum close to a total wall height of 5 meters, then the costs begin to outweigh the benefits (Figure 15.b)

Table 4: Reduction with respect to the new scenario, in area and damage costs for different scenarios.

	Inundated area [km^2]	**Area reduction [%]**	**Damage costs [MM USD]**	**Damage reduction [%]**
New scenario & wall + 0.5 m	13.0	3.0	12.3	5.2
New scenario & wall + 1 m	12.6	6.0	10.8	16.9
New scenario & wall + 2 m	11.7	12.7	8.6	33.7
New scenario & wall + 3 m	7.6	43.3	2.0	84.4
New scenario & wall + 4 m	7.2	45.6	1.9	85.3

This cost-benefit analysis performed only on the base of direct damage reductions and the cost of mitigation works. Nonetheless, even if it may give rise to a definition of an optimal sea wall height, it is important to emphasize that a more comprehensive analysis is necessary to provide a better answer to this question. In addition, there is need to consider as well a time window for life operation of the works, the probability of exceedance of certain tsunami hazard level each year, and a cash flow of costs and benefits. Nevertheless, massive concrete sea walls along the coast may also contribute negatively to the aesthetics of the town and hide the ocean from the view (Khew et al., 2015). Though difficult to quantify, these indirect effects are also important and should be considered in the design and decision process.

Probably, a combination of different measures, such as replacing some of the home materiality with reinforced concrete that resist inundations in combination with education and awareness programs to sustain evacuation response could be good alternatives (Favier, Eckert, et al., 2014).

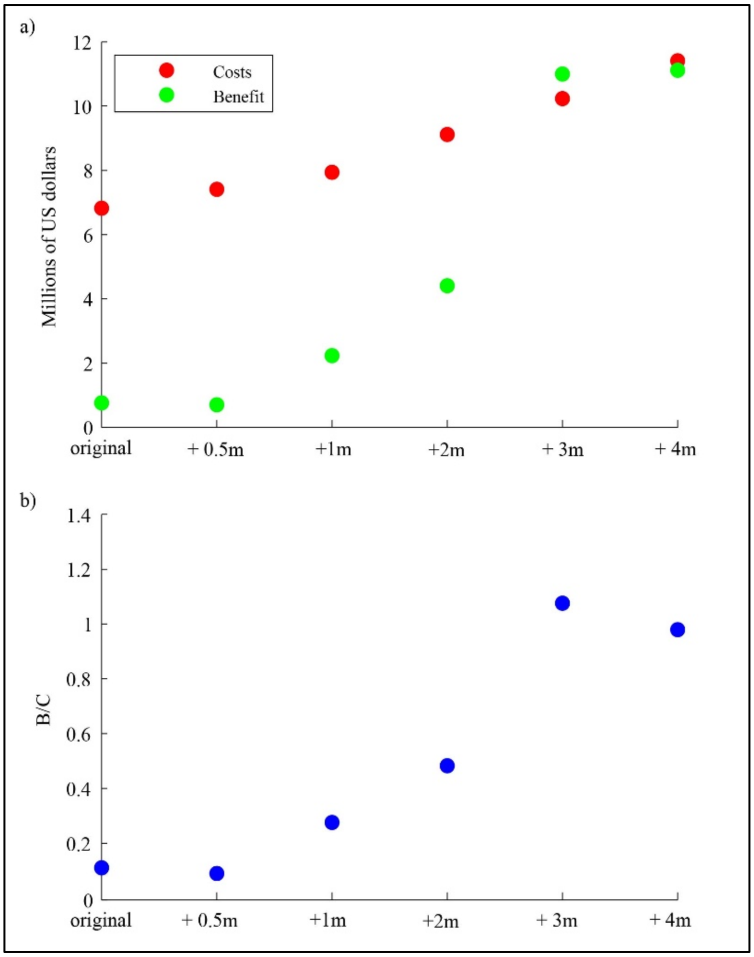

Figure 15: Benefits versus construction costs for different wall height scenarios.

6.3 Political considerations

The diverse Chilean natural environment presents permanent challenges for the definition of risk management policies and strategies. Moreover, being a country that has not yet become a developed country, short term government priorities often prevent the allocation of adequate resources to the long-term goal of risk mitigation. Usually, in the aftermath of large catastrophic disasters, the government is expected to take actions for reconstruction and improvements against future natural hazards.

There are myriads of factors to consider when pushing forward a reconstruction plan to promote resilience. In the case of Dichato (and possibly other cities), the government put forward an optimistic speech based on the premise that hard mitigation works would prevent disasters such as the one of the February 27th, 2010. Even if sea walls can mitigate tsunami or coastal hazards, and improve touristic activities if they are well designed, the emphasis should not be restricted to technological or hard works but keep the social considerations in clear view, as physical measures do not necessarily ensure proportionate increase of resilience (Khew et al., 2015). It seems thus necessary for government authorities to be more cautious about the way they communicate and decide mitigation solutions in the aftermath of catastrophic events since these decisions may have crucial consequences on the long-term risk perception of inhabitants.

Mitigation plans, should be deigned in a more integrative manner not only focusing on physical mitigation measures, but also accompanied by new urban planning, effective relocations, and educational efforts to improve long-term resilience. In the following years, Dichato has been reoccupied almost in the same way than before the 2010 tsunami, hence having a similar exposure level, even if mitigation works are in place (Martínez et al., 2016).

The delicacy of the situation is real, as the wall and channel in the town being studied may eventually be understood by a portion of the inhabitants as ‘anti-tsunamis’, which have been demonstrated not to be; these misunderstandings may create a false sense of security that in turn may lead to unsafe conducts or even the settlement around areas mistakenly thought to be completely risk-free (Shreve & Kelman, 2014). Fortunately, other actions have been taken to improve evacuation processes towards safe zones, which by themselves are an excellent effort towards addressing the safety of people’s lives in coastal areas (Robertson et al., 2012). The latter should be especially reinforced with educational activities to feed people’s awareness, and its permanent application should remain a high priority (Montenegro-Romero & Peña-Cortés, 2010).

