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Seismic and Coastal Vulnerability Assessment Model for Buildings in Chile

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Abstract: This article proposes a vulnerability assessment model for evaluating buildings' expected seismic performance, as well as their vulnerability to tsunamis. The objective of this assessment is to provide appropriate information for decision makers regarding the need of repairs and reinforcement of buildings or other mitigation measures that need to be applied in a territory. A procedure for assessing seismic vulnerability and another methodology for evaluating tsunami vulnerability faced by coastal structures is presented. Finally, a method that integrates both procedures is proposed, providing a combined index of vulnerability. The assessment model was applied to the central area of the city of Talcahuano, Chile, which was affected by the 2010 Maule earthquake and tsunami.

Keywords: seismic vulnerability; coastal vulnerability; structural assessment

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1. Introduction

Chile is one of the most seismically active countries in the world, where powerful earthquakes have occurred, frequently followed by destructive tsunamis, such as the events of Valparaiso 1730 (Mw ~9), Valdivia 1960 (Mw 9.5) and Maule 2010 (Mw 8.8) [1–3]. These events demonstrate the need to implement methods for determining buildings' susceptibility to damage and estimate how much communities will be affected by future events. While the territory's existing hazards cannot be changed, improving the community's response capacity will reduce their vulnerability and therefore reduce risk.

Structural vulnerability is defined as the susceptibility to damage that structures have in their foundation, columns, walls, beams and slabs [4]. Structural vulnerability began to be a topic of interest at the beginning of the 20th century, as a result of the need for measuring the impacts generated by large earthquakes that took thousands of lives and caused extensive material damage (San Francisco, 1906 and Japan, 1923). This situation motivated the scientific community to evaluate the effects of earthquakes on houses and buildings and propose measures that would minimize these effects in the future. In Latin America there are several recent studies that were conducted to assess damage after severe earthquakes in Chile [5,6] and México [7].

Astroza et al. [5] assessed the seismic vulnerability of a group of low-cost confined and reinforced masonry buildings using vulnerability indexes previously used in Italy (GNDT). This study concluded that the buildings would suffer different levels of damage for a seismic event similar to the Mw 7.8 1985 Chile earthquake. Buildings structurally modified by homeowners without proper professional advice were the most vulnerable to damage.

Later, Astroza and Roman [6] analyzed the seismic vulnerability of concrete block masonry houses using a vulnerability index that considers geometric characteristics (floor area, wall area in each direction, interstorey height), without considering irregularities. The information on damage observed in houses located in areas with seismic intensity between VII and VIII degrees on the MSK-64 scale was used. As a result of this study, a relationship was established between the proposed vulnerability index and the degree of observed damage.

More recently, Díaz-Fuentes et al. [7] introduced a preliminary damage assessment of 60 Mexican churches after the two earthquakes that occurred in September 2017 (Mw 8.2 and Mw 7.1). The data was collected through a systematic survey campaign and application of a damage assessment form based on the Italian experience, considering recurring damage mechanisms for different church typologies. The work concluded with a statistical analysis of the seismic damage carried out with the damage probability matrixes and fragility curves. This procedure assessed seismic damage on a scale from 0 (no damage) to 5 (collapse).

Coastal vulnerability focuses on a territorial perspective. It aims to determine a coastal area's susceptibility to be damaged by its interaction with the sea or another water body.

El-Hattab [8] analyzed 300 km of the northern Mediterranean coast of the Nile Delta, using LANDSAT images. This study considered variables, such as, geology, geomorphology, height above sea level, terrain slope, erosion/accretion patterns on the coast, average increase of sea level and coastal protection. Using this index, the researcher classified vulnerability into four levels (low, moderate, high and very high), identifying critical points, mainly along the Nile Delta coast, areas to the southeast of Abu Qir and areas to the southwest of the city of Alexandria. Based on the obtained results, the researcher proposed modifying the critical action plan for the Egyptian Mediterranean coastal area.

Serafim et al. [9] evaluated coastal vulnerability in Santa Catarina (southern Brazil), using a coastal vulnerability index (CVI) that considered physical, socioeconomic and location variables. Additionally, they categorized the relevance of the variables used in the CVI by using an analytic hierarchy process. This study determined that there is a higher degree of vulnerability in the southern area of the state, because of a low per capita income and a lower number of second homes than in the northern area. At the same time, it was determined that the northern area has higher percentages of development, predominately located along segments of land that are susceptible and vulnerable. The results emphasize the importance of including the physical variables to define coastal management measures and presents substantial progress for future CVI, integrating socioeconomic data and physical data in a Geographic Information System.

More recently, Hoque et al. [10] studied coastal vulnerability in the Eastern region of Bangladesh, which is often threatened by tropical cyclones, flooding, coastal erosion and saltwater intrusion. A multirisk event CVI was developed, which considered eight, mainly physical, parameters. The results were classified as very high, high, moderate, low and very low vulnerability. Findings indicate that 121 km (32%) of the studied coastal area was in zones with high to very high vulnerability. The moderately vulnerable area covered approximately 119 km (32%) of the coast, while 137 km (37%) of the coast could be classified with a low or very low vulnerability.

Experiences in coastal and seismic vulnerability assessment in Chile are scarce and have been mainly reported in local journals.

Contreras et al. [11] assessed 227 buildings located in the tsunami flooding area in the city of Valparaíso, Chile. This study used the Papathoma Tsunami Vulnerability Assessment (PTVA) method [12,13] and determined that most of the buildings could be classified in the low vulnerability range. However, in this assessment, seismic and coastal vulnerability were analyzed separately, without determining the joint effect of an earthquake and a tsunami.

Igualt [14] evaluated post-tsunami physical vulnerability in Concón, Chile. The study analyzed and assessed the physical vulnerability of urban infrastructure, located at the mouth of the Aconcagua River. The study used the PTVA methodology [12,13] for the assessment. The results demonstrated a high degree of physical vulnerability in buildings associated with tourism and gastronomy, the presence of residential infrastructure in exposed areas and an increase of services in the sector affected by the 2015 tsunami. This revealed the need to evaluate buildings located in coastal areas in order to propose adaptability strategies.

Aránguiz et al. [15] developed a tsunami fragility curve based on physical conditions of terrain and structures for the city of Coquimbo using field survey data and tsunami numerical simulations. These fragility curves were used to estimate the damage by possible future tsunamis in the area. The damage assessment showed that ~50% of the structures in the lower area of Coquimbo have a high probability of damage in case of a tsunami generated off the coast of the study area if the city is rebuilt with the same type of structures.

Izquierdo et al. [16] implemented the PTVA [12,13] model to evaluate the effect of tsunami in the cities of La Serena and Coquimbo (Chile). When compared to the actual damage observed during the 2015 tsunami, the model showed similar distribution to the actual damages. These results suggested this model can be used in Chilean coastal cities in future land-use or mitigation planning.

