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MASTER THESIS

The role of Architecture in tsunami-risk management
Proposal for a tsunami vertical evacuation system in
Viña del Mar, Chile

e[ad]
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ABSTRACT

The urban built environment offers a fundamental mean to reduce the risk posed by natural hazards, thereby preventing natural disasters. Disciplines like Architecture and Urban Planning become effective instruments to reinforce disaster risk governance and foster resilience. The following thesis investigates the relationship between natural disasters and built environment, focusing on the earthquake and tsunami hazard that threaten the Chilean coastal cities. It explores the coastal management strategies and the main existing mitigation systems for shore protection, both natural and engineered.

Focusing on a case study, the city of Viña del Mar, it analyzes the reasons that led to the urban densification of the waterfront and the consequent risks that come from its exposure to inundation and tsunami hazard. The proposition for a tsunami vertical evacuation system in the Población Vergara has the objective of combining an effective tsunami mitigation strategy with the urban environment demonstrating the role of architecture inside the disaster management cycle. The design process, developed in three phases, consists in the draft of an assessment model for potential Tsunami Vertical Evacuation Building's sites, the design of a vertical evacuation system composed of 22 tsunami shelters and finally the drawing of the new evacuation plan resulting from the implementation of the existing horizontal one with the new vertical evacuation system which will guarantee the rapid evacuation of all the sectors at risk.

CONTENTS

INTRODUCTION

Cities have become hotspots for nature-originated disasters. Many coastal communities throughout the world are threatened by tsunami hazard. A tsunami is a sequence of waves with very long length and period, usually generated by disturbances associated with earthquakes occurring under or near the ocean floor. The most devastating have proven to be local tsunamis, generating rapid onset crises where the population must carry out critical response activities, evacuation and sheltering, in a very short time and without or with limited official guidance. The tsunamis affecting Chile in 2014[1] and 2015[2] showed that tsunami arrival times can be as short as 12 minutes, almost equating the time that the SHOA, Chilean Navy Agency for Tsunami Research, needs to collect and process the seismic data to release an official tsunami warning.

Given the little time after recognizing the potential hazard, horizontal evacuation outside the tsunami inundation zone is not always effective. Vehicular-based evacuations are not an option due to damaged roads after the initial earthquake, traffic congestion and traffic-signal failures. Most efforts in mitigating tsunami risk have generally focused on developing more effective warning systems, improved inundation maps, and greater tsunami awareness. But in an increasingly urbanized world most responses to rapid onset disasters have to be undertaken within the built environment, whose characteristics can increase communities' abilities to deal with crises and achieve resilience.

Viña del Mar (33.0153° S, 71.5500° W) is a city located in the Region of Valparaiso, the central zone of Chile, on the Pacific coast about 120km from the capital Santiago. It is the fourth largest city of the country with an area of 122km^2 and a population of 334.248[3], which considerably increases in the summer season with a floating population that exceeds 1 million people per year. Its site comprises a large coastal plain, approximately 1.5x1.5km wide and with a maximum elevation of roughly 20m. Given its geography, with 8km of coastline, and its residential character, it

[1] Aránguiz, R., et al., "The 16 September 2015 Chile tsunami from the post-tsunami survey and numerical modeling perspectives," *Pure and Applied Geophysics* 173, no. 2 (2016): 333-348, https://doi.org/10.1007/s00024-015-1225-4.

[2] Catalán, P., et al., "The 1 April 2014 Pisagua tsunami: observations and modeling," *Geophysical Research Letters* 42, no. 8 (2015): 2918-2925., https://doi.org/10.1002/2015GL063333.

[3] INE, Cenus 2017, http://www.inevalparaiso.cl/contenido.aspx?id_contenido=13.

[4] "Nuestra Ciudad," Ilustre municipalidad de Viña del Mar, accessed April 22, 2018, http://www.vinadelmarchile.cl/seccion/2/nuestra-ciudad.html.

has historically maintained the status of a holiday-escape town and it is today considered the tourist capital of Chile[4].
The current flood map of the city developed by SHOA shows that large urban areas, especially in the district of Población Vergara, are vulnerable to tsunami hazard. In the last years, the population of the Población Vergara has grown as the result of a densification process through high-rise apartment buildings. Moreover, large-scale facilities like shopping malls, schools, governmental offices and hotels are mostly located in the district, fostering daily commuters. These characteristics summed to the district's narrow streets, few open public spaces and high levels of traffic expose the area to the threat.

The aim of this thesis is to investigate the relationship between natural hazards and built environment, focusing firstly on how earthquake and tsunamis affect the coasts of Chile, more precisely the coastal area of the city of Viña del Mar, and secondly the role of architecture inside the disaster management cycle and how can the built environment help the population achieve a higher level of resilience and prevent life losses. The work will be based on the following hypotheses:

- Architecture and Urban Planning, in addition to the current risk management strategies can reduce the exposure of coastal cities, like Viña del Mar, to tsunami risk, increasing their resilience capacity;
- where horizontal evacuation is neither possible nor efficient, a tsunami vertical evacuation (TVE) system can be planned as integration of the horizontal evacuation system to limit life losses;
- structure designed using appropriate architectural forms and materials can withstand the forces generated by a tsunami and its triggering earthquake;
- it is possible to combine the characteristics of public buildings and squares with the necessities of vertical evacuation.