6.4 Other mitigation measures

Hard mitigation measures extend further than the ones visited here, as shelters inside the inundation-prone areas can be considered as safe spots in case of a tsunami. However, these shelters must be considered with caution as some attempts elsewhere have been known to fail (Anawat Suppasri et al., 2013), but considering Dichato’s environment reinforced concrete building might an effective mitigation measure (Anawat Suppasri et al., 2012).

Another mitigation measure alternative consists of ‘mitigation forests’. The plantation of these forests are intended to reduce the impact of an incoming tsunami wave by reducing the velocity of the flow and trap floating debris. This plantations can even be displayed across dunes, which in turn present another mitigation structure, to increase their efficacy (Nandasena et al., 2012). Nevertheless they must be applied cautiously, as when overcome the trees themselves turn into dangerous bodies of debris that can impact structures or even individuals (Anawat Suppasri et al., 2013).

Soft mitigation measures may also be effective to improve resilience. Actually, according to Suppasri et al. (2013) (Anawat Suppasri et al., 2013), evacuation remains being the best method when it comes to saving lives, and aside from refuges and evacuation routes, it is reinforced by keeping disaster awareness in coastal populations (Aránguiz et al., 2016; Fritz et al., 2011; Mitsoudis et al., 2012; Robertson et al., 2012; Anawat Suppasri et al., 2013). Evacuation procedures can be improved by educational policies and early warning systems, but also due to past similar events, as it has been proven many times (Japan Science and Technology Agency (JST), 2010; Palermo et al., 2013). Also, tsunami memorials like some that were built in Dichato, incite a culture of awareness that can transcend generations.

Finally, land use planning represents a fundamental complement to what has been reviewed so far, as moving away from tsunami-prone land will always be a safe bet, while keeping in mind other possible hazards if considering higher grounds (Anawat Suppasri et al., 2013).

7 CONCLUSION

The position in which Chile lies as a country where earthquakes and tsunamis have manifested frequently requires to constantly improve the preparedness and ability to withstand their impacts. The present investigation proposes a methodology to quantify mitigation works conducted in Dichato in the aftermath of the 2010 tsunami. The obtained results indicate that there was a reduction of 6.2 % in the costs from tsunami damage in the new scenario, which correspond to a little less than 800 thousand US dollars. Also, there was an increase in evacuation time for an area close to the river, and the works considered could be effective against minor tsunamis or storm waves or surges. However, the wall and channel constructed in Dichato would not be able to significantly reduce the damage if faced against a tsunami similar to the one that hit the town in 2010, evacuation time for an area close to the river is gained, and the works considered could be effective against minor tsunamis or storm waves or surges.

Our methodology could be applied as an ex-post analysis of other mitigation measures in different locations, or even as an evaluation of a possible project that might be in consideration. With a proper definition and characterization of exposure and vulnerability, this methodology can be enriched with more elaborated procedures to include other aspects of damage.

It is essential to propose and evaluate mitigation projects from a more complex perspective. In all, the building of a resilient community involves much more than only physical mitigation, as a proper educational plan is an essential aspect, as well as appropriate use of the land available in tsunami-prone areas. A resilient community must anticipate and be able to speedily recover from a natural disaster without presenting permanent harm, and is the duty of our authorities to assume this responsibility and promote the formation of a tougher urban settlement (Godschalk, 2003).

Based on this investigation, the authors suggest that to perform such work, the government must initiate a more inclusive work with the local communities focusing on what can be learned from the previous experiences and boost a responsible and smart development of the zones most prone to tsunamis, to reduce the exposure and vulnerability for future events to come.

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ANNEX

A Valuation of mitigation works

To perform an approximate valuation of the mitigation works, a simplified version of the wall and channels' structures were considered, as composed by fewer materials. This simplification was carried out because of practical matters. All the information used to perform this valuation was provided by the Dirección de Obras Portuarias (DOP) and the Ondac catalogue, and in Table A. is a detail of the materials considered both in the wall and channel. The prices are according to the Chilean market, and include workforce and other minor materials required.

Table A.1: Detail of the materials considered for the valuation of the mitigation works.

Material detail	**Unit**	**Price [USD]**
Hormigón H-20 (RC)	m3	79.78
Hormigón HN-25 (RC)	m3	68.87
Hormigón H-30 (RC)	m3	97.24
Enfierradura D=10 mm a 44-28 (Iron)	kg	1.18
Relleno con material de obra (Filling)	m3	5.72
Compactación con rodillo e=30 cm (Compacting)	m2	0.32
Relleno con bolón (Filling)	m3	31.53
Bombeo de hormigón (RC pumping)	m3	13.89
Excavación terreno blando a=1mt (Excavations)	m3	4.52

A.1 Wall

The wall's construction was divided in three sectors, each with a different set of profiles. The profiles each have different sizes and material proportions that define their construction costs, so to obtain the total cost of the wall's construction it is necessary to calculate the amount of each material required for each profile along every set. Every profile's length, together with the materiality information was obtained from a set of drawings provided by the DOP. The following tables specify the amount of each material used per profile and their length for each sector. The excavations along each sector were calculated using a mean area, which in the case of Litril Sector is 22.50 m2, for Etapa 1 Sector is 13.05 m2 and for Estero Sector is 9.88 m2.

Table A.2: Amount of material used for the construction of the wall in Litril Sector.

LITRIL SECTOR					
Profile	**Length [m]**	**RC [m2]**	**Crushed stone [m2]**	**Layer compaction [m]**	**Rock fill [m2]**
A	320.50	7.16	2.16	4.31	1.43
B	126.56	6.75	2.16	4.31	0.00
C	139.65	3.77	1.58	3.16	1.43
D	133.37	0.76	1.04	2.07	3.28
E	28.48	5.90	2.06	4.11	0.00
Total	748.56	24.33	8.98	17.96	6.13

Table A.3: Amount of material used for the construction of the wall in Etapa 1 Sector.