Castillo et al. [17] carried out tsunami vulnerability assessment in central Chile, where socioeconomic, educational and physical vulnerability to a tsunami were evaluated in the city of Tirúa, Chile. In the study, a methodology was designed to assess vulnerability. The results showed that 41.6% of the population in this city is exposed to tsunami effects; of the exposed population, 75% has high socioeconomic vulnerability; 57% has a high educational vulnerability and finally, 96% of the exposed population presents a high physical vulnerability. They propose that the vulnerability variable be integrated into urban post disaster planning tools.

Rojas et al. [18] studied the zone affected by the 2010 tsunami in Chile, analyzing socioenvironmental effects, which tend to be dominant in poor communities. The study also considered socioeconomic vulnerability, as well as the perception of safety and environmental problems in rural areas that are highly vulnerable and depend on the extraction of marine resources. The results illustrated a decrease in household income, which mainly affected women; an increase in the population's insecurity; a slow reconstruction process; and a generalized decrease in the population's level and quality of life.

The previously presented studies show that the vulnerability assessment of structures located in a given territory does not solely depend on the buildings' physical variables and their surroundings. The structures' vulnerability is also influenced by their occupants' social, demographic and economic characteristics, as they could affect the communities' recovery capacity after a disaster. For this reason, several researchers [9,17–20] recommend incorporating some of these nonphysical variables in new proposals for a territorial vulnerability assessment model.

The objective of the study presented here is to formulate a model for assessing the joint vulnerability of buildings in areas that are susceptible to both earthquake and tsunami hazards. The aim of this tool is to objectively assess the expected minimum structural performance of existing buildings under seismic actions, as well as their susceptibility to tsunami damage. For this purpose, the study presents a tool for evaluating seismic vulnerability based on building age, location, soil class and easily observable characteristics combined with another tool that quantifies coastal vulnerability in terms of physical, structural and sociodemographic variables. This new model is based on a seismic vulnerability questionnaire implemented in New Zealand [21] and the coastal vulnerability index proposed by Gornitz [17,18].

The novelty of our model is, on one hand, related to the simplifications implemented for the original seismic assessment model in a way that it does not necessarily need to be performed by an expert and does not require extensive fieldwork. On the other hand, our model improves Gornitz's coastal vulnerability model by incorporating weighting factors that acknowledge the different relative importance of the vulnerability variables. In addition, the combination of both seismic and costal vulnerability in one single index is more realistic, as the extended experience in Chile demonstrates that tsunamis are usually preceded by destructive earthquakes. Each component of this assessment tool provides valuable and complementary information for decision makers regarding repairs and reinforcement of buildings or other mitigation measures need to be applied in a territory.

This paper uses the center of Talcahuano, Chile (Figure 1) as its study area. This area was severely affected by the 2010 Maule earthquake and tsunami [3]. Most of the city's commercial and public buildings are concentrated in this area, including the municipality as well as police and fire stations.

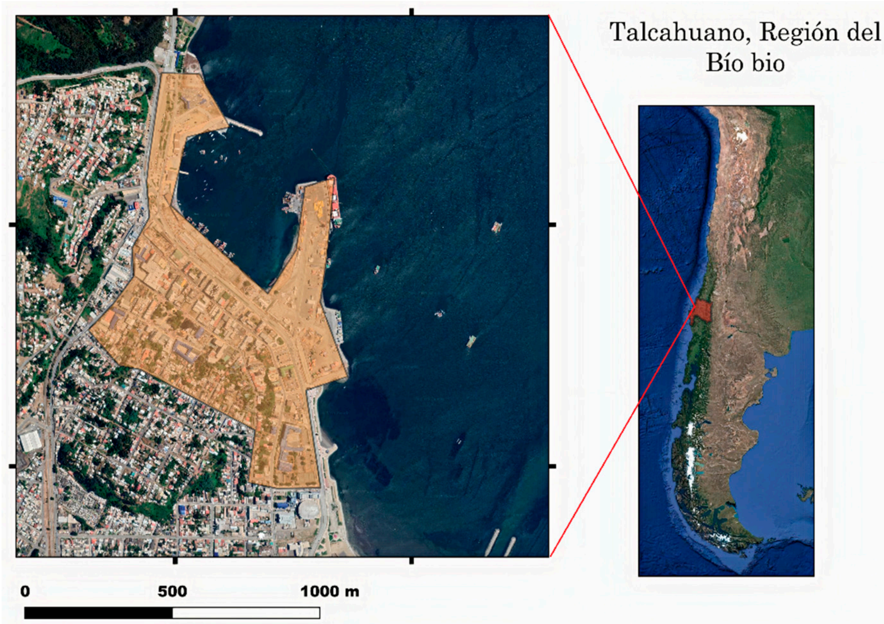

Figure 1. Study area: Talcahuano central area, Chile.

2. Materials and Methods

2.1. Seismic Vulnerability Assessment

The methodology used in this study is based on guidelines established by the government and professional associations of New Zealand for seismic assessment of existing buildings [21], which were adapted to Chilean practice and regulations.

In general terms, this methodology calculates the percentage of resistance that an existing building is capable of withstanding, compared with the resistance that a new building should have according to current regulations (%NBS). For this study, the buildings' resistance has been preliminary assessed based on the minimum resistance that they should meet according to the seismic design building standards that were valid in Chile the year they were constructed. Therefore, the assessment methodology requires identifying: (i) the building's age in order to determine which regulation or standard should have governed its original design, (ii) the building's location in order to determine its seismic risk and (iii) the soil class for evaluating local effects. Additionally, based on the building's location and age, an accumulated deterioration index was established, related to the number of seismic events the building has withstood. It is important to note that in the case of structures' that have undergone retrofitting or repair interventions on over 60% of their area, the date of said interventions is considered as the construction date, as it is assumed that these interventions were done according to the codes existing at that time and are sufficiently extensive to consider the building as a new structure.

Building observation and additional gathered information allow for identifying the structural typologies that could affect the building's seismic performance, such as floor and vertical irregularities, pounding between adjacent buildings and soft story effects. Moreover, the interventions that could positively affect the structure's performance, such as reinforcements and repairs, were also considered.

The %NBS evaluates a building's minimum resistance in comparison to a similar, new building in terms of life protection. The %NBS does not directly measure the building's actual strength or potential seismic performance nor its ability to function after an earthquake. Nonetheless, a building with a NBS over 67% is considered to have an acceptable seismic risk, and rehabilitation will not be required. A building with a NBS rating less than 67% is considered to be at risk for earthquake damage and requires additional studies to evaluate whether rehabilitation is necessary. A building with a NBS rating less than 34% is classified as prone to suffer damage from an earthquake and requires mitigation actions or demolition [21].

2.1.1. Calculating the New Building Standard Capacity (%NBS)

The previously described %NBS is obtained by Equation (1), which considers the building's nominal New Building Standard capacity ($\%NBS_{nom}$), which is applied to a Structural Performance Index (SPI).

$$\%NBS = \%NBS_{nom} \times SPI \tag{1}$$

The $\%NBS_{nom}$ and SPI are calculated according to Equations (2) and (3):

$$\%NBS_{nom} = A \times B \tag{2}$$

$$SPI = C \times D \times E \times F \times G \tag{3}$$

where A to G are factors to be calculated as follows.