According with the formulated hypotheses the objectives expected to be accomplished are:

- contribute to the discussion on how natural hazards affect coastal cities and how flooding prone coastal areas can achieve higher levels of resilience through the adaptation of architecture and urban planning;
- design of a new tsunami evacuation system for the city of Viña del Mar that combines the existing evacuation plan with a vertical evacuation system to guarantee rapid and safe evacuation of the totality of the population at risk, without modifying its relationship with the ocean and its structure of seaside-resort city;
- design of the prototypes of the new evacuation structures for the Población Vergara, focusing on the accessibility and internal circulation of each building;
- assign to each shelter a potential program compatible with the evacuation needs that can guarantee the maintenance of the structures and enhance the quality of life the inhabitants while generating community disaster awareness.

To achieve the objectives established above, the work starts with an investigation regarding natural hazards and disasters, mitigation strategies and evacuation plans through the existing literature review and experts' interviews. Followed by analysis of a case study, the Población Vergara in Viña del Mar, through the existing literature review, experts' interviews, on field observations and mapping. The work ends with the drawing of the new evacuation plan for the Población Vergara with the prototypes of the new Tsunami Vertical Evacuation Buildings, TVEBs.

1

NATURAL DISASTERS

1.1. From natural hazard to natural disaster

Geophysical events such as earthquakes, floods, lands slides, tsunamis and many others are phenomena that exist since the beginning of time but, originally, they were a threat only to the flora and fauna. The evolutions of these phenomena into natural disasters occurred simultaneously with the development of human's processes and systems that link human beings to nature, exposing them to the threat. When the natural vulnerability caused by the hazards and the human vulnerability caused by its systems coexist in the same space and time a natural disaster can occur[5] (see figure 1). So, if the hazards causing the disasters are natural, the disaster itself it is not and the frequency which they occur augmented together with the growth of population[6].

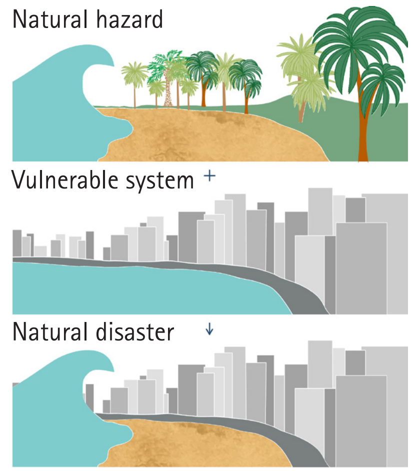


Figure 1: Origin of a natural disaster
Source: Eleonora F. Serpi.

The escalation of natural disasters worldwide is not an unforeseen event: the increase of population and human disparity incremented the social and environmental vulnerability to natural hazards and their intensity[7]. Even if natural disasters happen worldwide, they have a stronger effect on developing countries which are mostly located in areas with both strong natural and human vulnerability where the resources to prevent, respond and mitigate the consequences of a natural hazard are not available. In order to reduce life losses and material damages, on the 1st January 1990, the United Nations launched the International Decade for Natural Disaster Reduction (IDNDR). The intent is the adoption of universal prevention strategies drafted on the specific threatened areas and based on the interaction of the human system with various kinds of natural phenomena[8].

Hazards are aggravated by other factors like climate change, underdevelopment, poverty, lack of education and bad governance[9]. Developing countries around the world have to deal with all the

[5] Irasema Alcantara-Ayala, "Geomorphology, natural hazards, vulnerability and prevention of natural disasters in developing countries," *Geomorphology* 47, no. 2-4 (October 2002): 107, https://doi.org/10.1016/S0169-555X(02)00083-1.

[6] United Nations, *Natural hazards*, unnatural disasters: the economics of effective prevention. (Washington DC: The World Bank, 2010), 1.

[7] Jorge Enrique Vargas, *Políticas públicas para la reducción de la vulnerabilidad frente a los desastres naturales y socio-naturales*. (Santiago de Chile: CEPAL, 2002), 10.

[8] Alcantara-Ayala, 108.

[9] "Types of disasters: Definition of hazard," International Federation of Red Cross and Red Crescent Societies, accessed March 12, 2018. http://www.ifrc.org/en/what-we-do/disaster-management/about-disasters/definition-of-hazard/.

above-mentioned factors. Moreover, they do not have the economic resources to invest in research, preparedness plan or alarm system which would help them face a natural disaster. Sometimes they do not even have the time to recover from a disaster before a new one strikes. One example is Haiti, where in 2010 a catastrophic earthquake, with epicenter near the capital Port au Prince, caused more than 200.000 deaths and major destructions[10] and in 2016 Hurricane Matthew, newly affected the population that had not yet recover from the previous disaster (see figure 2).

The response to a natural disaster is influenced by the characteristics of the hazard causing it (see table 1) and the level of resilience of the affected community intended as its capacity to cope and recover from crisis situations. Among the characteristics, frequency and magnitude are fundamental for its assessment[11]. Together with predictability, speed of onset, length of forewarn, duration and cause, scope of impact, destructive potential and controllability they allow the community to manage the risk developing appropriate risk management plan and warning system.

[10] Alcantara-Ayala, 108.

[11] Ibid, 109.

[12] Arturo Vittori, Warka Water, Haiti, 2016.

Figure 2:
Destruction caused by Hurricane Matthew in Haiti, 2016
Source:
Arturo Vittori[12].

Therefore, an accurate study of the phenomenon is essential to undertake mitigation measures before disaster takes place[13].

Natural hazards cannot be prevented, but Geomorphology can help predicting patterns of behavior able to reduce physical vulnerability through the elaboration of vulnerability maps. In general, these evaluations consist of various phases like the elaboration of maps, numerical models, prediction schemes and management plans, drafted on field observations, photogrammetry and GIS. The realization of hazard prediction models helps having a better understanding of the phenomenon which consequently leads to a better response when it strikes but, still, only in the most developed country where such technologies and funds are available for research[14]. The understanding of natural and human vulnerability is the key in the comprehension of how natural hazards turn into natural disasters and their destructive consequences.

