Ex post analysis of engineered tsunami mitigation measures in the town of Dichato, Chile

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Received: 22 May 2018 / Accepted: 24 April 2020 / Published online: 11 May 2020
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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 countermeasures to mitigate their impacts and to improve the country's resilience. Mitigation measures are key to accomplish these objectives. Therefore, this investigation adopts a tsunami damage assessment framework to evaluate the direct benefits of tsunami mitigation works implemented by the Chilean government in the town of Dichato in the aftermath of the 2010 tsunami. We perform an ex post analysis of the potential damage reduction produced by these works studying what would have been the consequences on the built environment if they were in place for the tsunami that hit this area after the Maule earthquake in February 27, 2010. We use state-of-the-art tsunami simulation models at high resolution to assess the reduction in tsunami intensity measures, which serve as input to evaluate the benefit from averted damage against the costs of the mitigation measures. The obtained results 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 largest waves. In conclusion, the tsunami mitigation measures would not have been effective to reduce the impact of the tsunami generated by the Maule earthquake in the town of Dichato, but could have had a benefit in retarding the inundation of low-land areas for the first smaller tsunami waves. The latter suggests that these works might be useful to mitigate storm waves or tsunamis of much smaller scales than the one that hit central-south Chile in 2010.

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Keywords Tsunami · Mitigation measures · Cost–benefit analysis

1 Introduction

Chile is a highly seismic country, mainly due to the subduction process of the Nazca Plate underneath the South American plate (Lomnitz 1970; Araya 2007; Fritz et al. 2011; Centro Sismológico Nacional 2013), where the trench is located very close to the coastline. Many megathrust earthquakes have generated tsunamis, with very short arrival times. Over the past 10 years, four large-magnitude events ($M_w > 7.5$) have occurred in the country, which generated tsunamis with varying levels of destructiveness. These include the Mw 8.8 Maule earthquake (Fritz et al. 2011) in 2010, the Mw 8.2 Pisagua earthquake (Catalán et al. 2015) in 2014, the Mw 8.3 Illapel earthquake (Aránguiz et al. 2016) in 2015, and the Mw 7.6 Melinka earthquake (Xu 2017) in 2016. The 2010 event caused large-scale economical, structural, and human impacts in central and southern Chile (Gobierno Regional del Bío-Bío 2010; Fritz et al. 2011). This event also triggered an increase in basic and applied research in the country. In addition, the Chilean government invested in several tsunami mitigation projects and reconstruction plans (Siembieda et al. 2012; Herrmann Lunecke 2015; Khew et al. 2015), including hard structures.

Among the most damaged coastal towns in 2010 was Dichato, a relatively small settlement with three thousand inhabitants (according to the last census) (Koshimura et al. 2010), located north of the epicenter, that suffered the destruction of houses and infrastructures near the beach and estuary (Koshimura et al. 2010; Yamazaki et al. 2010; Martínez et al. 2016). After the event, the government proposed a tsunami mitigation plan, which included hard structural countermeasures to reduce the impact of tsunamis. The setting of this new infrastructure provides the opportunity to compare the effect of the tsunami with and without the presence of such mitigation works.

The significant impacts associated with recent tsunamigenic events worldwide have motivated the development of numerous studies devoted to hazard assessment and tsunami modeling (e.g., Arcas and Titov 2006; González et al. 2009; Montenegro-Romero and Peña-Cortés 2010; Nandasena et al. 2012; Imamura et al. 2012; Suppasri et al. 2013; Melgar and Bock 2013; Adriano et al. 2014, 2016; Ozer Sozdinler et al. 2015; Catalán et al. 2015; Goda et al. 2015; Park and Cox 2016; Santa María et al. 2016; Aránguiz et al. 2016; Martínez et al. 2016). For example, the Great Eastern Japan Earthquake and tsunami offered the opportunity to evaluate different types of mitigation measures. Nandasena et al. (2012) made an ex post assessment of the effectiveness of tsunami mitigation works, including vegetated dunes, coastal forest, and seawalls. These are tested using numerical modeling to determine how they influence inundation extent, and other hydrodynamic properties such as momentum flux and velocities (Nandasena et al. 2012). Adriano et al. (2016) evaluated the effect of breakwaters in the coast through similar tsunami modeling approaches, concluding that the breakwater present in Onagawa at the time of the tsunami attack reduced the tsunami impact by diminishing the maximum inundation depth in 2 m, even if it was completely destroyed by the flow (Adriano et al. 2016). The performance of a breakwater located in Kamaishi is assessed by Ozer Sozdinler et al. (2015), who state that even though the presence of a breakwater may generate higher flow velocities, these hard countermeasures were beneficial in decreasing inundation depths and retarding the arrival of peak tsunami inundation. Moreover, it was found that a damaged breakwater could still provide some degree of protection.

In Chile, no studies on the effectiveness of tsunami mitigation works have been published to date, but some efforts have produced data and relevant information that are worth mentioning. Santa María et al. (2016) produced an exposure model for residential structures that classifies them by characteristics such as construction materials, geo-localization and estimated replacement costs. Martínez et al. (2016) presented an assessment of the vulnerability of Dichato considering physical, socioeconomic, and educational dimensions, comparing pre- and post-event conditions. It is claimed that vulnerability remains large in this town, despite the existence of new tsunami mitigation measures.

In the present work, we aim to assess the benefits that the presence of new mitigation works in Dichato may have generated, if they had been present during the tsunami of February 27, 2010. To this end, we implement a methodology to estimate the direct damage from the tsunami inundation and compare its results with and without the new infrastructure in place. The methodology used is intended to provide ex post evaluation, for the first time in Chile, on the tsunami impact reduction that such works may produce.

The manuscript is organized as follows: Sect. 2 shows a brief overview of the important definitions and concepts being considered here, along with a characterization of the case under study. Section 3 describes the methodology, while in Sects. 4 and 5, we present the main results of the study and a discussion on their potential implications. The conclusions are summarized in Sect. 6.

2 Background

2.1 Definitions

2.1.1 Risk, hazard, exposure, and vulnerability

In what follows, risk is considered to be composed of three factors: hazard, exposure, and vulnerability (Weichselgartner 2001; González et al. 2009; Venegas San Martín 2012). The hazard is quantified by intensity variables that reflect the capability of a certain geophysical phenomenon to inflict harm (González et al. 2009). While in the risk analysis framework it is necessary to assess all the possible events that may occur in the area of interest to yield a probabilistic hazard assessment (Cutter et al. 2000; Pelling et al. 2004), here we limit ourselves to a scenario-based analysis using the actual 2010 tsunami, following similar lines as Suppasri et al. (2013).

The characterization of exposure requires an inventory of all the elements that could be affected by the hazard, such as communities and physical infrastructure (Pelling et al. 2004), identifying those located in the flooded area by the tsunami (Penning-Rowsell et al. 2005). Lastly, in the context of this study, vulnerability is accounted for structural elements only (i.e., buildings), by means of fragility curves which allow to link hazard intensity variables with the damage probability. Linking hazard, exposure, and vulnerability provides means of assessing the risk level and gives the opportunity to quantify damage reductions from the benefits associated with mitigation measures (e.g., urban planning and relocation, engineered mitigation measures, educational programs, etc.).

2.1.2 Estimation of the benefit from averted damage

The damage reduction of the mitigation works in Dichato can be quantified using a cost–benefit analysis that considers the investment of such works and the benefits they produce against a tsunami. It must be noted that these benefits are exclusively evaluated over direct damage assessment, as other less tangible benefits are beyond the scope of this research. The benefit of the project (B) is estimated as (Ministerio de Desarrollo Social 2013):

$$B = \int_0^{\infty} P(i) \times [C_{NP}(i) - C_{WP}(i)] di, \quad (1)$$

where $P(i)$ 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 a scenario-based analysis is used in this study, the consideration of the probability of its occurrence is beyond the scope of the investigation. Therefore, Eq. (1) will be adapted, as explained in Sect. 3.2.3.