- Factor A

Factor A represents the ratio between the spectral acceleration determined by the seismic code valid on the date the structure was built ($Sa_{NCh\_original}$) and the spectral acceleration mandated by the current seismic code ($Sa_{NCh\_current}$), as indicated in Equation (4).

$$\text{Factor A} = \frac{Sa_{NCh\_original}}{Sa_{NCh\_current}} \tag{4}$$

Chilean seismic code NCh433 Of.72 [22] defined spectral acceleration by the following equations:

$$Sa_{NCh1972} = 0.1 \times K_1 \times K_2, \text{ for } T < T_0 \tag{5}$$

$$Sa_{NCh1972} = 0.1 \times K_1 \times K_2 \times \frac{2 \times T \times T_0}{T^2 \times T_0^2}, \text{ for } T > T_0 \tag{6}$$

where, K_1 is a coefficient related to the building's use, K_2 is a coefficient related to the structural form, T is the structure's natural period and T_0 period according to soil class.

Then, in the following versions of the Chilean seismic code (NCh433 Of.93 [23] and NCh433 Of.96 [24]), this acceleration was calculated by:

$$Sa_{NCh1993/1996} = \frac{I \times A_0 \times \alpha}{R^*} \tag{7}$$

where, I represents the importance coefficient, A_0 depends on the seismic area, α is the spectral shape factor that at the same time directly depends on the structure's natural period and the soil's period and R^* is the structural response's reduction factor.

Finally, the current Chilean seismic code (NCh433 Of.96 Mod.2012 [25]), introduces a new factor (S) associated with soil class, as illustrated in Equation (8).

$$Sa_{NCh2012} = \frac{S \times I \times A_0 \times \alpha}{R^*} \tag{8}$$

The different values that factor could adopt for the different seismic codes, different soil classes and different period ranges were calculated based on these equations, obtaining a final group of conservative recommended factors for buildings according to their year of construction, as indicated in Table 1.

Table 1. Factor A according to building's ground type and year of construction.

Soil Class	Factor A				
	Pre 1972	1972–1992	1993–1995	1996–2012	Post 2012
A	0.7	1.0	0.9	1.0	1.0
B	0.7	1.0	0.8	1.0	1.0
C	0.7	1.0	0.8	0.9	1.0
D	0.7	1.0	0.7	0.8	1.0
E	0.7	1.0	0.7	0.8	1.0

Table 1 shows that the buildings constructed before 1972 did not have a code regulating their seismic design; therefore, there is no spectral acceleration that allows for evaluating Factor A. Considering this, a conservative Factor A of 0.7 was assigned to any construction prior to 1972. Meanwhile, for buildings constructed between 1972 and 1993, the Factor A has a value of 1, as the NCh433 Of72 [22], which was in force until 1993, overestimated the spectral accelerations, reaching values over what was provided by the NCh433 Of96 Mod.2012 [25], obtaining spectral ratios greater than 1. Therefore, a conservative value of 1 was assigned to the Factor A.

- Factor B

Factor B represents the deterioration that a building may potentially have accumulated because of the different earthquakes it has had to withstand throughout history. Basically, it indicates how functional a building is expected to be after being affected by a certain number of seismic events, as indicated in Table 2. This functionality has been defined based on the methodology proposed by Hwang and Lin [26].

Table 2. Damage type and deterioration factors.

Damage Type	Description of the Damage	Deterioration Factor
Total destruction	Implies that the structure suffered a total collapse of beams and columns	0.10
Irrecoverable damage	Implies that the building is at risk of collapsing.	0.25
Severe damage	The safety of the building's residents is at risk.	0.50
Partial damage	Nonstructural damage to the building (more than slight), recoverable, does not hinder its habitability.	
Recoverable damage	Nonstructural damage to doors, windows, glass, nonstructural walls, ceilings; minor damage to plumbing installations, etc. (caused by the catastrophe).	0.75
No damage	There is no damage that affects functionality.	1.00

The effect of earthquakes in Chile over that last 100 years that were greater than Mw 5.0 in magnitude was evaluated to determine the deterioration factor. This information was obtained from the seismic catalogues from the United States Geological Survey (USGS) [27], the National Seismological Center (CSN for its name in Spanish) [28] and the Global Centroid-Moment-Tensor (GCMT) [29]. From an initial database of over 3000 earthquakes, the 12 most destructive were identified, and their effects on different structural typologies (adobe, timber, masonry and reinforced concrete) were assessed based on available historical and press information [30–38].

All the previous information was used to determine Factor B, which represents the accumulated deterioration according to the building's age and material (Tables 3–6). This factor assigns a value of 1 to those buildings that have never experienced an earthquake and it progressively decreases as seismic events are accumulated, until reaching a value of

0.1, which represents near total damage (a value of 0 was not used to avoid a null value of NBS_{nom}).

Table 3. Factor B for adobe buildings.

Year	Number Earthquakes				
	0	1	2	3	4
pre 1972	1.00	0.10	0.10	0.10	0.10
1972–1992	1.00	0.25	0.10	0.10	0.10
1993–1995	1.00	0.25	0.10	0.10	0.10
1996–2012	1.00	0.25	0.25	0.10	0.10
post 2012	1.00	0.25	0.25	0.25	0.10

Table 4. Factor B for timber buildings.

Year	Number Earthquakes				
	0	1	2	3	4
pre 1972	1.00	0.25	0.10	0.10	0.10
1972–1992	1.00	0.25	0.10	0.10	0.10
1993–1995	1.00	0.50	0.25	0.10	0.10
1996–2012	1.00	0.50	0.50	0.25	0.10
post 2012	1.00	0.50	0.50	0.25	0.25

Table 5. Factor B for masonry buildings.

Year	Number Earthquakes				
	0	1	2	3	4
pre 1972	1.00	0.25	0.10	0.10	0.10
1972–1992	1.00	0.25	0.10	0.10	0.10
1993–1995	1.00	0.50	0.25	0.10	0.10
1996–2012	1.00	0.50	0.50	0.25	0.10
post 2012	1.00	0.50	0.50	0.25	0.25

Table 6. Factor B for reinforced concrete buildings.

Year	Number Earthquakes				
	0	1	2	3	4
pre 1972	1.00	0.25	0.10	0.10	0.10
1972–1992	1.00	0.50	0.10	0.10	0.10
1993–1995	1.00	0.50	0.25	0.10	0.10
1996–2012	1.00	0.75	0.50	0.25	0.10
post 2012	1.00	0.75	0.50	0.25	0.25

- Structural Performance Indicator (SPI) Factors

Previous studies have identified structural forms that persistently present problems during seismic events. Recently, these pathologies have been typified using rubrics proposed by New Zealand's professional and scientific associations [21], which allow for classifying their severity. The main pathologies are illustrated in Figure 2. The effect of these pathologies is represented in SPI by Factors C to G. A description of Factor C to F and their severity is quantified in Table 7. Factor G represents the interventions a structure may have undergone that has improved its original structural performance. This factor could increase the original resistance by up to 20%, but for the moment this parameter depends on the existence of design records and/or technical studies that support an expert evaluation.

Table 7. Guide to the severity of critical structural weaknesses. (Adapted from [21]).