ETAPA 1 SECTOR					
Profile	**Length [m]**	**RC [m2]**	**Crushed stone [m2]**	**Layer compaction [m]**	**Rock fill [m2]**
A	485.38	8.67	2.47	4.99	4.35
B	158.98	8.82	2.47	4.99	0.00
C	260.70	5.08	1.83	3.65	4.35
D	252.48	0.61	1.00	2.00	4.71
E	93.28	7.94	2.47	4.99	0.00
Total	1250.82	31.12	10.23	20.62	13.40

Table A.4: Amount of material used for the construction of the wall in Estero Sector.

ESTERO SECTOR					
Profile	**Length [m]**	**RC [m2]**	**Crushed stone [m2]**	**Layer compaction [m]**	**Rock fill [m2]**
A	193.80	8.99	2.47	4.89	3.20
B	15.15	8.58	2.47	4.88	0.00
C	12.64	4.84	1.83	3.65	3.20
D	25.29	0.59	1.00	2.00	3.66
G	12.65	3.16	1.63	3.25	5.27
H	16.80	5.60	2.17	4.39	0.00
I	94.65	5.72	2.12	4.28	3.20
Total	370.98	37.48	13.67	27.34	18.51

It should be noted that the geometry of every profile was simplified into basic geometric elements, such as squares and triangles.

An example of the different profiles used in Sector Litril is presented in Figure A.1

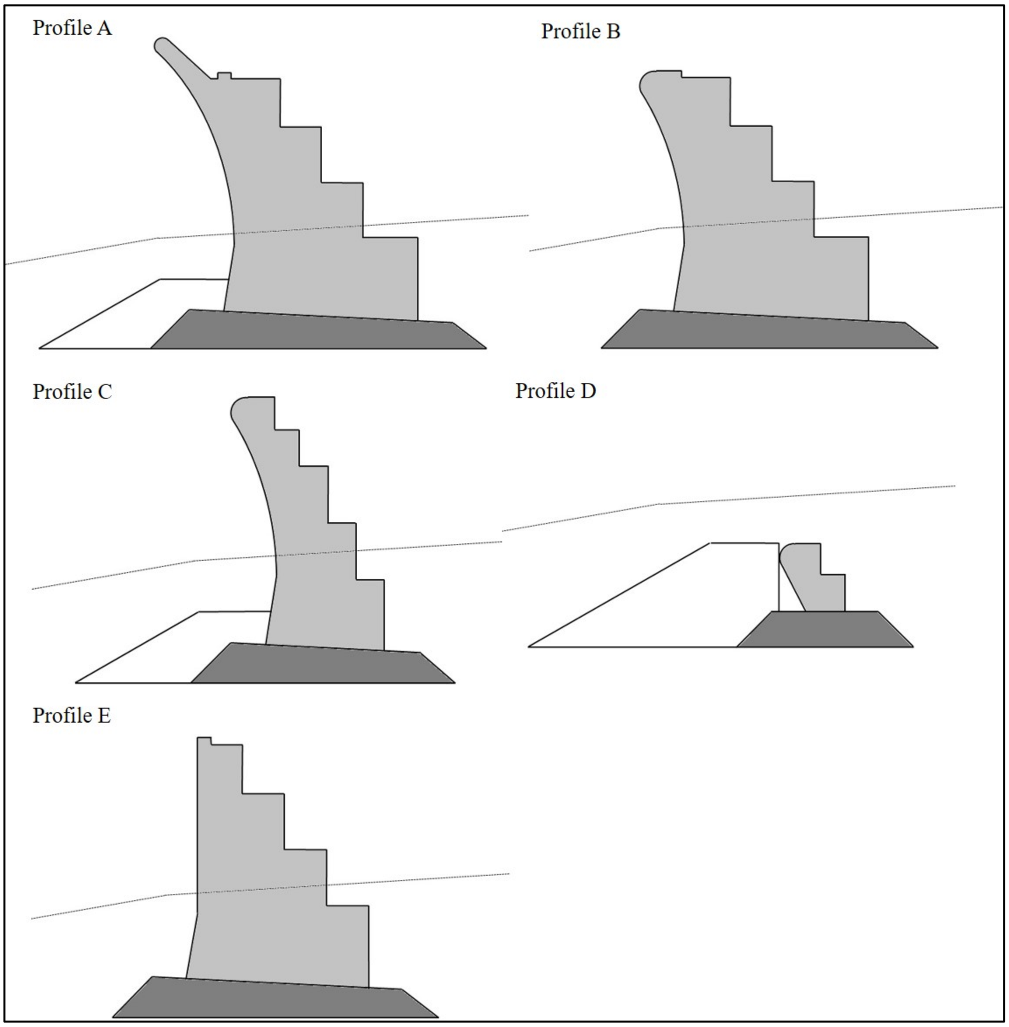

Figure A.1: Different profiles of the wall along Sector Litril.

A.2 Channel

In the case of the channel, there was one average profile used along the 286 meters of its length. Thus, the material summary of it is shown in Table A.5.

Table A.5: Amount of material used for the construction of the channel.

CHANNEL				
Length [m]	**Shotcrete [m2]**	**Filling [m2]**	**Layer compaction [m]**	**Excavation [m2]**
286	5.18	17.12	9.85	18.22

B Selection of fragility curves

The fragility curves used correspond to a work by Suppasri et al. 2012 [32] where 6 levels of damage were defined as 1: minor damage, 2: moderate damage, 3: major damage, 4: complete damage, 5: collapse and 6: washed away. All six levels were conceived for wood, masonry, reinforced concrete and steel frames, as shown in the following figure.