2.1.3 Estimation of damage

A tsunami fragility function or fragility curve constitutes a direct relation between a hydrodynamic feature of the tsunami flow and the probability of damage of a structure (Koshimura et al. 2009a, b; Mas et al. 2012; Suppasri et al. 2012; Adriano et al. 2014; Favier et al. 2014a; Urrea Espinoza 2015). They are usually built empirically from different data sources (Koshimura et al. 2009a). As a result, the level of refinement in the data and its categorization (such as construction material and number of stories of the structure) may affect the outcome of the analysis (Goda et al. 2015). Despite this potential shortcoming, fragility functions are essential in the methodology to estimate tsunami damage. The characteristics of the ones used here are described in Sect. 3.2.3.

2.2 Description of Dichato and the local impact of the 2010 tsunami

Dichato is located at the south end of the Coliumo Bay, almost 40 km north of Concepción (see Fig. 1). It consists of over 3000 inhabitants according to the last official census in 2002 (Instituto Nacional de Estadísticas) and about 2000 homes. The most common construction materials of buildings are wood and masonry (Servicio de Impuestos Internos). The Coliumo Bay has low wave energy, owing to the protection provided by the Tumbes Peninsula to SW incoming waves. On the other hand, its horseshoe shape may induce long wave resonance (Gobierno Regional del Bío-Bío 2010). The 2.4-km-long beach of Dichato makes the area a touristic attraction, especially during summer, when the population can increase up to 5000 inhabitants (Koshimura et al. 2010; Venegas San Martín 2012).

At 3:34 a.m. (local time) in February 27, 2010, a violent earthquake shook the central region of Chile. The epicenter was located off the Chilean coast, about 105 km north-east from the city of Concepción (Saito et al. 2010; Yamazaki et al. 2010) with a reported moment magnitude (Mw) of 8.8 (Pulido et al. 2010; Saito et al. 2010; Mas et al. 2012; Robertson et al. 2012). The tsunami generated free surface disturbances observed all around the Pacific Ocean basin, including the coast of Japan (Koshimura et al. 2010; Robertson et al. 2012). Five hundred and twenty-one people died as a direct result of either

Fig. 1 **a** Location of the town of Dichato in Chile. **b** Coseismic vertical displacement produced by the Maule earthquake computed from Delouis et al. (2010) seismic source. **c** Topography of Dichato: the regions in red are higher in the new scenario compared to the base scenario, and regions in blue are lower. The green line represents the layout of the seawall constructed after the tsunami

the earthquake or tsunami. The tsunami itself claimed 124 victims and 46 missing, mainly in the coastal regions between latitudes 34.5° and 38° south (Nahuelpan López and Varas Insunza 2010; Fritz et al. 2011). Nearly 370,000 homes were damaged and the economic

loss was estimated in USD 30 billion, which was roughly 15% of Chile's gross domestic product in 2010 (Yamazaki et al. 2010).

Dichato was one of the most affected locations. Inundation depths in Dichato were estimated by post-tsunami surveys to be around 8 m, and water penetrated as far as 1.3 km inland (Martínez et al. 2016). Though most people were able to evacuate, there were 66 fatalities in Dichato, mostly tourists and elders who underestimated the intensity of the phenomenon (Mas et al. 2012). More than 1200 families reported damages to their properties (Koshimura et al. 2010), and approximately 80% of the exposed built structures were washed away (Gobierno Regional del Bío-Bío 2010), evidencing the high degree of destruction from the tsunami (Venegas San Martín 2012; Martínez et al. 2016). This level of damage can be explained by the existence of wood houses, which were unable to uphold the large inundation depths and velocities. Damage was also induced by floating debris, including loose boats that collided against structures.

2.3 Mitigation works and relocation

Due to the tsunami impact in 2010, the Chilean government financed a mitigation project aimed to provide protection for Dichato and the community against future tsunamis (Martínez et al. 2016). This mitigation project consists of a low-height seawall approximately 4 m tall and 1.7 km long, made of reinforced concrete along the coastline, and a channeling of the Dichato Estuary at its mouth (see Fig. 1c). With the information provided by the Division of Port Infrastructure of the Minister of Public Works (Dirección de Obras Portuarias—DOP) and reference prices from a catalogue (Portal Ondac Construcción), the estimated construction costs of the wall and channel are US\$ 6.8 million (details of this estimation are given in “Appendix 1,” Fig. 8 and Tables 4, 5, 6, 7, 8). On the other hand, five neighborhoods were relocated either to higher areas or to piloted houses north of the Bay. Building restrictions were established in the town, allowing only commerce-related infrastructure along the coastline of the town. In this area, there is also a mitigation park, consisting of trees planted along the coastline, but its construction only started in 2015 (Martínez et al. 2016).

3 Methodology

The tsunami hazard associated with the 2010 tsunami is estimated by means of numerical modeling. Exposure is assessed from building inventories, and the vulnerability is estimated through fragility curves.

The benefit of tsunami damage reduction from engineered mitigation measures on the coastal urban area is evaluated by a cost–benefit analysis of direct costs associated with the inflicted damage to buildings by the tsunami, and the investment costs for the mitigation measures. Hence, by taking the difference between results considering the situation with and without mitigation works, we can estimate the potential improvement that the project would have produced. We are not attempting to give a comprehensive economic evaluation of the future benefits, but to provide a quantification of the potential improvement that this works could produce if the town was subjected to a similar event on a *ceteris paribus* framework.

3.1 Tsunami modeling

We employ the open source code GeoClaw to perform the tsunami modeling. 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 (MacInnes et al. 2013; Melgar and Bock 2013; Arcos and LeVeque 2015). Tsunami waves along the coast of Chile have been known to last several hours (Catalán et al. 2015), including the 2010 event (Venegas San Martín 2012); hence, the simulation time is set to 8 h, which is considered sufficient to model the largest late-arriving waves (Yamazaki and Cheung 2011).

The information available did not allow us to include buildings in the topography, so a spatially constant Manning roughness coefficient of $0.2 \text{ s/m}^{1/3}$ is considered, as it produces the best agreement with in situ measurements (see Sect. 4.1). The spatial grid for the tsunami simulation is composed of eight rectangular nested grids, with a threefold increase in resolution between each one. The smallest computational grid, enclosing the Coliumo Bay, is built from bathymetric data collected before the event (2009) and has a resolution of 2 m (see Fig. 1c), while the spatial discretization in the largest grid is 1 km. The time steps in the simulations are adjusted dynamically to enforce the fulfillment of the Courant–Friedrichs–Lewy (CFL) stability conditions. The reference level used for the bathymetry and topography was the mean sea level, corrected by the tide level at the time of the event.

To incorporate the mitigation measures in the tsunami modeling, an in situ campaign was carried out to obtain the updated topography with high resolution (wall, park, channels) using differential GPS. Data were corrected by means of the Ntrip network. As a result, the topography for the tsunami simulation considered the aggregate of the data collected before and after the event. The difference between the digital elevation model (DEM) including mitigation works and the original can be appreciated in Fig. 1c. The most important changes are around the wall and along the estuary.

The finite fault seismic source model proposed by Delouis et al. (2010) is used and validated. The initial condition of the displacement of the ocean's free surface is obtained from the Okada formulation (Okada 1985). Figure 1b shows this displacement surface where it can be seen that Dichato is located slightly north of one of the two maxima.

3.2 Damage estimation

3.2.1 Exposed buildings

The exposed residential buildings in Dichato and the tsunami effect on them are considered in this study. For simplicity, only the physical damage induced by the tsunami waves to these buildings is considered. The social impacts or other economic losses are beyond the scope of this work because of the difficulty in quantifying their vulnerability, especially when it comes to social vulnerability (Cutter et al. 2003). The characteristics of houses, construction materials, price values, and year of construction were estimated from a database provided by the Revenue Service (Servicio de Impuestos Internos). This database consists of 1878 houses; however, during the fieldwork, only 452 of them could be properly identified and geo-localized of the database. Hence, we use herein only the identified buildings which are considered as a sample of nearly 40% of the houses directly exposed to the tsunami waves. The characteristics and the spatial distribution of the inventory can be

Fig. 2 Inventory of houses in Dichato. **a** Price distribution (in thousands USD) of the household sample, **b** materiality distribution of the household sample, and **c** spatial distribution of the sample of houses in Dichato, where colored triangles represent the individual households

seen in Fig. 2. Most of the houses in Dichato are built with wood and masonry, while the rest are built with concrete, steel or other less common materials (see Fig. 2b). On the other hand, the majority of houses were valued in approximately US\$7000 (Servicio de Impuestos Internos) (see Fig. 2a).