Factor	Structural Characteristics	Effect on Structural Performance		
		Severe Factor = 0.4	**Significant Factor = 0.7**	**Insignificant Factor = 1.0**
Factor C	L-shape, T-shape, E-shape	Two or more wings >3.0 in length/width, or one wing >4 in length/width >4	One wing length/width >3.0	All wings length/width ≤3.0
	Long narrow building where spacing of lateral load resisting elements is:	>4 times building width	>2 times building width	≤2.0 times building width
	Torsion (corner building)	Mass to center of rigidity offset >0.5 width	Mass to center of rigidity offset >0.3 width	Mass to center of rigidity offset ≤0.3 width, or effective torsional resistance available from elements orientated perpendicularly
	Ramps, stairs, walls, stiff partitions	Clearly grouped, clearly an influence	Apparent collective influence	No or slight influence
Factor D	Soft story	Lateral stiffness of any story <0.7 of lateral stiffness of any adjoining stories	Lateral stiffness of any story <0.9 of lateral stiffness of the adjoining stories	Lateral stiffness of any story ≥0.9 of lateral stiffness of the adjoining stories
	Mass variation	Mass of any story <0.7 of mass of adjoining story	Mass of any story <0.9 of mass of adjoining story	Mass of any story ≥0.9 of mass of adjoining story
	Vertical discontinuity	Any element contributing >0.3 of the stiffness/strength of the lateral force resisting system discontinues vertically	Any element contributing >0.1 of the stiffness/strength of the lateral force resisting system discontinues vertically	Only elements contributing ≤0.1 of the stiffness/strength of the lateral force resisting systems discontinue vertically
Factor E	Columns <70% story height between floors clear of confining infill, beams or spandrels	Either >80% short columns in any one side, or >80% short columns in any story	>60% short columns in any one side, or >60% columns in any one story	No, or only isolated, short columns, or columns with width > 1.2 m, or Free column height/column width ≥2.5.
Factor F	F1: Pounding Vertical differences between floors >20% story height of building under consideration	0 < separation < 0.005 h	0.005 H < separation < 0.01 h	Separation > 0.01 h
	F2: Height difference Height difference in 2 to 4 stories	0 < separation < 0.005 H	0.005 H < separation < 0.01 H	Separation > 0.01 H
	Height difference in more than 4 stories	0 < separation < 0.005 H	0.005 H < separation < 0.01 H	Separation >0.01 H, or floors aligning and height difference <2 stories, or at least one building is lightweight construction

h = height to the level of the floor being considered; H = height of the lower building and separation is measured at H.

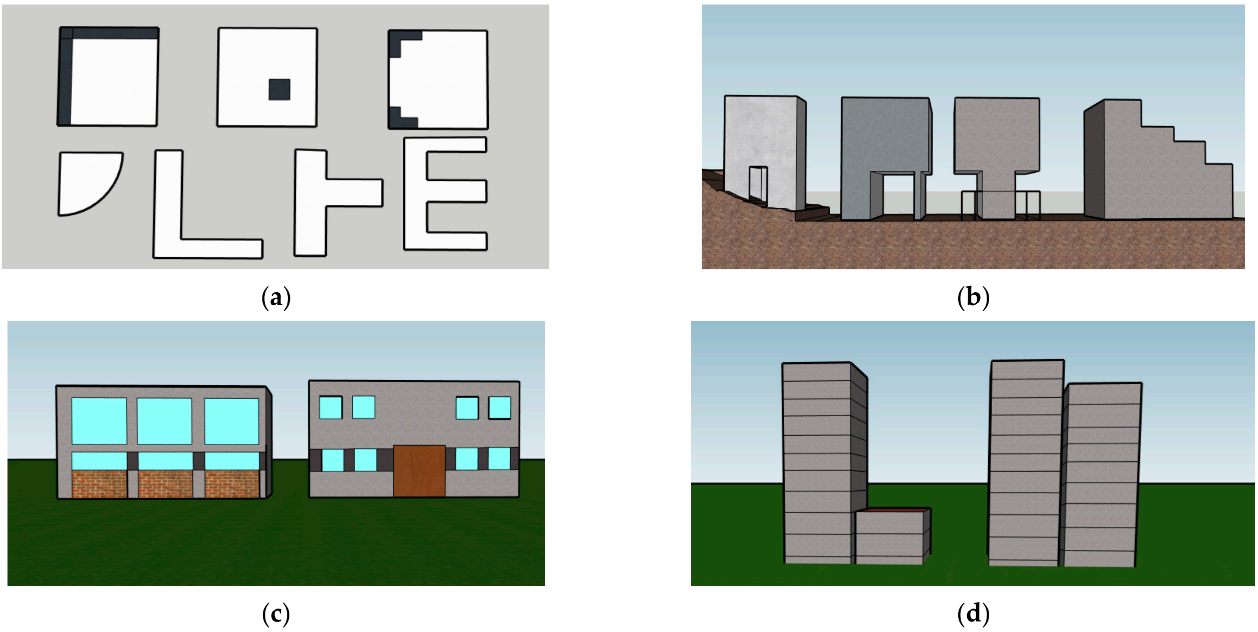

Figure 2. Recurrent pathologies in buildings. (**a**) Horizontal irregularities, (**b**)Vertical irregularities, (**c**) Short columns and (**d**) Risk of pounding between adjacent buildings.

2.1.2. Building Rating

A seismic vulnerability assessment (SVA) rating on a scale from 0 to 5 is assigned based on the %NBS calculation. The exact value of the SVA is obtained by the equation defined for each interval, according to Table 8.

Table 8. Seismic vulnerability assessment rating.

%NBS	SVA Rating	Level of Vulnerability
≥100	SVA = 1.00	Very low
80–99	SVA = 6.00 − 5.00·NBS	Low
34–79	SVA = 3.74 − 2.17·NBS	Medium
–33	SVA = 5.42 − 7.14·NBS	High
<20	SVA = 5.00 − 5.00·NBS	Very high

2.2. Coastal Vulnerability Assessment

Coastal vulnerability refers to a territory's susceptibility to suffering damage caused by its interaction with the sea, and more specifically because of tsunamis. Different authors have proposed indexes that quantify coastal vulnerability in a determined area. Gornitz et al. [19,20] proposed a series of coastal vulnerability indexes (CVI) that consider 6 physical variables according to Equation (9) through (12). These variables are: (a) geomorphology, (b) coastal slope, (c) sea level rise rate, (d) coastal erosion/accretion rate, (e) significant wave height and (f) tidal range. Gornitz's proposal suggests a 1 to 5 range be adopted by the formulations: very low (1), low (2), medium (3), high (4) and very high (5).

$$\mathrm{CVI1} = \frac{a \times b \times c \times d \times e \times f}{6} \tag{9}$$

$$\mathrm{CVI2} = \sqrt{\frac{a \times b \times c \times d \times e \times f}{6}} \tag{10}$$

$$\mathrm{CVI3} = \frac{a^2 + b^2 + c^2 + d^2 + e^2 + f^2}{6} \tag{11}$$

$$\mathrm{CVI4} = \frac{\mathrm{a} + \mathrm{b} + \mathrm{c} + \mathrm{d} + \mathrm{e} + \mathrm{f}}{6} \tag{12}$$

Our proposal considers 12 variables that represent the physical environment's influence, the characteristics of the structures in the area and sociodemographic aspects.