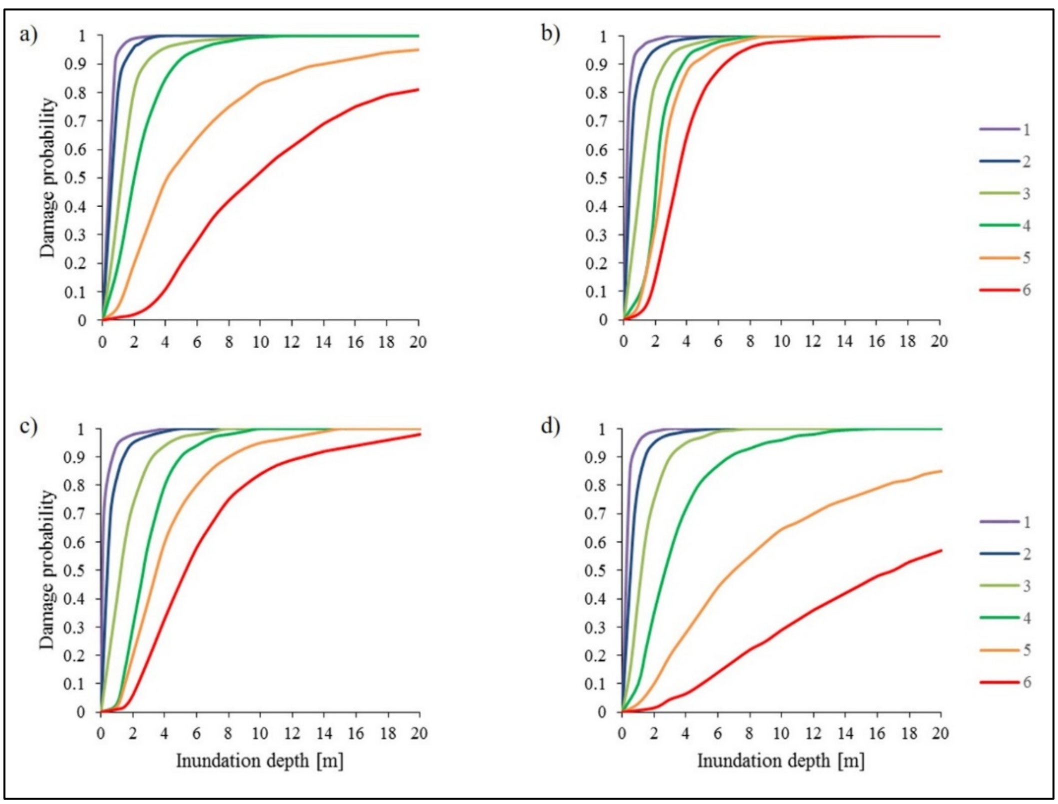

Figure B.1: Fragility curves for Steel (a), Wood (b), Masonry (c) and RC (d), for levels 1 through 6, where 1: minor damage, 2: moderate damage, 3: major damage, 4: complete damage, 5: collapse and 6: washed away (Anawat Suppasri et al., 2012).

B.1 Fragility curves for mixed materials

A fifth material is proposed in the present investigation, which corresponds to a mix between reinforced concrete and wood for a specific kind of two-story house. The way this was dealt was to consider the fragility curves for both reinforced concrete and wood, where the first story's materiality is considered to be reinforced concrete, while the second is made from wood. Thus, the idea is to apply an inundation height to each curve according to the level of inundation of the first and the second stories. Therefore, using Figure B.2 as a reference, an inundation level equal to h' would be considered for the RC's fragility curve, and in the case of the wood's curve, an inundation height equal to h^* is used. The final percentage of damage becomes the average between both curves.

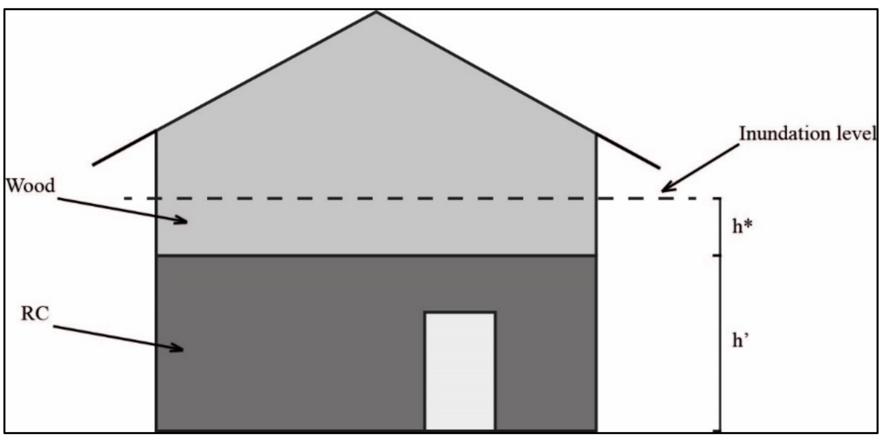

Figure B.2: Two-story house with mixed materiality.

C Valuation of Households

All the information utilized for the valuation of the households' sample was obtain from the *Servicio de Impuestos Internos* (SII), and is presented in Table C.1. The actual price of a household was considered to include the value of the terrain because of limitations in the available information.

Table C.1: Sample of households in Dichato with their location, materiality, year of construction and valuation in USD. Coordinates are in UTM.

X coordinate	**Y coordinate**	**Material**	**Valuation in USD**	**Year of construction**
684958.5	5953112	Masonry	$ 830	1920
684408.9	5953076	Masonry	$ 24,743	1938
684412.7	5953197	Wood	$ 10,066	1938
685000.3	5954351	Wood	$ 7,904	1940
684731.2	5953262	Masonry	$ 53,739	1940
684982.6	5953317	Masonry	$ 33,102	1940
684805.4	5953288	Wood	$ 166,069	1940
685486.9	5953714	Masonry	$ 8,201	1941
684179.3	5953205	Wood	$ 10,294	1942
684805.9	5953336	Masonry	$ 1,910	1943
684599.8	5953229	Wood	$ 10,839	1944
685174.1	5953349	Wood	$ 14,292	1944
684681.2	5953354	Wood	$ 6,674	1945
684399.7	5953119	Wood	$ 19,962	1945
684997.8	5952934	Wood	$ 13,204	1945
684165.5	5953120	Masonry	$ 8,757	1945
685018.4	5953294	Wood	$ 3,672	1946
685226.6	5953304	Wood	$ 14,050	1949
685370.7	5953693	Wood	$ 3,209	1950