3.2.2 Tsunami intensity measures

The hazard intensity is estimated by computing inundation depths, velocity, energy, and arrival times (Macabuag et al. 2016; Park and Cox 2016). Maximum inundation depths are considered as the most relevant parameter because when used in conjunction with fragility curves, they allow to evaluate the probability of damage of individual buildings (Cançado et al. 2008). Nevertheless, the other intensity measures are also of interest. Flow velocities, for instance, have been studied and utilized for the development of fragility curves for structural damage in buildings (Mas et al. 2012; Park and Cox 2016; De Risi et al. 2017), as they may contribute with information about the interactions between the flow and the topography that otherwise cannot be attained (Suppasri et al. 2012; Arcos and LeVeque 2015). In addition, both maximum inundation depths and velocities have been found to be applicable for the estimation of building damage due to tsunamis (Park and Cox 2016). Thus, maximum flow velocities and maximum energy—as an extension of the latter—are also estimated from the tsunami simulation as reference.

3.2.3 Damage estimation

Fragility curves are used to estimate the probability of damage generated by the tsunami to the physical infrastructures. Direct damage is thus considered to be the result of the interaction between hydrodynamic forces and the structures (Penning-Rowse et al. 2005). The damage depends on the construction material of buildings, and several damage levels can be considered.

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. These authors developed fragility curves with six damage levels for wood, masonry, reinforced concrete, and steel frame houses, with the damage levels shown in Table 1 (Suppasri et al. 2012). These fragility curves were chosen since they involved the same four main construction materials observed in Dichato, with the possibility of including different damage levels for each materiality.

Considering that a common type of building in Dichato is best represented as a concrete house in the first story (2 m in height), and as a wooden house in the second story, an additional fragility curve was arranged for the purpose of this investigation, by combining those of wooden and concrete fragility curves. More details are provided in “Appendix 2.1.”

With the probability of having the different damage levels for each building, the expected loss is quantified in monetary terms. The cost of repair (C_r) is assumed to be a percentage of the construction cost (C_t), as the more expensive the construction cost of a house would mean a more costly reparation as well. Likewise, if a building is constructed with cheap materials, the costs of repairing are assumed to be low. The relation between the two costs is a function of the damage level, which determines how much of the total construction cost the repairing cost is. Table 1 shows this relation. For example, if the building suffers minor damage, the repair cost is a fraction of the construction cost, assumed as $C_r=0.2C_t$. If the house is washed away, the repair cost is larger than the construction cost ($C_r=1.2C_t$). This estimated larger cost is attributed to the management and disposal of debris.

Finally, the total costs from the loss induced by the tsunami for each scenario are estimated as the aggregate of costs from all buildings. This is simply the sum of the product between the cost ratios and their probability of occurrence for every damage level and every type of material, i.e.,

$$C = \sum_k \sum_i P(ds_i) \times c_i \quad (2)$$

where ds_i stands for damage state i , c_i for the corresponding cost ratio C_r/C_t for the damage state i , and $P(ds_i)$ for the probability of damage for damage state i . Finally, the expected damage $\sum_i P(ds_i) * c_i$ for each building k is summed up to give the total expected damage.

The cost–benefit analysis considers the comparison between costs that are averted by the application of mitigation measures and those without mitigation (Penning-Rowsell et al. 2005; Ministerio de Desarrollo Social 2013; Iwata et al. 2014). Equation (1) is adapted to take into consideration only one realization:

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

$$B = C_{NP} - C_{WP}. \quad (3)$$

4 Results

4.1 2010 Tsunami impact without engineered mitigation measures

First, the tsunami modeling is carried out without mitigation works in order to estimate a reference scenario, and to validate the model. For the latter, results are compared to field data from in situ surveys summarizing observations from five campaigns, resulting in a set of 37 measurements (Imamura et al. 2010; Matsutomi et al. 2010; Fritz et al. 2011; Mikami et al. 2011).

To estimate the tsunami model performance, Aida's root-mean-square error (RMSE) method is used (Aida 1978), as done by Shuto (1991), Koshimura et al. (2009b), Suppasri et al. (2012), and Martínez et al. (2016). Parameters K and κ are presented in Eqs. (4) and (5), respectively, where K_i stands for the ratio between observed and simulated values of inundation height.

$$\log K = \frac{1}{n} \sum_{i=1}^n \log K_i \quad (4)$$

$$\log \kappa = \sqrt{\frac{1}{n} \sum_{i=1}^n (\log K_i)^2 - (\log K)^2} \quad (5)$$

In 2002, the Japan Society of Civil Engineers (JSCE) proposed that K and κ values in the range $0.95 < K < 1.05$ and $\kappa < 1.45$ indicate a good estimation (Tsunami Evaluation Subcommittee and Nuclear Civil Engineering Committee 2002).

The observed and numerical sets of inundation heights are used to evaluate the K_i coefficients from five post-tsunami surveys, resulting in a set of 37 observations (Imamura et al. 2010; Matsutomi et al. 2010; Fritz et al. 2011; Mikami et al. 2011). These 37 measurements are then compared with simulated data to obtain K_i , and by the use of Eqs. (4) and (5), the values of the parameter K and κ are found. The Dichato simulation yields $K = 0.97$ and $\kappa = 1.38$, which is within the recommended limits.

The tsunami simulation results are also qualitatively compared with inundation maps obtained by Mas et al. (2012) (Fig. 3a). Relative sea levels during the event are compared with the information registered at the Talcahuano port inside the Bay of Concepción, as seen in Fig. 3b and with data provided by a Deep-ocean Assessment and Reporting of Tsunamis (DART) Station off the coast of northern Chile and southern Peru (Fig. 3c).

Peak values of inundation depths, flow velocities, energy, and arrival times estimated with the tsunami model are shown in Fig. 4. The highest inundation depth was nearly 10.8 m. The maximum run-up reached 16 m. For flow velocities, the maximum value, as shown in Fig. 4b, is nearly 11.4 m/s. Local energy values are calculated using Bernoulli's expression $H = h + \frac{v^2}{2g}$, where h stands for inundation depth, v for flow depth-averaged velocity, g for the gravitational acceleration, and H for the hydraulic head. The results obtained for maximum energy are shown in Fig. 4c. Figure 4d also shows that

Fig. 3 **a** Comparison of the modeled maximum inundation (in red) with the post-tsunami survey from Mas et al. (2012). **b** Modeled (red) and measured (blue) sea level variations at DART buoy 32,412 ($17^{\circ}59'1''\text{S}$ $86^{\circ}22'28''\text{W}$). **c** Modeled (red) and measured (dotted blue) sea surface evolution at the Talcahuano tidal gage. **d** Modeled time series in the bay of Dichato

there is an inundation of low areas within 50 min, but that the larger inundation extent occurs after 100 min. The total costs for this scenario are of nearly USD \$ 2.9 million.

4.2 2010 Tsunami impact considering the engineered mitigation measures in place

Next, simulations including the mitigation works are carried out considering the updated topography. Figure 5 shows the differences between this modified scenario and the baseline scenario. Negative values denote the baseline scenario values exceed those of the modified case. Values for inundation depths and run-ups with the incorporation of mitigation works have maxima of 10.6 m and 16 m, respectively, which are very similar to the base scenario. Near the estuary, depths are larger owing to the channeling effect of the works. However, for the maximum hydraulic head, the modeled values in the modified situation are lower than the baseline scenario, which highlights the potential in reducing the energy of the flow. The total costs estimated for the direct damage in this case are \$USD 2.7 million.

A summary of these results is presented in Table 2.