- Physical variables
  a. Geomorphology (PV_1): Coastal areas are already vulnerable to coastal dangers, but they will become more vulnerable in the future because of climate change and increasing sea levels [39,40]. The coastal geomorphological categories are classified based on key visual interpretation.
  b. Average wave height (PV_2): The waves' energy increases as wave height increases, which leads to loss of land area caused by erosion and flooding along the coast. Because of this, coastal areas with high wave heights are considered to be more vulnerable. Therefore, the study of vulnerability based on wave height is an important step in the creation of a tsunami alert and risk management system [41]. Average wave height can be easily obtained from the tide charts generated by the maritime authority [42].
  c. Tidal range (PV_3): Tidal range is the vertical difference between the highest and lowest tides and is related to permanent and intermittent flooding risk. Tidal range can easily be obtained from the tide charts generated by the maritime authority [42].
  d. Beach width (PV_4): Beach width is measured from the backshore's coordinates to the mean low water mark. Because of variations in tidal range, this parameter was approximately measured using the Google Earth Pro v7.3 [43] application. To obtain a more precise calculation of the width of the beach, maritime authority recommends carrying out a topographic survey of the sector [44].
  e. Coastal slope (PV_5): This variable considers the average slope of each sector, over the line of the shortest distance to the coastline. The lower the slope, the greater the risk for possible flooding caused by a tsunami. Slope is calculated by dividing the difference in elevation by the horizontal difference that exists between the coast and the location under study.
  f. Distance to water body (PV_6): This physical variable corresponds to the shortest existing distance between the closest water body (coastline, river or estuary) and the location under study (in the case of a large area, the centroid of that area is used). The closer the sector is to the coast, the more susceptible it is to damage.
  g. Coastal protection (PV_7): This variable refers to whether the structure is or is not covered by some type of natural (hill, trees or other) or artificial protection. The absence of protection makes the structure more vulnerable.
- Structural variables
  a. Number of stories (SV_1): In the case of tsunami and fluvial floods, this parameter is important for determining a building's vulnerability, as a higher number of stories allows for the vertical evacuation of people and possessions.
  b. Structure's state of conservation (SV_2): This variable indicates the state of conservation of buildings within the study area, quantifying its vulnerability. A visual assessment was carried out, considering three categories (good, regular and bad). Good means that all the structural elements (columns, beams and walls) are in perfect condition. Regular indicates that the structural elements have surface cracks or slight deformations. Finally, bad means that the structural elements are cracked, the reinforcement's covering is detached or there are considerable deformations.
  c. Structure's material (SV_3): This variable indicates how vulnerable a building is to tsunami and floods based on the materials used for its construction. Three main building typologies were identified in the area of study: reinforced con-

crete (RC), masonry (M) and timber (T) buildings, in addition to combinations of them (RC + T and M + T). There were also precarious buildings (PB), made of deficient construction materials, typical of impoverished areas in South America. Each one of these typologies was assigned a level of vulnerability, depending on the building material.

- Sociodemographic variables
    a. Socioeconomic level (SDV_1): Although we are evaluating buildings, it is relevant to also examine their inhabitants' socioeconomic level. While the buildings may be in good condition, the occupants' capacity for recovering the structures will also be associated with their economic capacity to rehabilitate the structures in case of damage. There are many economic activities that could be negatively affected by coastal flooding, among them sailing, industry, tourism, agriculture, fishing, availability of potable water, private companies located in affected areas, etc. According to McLaughlin and Cooper [45], the selection of socioeconomic variables adds an inherent cultural bias to an index, as it should incorporate factors associated to economic prosperity from the determined productive sector. According to this statement, a coastal vulnerability assessment will be affected by the socioeconomic environment that is directly related to residents' income. Buildings owned by those with a high socioeconomic status are less vulnerable, as their rehabilitation is easier if the economic resources are available to do so. This is independent of the building's material or state of conservation. In this study, El-Hattab's [8] proposal was used, in which socioeconomic level depends on inhabitants' highest level of education, and subsequently, their occupation.
    b. Population density (SDV_2): It is uncommon to use population as a variable in coastal vulnerability assessment. While authors like Hughes and Brundrit [46] do not include it, they do recognize that a more populated area has greater economic value, reaching the conclusion that other studies should concentrate on the population dynamic and the effects of an increase in urbanization. Gornitz [19,20] also omitted population but indicated that further studies should take the coastal populations into consideration in order to help assess vulnerable areas. Thus, the greater the population density the more susceptible the area of study will be. Information available by block from the 2017 Census [47] was used to obtain the number of inhabitants.

All the previously described variables are classified according to five levels of coastal vulnerability. Table 9 shows the categorization for each parameter studied according to [8,48–50]. The current standards in Chile define tsunami risk zones as coastal areas that are less than 30 m over the medium sea level [51]. Therefore, this methodology for coastal vulnerability assessment was only applied to these cases. Buildings located higher than this level were not included. In that cases, coastal vulnerability was simply considered as very low.

The coastal vulnerability indexes (CVI) used in this study are based on Equation (11) but incorporate variables' weighting factors. CVIs were calculated considering the score of each variable and each kind of variable separately: physical, structural and sociodemographic variables.

$$\mathrm{CVI_P} = \frac{1}{7}\sum_{i=1}^{7}(\mathrm{PV_i} \times \alpha_i)^2 \quad (13)$$

$$\mathrm{CVI_S} = \frac{1}{3}\sum_{i=1}^{3}(\mathrm{SV_i} \times \beta_i)^2 \quad (14)$$

$$\mathrm{CVI_{SD}} = \frac{1}{2}\sum_{i=1}^{2}(\mathrm{SDV_i} \times \gamma_i)^2 \quad (15)$$

Table 9. Chart of vulnerability classification.

	Variable (Vulnerability Score)	Very Low (1)	Low (2)	Medium (3)	High (4)	Very High (5)
PV_1	Geomorphology	High cliffs	Medium cliffs	Low cliffs, hills or mountains	Alluvial plains, coastal lagoons	Beach, dune fields
PV_2	Average wave height (m)	<0.55	0.55–0.85	0.85–1.05	1.05–1.25	>1.25
PV_3	Average tidal range (m)	>6	4.1–6	2–4	1–1.9	<1
PV_4	Beach width (m)	>50	50–25	25–10 m	<10	No beach
PV_5	Coastal slope (%)	>15	15–10	10–5	5–2	<2
PV_6	Distance to water body (m)	>557	557–417	416–196	195–66	<66
PV_7	Coastal protection	Natural	–	Constructed	–	No protection
SV_1	Number of stories	Three levels	–	Two levels	–	One level
SV_2	State of conservation	Good	–	Regular	–	Bad
SV_3	Material	RC	M	RC + T/M + T	T	PB
SDV_1	Socioeconomic status	Professional	Technical	Production	Artisan	Agriculture
SDV_2	Pop. density (inhab/km^2)	<9000	9000–20,000	20,000–40,000	40,000–80,000	>80,000

Then each kind of CVI was normalized on a scale from 1 to 5, as presented in Table 10, to obtain the Normalized Costal Vulnerability Indexes (NCVIs). Finally, the coastal vulnerability assessment (CVA) rating is calculated by Equation (16), considering a new set of weighting factors applied to the NCVIs.

$$CVA = w_P \times NCVI_P + w_S \times NCVI_S + w_{SD} \times NCVI_{SD} \quad (16)$$

Table 10. Normalized Costal Vulnerability Index (NCVI) according to parameter ranges.