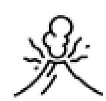
NATUTAL HAZARD	ORIGIN
Geothermal-originated hazards, like volcanic eruptions, ground deformations and tsunamis, are caused by transfer of heat from inside the deepest layer of the Earth to the surface.	
Wind-originated hazards, like storms, cyclones, tornadoes, hurricanes, typhoons and tidal waves, are mostly due to the combination of the warmth of the water ocean and the low atmospheric stability.	
Water-originated hazards, like floods, drought, dam bursts and excessive rain, can be considered as consequences of most of the wind-originated hazards, aggravated by the overexploitation of land.	
Seismic hazards like earthquakes, tsunamis, avalanches, landslides and volcanoes eruptions, are cause by the to constant movement and collision of the tectonic plates.	
Environmental hazards, like air and water pollution, diseases and epidemics, global warming, are caused by the dispersion of toxic chemicals and biological agents in the environment.	

Table 1:
Classification of natural disasters according to their origin
Source:
own elaboration from International Federation of Red Cross and Red Crescent Societies[16].

[13]Dennis E. Wenger, "Community response to disaster: functional and structural alterations," *Disasters: Theory and research* (1978): 17-47.

[14]Alcantara-Ayala, 109.

[15]Dennis E. Wenger, "Community response to disaster: functional and structural alterations," Disasters: Theory and research (1978): 17-47.

[16]"Types of disasters: Definition of hazard," International Federation of Red Cross and Red Crescent Societies.

1.1.1. Human and physical vulnerability

The interest in understanding the risk affecting a population living in an area prone to natural hazards led to the definition of human vulnerability.

> *"The degree to which a community is at risk from the occurrence of extreme physical or natural phenomena, where risk refers to the probability of occurrence and the degree to which socio-economic and socio-political factors affect the community's capacity to absorb and recover from extreme phenomena ability of households or communities to cope with and recover from outside events and particularly to shocks and sudden changes"*[17].

Due to its socio-cultural, economic and political aspects, human vulnerability cannot be considered as a homogenous entity, it is instead the result of the continues interactions of the different contexts the population lives in[18]. It can be classified according to the level of livelihood resilience, health and preparedness of a community[19].

While human vulnerability has a socio-economical character, physical vulnerability depends on the natural hazard with a strong relation to the geographical characteristics. The location determines the exposure of an area to hazards such as volcanic eruptions, tsunamis, landslides and floods. Therefore, some areas are more affected by natural disaster due to their geographical exposure. The result of the combination of the single types of vulnerability present in a given area determining the magnitude of the disaster, the level of resilience and the recovery process and it is referred as the total vulnerability[20] (see figure 3).

Physical vulnerability can be assessed applying pre-elaborated numerical models to a specific environment. These models usually use fixed parameters chosen both according the characteristics

[17]Phil O'Keefe, Ken Westgate and Ben Wisner. "Taking the naturalness out of natural disasters," *Nature* 260 (1976): 566.

[18]Alcantara-Ayala, 119.

[19]Piers Blaikie, et al., *At risk: natural hazards, people's vulnerability and disasters* (New York: Routledge, 2014), 21.

[20]Alcantara-Ayala, 119.

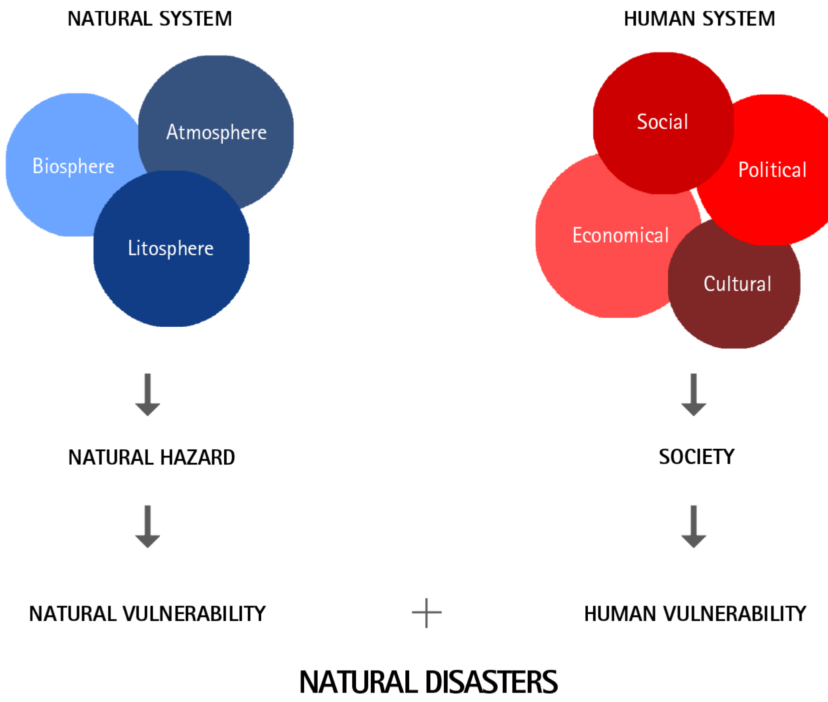


Figure 3:
Vulnerability and natural disasters
Source:
own elaboration from Alcantara-Ayala[21].