Fig. 4 Results of the simulation on Dichato's base scenario. The maximum values of **a** inundation depths, **b** flow velocities, **c** energy, and **d** tsunami arrival times

Fig. 5 Results of the simulation on Dichato considering the mitigation measures, in contrast to the base scenario. Red regions correspond to higher values in the new scenario, and blue when values are lower. Difference of maximum **a** inundation depths, **b** velocities, and **c** energy. **d** Arrival times for the new scenario

Table 2 Summary of results considering scenarios without and with mitigation works

	Inundated area (km ²)	Damage costs (MM USD)
Without mitigation measures	13.4	2.9
With mitigation measures	13.2	2.7
Direct benefit		0.2

Considering inundation depths are similar and that the damage estimation depends directly and solely on this variable, the benefit obtained with the presence of the mitigation works is estimated to be only of USD\$ 211,000, i.e., a reduction of 7%.

5 Discussion

The Dichato reconstruction plan incorporated hard mitigation measures to minimize future tsunami impacts in the bay, but our results show that when confronted to the 2010 tsunami, the level of direct damage reduction is only marginal. The most relevant mitigation aspect corresponds to a delay in arrival times of tsunami waves, as the inundation area of the second wave is reduced to approximately 40% in the presence of the seawall and channel. The time available to carry out an evacuation in the area located in the vicinity of the river mouth is thus increased to approximately an hour, as shown in Fig. 5d. This aspect is relevant for evacuation purposes, but it is a benefit that is not granted for other tsunamis since it is highly dependent on the characteristics of the seismic source; indeed for the 2010 tsunami, the largest tsunami waves that arrived to Dichato were not the first to come, but this situation could be different for other events. Indeed, the largest wave arrived 120 min after the earthquake in 2010 and inundated roughly the same area as it did in the case we simulated with the engineered structures in place. Hence, the conducted mitigation works 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 the largest tsunami waves generated by an event similar to the one that occurred in 2010.

This finding motivates us to evaluate alternatives for the wall height and to produce a sensitivity analysis on this design parameter. The rationale behind this analysis is that one would expect that a higher wall height should produce larger direct benefits than the costs of construction, and eventually, and optimum constrained to specific objectives or criteria could be found. Thus, we consider different wall heights from +0.5 m up to +4 m from its actual configuration, to assess potential mitigation effects and damage reductions in view of determining an optimal wall height (Favier et al. 2014b; Shimoazono and Sato 2016).

We thus perform additional tsunami simulations and re-assess the cost–benefit analysis considering walls 0.5, 1.0, 2.0, 3.0, and 4.0 m taller than the actual one of 5 m on average. Special structural designs or protection elements that would increase the construction costs of higher walls to ensure its correct performance in this situation are not included, since the costs are only assumed to be proportional to the height of the wall. It is also important to emphasize that a more comprehensive analysis would require the inclusion of a time window for life operation of the engineered works, the probability of exceedance of certain tsunami hazard level each year, and a cash flow for costs and benefits. Although difficult to quantify, these indirect impacts are also important and should be considered in the design and decision process.

The resulting inundation maps for the same 2010 event are shown in Fig. 6. As expected, as the wall height increases, the inundated area gradually decreases and the damage cost reduction increases, as summarized in Table 3. Indeed, when the height of the seawall is increased in 3 m, the flooded area is greatly reduced (43.3% of area reduction and an 88.9% reduction in damage costs). The different scenarios are summarized

Fig. 6 Results of the simulation on Dichato considering different wall heights. The maximum values of inundation depths for the **a** scenario with the existent mitigation works, **b** with a wall 0.5 m taller, **c** 1 m taller, **d** 2 m, **e** 3 m taller, and **f** 4 m taller

Table 3 Reductions with respect to the base scenario when increasing the height of the seawall

Increase in wall height (m)	Inundated area (km ²)	Area reduction (%)	Damage costs (MM USD)	Damage reduction with respect to the base scenario (%)
+0.5	13.0	3.0	2.8	4.5
+1	12.6	6.0	2.4	16.7
+2	11.7	12.7	1.9	34.9
+3	7.6	43.3	0.3	88.9
+4	7.2	45.6	0.3	90.1

Fig. 7 Benefits versus construction costs for different wall height scenarios

in Fig. 7, where it can be seen that the application of the methodology brings valuable technical information for decision making; nonetheless, this dimension constitutes only one element among many others that come into play before deciding investing in mitigation works. Indeed, the final decision has more to do with political issues, as it seems to have been the case in Dichato since we could not find any technical justification for the selected wall height in the official documents we could gather.

In addition to hard mitigation structures, which are not foolproof, other measures can also be considered. With this regard, sustaining education and awareness programs to ensure an effective evacuation response in case of a disaster should not be undermined (Favier et al. 2014b). Mitigation and risk communication strategies unbalanced toward hard measures may induce a false sense of security (Suppasri et al. 2013).

Urban planning is another important risk reduction tool that can be informed by the type hazard and damage assessment analysis presented here. The latter could be useful to improve the preparedness of Dichato against an event similar to the one that hit Chile in 2010. For example, if additional studies of potential evacuation are considered, restriction areas based on this information could be defined to ensure a prompt and safe evacuation (e.g., Imamura et al. 2012; León et al. 2019).

6 Conclusion

The present investigation provides an ex post analysis of the effectiveness of the mitigation measures that were built in the town of Dichato in the aftermath of the 2010 tsunami. This is the first study of this kind in Chile, but follows similar lines than research

published after the 2011 Tohoku tsunami in Japan. Our results suggest that the seawall and the channeling of the river account for a direct damage cost reduction of nearly 7% if faced to a similar tsunami than the one that hit this town in 2010, with an estimated cost of implementation of USD \$6.8 million. However, damage reduction could be increased if taller walls were considered, as a reduction of over 85% in damage costs is estimated with a wall 3 m taller than the reference one. Indeed, the direct benefits of the current measures are minor (approximately 200 thousand US dollars) and would deserve to be confronted with other indirect costs which should also include the impact on tourism and beach erosion over the operation lifetime of the mitigation works.

The most important effect of the conducted mitigation works is an increase in evacuation times for the area close to the river, which should bring additional indirect benefits that are not accounted for in the present study. The latter is explained by the particularities of the tsunami hydrodynamics at this location since the biggest wave is not much affected by the mitigation works, and it arrives 2 h after the nucleation of the earthquake. This can be a situation particular to this place and event, so these results should be treated as a first estimate of the benefit.

Despite this potential shortcoming, our simulations suggest that the mitigation works in place could be effective against minor tsunamis, storm waves or surges, but not against the biggest waves produced by a similar event than the one that occurred in 2010.

While the present research is important to provide an ex post assessment of the mitigation work effectiveness, a more comprehensive analysis for the definition of optimal measures should consider additional aspects that are not easy to evaluate such as probabilistic simulation of the tsunami hazard, risk perception, and cultural issues. Indeed, mitigation plans should be evaluated from more complex perspectives than direct damage reductions attributed to hard works, including community risk awareness, land use, and evacuation plans.

Acknowledgements This investigation was funded by Centro Nacional de Investigación para la Gestión Integrada de Desastres Naturales (CIGIDEN), ANID/Fondap/15110017 and CONICYT/PIA/Basal/FB0821. The authors extend their thanks to Dr. Paula Aguirre, Evans Aravena, Karla Contreras, Dr. Ian del Río, Juan Carlos Domínguez, Diego Espinoza, Dr. Philomène Favier, Dr. Carolina Martínez, Dr. Erick Mas, Georgette Mell, Dr. Luis Ignacio Rizzi, Andrea Vásquez, and Dr. Patricio Winckler who contributed to the investigation and to the whole team led by Dr. Rodrigo Cienfuegos.

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Appendix 1: Valuation of mitigation works

To perform an approximate valuation of the mitigation works, a simplified version of the wall and channels' structures was considered, as composed of 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 4 is a detail of the materials considered in both the

Table 4 Detail of the materials considered for the valuation of the mitigation works

Material detail	Unit	Price (USD)
Hormigón H-20 (RC)	m ³	79.78
Hormigón HN-25 (RC)	m ³	68.87
Hormigón H-30 (RC)	m ³	97.24
Enfierradura $D = 10$ mm a 44–28 (iron)	kg	1.18
Relleno con material de obra (filling)	m ³	5.72
Compactación con rodillo $e = 30$ cm (compacting)	m ²	0.32
Relleno con bolón (filling)	m ³	31.53
Bombeo de hormigón (RC pumping)	m ³	13.89
Excavación terreno blando $a = 1$ mt (excavations)	m ³	4.52

wall and channel. The prices are according to the Chilean market and include workforce and other minor materials required.