684039.6	5953221	Wood	$ 8,230	1950
684748.1	5953412	Wood	$ 14,409	1950
685379.6	5953671	Masonry	$ 6,954	1950
685411.1	5953611	Wood	$ 4,780	1950
684438	5953081	Masonry	$ 11,005	1950
685402	5953646	Wood	$ 12,416	1950
685418.8	5953641	Wood	$ 26,206	1950
683842.4	5953251	Wood	$ 31,172	1952
684405.3	5953066	Wood	$ 3,975	1953
684119.1	5953226	Wood	$ 5,513	1957
685168.2	5953340	Wood	$ 18,832	1957
684532.3	5953155	Wood	$ 1,740	1960
684369.9	5953219	Wood	$ 7,364	1960
684090.1	5953199	Wood	$ 7,149	1960
684039.9	5953202	Masonry	$ 6,470	1960
684448.6	5953199	Wood	$ 8,567	1960
683891.7	5953221	Wood	$ 24,120	1960
684369.2	5953119	Wood	$ 796	1960
684519.6	5953091	Wood	$ 5,254	1960
684804.6	5953187	Wood	$ 2,417	1960
684946.6	5953114	Wood	$ 6,457	1960
685338.6	5953615	Wood	$ 278	1960

685406.5	5953613	Wood	$	36,151	1960
683861.9	5953236	Wood	$	7,397	1960
684562.5	5953153	Wood	$	11,464	1961
685376.9	5953690	Wood	$	3,228	1962
684951.8	5953121	Wood	$	8,907	1962
685227.9	5953316	Wood	$	514	1962
685171.6	5954074	Wood	$	707	1963
684953.2	5953307	Masonry	$	31,387	1963
685405.2	5953658	Wood	$	7,477	1963
684858.6	5953360	Masonry	$	6,629	1964
684862.9	5953134	Wood	$	10,151	1964
685067.5	5954085	Wood	$	13,160	1965
684581	5953115	Wood	$	13,923	1965
685018.1	5953273	Wood	$	6,232	1965
684503	5953095	Wood	$	18,785	1965
684853.2	5952913	Wood	$	9,258	1966
685182.5	5953331	Wood	$	7,186	1966
685189.8	5953329	Wood	$	6,511	1966
685140.5	5953318	Masonry	$	6,976	1966
683862.7	5953259	Wood	$	8,387	1967
684988.4	5954407	Wood	$	6,648	1968
684864.5	5953137	Wood	$	7,427	1968

685357.8	5953586	Wood	$	9,208	1968
683906.2	5953236	Wood	$	3,210	1968
685196	5953338	Wood	$	11,152	1968
684529.4	5953210	Wood	$	947	1969
684878.5	5953294	Wood	$	9,782	1969
685424.2	5953638	Wood	$	15,636	1969
685167	5953354	Wood	$	9,359	1969
684685	5953326	Masonry	$	8,084	1970
684659.2	5953197	Wood	$	14,010	1970
684950.9	5953101	Masonry	$	10,096	1970
685390.8	5953618	Wood	$	274	1970
685163.3	5953355	Wood	$	11,375	1970
685162.7	5953343	Wood	$	19,020	1970
685152.9	5953348	Wood	$	7,580	1970
685149.9	5953310	Wood	$	2,220	1970
685155.1	5953310	Wood	$	2,206	1970
684977	5953544	Wood	$	13,697	1971
684725.4	5953257	Masonry	$	24,775	1972
685184.8	5954044	Wood	$	6,188	1972
684587.2	5953125	Wood	$	15,535	1973
685175.6	5953854	Wood	$	402	1973
685155.2	5953347	Masonry	$	21,943	1973

685003	5953609	Wood	$	6,301	1974
684964.7	5953304	Wood	$	5,323	1975
685026	5953268	Wood	$	10,642	1975
684852.5	5953399	Wood	$	7,966	1975
684518.6	5953195	Wood	$	3,396	1976
685372.7	5953621	Wood	$	12,444	1976
684874.3	5953155	Other	$	2,577	1977
684868.3	5953164	Other	$	2,273	1977
684859.9	5953152	Other	$	2,273	1977
684863.2	5953157	Other	$	2,273	1977
684876	5953177	Other	$	2,273	1977
684820.9	5953106	Other	$	2,577	1977
684742.2	5952990	Other	$	3,298	1977
684782	5952982	Other	$	3,811	1977
684843.4	5952967	Wood	$	1,924	1977
684962.7	5952943	Wood	$	1,829	1977
684978.1	5952890	Other	$	2,509	1977
685283	5953642	Other	$	2,273	1977
685288.5	5953639	Other	$	2,273	1977
685301	5953634	Other	$	2,273	1977
685311.6	5953627	Other	$	2,273	1977
685318.6	5953624	Other	$	2,273	1977

685324.3	5953621	Other	$	2,273	1977
685331.3	5953618	Other	$	2,509	1977
683898.5	5953220	Wood	$	10,587	1977
685233.3	5953313	Masonry	$	5,151	1977
685203.6	5953319	Masonry	$	5,151	1977
685202.4	5953296	Masonry	$	5,151	1977
685207.3	5953292	Other	$	2,170	1977
685214.6	5953288	Other	$	2,170	1977
685195.6	5953285	Other	$	2,170	1977
685217.8	5953287	Masonry	$	5,151	1977
685198.8	5953284	Masonry	$	5,151	1977
685208.3	5953278	Other	$	2,273	1977
685210.4	5953276	Other	$	2,523	1977
685237.7	5953275	Other	$	2,319	1977
685223.5	5953270	Other	$	2,319	1977
685229.8	5953265	Other	$	2,319	1977
685253.6	5953266	Other	$	2,319	1977
685239.8	5953260	Other	$	2,523	1977
685002.3	5954343	Wood	$	1,358	1978
685350.1	5953610	Wood	$	3,595	1978
685370.4	5953654	Wood	$	14,641	1978
684994	5953310	Wood	$	9,807	1979