Index	Very Low	Low	Medium	High	Very High
CVI_P	<0.28	0.28–0.64	0.64–1.19	1.19–1.92	1.92<
CVI_S	<1.44	1.44–2.78	2.78–5.26	5.26–7.93	7.93<
CVI_{SD}	<1.25	1.25–3.25	3.25–6.25	6.25–10.25	10.25<
NCVI	1	2	3	4	5

- Weighting factors calculation

As can be observed in Equation (13) through (16), different weights have been considered for each of the parameters (α_i, β_i, γ_i, w_P, w_S and w_{SD}). These weighting factors were introduced to acknowledge the different relative importance of the variables considered when assessing coastal vulnerability. To avoid an arbitrary weighting assignment, Analytical Hierarchical Process proposed by Saaty [52] was applied. This is a multicriteria decision-making method used for assigning relative weight to variables [53,54]. This weighting technique allows for classifying the variables in degrees of importance, which leads to a better representativity of the selected descriptors on the final index. By applying the Saaty method, a comparison is made of variable pairs through a quadratic reciprocal matrix. In the construction of pair comparison matrixes, each variable is evaluated against the other by assigning a relative dominion value of 1 (same importance), 3 (moderate), 5 (strong), 7 (very strong) and 9 (extremely important). According to Saaty [55], even though this method is based on subjective judgments that are not always consistent, a logical coherence is linked to human beings' ability to establish relationships between objects or ideas, so that they are consistent. In this sense, the method allows the calculation of the consistency ratio for the reciprocal matrices to verify the effectiveness of the measurements and judgments.

The weights were obtained by interviewing 14 experts, generating 47 quadratic reciprocal matrices for each interviewee. The combined weight was obtained through the arithmetic mean of the weights assumed by each of the experts. The interviewees included structural, hydraulic, coastal and industrial engineers, as well as professionals working in territorial management, risk management and construction. Even though the number of interviewees might seem small, this is an improvement to the classical Gornitz's proposal [19,20] that uses the same weighting for all variables (see Equations (9)–(12)). The results of this analysis are presented in Table 11.

Table 11. Weights for each variable.

Variable Type	Variable Weights							Variable Type Weights
Physical	α_1 0.30	α_2 0.20	α_3 0.22	α_4 0.09	α_5 0.11	α_6 0.03	α_7 0.04	w_P 0.46
Structural	β_1 0.33	β_2 0.40	β_3 0.27	– –	– –	– –	– –	w_S 0.29
Sociodemographic	γ_1 0.86	γ_2 0.14	– –	– –	– –	– –	– –	w_{SD} 0.25

2.3. Combined Vulnerability Assessment Model

The vulnerability assessment (VA) model considers the seismic vulnerability assessment (SVA) and the coastal vulnerability assessment (CVA). The results of both assessments allow for classifying structural vulnerability according to Equation (17), which considers a weight for each vulnerability (w_S and w_C), depending on the study areas distance to the coast.

$$VA = w_S \cdot SVA + w_C \cdot CVA, \tag{17}$$

Table 12 presents the weights according to the analyzed structure's distance to the coast. The maximum horizontal distance of the floodable area (D) was considered according to tsunami flooding maps of the zone, if available, or to the terrain line of 30 m over the medium sea level [51]. For the case of buildings located at a distance larger than D, the effect of tsunami is negligible, and therefore the vulnerability only depends on the seismic vulnerability. However, when the building is located closer to the coast, the importance of the costal vulnerability increases. The experience in Chile [56] has shown that at a distance between D and D/2, the water usually rises to 1 m high in the event of a tsunami. This water height and the water velocities affect the structure and increase the damage produced by earthquakes, especially in the building's lower levels. Meanwhile, at a distance closer than D/4 to the coast, where the water can reach 2 to 6 m high, the damage associated to tsunami is more critical than the effects of the preceding earthquake.

Table 12. Weights according to distance to the coast.

Distance to Coast (m)	Weights	
	w_S	w_C
>D	1.0	0
D–D/2	0.5	0.5
D/2–D/4	0.4	0.6
<D/4	0.3	0.7

The VA value obtained is finally used to classify the structure's vulnerability according to Table 13 using the same vulnerability scale between 0 and 5.

Table 13. Classification according to VA ranges.

Vulnerability Assessment	Very Low	Low	Medium	High	Very High
VA	≤1.0	1.1–2.0	2.1–3.0	3.1–4.0	≥4.1

3. Results

3.1. Case Study 1: Building Assessment

The Dante Theater (Figure 3) is a building located in central Talcahuano, Chile, within our study area. It was built in 1940, mainly from masonry and concrete. It functioned as the main entertainment center in the city until 1980, when it was closed and abandoned. The structure was in a regular state until the earthquake of 27 February 2010, which severely damaged it. In 2018, the Municipality of Talcahuano decided to rebuild the structure, maintaining the existing façade, transforming it into the city's new cultural center.

(**a**) (**b**) (**c**)

Figure 3. Dante Theater (**a**) Pre 2010; (**b**) Post 2010; (**c**) Post 2018.

Because of the great changes the structure has undergone, it was decided that assessments at three stages should be done using the methodology described in this study. The results for each condition are displayed in Table 14. The first assessment was done using only the information that existed before the 2010 earthquake. The information available to carry out this assessment included structural images that allowed for seeing the building's material and structuring, as well as records of the earthquakes the building had withstood up until that date. The second assessment focused on the post-earthquake building, based on the previously available information and adding records of the 2010 earthquake. Finally, the third assessment was done once the structure was repaired. For this study, we already had further information on its design as well as the applied standards, a description of the structural elements and the reparation and reinforcement strategy.

Table 14. Summary of the seismic vulnerability assessment (SVA) result.

Factor	A	B	C	D	E	F	G	%NBS	SVA
Pre-2010	0.7	0.25	0.70	1.00	1.00	1.00	1.00	12.3%	4.39
Post-2010	0.7	0.10	0.70	1.00	1.00	1.00	1.00	4.9%	4.76
Post-2018	1.00	1.00	0.70	1.00	1.00	1.00	1.00	70.0%	2.22

In Table 14, it can be observed that the Factor A is equal to 0.7 for the cases Pre-2010 and Post-2010, because it had been constructed before 1972, and no seismic code was enforced by that time. For the case Post-2018, the building was considered as a new structure, as extensive repairs following current seismic standards were done. These interventions involved a complete replacement of the internal resistant system, replacing most of confined masonry walls with reinforced concrete elements, and the construction of concrete slabs, following all the current mandatory seismic requirements in Chile. Only the façade and access hall of the building were preserved [57].