The mitigation works can be better appreciated in Fig. 8.

Appendix 1.1: 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 (Tables 5, 6, 7).

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

Fig. 8 **a** Wall and **b** channel built in Dichato after the 2010 event. **c** Detail of wall and channel **(d)**

Table 5 Amount of material used for the construction of the wall in Litril Sector

Litril Sector					
Profile	Length (m)	RC (m ²)	Crushed stone (m ²)	Layer compaction (m)	Rock fill (m ²)
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 6 Amount of material used for the construction of the wall in Etapa 1 Sector

Etapa 1 Sector					
Profile	Length (m)	RC (m ²)	Crushed stone (m ²)	Layer compaction (m)	Rock fill (m ²)
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 7 Amount of material used for the construction of the wall in Estero Sector

Estero Sector					
Profile	Length (m)	RC (m ²)	Crushed stone (m ²)	Layer compaction (m)	Rock fill (m ²)
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

Appendix 1.2: Channel

In the case of the channel, there was one average profile used along the 286 m of its length. Thus, the material summary of it is shown in Table 8.

Table 8 Amount of material used for the construction of the channel

Channel				
Length (m)	Shotcrete (m ²)	Filling (m ²)	Layer compaction (m)	Excavation (m ²)
286	5.18	17.12	9.85	18.22

Appendix 2: Selection of fragility curves

The fragility curves used correspond to a work by Suppasri et al. (2012) where six 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 Fig. 9.

Fig. 9 Fragility curves for steel (a), wood (b), masonry (c) and RC (d), for levels 1 through 6, where 1 is minor damage, 2 is moderate damage, 3 is major damage, 4 is complete damage, 5 is collapse, and 6 is washed away (Suppasri et al. 2012)

Fig. 10 Two-story house with mixed materiality

Appendix 2.1: Fragility curve for mixed materials

A fifth typology is proposed in the present investigation, which corresponds to a mix between reinforced concrete and wood for a specific kind of two-story houses. To this end, we consider the fragility curves for both reinforced concrete and wood, where the first story's materiality is reinforced concrete, while the second is made from wood. Thus, the idea is to apply an inundation height to each curve according to the relative (with respect of the base of each story) level of inundation of the first and the second stories. Therefore, using Fig. 10 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.

For instance, if a house built with mixed materials is exposed to an inundation height of 2.5 m, the total damage would be an average of the damage on the RC first story with an inundation of $h' = 2$ m and the damage on the wooden second story with an inundation of $h^* = 0.5$ m. The RC curve shows that with a 2 m inundation, the approximated damage probabilities are: 100% chance of minor damage, 95% chance of moderate damage, 80% chance of major damage, 40% chance of complete damage, 10% chance of collapse, and 0% of washed away. On the other hand, the wood curve shows that with a 0.5 m inundation, the approximated damage probabilities are 85%, 60%, 20%, 5%, 0%, 0%, respectively. With these numbers, it is possible to apply the methodology explained in Sect. 3.2.3, with Eq. (2) and the information presented in Table 1.

Appendix 3: Valuation of buildings

All the information utilized for the valuation of the buildings' sample was obtained from the Servicio de Impuestos Internos (SII) and is presented in Table 9. The actual price of a building was considered to include the value of the terrain because of limitations in the available information.

Table 9 Sample of buildings in Dichato with their location, materiality, year of construction, and valuation in USD

X coordinate	Y coordinate	Material	Valuation in USD	Year of construction
684,958.5	5,953,112	Masonry	\$830	1920
684,408.9	5,953,076	Masonry	\$24,743	1938
684,412.7	5,953,197	Wood	\$10,066	1938
685,000.3	5,954,351	Wood	\$7904	1940
684,731.2	5,953,262	Masonry	\$53,739	1940
684,982.6	5,953,317	Masonry	\$33,102	1940
684,805.4	5,953,288	Wood	\$166,069	1940
685,486.9	5,953,714	Masonry	\$8201	1941
684,179.3	5,953,205	Wood	\$10,294	1942
684,805.9	5,953,336	Masonry	\$1910	1943
684,599.8	5,953,229	Wood	\$10,839	1944
685,174.1	5,953,349	Wood	\$14,292	1944
684,681.2	5,953,354	Wood	\$6674	1945
684,399.7	5,953,119	Wood	\$19,962	1945
684,997.8	5,952,934	Wood	\$13,204	1945
684,165.5	5,953,120	Masonry	\$8757	1945
685,018.4	5,953,294	Wood	\$3672	1946
685,226.6	5,953,304	Wood	\$14,050	1949
685,370.7	5,953,693	Wood	\$3209	1950
684,039.6	5,953,221	Wood	\$8230	1950
684,748.1	5,953,412	Wood	\$14,409	1950
685,379.6	5,953,671	Masonry	\$6954	1950
685,411.1	5,953,611	Wood	\$4780	1950
684,438	5,953,081	Masonry	\$11,005	1950
685,402	5,953,646	Wood	\$12,416	1950
685,418.8	5,953,641	Wood	\$26,206	1950
683,842.4	5,953,251	Wood	\$31,172	1952
684,405.3	5,953,066	Wood	\$3975	1953
684,119.1	5,953,226	Wood	\$5513	1957

Table 9 (continued)

X coordinate	Y coordinate	Material	Valuation in USD	Year of construction
685,168.2	5,953,340	Wood	\$18,832	1957
684,532.3	5,953,155	Wood	\$1740	1960
684,369.9	5,953,219	Wood	\$7364	1960
684,090.1	5,953,199	Wood	\$7149	1960
684,039.9	5,953,202	Masonry	\$6470	1960
684,448.6	5,953,199	Wood	\$8567	1960
683,891.7	5,953,221	Wood	\$24,120	1960
684,369.2	5,953,119	Wood	\$796	1960
684,519.6	5,953,091	Wood	\$5254	1960
684,804.6	5,953,187	Wood	\$2417	1960
684,946.6	5,953,114	Wood	\$6457	1960
685,338.6	5,953,615	Wood	\$278	1960
685,406.5	5,953,613	Wood	\$36,151	1960
683,861.9	5,953,236	Wood	\$7397	1960
684,562.5	5,953,153	Wood	\$11,464	1961
685,376.9	5,953,690	Wood	\$3228	1962
684,951.8	5,953,121	Wood	\$8907	1962
685,227.9	5,953,316	Wood	\$514	1962
685,171.6	5,954,074	Wood	\$707	1963
684,953.2	5,953,307	Masonry	\$31,387	1963
685,405.2	5,953,658	Wood	\$7477	1963
684,858.6	5,953,360	Masonry	\$6629	1964
684,862.9	5,953,134	Wood	\$10,151	1964
685,067.5	5,954,085	Wood	\$13,160	1965
684,581	5,953,115	Wood	\$13,923	1965
685,018.1	5,953,273	Wood	\$6232	1965
684,503	5,953,095	Wood	\$18,785	1965

Table 9 (continued)