685345.2	5953612	Wood	$	5,391	1979
684422.1	5953028	Wood	$	5,603	1980
684529.6	5953001	Wood	$	11,174	1980
684524	5953114	Wood	$	7,005	1980
685063	5954097	Wood	$	8,005	1980
685421.6	5953651	Wood	$	5,261	1980
684454.1	5953196	Wood	$	9,272	1980
685175.8	5953334	Wood	$	22,006	1980
685148.5	5953352	Wood	$	8,160	1980
685154.7	5953364	Wood	$	5,223	1980
685428.4	5953636	Wood	$	16,223	1981
684548.1	5953369	Masonry	$	609	1982
684957	5953306	Wood	$	21,363	1982
684946.1	5953091	Wood	$	7,898	1982
684936.6	5953102	Masonry	$	6,472	1982
683830.9	5953267	Wood	$	24,565	1983
685157.1	5953321	Masonry	$	7,119	1983
684283.5	5953214	Masonry	$	26,750	1984
685392	5953663	Wood	$	9,162	1984
684655	5953005	Wood	$	6,055	1985
684583.3	5953177	Wood	$	7,543	1985
685205.8	5953281	Wood	$	2,892	1985

684816.5	5953429	Masonry	$	21,491	1986
683849.1	5953247	Wood	$	9,439	1987
685159.9	5953319	Wood	$	3,539	1987
684503	5953095	Masonry	$	27,104	1988
684189.6	5953206	Wood	$	11,009	1988
685279.3	5953734	Wood	$	9,313	1989
684648.3	5953314	Masonry	$	274,267	1989
684664.6	5953369	Wood	$	5,138	1989
685401.9	5953615	Wood	$	3,343	1989
685408	5953645	Wood	$	7,540	1989
685364.3	5953695	Wood	$	4,649	1990
685379.8	5953687	Wood	$	2,965	1990
685407.7	5953682	Wood	$	2,353	1990
685414.9	5953678	Wood	$	3,523	1990
685421.5	5953676	Wood	$	2,312	1990
685432.9	5953675	Wood	$	3,535	1990
685437	5953677	Wood	$	2,623	1990
685422.4	5953700	Wood	$	3,337	1990
684977	5954433	Wood	$	16,767	1990
684448.6	5953199	Wood	$	6,674	1990
684473.3	5953101	Masonry	$	5,915	1990
684872.7	5953152	Wood	$	10,574	1990

684649	5953203	Wood	$	3,731	1990
684669.2	5953304	Wood	$	3,365	1990
684743.8	5953408	Wood	$	3,214	1990
685326.9	5953656	Wood	$	187	1990
685411.4	5953655	Masonry	$	6,818	1990
684336.6	5953217	Steel	$	54,980	1991
684838	5953414	Masonry	$	8,929	1991
685128.7	5953949	Masonry	$	18,811	1993
685374.4	5953662	Wood	$	4,610	1993
685003.8	5953281	Wood	$	31,303	1994
684418.7	5953010	Wood	$	7,430	1994
685151.3	5953325	Wood	$	4,546	1994
685183.9	5953850	Masonry	$	21,943	1995
684827.6	5953280	Masonry	$	8,962	1995
685010.5	5954284	Wood	$	6,937	1995
685229.9	5953281	Masonry	$	9,824	1995
684737.7	5953379	Masonry	$	21,649	1996
683839.1	5953291	Wood	$	15,571	1997
684762.6	5953392	Masonry	$	11,472	1998
684858.5	5953146	Wood	$	15,901	1998
684641.6	5953277	Wood	$	3,155	1998
684999.6	5954309	Wood	$	4,684	1998

685385.8	5953620	Wood	$ 414	1998
684992.5	5954488	Wood	$ 4,595	1998
685156.9	5953880	Wood	$ 7,623	1998
684536.9	5953188	Masonry	$ 17,918	1998
685213.6	5953326	Wood	$ 9,051	1998
685000	5954319	Wood	$ 3,646	1999
685221.5	5953321	Wood	$ 7,330	1999
685382.8	5953689	Masonry	$ 301	2000
684894.7	5953409	Masonry	$ 747	2000
684898.8	5953413	Masonry	$ 747	2000
685414.3	5953608	Masonry	$ 23,604	2000
685417	5953608	Wood	$ 10,503	2000
685218.1	5953310	Wood	$ 18,596	2000
684625.9	5953294	Wood	$ 8,150	2001
684486	5953123	Wood	$ 30,163	2001
684723.5	5953168	Wood	$ 4,634	2001
684901.2	5953416	Masonry	$ 17,260	2002
684954	5953107	Masonry	$ 8,785	2002
685377.8	5953667	Wood	$ 2,047	2002
684290.7	5953252	RC	$ 697,079	2003
684290.7	5953252	RC	$ 697,079	2003
684290.7	5953252	RC	$ 15,545	2003

684290.7	5953252	RC	$ 27,756	2003
684290.7	5953252	RC	$ 12,777	2003
684290.7	5953252	RC	$ 22,813	2003
684290.7	5953252	RC	$ 15,545	2003
684290.7	5953252	RC	$ 27,756	2003
684290.7	5953252	RC	$ 651	2003
684290.7	5953252	RC	$ 27,756	2003
684290.7	5953252	RC	$ 22,813	2003
684290.7	5953252	RC	$ 27,756	2003
684290.7	5953252	RC	$ 1,085	2003
684290.7	5953252	RC	$ 27,756	2003
684290.7	5953252	RC	$ 22,813	2003
684290.7	5953252	RC	$ 27,756	2003
684290.7	5953252	RC	$ 27,756	2003
684290.7	5953252	RC	$ 22,813	2003
684290.7	5953252	RC	$ 27,756	2003
684290.7	5953252	RC	$ 27,756	2003
684290.7	5953252	RC	$ 22,813	2003
684290.7	5953252	RC	$ 27,756	2003
684290.7	5953252	RC	$ 27,756	2003
684290.7	5953252	RC	$ 22,813	2003
684290.7	5953252	RC	$ 27,756	2003