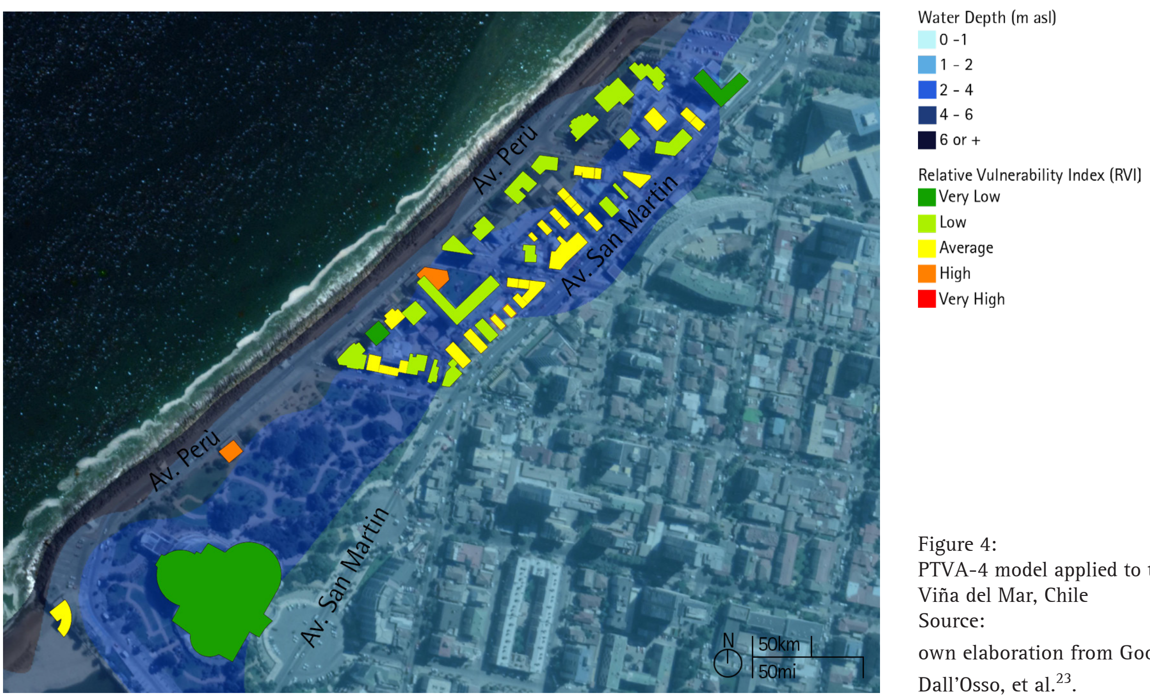


Figure 4:
PTVA-4 model applied to the Av. Peru,
Viña del Mar, Chile
Source:
own elaboration from Google Earth[22] and F. Dall'Osso, et al.[23].

of the hazard that can occur and a specific area both the characteristics of the affected environment. For example, the Papathoma Tsunami Vulnerability Assessment (PTVA) model of urban environments has been elaborated with the purpose of assessing the vulnerability of the built environment in case of tsunami. To establish the Relative Vulnerability Index (RVI), the models take in consideration numbers of floors, material, shape and orientation, hydrodynamic resistance and construction year of a building. All the above parameters are inserted in a formula that allow to establish the RVI of a building ranging from minor to very high vulnerability to tsunami inundation[24] (see figure 4).

1.2. Prevention of a natural disaster

Mankind is considered the main reason why natural hazards turn into natural disasters and therefore a threat to the environment. Ideally, to prevent natural disasters, we wouldn't have only to respect the ecosystem but also recover its original condition. Since disaster are not inevitable, it is prevention through the establishment of alarm systems, mitigation plans and the creation of infrastructures can maximize the protection of a community. The aim is to reduce the vulnerability of societies and territories dealing with the activities that cause or aggravate natural hazards.

> *"It is not easy to promote a culture of prevention, because its costs have to be paid in the present while its benefits only come in the future, because there are no simple and general solutions, treatments are different according to the risks of each territory and community, and because success does not depend on the management of a single agency but requires the active participation of the community and the mobilization of many public and private entities"*[25].

So, even if the adoption of efficient prevention approaches would help saving billions of dollars, avoid material and human losses, most of

[21] Alcantara-Ayala, 120.

[22] "Población Vergara," 33°01'00.77"S and 71°33'32.42"W, Google Earth, Google, last modified December 3, 2018.

[23] F. Dall'Osso, et al., "Revision and improvement of the PTVA-3 model for assessing tsunami building vulnerability using "international expert judgment: introducing the PTVA-4 model," *Natural Hazards* 83, no. 2 (2016): 1229-1256.

[24] F. Dall'Osso, et al., 1229-1256.

[25] Vargas, 10.

the resources are still spent on relief efforts. Instead, they should be used to promote equitable and sustainable development (see figure 4) that reduces vulnerability to natural hazards. Reducing vulnerability is the essential condition to preserve human well-being and economic growth[26].

1.2.1. Disaster management cycle

Disaster management correspond to the organization and control of administrative decisions and operational activities corresponding to the various stages of a disaster. It can be divided chronologically into preparedness, before the disaster strikes, resistance, during the disaster, and recovery and adaptability, after the disaster (see table 2 and figure 5). This division helps having a clearer view and understanding of the measures that have to be undertaken in place in case of hazard. A disaster management plan is drafted as a cycle: after a disaster strikes and the affected community recovers, the process starts again to avoid future losses and damages[27].

[26]Ibid, 10.