X coordinate	Y coordinate	Material	Valuation in USD	Year of construction
684,853.2	5,952,913	Wood	\$9258	1966
685,182.5	5,953,331	Wood	\$7186	1966
685,189.8	5,953,329	Wood	\$6511	1966
685,140.5	5,953,318	Masonry	\$6976	1966
683,862.7	5,953,259	Wood	\$8387	1967
684,988.4	5,954,407	Wood	\$6648	1968
684,864.5	5,953,137	Wood	\$7427	1968
685,357.8	5,953,586	Wood	\$9208	1968
683,906.2	5,953,236	Wood	\$3210	1968
685,196	5,953,338	Wood	\$11,152	1968
684,529.4	5,953,210	Wood	\$947	1969
684,878.5	5,953,294	Wood	\$9782	1969
685,424.2	5,953,638	Wood	\$15,636	1969
685,167	5,953,354	Wood	\$9359	1969
684,685	5,953,326	Masonry	\$8084	1970
684,659.2	5,953,197	Wood	\$14,010	1970
684,950.9	5,953,101	Masonry	\$10,096	1970
685,390.8	5,953,618	Wood	\$274	1970
685,163.3	5,953,355	Wood	\$11,375	1970
685,162.7	5,953,343	Wood	\$19,020	1970
685,152.9	5,953,348	Wood	\$7580	1970
685,149.9	5,953,310	Wood	\$2220	1970
685,155.1	5,953,310	Wood	\$2206	1970
684,977	5,953,544	Wood	\$13,697	1971
684,725.4	5,953,257	Masonry	\$24,775	1972
685,184.8	5,954,044	Wood	\$6188	1972
684,587.2	5,953,125	Wood	\$15,535	1973

Table 9 (continued)

X coordinate	Y coordinate	Material	Valuation in USD	Year of construction
685,175.6	5,953,854	Wood	\$402	1973
685,155.2	5,953,347	Masonry	\$21,943	1973
685,003	5,953,609	Wood	\$6301	1974
684,964.7	5,953,304	Wood	\$5323	1975
685,026	5,953,268	Wood	\$10,642	1975
684,852.5	5,953,399	Wood	\$7966	1975
684,518.6	5,953,195	Wood	\$3396	1976
685,372.7	5,953,621	Wood	\$12,444	1976
684,874.3	5,953,155	Other	\$2577	1977
684,868.3	5,953,164	Other	\$2273	1977
684,859.9	5,953,152	Other	\$2273	1977
684,863.2	5,953,157	Other	\$2273	1977
684,876	5,953,177	Other	\$2273	1977
684,820.9	5,953,106	Other	\$2577	1977
684,742.2	5,952,990	Other	\$3298	1977
684,782	5,952,982	Other	\$3811	1977
684,843.4	5,952,967	Wood	\$1924	1977
684,962.7	5,952,943	Wood	\$1829	1977
684,978.1	5,952,890	Other	\$2509	1977
685,283	5,953,642	Other	\$2273	1977
685,288.5	5,953,639	Other	\$2273	1977
685,301	5,953,634	Other	\$2273	1977
685,311.6	5,953,627	Other	\$2273	1977
685,318.6	5,953,624	Other	\$2273	1977
685,324.3	5,953,621	Other	\$2273	1977
685,331.3	5,953,618	Other	\$2509	1977
683,898.5	5,953,220	Wood	\$10,587	1977

Table 9 (continued)

X coordinate	Y coordinate	Material	Valuation in USD	Year of construction
685,233.3	5,953,313	Masonry	\$5151	1977
685,203.6	5,953,319	Masonry	\$5151	1977
685,202.4	5,953,296	Masonry	\$5151	1977
685,207.3	5,953,292	Other	\$2170	1977
685,214.6	5,953,288	Other	\$2170	1977
685,195.6	5,953,285	Other	\$2170	1977
685,217.8	5,953,287	Masonry	\$5151	1977
685,198.8	5,953,284	Masonry	\$5151	1977
685,208.3	5,953,278	Other	\$2273	1977
685,210.4	5,953,276	Other	\$2523	1977
685,237.7	5,953,275	Other	\$2319	1977
685,223.5	5,953,270	Other	\$2319	1977
685,229.8	5,953,265	Other	\$2319	1977
685,253.6	5,953,266	Other	\$2319	1977
685,239.8	5,953,260	Other	\$2523	1977
685,002.3	5,954,343	Wood	\$1358	1978
685,350.1	5,953,610	Wood	\$3595	1978
685,370.4	5,953,654	Wood	\$14,641	1978
684,994	5,953,310	Wood	\$9807	1979
685,345.2	5,953,612	Wood	\$5391	1979
684,422.1	5,953,028	Wood	\$5603	1980
684,529.6	5,953,001	Wood	\$11,174	1980
684,524	5,953,114	Wood	\$7005	1980
685,063	5,954,097	Wood	\$8005	1980
685,421.6	5,953,651	Wood	\$5261	1980
684,454.1	5,953,196	Wood	\$9272	1980
685,175.8	5,953,334	Wood	\$22,006	1980

Table 9 (continued)

X coordinate	Y coordinate	Material	Valuation in USD	Year of construction
685,148.5	5,953,352	Wood	\$8160	1980
685,154.7	5,953,364	Wood	\$5223	1980
685,428.4	5,953,636	Wood	\$16,223	1981
684,548.1	5,953,369	Masonry	\$609	1982
684,957	5,953,306	Wood	\$21,363	1982
684,946.1	5,953,091	Wood	\$7898	1982
684,936.6	5,953,102	Masonry	\$6472	1982
683,830.9	5,953,267	Wood	\$24,565	1983
685,157.1	5,953,321	Masonry	\$7119	1983
684,283.5	5,953,214	Masonry	\$26,750	1984
685,392	5,953,663	Wood	\$9162	1984
684,655	5,953,005	Wood	\$6055	1985
684,583.3	5,953,177	Wood	\$7543	1985
685,205.8	5,953,281	Wood	\$2892	1985
684,816.5	5,953,429	Wood	\$21,491	1986
683,849.1	5,953,247	Masonry	\$9439	1987
685,159.9	5,953,319	Wood	\$3539	1987
684,503	5,953,095	Masonry	\$27,104	1988
684,189.6	5,953,206	Wood	\$11,009	1988
685,279.3	5,953,734	Wood	\$9313	1989
684,648.3	5,953,314	Wood	\$274,267	1989
684,664.6	5,953,369	Masonry	\$5138	1989
685,401.9	5,953,615	Wood	\$3343	1989
685,408	5,953,645	Wood	\$7540	1989
685,364.3	5,953,695	Wood	\$4649	1990
685,379.8	5,953,687	Wood	\$2965	1990
685,407.7	5,953,682	Wood	\$2353	1990

Table 9 (continued)

X coordinate	Y coordinate	Material	Valuation in USD	Year of construction
685,414.9	5,953,678	Wood	\$3523	1990
685,421.5	5,953,676	Wood	\$2312	1990
685,432.9	5,953,675	Wood	\$3535	1990
685,437	5,953,677	Wood	\$2623	1990
685,422.4	5,953,700	Wood	\$3337	1990
684,977	5,954,433	Wood	\$16,767	1990
684,448.6	5,953,199	Wood	\$6674	1990
684,473.3	5,953,101	Masonry	\$5915	1990
684,872.7	5,953,152	Wood	\$10,574	1990
684,649	5,953,203	Wood	\$3731	1990
684,669.2	5,953,304	Wood	\$3365	1990
684,743.8	5,953,408	Wood	\$3214	1990
685,326.9	5,953,656	Wood	\$187	1990
685,411.4	5,953,655	Masonry	\$6818	1990
684,336.6	5,953,217	Steel	\$54,980	1991
684,838	5,953,414	Masonry	\$8929	1991
685,128.7	5,953,949	Masonry	\$18,811	1993
685,374.4	5,953,662	Wood	\$4610	1993
685,003.8	5,953,281	Wood	\$31,303	1994
684,418.7	5,953,010	Wood	\$7430	1994
685,151.3	5,953,325	Wood	\$4546	1994
685,183.9	5,953,850	Masonry	\$21,943	1995
684,827.6	5,953,280	Masonry	\$8962	1995
685,010.5	5,954,284	Wood	\$6937	1995
685,229.9	5,953,281	Masonry	\$9824	1995
684,737.7	5,953,379	Masonry	\$21,649	1996
683,839.1	5,953,291	Wood	\$15,571	1997

Table 9 (continued)