684290.7	5953252	RC	$ 27,756	2003
684290.7	5953252	RC	$ 22,813	2003
684290.7	5953252	RC	$ 27,756	2003
684290.7	5953252	RC	$ 868	2003
684290.7	5953252	RC	$ 27,756	2003
684290.7	5953252	RC	$ 22,053	2003
684290.7	5953252	RC	$ 44,486	2003
684290.7	5953252	RC	$ 426	2003
684290.7	5953252	RC	$ 868	2003
684290.7	5953252	RC	$ 319	2003
684290.7	5953252	RC	$ 651	2003
684290.7	5953252	RC	$ 319	2003
684290.7	5953252	RC	$ 651	2003
684290.7	5953252	RC	$ 319	2003
684290.7	5953252	RC	$ 651	2003
684290.7	5953252	RC	$ 169	2003
684290.7	5953252	RC	$ 434	2003
684290.7	5953252	RC	$ 319	2003
684290.7	5953252	RC	$ 651	2003
684290.7	5953252	RC	$ 319	2003
684290.7	5953252	RC	$ 651	2003
684290.7	5953252	RC	$ 852	2003

684290.7	5953252	RC	$ 1,737	2003
684290.7	5953252	RC	$ 426	2003
684290.7	5953252	RC	$ 868	2003
684290.7	5953252	RC	$ 319	2003
684290.7	5953252	RC	$ 651	2003
684290.7	5953252	RC	$ 319	2003
684290.7	5953252	RC	$ 651	2003
684290.7	5953252	RC	$ 426	2003
684290.7	5953252	RC	$ 868	2003
684290.7	5953252	RC	$ 319	2003
684290.7	5953252	RC	$ 651	2003
684290.7	5953252	RC	$ 532	2003
684290.7	5953252	RC	$ 1,085	2003
684290.7	5953252	RC	$ 426	2003
684290.7	5953252	RC	$ 868	2003
684290.7	5953252	RC	$ 169	2003
684290.7	5953252	RC	$ 434	2003
684290.7	5953252	RC	$ 213	2003
684290.7	5953252	RC	$ 434	2003
684290.7	5953252	RC	$ 426	2003
684290.7	5953252	RC	$ 868	2003
684290.7	5953252	RC	$ 746	2003

684290.7	5953252	RC	$ 1,520	2003
684290.7	5953252	RC	$ 532	2003
684290.7	5953252	RC	$ 1,085	2003
684290.7	5953252	RC	$ 319	2003
684290.7	5953252	RC	$ 651	2003
684290.7	5953252	RC	$ 319	2003
684290.7	5953252	RC	$ 651	2003
684290.7	5953252	RC	$ 426	2003
684290.7	5953252	RC	$ 868	2003
684290.7	5953252	RC	$ 213	2003
684290.7	5953252	RC	$ 434	2003
684448.6	5953199	Wood	$ 8,646	2005
684760.5	5953144	Masonry	$ 25,844	2005
684584.3	5953154	Masonry	$ 29,258	2005
684661.5	5953339	Wood	$ 11,752	2006
685127.1	5953301	Masonry	$ 6,247	2007
685130.9	5953298	Masonry	$ 6,072	2007
685138.2	5953291	Masonry	$ 6,072	2007
685142.2	5953289	Masonry	$ 6,072	2007
685149.2	5953285	Masonry	$ 6,072	2007
685151.8	5953283	Masonry	$ 6,072	2007
685159.4	5953280	Masonry	$ 6,072	2007

685164.2	5953278	Masonry	$	6,051	2007
685177.6	5953270	Masonry	$	6,065	2007
685180.6	5953269	Masonry	$	6,065	2007
685188	5953265	Masonry	$	6,065	2007
685191.8	5953262	Masonry	$	6,065	2007
685199	5953258	Masonry	$	6,065	2007
685202.9	5953256	Masonry	$	6,065	2007
685209.4	5953252	Masonry	$	6,065	2007
685213	5953250	Masonry	$	6,065	2007
685220.3	5953246	Masonry	$	6,065	2007
685223.5	5953245	Masonry	$	6,065	2007
685231.5	5953240	Masonry	$	6,065	2007
685234.8	5953239	Masonry	$	6,065	2007
685242	5953235	Masonry	$	6,065	2007
685245.2	5953233	Masonry	$	6,065	2007
685251	5953229	Masonry	$	6,065	2007
685256.3	5953226	Masonry	$	6,320	2007
685263.6	5953223	Masonry	$	7,002	2007
684567	5953104	Masonry	$	6,106	2007
684594.8	5953091	Masonry	$	6,099	2007
684743	5953235	Masonry	$	6,072	2007
684802.8	5953332	Masonry	$	6,072	2007

684763.2	5953289	Masonry	$	6,092	2007
684834.9	5953332	Masonry	$	6,085	2007
684793.7	5953320	Masonry	$	6,072	2007
684827.1	5953322	Masonry	$	6,072	2007
684834.9	5953370	Masonry	$	6,072	2007
684845.3	5953379	Masonry	$	6,058	2007
684951.9	5953471	Masonry	$	6,072	2007
684996.3	5953520	Masonry	$	6,051	2007
684383.4	5953271	Masonry	$	6,072	2007
684421	5953175	Masonry	$	6,051	2007
684450.6	5953300	Masonry	$	6,072	2007
684508.6	5953283	Masonry	$	6,058	2007
684755.3	5953151	Masonry	$	6,058	2007
684528.4	5953178	Masonry	$	6,092	2007
684749.5	5953153	Masonry	$	6,092	2007
684918.1	5953222	Masonry	$	6,092	2007
684928	5953218	Masonry	$	6,187	2007
684705.1	5953182	Masonry	$	6,187	2007
684858.9	5953261	Masonry	$	6,181	2007
684757.1	5953318	Masonry	$	6,174	2007
684993.6	5953183	Masonry	$	6,160	2007
684836.9	5953298	Masonry	$	6,079	2007