[27]Julie Dean Rosati, Katherine Flynn Touzinsky, and W. Jeff Lillycrop, "Quantifying coastal system resilience for the US Army Corps of Engineers," Environment Systems and Decisions 35, no.2, (2015): 201.

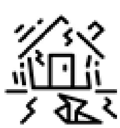
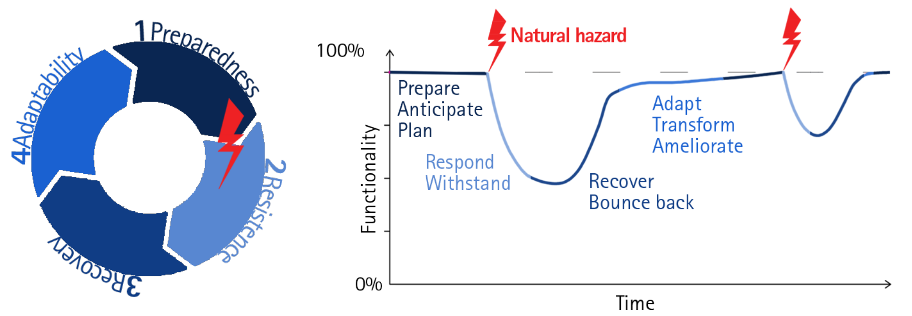
STAGE	PHASE	NATURAL HAZARD
	Preparedness	Activities aiming at preventing a disaster, reducing the probability of its occurrence and the damages, like community awareness programs and plans and safety measures. These activities increase the chances of a positive hazard response.
	Resistance	Activities that aim at withstanding and absorbing the disturbance and at maintaining a certain level of functionality to ensure that the needs and provisions of victims are met, and suffering is minimized.
	Recovery	Activities that help recover, "bounce back", to the safety conditions and well-being previous the disaster. If the previous phases accomplished their goals the recovery process will be short and affordable.
	Adaptability	Activities that aim at adapting and ameliorating a system, ''bounce forward'', to a state that is more capable to withstand and recover from a future disaster. This adaptation process should ideally result in a smaller loss during a future disaster and a quicker recovery time.

Table 2: Disaster management activities.Source: own elaboration from Julie Dean Rosati, et al.[28].

Figure 5:
Disaster management cycle
Source:
own elaboration from Julie Dean Rosati, Katherine Flynn Touzinsky, and W. Jeff Lillycrop[29].



1.2.2. Personal and community awareness

Populations at risk need to be aware of potential hazards, how, when and where they are likely to occur and the problems which may result, to be able to cope with their effects. During the disaster occurrence there will be delay before outside help arrives. Therefore, at first, self-help is essential and depends on the preparedness of a community. A population can be considered prepared when it isit’s informed and aware of the possible danger, when it takes mitigation measures, it isit’s actively involved in the local governance and knows how to actuate the necessary response plan[30].

[28] Julie Dean Rosati, Katherine Flynn Touzinsky, and W. Jeff Lillycrop, 201.

[29] Ibid, 201.

[30] Ibid, 8.

2

EARTHQUAKES AND TSUNAMIS

2.1. Earthquakes

An earthquake, also called quake, tremor or temblor, consists in the shaking of the surface of the Earth. They are caused by a sudden shift of blocks of earth due to the movement of the tectonic plates. Seismic waves are generated by sudden release of energy in the Earth's lithosphere. These waves can be felt both by people and structures. Depending on the amplitude of the movement (shift, speed and ground acceleration) and its duration, an earthquake has stronger or minor intensity[31].

The tectonic plates resemble the pieces of puzzle that cover most of the external layer of the Earth. They are not still but they bump into each other sliding by one another. Their edges, known as plate boundaries, are made up of many faults where most of the earthquakes occur worldwide. Since the edges of the plates are rough, they get stuck while the rest of the plate keeps moving, when the edges of the plate get loose an earthquake originates[32].

Seisms can be characterized according to their magnitude or their intensity. The magnitude corresponds to the energy released during the earthquake, and it i's measured either through the Richter Magnitude Scale (M_L), "a mathematical device to compare the size of earthquakes", or through the Moment Magnitude Scale (M_W). The magnitude of an earthquake is determined from the logarithm of the amplitude of waves recorded by seismographs. Adjustments are included for the variation in the distance between the various seismographs and the epicenter of an earthquakes[33] (see figure 6).

[31]"Sismo," Centro Sismológico Nacional Universidad de Chile, accessed March 17, 2018. http://www.sismologia.cl/.

[32] "The Science of Earthquakes," USGS, accessed March 17, 2018. https://earthquake.usgs.gov/learn/kids/eqscience.php.

[33]"Measuring the Size of an Earthquake," USGS, accessed March 17, 2018. https://earthquake.usgs.gov/learn/topics/measure.php.

[34]"Sismo," Centro Sismológico Nacional Universidad de Chile, accessed March 17, 2018. http://www.sismologia.cl/.

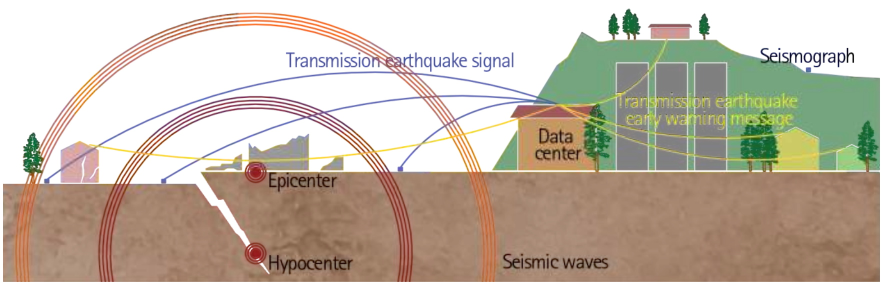


Figure 6: Earthquake generation and propagation.