X coordinate	Y coordinate	Material	Valuation in USD	Year of construction
684,762.6	5,953,392	Masonry	\$11,472	1998
684,858.5	5,953,146	Wood	\$15,901	1998
684,641.6	5,953,277	Wood	\$3155	1998
684,999.6	5,954,309	Wood	\$4684	1998
685,385.8	5,953,620	Wood	\$414	1998
684,992.5	5,954,488	Wood	\$4595	1998
685,156.9	5,953,880	Wood	\$7623	1998
684,536.9	5,953,188	Masonry	\$17,918	1998
685,213.6	5,953,326	Wood	\$9051	1998
685,000	5,954,319	Wood	\$3646	1999
685,221.5	5,953,321	Wood	\$7330	1999
685,382.8	5,953,689	Masonry	\$301	2000
684,894.7	5,953,409	Masonry	\$747	2000
684,898.8	5,953,413	Masonry	\$747	2000
685,414.3	5,953,608	Masonry	\$23,604	2000
685,417	5,953,608	Wood	\$10,503	2000
685,218.1	5,953,310	Wood	\$18,596	2000
684,625.9	5,953,294	Wood	\$8150	2001
684,486	5,953,123	Wood	\$30,163	2001
684,723.5	5,953,168	Wood	\$4634	2001
684,901.2	5,953,416	Masonry	\$17,260	2002
684,954	5,953,107	Masonry	\$8785	2002
685,377.8	5,953,667	Wood	\$2047	2002
684,290.7	5,953,252	RC	\$697,079	2003
684,290.7	5,953,252	RC	\$697,079	2003
684,290.7	5,953,252	RC	\$15,545	2003
684,290.7	5,953,252	RC	\$27,756	2003

Table 9 (continued)

X coordinate	Y coordinate	Material	Valuation in USD	Year of construction
684,290.7	5,953,252	RC	\$12,777	2003
684,290.7	5,953,252	RC	\$22,813	2003
684,290.7	5,953,252	RC	\$15,545	2003
684,290.7	5,953,252	RC	\$27,756	2003
684,290.7	5,953,252	RC	\$651	2003
684,290.7	5,953,252	RC	\$27,756	2003
684,290.7	5,953,252	RC	\$22,813	2003
684,290.7	5,953,252	RC	\$27,756	2003
684,290.7	5,953,252	RC	\$1085	2003
684,290.7	5,953,252	RC	\$27,756	2003
684,290.7	5,953,252	RC	\$22,813	2003
684,290.7	5,953,252	RC	\$27,756	2003
684,290.7	5,953,252	RC	\$27,756	2003
684,290.7	5,953,252	RC	\$22,813	2003
684,290.7	5,953,252	RC	\$27,756	2003
684,290.7	5,953,252	RC	\$27,756	2003
684,290.7	5,953,252	RC	\$22,813	2003
684,290.7	5,953,252	RC	\$27,756	2003
684,290.7	5,953,252	RC	\$27,756	2003
684,290.7	5,953,252	RC	\$22,813	2003
684,290.7	5,953,252	RC	\$27,756	2003
684,290.7	5,953,252	RC	\$27,756	2003
684,290.7	5,953,252	RC	\$22,813	2003
684,290.7	5,953,252	RC	\$27,756	2003
684,290.7	5,953,252	RC	\$27,756	2003
684,290.7	5,953,252	RC	\$22,813	2003
684,290.7	5,953,252	RC	\$27,756	2003
684,290.7	5,953,252	RC	\$868	2003
684,290.7	5,953,252	RC	\$27,756	2003
684,290.7	5,953,252	RC	\$22,053	2003

Table 9 (continued)

X coordinate	Y coordinate	Material	Valuation in USD	Year of construction
684,290.7	5,953,252	RC	\$44,486	2003
684,290.7	5,953,252	RC	\$426	2003
684,290.7	5,953,252	RC	\$868	2003
684,290.7	5,953,252	RC	\$319	2003
684,290.7	5,953,252	RC	\$651	2003
684,290.7	5,953,252	RC	\$319	2003
684,290.7	5,953,252	RC	\$651	2003
684,290.7	5,953,252	RC	\$169	2003
684,290.7	5,953,252	RC	\$434	2003
684,290.7	5,953,252	RC	\$319	2003
684,290.7	5,953,252	RC	\$651	2003
684,290.7	5,953,252	RC	\$319	2003
684,290.7	5,953,252	RC	\$651	2003
684,290.7	5,953,252	RC	\$852	2003
684,290.7	5,953,252	RC	\$1737	2003
684,290.7	5,953,252	RC	\$426	2003
684,290.7	5,953,252	RC	\$868	2003
684,290.7	5,953,252	RC	\$319	2003
684,290.7	5,953,252	RC	\$651	2003
684,290.7	5,953,252	RC	\$319	2003
684,290.7	5,953,252	RC	\$651	2003
684,290.7	5,953,252	RC	\$426	2003
684,290.7	5,953,252	RC	\$868	2003
684,290.7	5,953,252	RC	\$319	2003
684,290.7	5,953,252	RC	\$651	2003

Table 9 (continued)

X coordinate	Y coordinate	Material	Valuation in USD	Year of construction
684,290.7	5,953,252	RC	\$532	2003
684,290.7	5,953,252	RC	\$1085	2003
684,290.7	5,953,252	RC	\$426	2003
684,290.7	5,953,252	RC	\$868	2003
684,290.7	5,953,252	RC	\$169	2003
684,290.7	5,953,252	RC	\$434	2003
684,290.7	5,953,252	RC	\$213	2003
684,290.7	5,953,252	RC	\$434	2003
684,290.7	5,953,252	RC	\$426	2003
684,290.7	5,953,252	RC	\$868	2003
684,290.7	5,953,252	RC	\$746	2003
684,290.7	5,953,252	RC	\$1520	2003
684,290.7	5,953,252	RC	\$532	2003
684,290.7	5,953,252	RC	\$1085	2003
684,290.7	5,953,252	RC	\$319	2003
684,290.7	5,953,252	RC	\$651	2003
684,290.7	5,953,252	RC	\$319	2003
684,290.7	5,953,252	RC	\$651	2003
684,290.7	5,953,252	RC	\$426	2003
684,290.7	5,953,252	RC	\$868	2003
684,290.7	5,953,252	RC	\$213	2003
684,290.7	5,953,252	RC	\$434	2003
684,448.6	5,953,199	Wood	\$8646	2005
684,760.5	5,953,144	Masonry	\$25,844	2005
684,584.3	5,953,154	Masonry	\$29,258	2005
684,661.5	5,953,339	Wood	\$11,752	2006
685,127.1	5,953,301	Masonry	\$6247	2007

Table 9 (continued)

X coordinate	Y coordinate	Material	Valuation in USD	Year of construction
685,130.9	5,953,298	Masonry	\$6072	2007
685,138.2	5,953,291	Masonry	\$6072	2007
685,142.2	5,953,289	Masonry	\$6072	2007
685,149.2	5,953,285	Masonry	\$6072	2007
685,151.8	5,953,283	Masonry	\$6072	2007
685,159.4	5,953,280	Masonry	\$6072	2007
685,164.2	5,953,278	Masonry	\$6051	2007
685,177.6	5,953,270	Masonry	\$6065	2007
685,180.6	5,953,269	Masonry	\$6065	2007
685,188	5,953,265	Masonry	\$6065	2007
685,191.8	5,953,262	Masonry	\$6065	2007
685,199	5,953,258	Masonry	\$6065	2007
685,202.9	5,953,256	Masonry	\$6065	2007
685,209.4	5,953,252	Masonry	\$6065	2007
685,213	5,953,250	Masonry	\$6065	2007
685,220.3	5,953,246	Masonry	\$6065	2007
685,223.5	5,953,245	Masonry	\$6065	2007
685,231.5	5,953,240	Masonry	\$6065	2007
685,234.8	5,953,239	Masonry	\$6065	2007
685,242	5,953,235	Masonry	\$6065	2007
685,245.2	5,953,233	Masonry	\$6065	2007
685,251	5,953,229	Masonry	\$6065	2007
685,256.3	5,953,226	Masonry	\$6320	2007
685,263.6	5,953,223	Masonry	\$7002	2007
684,567	5,953,104	Masonry	\$6106	2007
684,594.8	5,953,091	Masonry	\$6099	2007
684,743	5,953,235	Masonry	\$6072	2007