Pre- and Post-2010, Factor B does not equal one, which indicates that the building presents deterioration associated with the number of earthquakes it has had to withstand (1 earthquake Pre-2010 and 2 earthquakes Post-2010). Post-2018, the building was considered as a new structure and, therefore, it has not experienced any earthquakes.

Factor C is 0.7 in all cases, because the theater has an irregular floor design, which has not changed with the 2018 interventions. All the other factors are equal to 1.0.

Finally, it can be observed that in the period prior to 2010, the building obtained a %NBS of 12.3%, which corresponds to a very high level of vulnerability. This means that the theater was prone to suffering damage in case of an earthquake, as it was later observed during the 2010 earthquake [57]. In fact, the results of the Post-2010 assessment predicted a very high level of vulnerability, as its %NBS is only 4.9%. The results obtained in 2019, after all the repairs had been done, give a medium level of vulnerability (70% of %NBS), which is an acceptable level of seismic risk.

The coastal vulnerability assessment was also performed considering the three previous stages. Table 15 presents the scores assigned to each coastal vulnerability variable. It can be noted that the structure has the same classification in the physical and sociodemographic variables because the structure did not change its location and use. Meanwhile, the structural variables change, as Pre-2010, the structure had two floors, its state of conservation was regular (it had cracks and reinforcement spading in beams) and its dominant material was masonry. However, Post-2010, the structure presented severe damage, the interstory timber diaphragm collapsed (the structure is considered as a single-story building) and it had a poor state of conservation. Finally, Post-2018 implied the construction of a new interstory slab, achieving a good state of conservation, and the building was rebuilt using reinforced concrete as the predominant material.

Table 15. Summary of the coastal vulnerability assessment (CVA) result.

Variable	PV_1	PV_2	PV_3	PV_4	PV_5	PV_6	PV_7	SV_1	SV_2	SV_3	SDV_1	SDV_2	CVA
Pre-2010	5	3	5	3	4	3	3	3	2	2	3	1	3.17
Post-2010	5	3	5	3	4	3	3	5	5	2	3	1	3.75
Post-2018	5	3	5	3	4	3	3	3	1	1	3	1	2.88

Noting that the Dante Theater is located 247 m away from the coastline and the flooding distance in Talcahuano is D = 1000 m, the combined vulnerability assessment (VA) was performed considering a 30% and 70% contribution of the seismic (SVA) and coastal vulnerability (CVA), respectively, as presented in Table 16. It can be observed that the combination of seismic and coastal vulnerability demonstrates the building's high susceptibility to damage before the 2010 earthquake, which was subsequently increased by this event to a very high vulnerability condition. Considering that, structural interventions were critical or demolition would be imminent. The 2018 repairing interventions reduced the building's seismic and coastal vulnerability, moving it to an acceptable medium level of vulnerability.

Table 16. Summary of the VA result.

Variable	SVA	CVA	VA	Vulnerability Level
Pre-2010	4.39	3.17	3.53	High
Post-2010	4.76	3.75	4.05	Very High
Post-2018	2.22	2.88	2.68	Medium

3.2. Case Study 2: Territorial Assessment

Figure 4 displays the location of 18 buildings within the area of study selected for the territorial assessment. Six of these buildings correspond to educational buildings (EB), six are public buildings (PuB) and the other six are commercial (CB) or private (PrB) buildings.

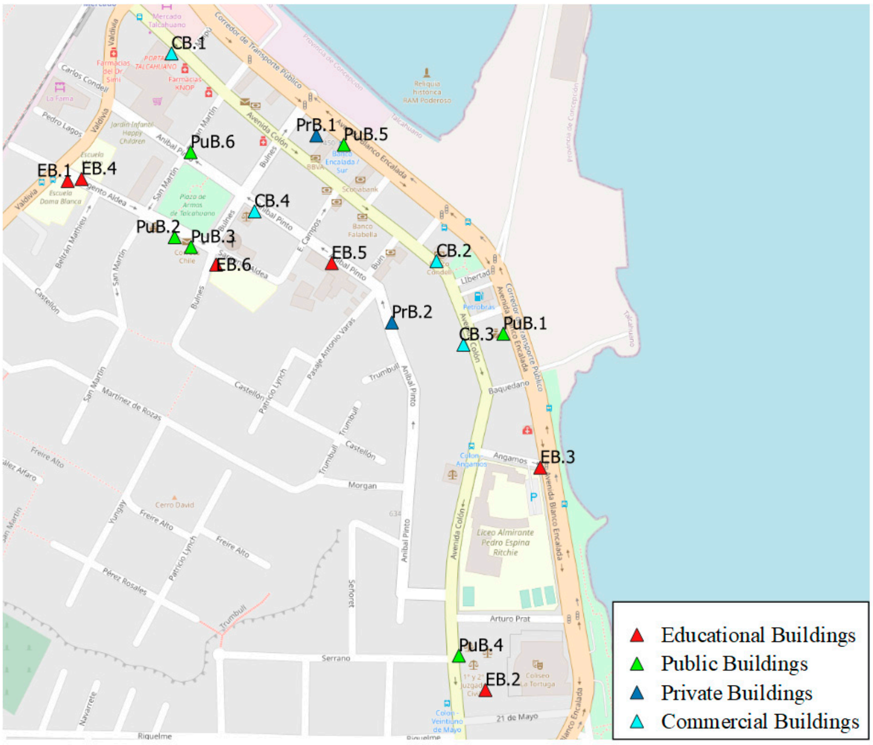

Figure 4. Buildings' location in the study area.

The results obtained from the seismic vulnerability assessment (SVA) are displayed in Figure 5. It is observed that only 22% of the buildings have a high level of vulnerability. This means that these buildings are prone to earthquake damage caused by earthquakes and further studies are needed to define possible repairing or retrofitting interventions. It should be noted that they are buildings built prior to 1972.

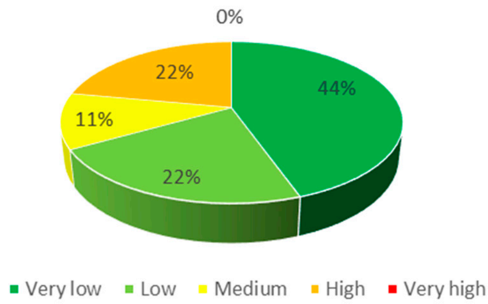

Figure 5. Results of the seismic vulnerability assessment.

The coastal vulnerability assessment classified all of the buildings at a medium level of vulnerability. This is because the physical parameters are predominant in the assessment and they are the same for all the buildings. Additionally, the analyzed building typologies are very similar (three-story reinforced concrete buildings). Hence, the structural parameters were also similar. Finally, the buildings' population density is also very similar, as these are educational, public or commercial buildings.

To complete the analysis of the combined Vulnerability Assessment (VA), the floodable coastal plain due to tsunami was approximately 1000 m in width, according to flooding maps provided by the maritime authority [56]. Consequently, the maximum floodable distance to be considered in Table 12 is D = 1000 m. As all the studied buildings were within a distance of 250 m from the coastline, the VA rating was calculated by using Equation (17) and the results are presented in Table 17.