Source: own elaboration from Centro Sismológico Nacional Universidad de Chile[34].

The intensity of an earthquake is related not to the phenomenon itself but to its effects, “the intensity is a number (written as a Roman numeral) describing the severity of an earthquake in terms of its effects on the Eearth’s surface and on humans and their structures”[34]. The scale used to measure the intensity of an earthquake is the Modified Mercalli Intensity Scale. Different intensities can be registered for the same earthquake, depending on the distance from the epicenter, unlike the magnitude, which is unique for each earthquake[35].

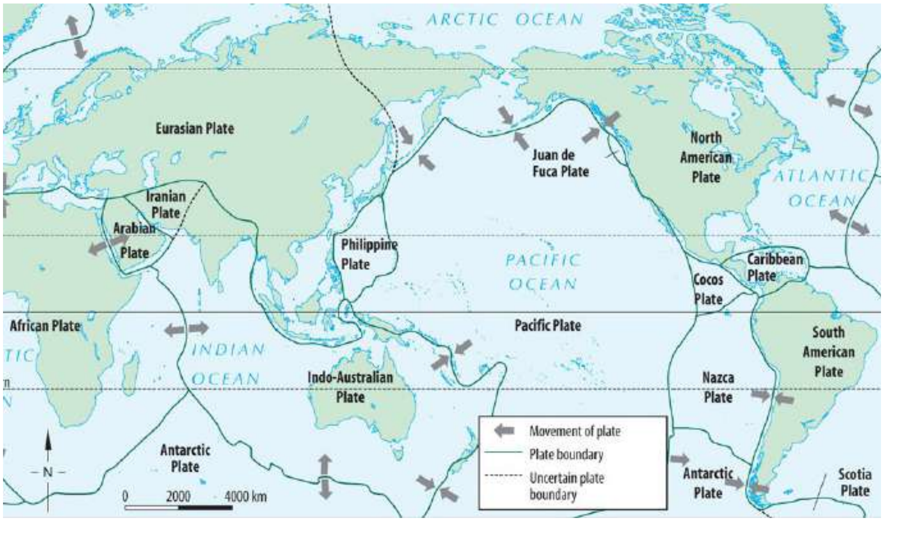
2.1.1. The Plate Tectonic Theory

The Plate Tectonic Theory is based on the Earth model composed of several lithospheric plates which contain the continents and the oceanic floor. The major plates, with an area greater than 20 million Km2, are the North American, the Pacific, the Eurasian, the African, the Antarctic, the Indo-Australian and the South American (see figure 7). The lithospheric plates move up to 8cm per year, deforming the asthenosphere, as confirmed by satellite Global Position System (GPS) measurement. Some plates separate, others collide, and others slide under, over, or past one another

[34]“Earthquake Glossary: Intensity,” USGS, accessed March 17, 2018. https://earthquake.usgs.gov/learn/glossary/?term=intensity.

[35] Donald Hyndman, and David Hyndman, *Natural hazards and disasters* (Cengage Learning, 2016), 19.

[36]Alvin Lucero. *The Theory of Plates Techtonics.* Dynamic Earth: Plate Techtonics. Available on: https://platetectonicsalvin.weebly.com/the-theory-of-plate-tectonics.html (accessed on April 8, 2018).



Fugure 7: Plate tectonic.

Source: Alvin Lucero[36].

originating earthquakes on the surface (see figure 8).
Almost all the deepest earthquakes (deeper than 300km), the medium-dept earthquake (70-300km) and the 75% of the superficial ones (less than 70km) happen in correspondence of the subduction areas. A subduction zone corresponds to the boundary of a tectonic plate that, when colliding into another plate, shifts under it (see figure 9). All the rest of the seism, especially the most superficial, happen in correspondence of the oceanic dorsal and the transformation faults. Thanks to the Plate Tectonic Theory scientists have been able to determine approximately the zones most affected[37].
The Ring of Fire (or Circum-Pacific Belt), is the area with the highest incidence of geological hazards like earthquakes, landslides, volcanic eruptions and consequent tsunamis (see figure 10). Its name refers to the numerous volcanoes, about 75% of the Earth's volcanoes, found along its length. Chile is one of the most affected areas, with active volcanoes and frequent earthquakes due to the subduction of the Nazca Plate under the South American plate[38].

2.2. Tsunamis

The name "Tsunami" has Japanese origins and it means harbor "tsu" wave "nami". It is a sequence of waves with very long length and period, usually generated by disturbances associated with earthquakes occurring under or near the ocean floor. Known also as seismic waves, they are notaren't generated only by earthquakes, they can result from volcanic eruptions, underwater landslides, coastal landslides, meteorite impact on the sea surface and meteorological or atmospheric perturbances (see figure 11). Even if it isit's not the only cause, tsunamis are generated mostly by tectonic dislocations in subduction areas.
The blocks of the earth's crust, shifting up and down, transmit potential energy to the body of water above it, altering the sea level of the affected region. The energy, thus transmitted, spreads