Table 9 (continued)

X coordinate	Y coordinate	Material	Valuation in USD	Year of construction
684,802.8	5,953,332	Masonry	\$6072	2007
684,763.2	5,953,289	Masonry	\$6092	2007
684,834.9	5,953,332	Masonry	\$6085	2007
684,793.7	5,953,320	Masonry	\$6072	2007
684,827.1	5,953,322	Masonry	\$6072	2007
684,834.9	5,953,370	Masonry	\$6072	2007
684,845.3	5,953,379	Masonry	\$6058	2007
684,951.9	5,953,471	Masonry	\$6072	2007
684,996.3	5,953,520	Masonry	\$6051	2007
684,383.4	5,953,271	Masonry	\$6072	2007
684,421	5,953,175	Masonry	\$6051	2007
684,450.6	5,953,300	Masonry	\$6072	2007
684,508.6	5,953,283	Masonry	\$6058	2007
684,755.3	5,953,151	Masonry	\$6058	2007
684,528.4	5,953,178	Masonry	\$6092	2007
684,749.5	5,953,153	Masonry	\$6092	2007
684,918.1	5,953,222	Masonry	\$6092	2007
684,928	5,953,218	Masonry	\$6187	2007
684,705.1	5,953,182	Masonry	\$6187	2007
684,858.9	5,953,261	Masonry	\$6181	2007
684,757.1	5,953,318	Masonry	\$6174	2007
684,993.6	5,953,183	Masonry	\$6160	2007
684,836.9	5,953,298	Masonry	\$6079	2007
684,583	5,953,294	Masonry	\$6079	2007
684,525.5	5,953,326	Masonry	\$6079	2007
684,534.2	5,953,321	Masonry	\$6085	2007
684,567.1	5,953,303	Masonry	\$6079	2007

Table 9 (continued)

X coordinate	Y coordinate	Material	Valuation in USD	Year of construction
684,658.2	5,953,253	Masonry	\$6085	2007
684,881.8	5,953,127	Masonry	\$6208	2007
684,892.7	5,953,122	Masonry	\$6085	2007
684,895.6	5,953,120	Masonry	\$6330	2007
684,905.7	5,953,115	Masonry	\$6085	2007
684,915.8	5,953,110	Masonry	\$6085	2007
684,919	5,953,108	Masonry	\$6085	2007
684,974.8	5,953,076	Masonry	\$6085	2007
684,992.5	5,953,066	Masonry	\$6085	2007
685,002.4	5,953,059	Masonry	\$6085	2007
684,769.8	5,953,401	Masonry	\$6339	2007
685,012.8	5,953,457	Masonry	\$6072	2007
684,814.7	5,953,164	Masonry	\$6072	2007
684,819.7	5,953,171	Masonry	\$6072	2007
684,823.6	5,953,176	Masonry	\$6072	2007
684,826	5,953,181	Masonry	\$6072	2007
684,828.6	5,953,186	Masonry	\$6072	2007
684,833.5	5,953,192	Masonry	\$6072	2007
684,836.7	5,953,196	Masonry	\$6072	2007
684,841.6	5,953,203	Masonry	\$6072	2007
684,843.5	5,953,208	Masonry	\$6072	2007
685,026.9	5,953,472	Masonry	\$6072	2007
684,847.7	5,953,216	Masonry	\$6072	2007
684,998.1	5,953,438	Masonry	\$6079	2007
684,955.8	5,953,346	Masonry	\$6072	2007
684,971.6	5,953,365	Masonry	\$6058	2007
684,909.3	5,953,288	Masonry	\$6051	2007

Table 9 (continued)

X coordinate	Y coordinate	Material	Valuation in USD	Year of construction
684,817.7	5,953,211	Masonry	\$6058	2007
684,970.7	5,953,400	Masonry	\$6051	2007
685,043.5	5,953,325	Masonry	\$6079	2007
685,016	5,953,340	Masonry	\$6072	2007
685,029.9	5,953,334	Masonry	\$6092	2007
685,036.4	5,953,331	Masonry	\$6072	2007
685,001.4	5,953,348	Masonry	\$6072	2007
685,007.8	5,953,346	Masonry	\$6051	2007
684,878.5	5,952,909	Masonry	\$24,248	2008
684,454.1	5,953,196	Wood	\$12,772	2008
683,933.9	5,953,214	Wood	\$21,068	2008
685,333.4	5,953,652	Steel	\$3633	2009
685,340.7	5,953,649	Steel	\$3680	2009
685,345.8	5,953,645	Steel	\$3673	2009
685,362.1	5,953,598	Steel	\$3680	2009
685,346.2	5,953,594	Steel	\$3775	2009
685,361.5	5,953,594	Steel	\$3796	2009
685,349.7	5,953,603	Steel	\$3768	2009
685,363.4	5,953,605	Steel	\$3830	2009
685,366.1	5,953,611	Steel	\$3864	2009
685,371.1	5,953,618	Steel	\$3918	2009
685,170.7	5,953,337	Wood	\$13,079	2009
685,242.7	5,953,258	Wood	\$914	2009
685,166.5	5,953,317	Steel	\$3694	2009
685,166.8	5,953,302	Steel	\$3694	2009
685,171	5,953,314	Steel	\$3694	2009
685,180.2	5,953,278	Steel	\$3694	2009

Table 9 (continued)

X coordinate	Y coordinate	Material	Valuation in USD	Year of construction
685,178.1	5,953,307	Steel	\$3694	2009
685,193.1	5,953,303	Steel	\$3694	2009
685,182	5,953,313	Steel	\$3694	2009
685,197.8	5,953,308	Steel	\$3694	2009
685,187.1	5,953,319	Steel	\$3694	2009
685,200.2	5,953,312	Steel	\$3694	2009
685,188.2	5,953,325	Steel	\$3694	2009
685,169.2	5,953,285	Steel	\$3694	2009
685,185.4	5,953,288	Steel	\$3694	2009
685,170.2	5,953,289	Steel	\$3694	2009
685,191.7	5,953,299	Steel	\$3694	2009
684,124.7	5,953,322	Steel	\$3694	2009
684,623.2	5,953,390	Steel	\$3694	2009
684,605.6	5,953,384	Steel	\$3612	2009
684,715.6	5,953,423	Steel	\$3796	2009
684,612	5,953,387	Steel	\$3612	2009
684,734.3	5,953,433	Steel	\$3721	2009
684,805.8	5,953,466	Steel	\$3612	2009
684,927.1	5,953,479	Steel	\$3721	2009
684,956.3	5,953,517	Steel	\$3721	2009
684,961.6	5,953,525	Steel	\$3721	2009
685,029.6	5,953,565	Steel	\$3748	2009
684,799	5,953,329	Steel	\$3796	2009
685,189.5	5,953,670	Steel	\$3694	2009
684,552.5	5,952,958	Steel	\$3694	2009
684,567.7	5,953,061	Steel	\$3680	2009
684,664.7	5,953,148	Steel	\$3694	2009

Table 9 (continued)

X coordinate	Y coordinate	Material	Valuation in USD	Year of construction
684,924.3	5,953,478	Steel	\$3694	2009
684,587.7	5,953,081	Steel	\$3694	2009
684,729.7	5,953,222	Steel	\$3694	2009
684,740.1	5,953,215	Steel	\$3694	2009
684,735.2	5,953,227	Steel	\$3694	2009
684,716.8	5,953,245	Steel	\$3596	2009
684,769.1	5,953,245	Steel	\$3694	2009
684,749.6	5,953,240	Steel	\$3782	2009
684,845.9	5,953,342	Steel	\$3843	2009
684,854.5	5,953,352	Steel	\$3870	2009
684,851.2	5,953,347	Steel	\$3694	2009
684,822.1	5,953,358	Steel	\$3694	2009
684,536.5	5,953,050	Steel	\$3925	2009
685,004	5,953,528	Steel	\$3694	2009
684,793.7	5,953,320	Steel	\$3694	2009
684,555.1	5,952,977	Steel	\$3694	2009
684,558.2	5,953,028	Steel	\$6770	2009

Coordinates are in UTM

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