Table 17. Vulnerability assessment results.

Building Code	SVA	CVA	VA	Vulnerability
EB1	4.10	2.88	3.25	High
EB2	1.00	2.88	2.32	Medium
EB3	1.00	2.88	2.32	Medium
EB4	4.10	2.88	3.25	High
EB5	2.65	2.88	2.81	Medium
EB6	2.98	2.88	2.91	Medium
PuB1	1.00	2.88	2.32	Medium
PuB2	1.00	2.88	2.32	Medium
PuB3	4.10	2.88	3.25	High
PuB4	1.00	2.88	2.32	Medium
PuB5	1.00	2.88	2.32	Medium
PuB6	1.00	2.88	2.32	Medium
PrB1	2.43	2.88	2.75	Medium
PrB2	2.43	2.88	2.75	Medium
CB1	1.00	2.88	2.32	Medium
CB2	4.10	2.88	3.25	High
CB3	2.43	2.88	2.75	Medium
CB4	2.43	2.88	2.75	Medium

Figure 6 shows the location and vulnerability of each building. It can be seen that most of the buildings classified with a high level of vulnerability are further from the coast. This is because they are old structures and have damage to their facades due to the 2010 earthquake; while buildings at the coast were repaired and refurbished after 2010.

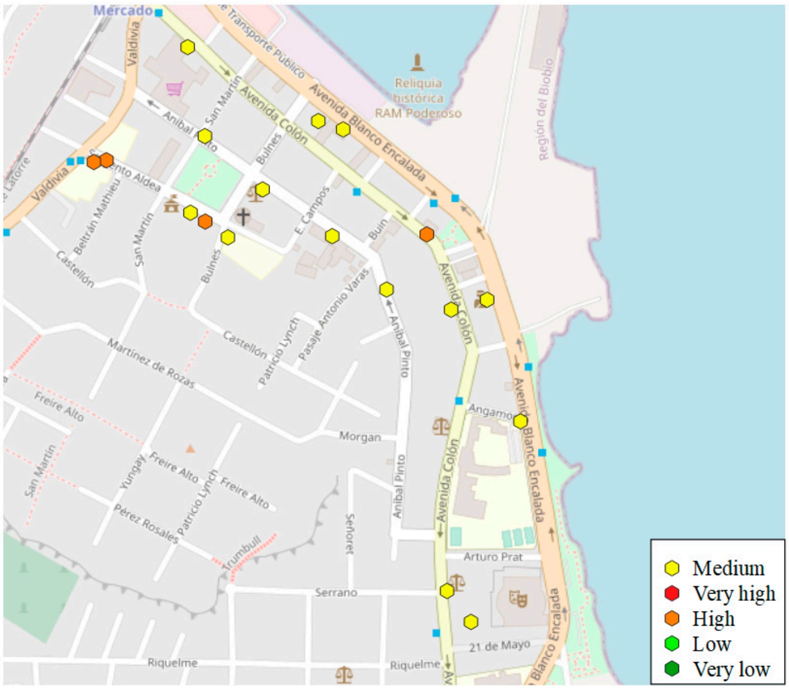

Figure 6. Vulnerability assessment map.

4. Discussion

The results of the assessment of the Dante Theater show that the building was in a vulnerable condition prior to 2010 seismic event (VA = 3.53) and, as expected, it was severely affected by the 2010 Maule earthquake (VA = 4.05). The interventions applied in 2018 restored its structural integrity and reduced its seismic vulnerability to a medium level (VA = 2.68), which is an acceptable level of seismic risk for this kind of structure. It is important to point out that the proposed method provides only a preliminary vulnerability assessment based on general characteristics. The building's actual strength capacity and potential structural performance still need to be determined by more detailed studies, such as specific damage surveys, material characterization, structural health monitoring, numerical model and others.

From the territorial point of view, the results obtained from SVA revealed that 22% of the 18 evaluated buildings are prone to damage caused by earthquakes. Meanwhile, the results obtained by the territorial CVA classified the 18 studied structures at a medium vulnerability. These results demonstrate that SVA is related to the individual structural characteristic of the buildings and CVA is more related to general territorial characteristics, especially when structural typologies are similar. Finally, the combined vulnerability assessment (VA) identified four buildings as highly vulnerable and 14 with medium vulnerability. Hence, the proposed method is useful for identifying those buildings potentially vulnerable and helps the decision makers to prioritize actions to determine the actual performance expected for these structures and to define possible repairing or retrofitting interventions, if needed.

In this sense, the results for the Educational Buildings, presented in Table 17 stand out. One third of them are classified at a high level of vulnerability and the other 2/3 presented a medium level of vulnerability. Being that these structures are mainly used by children, one would expect that safety requirements should be stricter and lower levels of vulnerability should be required. Currently, this kind of analysis is not considered in Chile, but this could be a point to consider in the territorial planning of coastal cities in Chile. The situation is similar with public buildings, but in this case safety requirements might be relaxed considering medium levels of vulnerability as acceptable.

Finally, it is worth mentioning that this study faced two challenges in implementing this methodology:

- Basic information (building's year of construction and soil class) needed to perform SVA was not readily available for the general public and had to be requested through official procedures; it takes 20 business days for an answer to be provided. The SVA could be quickly and easily applied if the municipalities made this information available as a policy.
- Originally, this study considered extensive field work for performing visual inspections of the buildings and collecting sociodemographic data. However, the 2020 world health crisis forced us to redesign these kinds of surveys. Consequently, the visual inspection was done using Google Street View [43] and the sociodemographic parameters were obtained by telephone surveys and census information. Hence, the COVID-19 crisis helped to demonstrate that the proposed methodology does not require extensive field work and most (if not all) the procedures can be performed remotely.

5. Conclusions

A combined seismic and coastal vulnerability assessment method was proposed in this study. First, a model for assessing the buildings' seismic vulnerability (SVA) was proposed based on New Zealand guidelines and adapted to Chilean regulations. This method is proven to be a fast and easy tool capable of providing substantial information for decision making regarding what kind of actions to take on a building with possible damage after an earthquake. To apply the assessment, only three fundamental parameters are required for each studied building: year of construction, seismic zone and soil class. Second, a coastal vulnerability assessment (CVA) model was proposed, combining physical, structural and sociodemographic parameters. Additionally, different weights of importance were implemented to each variable, which is an improvement to the Gornitz model used as reference. The evaluation surveys included 12 essential parameters for a complete coastal vulnerability assessment. Finally, both vulnerability assessments are combined into a single model (VA), assigning different weighting to the SVA and the CVA.

The method proposed by this study proves to be an objective tool for assessing existing buildings' expected structural performance under seismic actions, as well as their susceptibility to tsunami damage. Each component of this assessment tool provides valuable and complementary information for decision makers regarding repairs and reinforcement of buildings or other mitigation measures that need to be applied in a territory. This information is especially critical for communities in Chile and particularly for Talcahuano, which has been struck by three destructive tsunamis in the last two centuries.

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