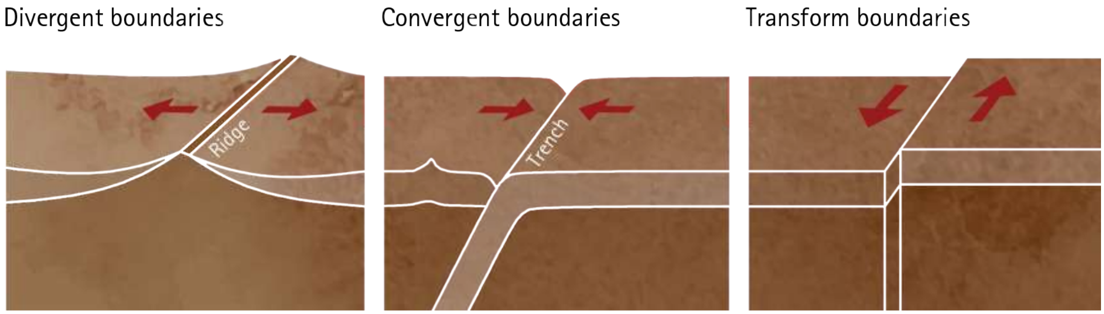
[37]Donald Hyndman, and David Hyndman, *Natural hazards and disasters* (Cengage Learning, 2016), 16-20.

[38]Donald Hyndman, and David Hyndman, 25-30.

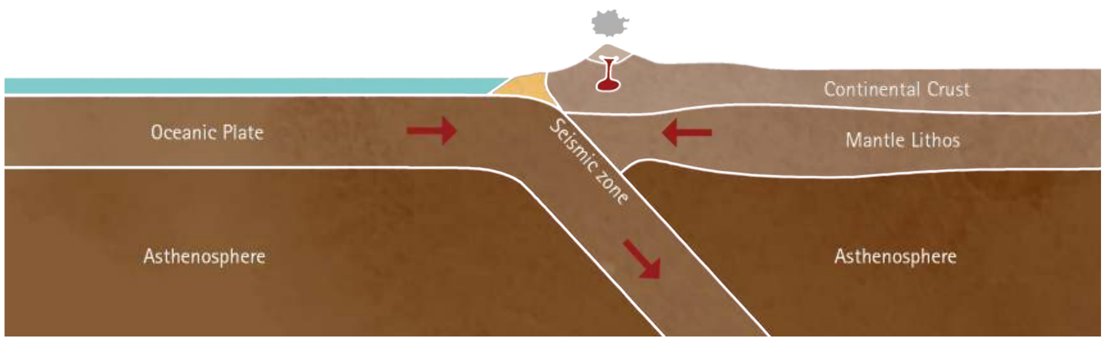
[39]"There are three kinds of plate tectonic boundaries: divergent, convergent, and transform plate boundaries," Nacional Oceanic and Athmosperic Administration, accessed July 8, 2018, https://oceanexplorer.noaa.gov/facts/plate-boundaries.html.

[40]"Subduction Fault Zone Diagram," USGS, accessed July 7, 2018, https://www.usgs.gov/media/images/subduction-fault-zone-diagram.

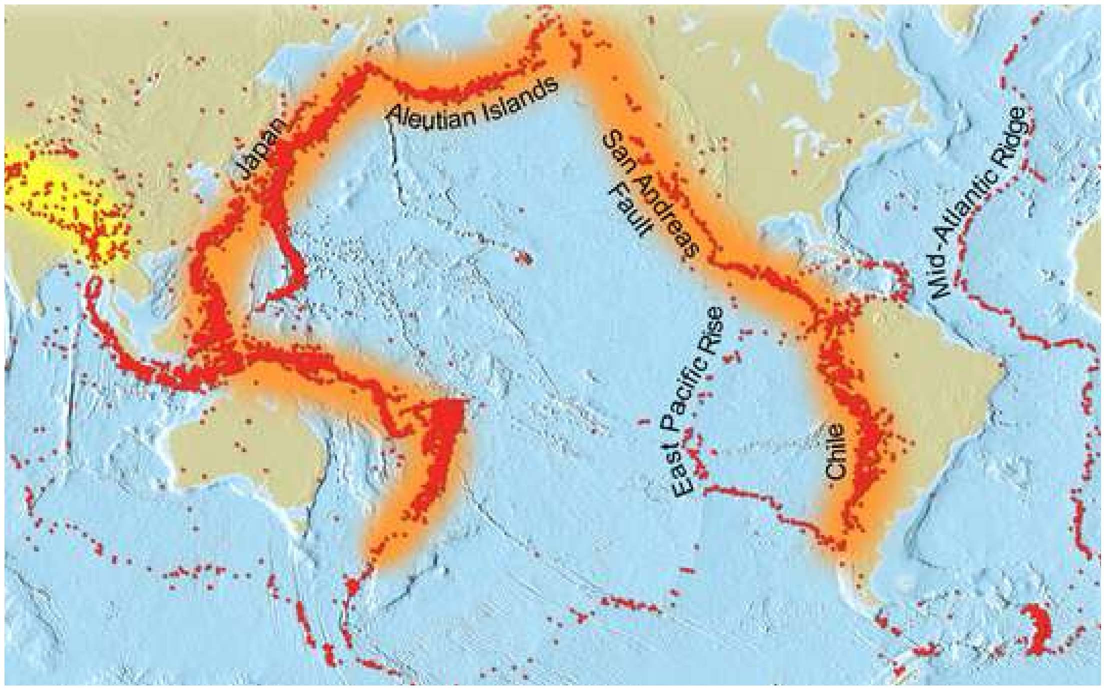
[41]Tasa Graphic Arts. *Circum-pacific Belt*. Archives of Tasa Graphic Arts. Available on: http://www.tasagraphicarts.com/discovertectonics.html (accessed April 8, 2018).



Fugure 8: Tectonic plates boundaries. Source: own elaboration from U.S. Geological Survey[39].