684583	5953294	Masonry	$ 6,079	2007
684525.5	5953326	Masonry	$ 6,079	2007
684534.2	5953321	Masonry	$ 6,085	2007
684567.1	5953303	Masonry	$ 6,079	2007
684658.2	5953253	Masonry	$ 6,085	2007
684881.8	5953127	Masonry	$ 6,208	2007
684892.7	5953122	Masonry	$ 6,085	2007
684895.6	5953120	Masonry	$ 6,330	2007
684905.7	5953115	Masonry	$ 6,085	2007
684915.8	5953110	Masonry	$ 6,085	2007
684919	5953108	Masonry	$ 6,085	2007
684974.8	5953076	Masonry	$ 6,085	2007
684992.5	5953066	Masonry	$ 6,085	2007
685002.4	5953059	Masonry	$ 6,085	2007
684769.8	5953401	Masonry	$ 6,339	2007
685012.8	5953457	Masonry	$ 6,072	2007
684814.7	5953164	Masonry	$ 6,072	2007
684819.7	5953171	Masonry	$ 6,072	2007
684823.6	5953176	Masonry	$ 6,072	2007
684826	5953181	Masonry	$ 6,072	2007
684828.6	5953186	Masonry	$ 6,072	2007
684833.5	5953192	Masonry	$ 6,072	2007

684836.7	5953196	Masonry	$ 6,072	2007
684841.6	5953203	Masonry	$ 6,072	2007
684843.5	5953208	Masonry	$ 6,072	2007
685026.9	5953472	Masonry	$ 6,072	2007
684847.7	5953216	Masonry	$ 6,072	2007
684998.1	5953438	Masonry	$ 6,079	2007
684955.8	5953346	Masonry	$ 6,072	2007
684971.6	5953365	Masonry	$ 6,058	2007
684909.3	5953288	Masonry	$ 6,051	2007
684817.7	5953211	Masonry	$ 6,058	2007
684970.7	5953400	Masonry	$ 6,051	2007
685043.5	5953325	Masonry	$ 6,079	2007
685016	5953340	Masonry	$ 6,072	2007
685029.9	5953334	Masonry	$ 6,092	2007
685036.4	5953331	Masonry	$ 6,072	2007
685001.4	5953348	Masonry	$ 6,072	2007
685007.8	5953346	Masonry	$ 6,051	2007
684878.5	5952909	Masonry	$ 24,248	2008
684454.1	5953196	Wood	$ 12,772	2008
683933.9	5953214	Wood	$ 21,068	2008
685333.4	5953652	Steel	$ 3,633	2009
685340.7	5953649	Steel	$ 3,680	2009

685345.8	5953645	Steel	$	3,673	2009
685362.1	5953598	Steel	$	3,680	2009
685346.2	5953594	Steel	$	3,775	2009
685361.5	5953594	Steel	$	3,796	2009
685349.7	5953603	Steel	$	3,768	2009
685363.4	5953605	Steel	$	3,830	2009
685366.1	5953611	Steel	$	3,864	2009
685371.1	5953618	Steel	$	3,918	2009
685170.7	5953337	Wood	$	13,079	2009
685242.7	5953258	Wood	$	914	2009
685166.5	5953317	Steel	$	3,694	2009
685166.8	5953302	Steel	$	3,694	2009
685171	5953314	Steel	$	3,694	2009
685180.2	5953278	Steel	$	3,694	2009
685178.1	5953307	Steel	$	3,694	2009
685193.1	5953303	Steel	$	3,694	2009
685182	5953313	Steel	$	3,694	2009
685197.8	5953308	Steel	$	3,694	2009
685187.1	5953319	Steel	$	3,694	2009
685200.2	5953312	Steel	$	3,694	2009
685188.2	5953325	Steel	$	3,694	2009
685169.2	5953285	Steel	$	3,694	2009

685185.4	5953288	Steel	$	3,694	2009
685170.2	5953289	Steel	$	3,694	2009
685191.7	5953299	Steel	$	3,694	2009
684124.7	5953322	Steel	$	3,694	2009
684623.2	5953390	Steel	$	3,694	2009
684605.6	5953384	Steel	$	3,612	2009
684715.6	5953423	Steel	$	3,796	2009
684612	5953387	Steel	$	3,612	2009
684734.3	5953433	Steel	$	3,721	2009
684805.8	5953466	Steel	$	3,612	2009
684927.1	5953479	Steel	$	3,721	2009
684956.3	5953517	Steel	$	3,721	2009
684961.6	5953525	Steel	$	3,721	2009
685029.6	5953565	Steel	$	3,748	2009
684799	5953329	Steel	$	3,796	2009
685189.5	5953670	Steel	$	3,694	2009
684552.5	5952958	Steel	$	3,694	2009
684567.7	5953061	Steel	$	3,680	2009
684664.7	5953148	Steel	$	3,694	2009
684924.3	5953478	Steel	$	3,694	2009
684587.7	5953081	Steel	$	3,694	2009
684729.7	5953222	Steel	$	3,694	2009

684740.1	5953215	Steel	$	3,694	2009
684735.2	5953227	Steel	$	3,694	2009
684716.8	5953245	Steel	$	3,596	2009
684769.1	5953245	Steel	$	3,694	2009
684749.6	5953240	Steel	$	3,782	2009
684845.9	5953342	Steel	$	3,843	2009
684854.5	5953352	Steel	$	3,870	2009
684851.2	5953347	Steel	$	3,694	2009
684822.1	5953358	Steel	$	3,694	2009
684536.5	5953050	Steel	$	3,925	2009
685004	5953528	Steel	$	3,694	2009
684793.7	5953320	Steel	$	3,694	2009
684555.1	5952977	Steel	$	3,694	2009
684558.2	5953028	Steel	$	6,770	2009