Fugure 9: Subduction fault. Source: own elaboration from USGS[40].



Fugure 10: The Ring of Fire. Source: Tasa Graphic Arts[41].

from the origin in the form of long-period waves with changeable speed, constantly accelerating or decelerating depending on the depth of the ocean[42]. There is not an exact model that can state whether an earthquake is tsunamigenic. The experience refers to the magnitude of the earthquake: normally if the seism magnitude is higher than 7.5 Mw and it can generate a tsunami but the magnitude, the intensity and the height of the resulting waves is not sure. In the past, seism with a magnitude lower than 7 Mw but with long duration caused tsunamis bigger than expect, like the tsunami that hit in Nicaragua in 1992[43].

2.2.1. Characteristics of a tsunami

Tsunami waves do not have to be mistaken for the waves that are normally seen at the beach. The "normal" waves, also known as wind waves, are generated by the difference between the wind speed and waves speed. If the wind speed is lower than the wave speed the latter is not affected but, on the contrary, if the wind speed it is greater it originates big waves that can look as tsunamis but only superficial[44]. The main characteristics featuring a tsunami can be resumed in its sswavelength, period, flood height (h), flood depth (d), intrusion (I) and run up (R) (see figure 12).
The wavelength of the tsunami it is the horizontal distance between similar points of two consecutive waves measured perpendicular to the ridge. For tsunamis generated by earthquakes, the typical wavelength range is between 20 and 300km. For tsunamis generated by landslides, it isit's between 100m and 10km. Wavelength and period of a tsunami provide information about its the source. The period is the time it takes a wave to complete a cycle or a wavelength, normally it lasts from 5 to 60 minutes. It is calculated with a mareogram that establishes the difference between the arrival time of the highest peak and the following crest. The flood height, also called "height of the tsunami" is the height of the sea level measured in relationship with a given datum, like

[42]Comisión Oceanográfica Intergubernamental, *Glosario de tsunamis* (Paris: UNESCO, 2013), 7.

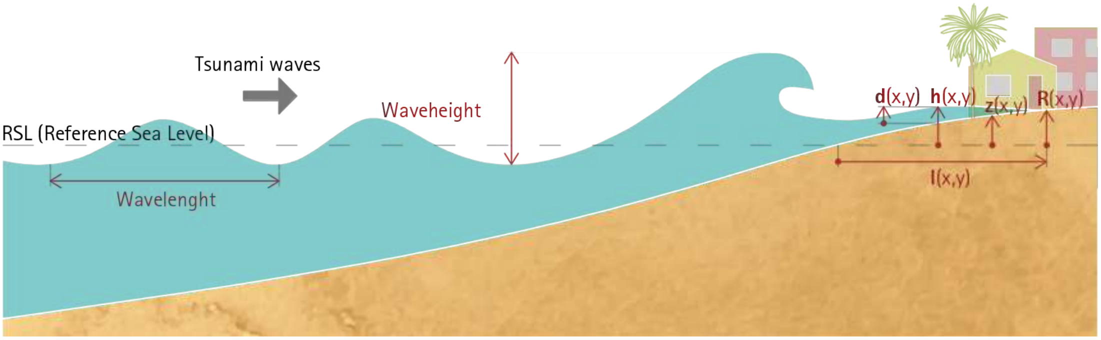
[43]Daniel Saavedra, *"Análisis y evaluación de vulnerabilidad a amenazas naturales y socioeconómicas en la ciudad de Puerto Montt y sus áreas de expansión"* (Grad. Diss., Universidad de Chile, 2007), 87-88.

[44]Centro Nacional de Estimación, Prevención y Reducción del Riesgo de Desastre, *Manual para la evaluación del riesgo por tsunamis* (Lima: CENEPRED, 2017), 29.

[45]Manuel Contreras, and Patricio Winckler, "Pérdidas de vidas, viviendas, infraestructura y embarcaciones por el tsunami del 27 de Febrero de 2010 en la costa central de Chile", Obras y Proyectos, no.14, 2013. http://dx.doi.org/10.4067/S0718-28132013000200001.

[46]Unknow Author. *Tsunami in Sendai*, Japan. 2010. State of California, Department of conservation. Available from: http://www.conservation.ca.gov/cgs/geologic_hazards/Tsunami/Pages/2011_Tohoku.aspx (accessed April 5, 2018).

Fugure 11:
Destruction caused by a tsunami in Sendai, 2016.
Source:
Unknown Author[46].



Fugure 12:
Characteristics of a tsunami.
Source:
own elaboration from Manuel Contreras and Patricio Winckler[45].

the average water level or the water level at the time of the arrival of the tsunami, at a specific flood distance. Flood height is the sum of the depth of the water and the local topographic altitude. The runup can be measured as the difference between the maximum height of intrusion of a tsunami, flood line, and sea level at the time of the tsunami. Or, as the elevation reached by the sea measured in relation with a fixed level such as the reference sea level. Ideally, it is measured at the maximum local point of the horizontal flood. Where the elevation is not measured in relation the maximum horizontal flood, it is called "height of the flood"[47].

2.2.2. Propagation of a tsunami

In deep waters, tsunami' travel speed ranges between 500 and 1000km/h; while near the shore they it decreases to about 30km/h50[48]. The height of the waves depends on the water depth, a tsunami that is only 1m high in the deep ocean can grow up to more than 10m once it reaches the coast. Its energy stretches up to the bottom of the ocean and once it reaches the travel coast, it concentrates in the vertical direction as the depth of the water diminishes and the speed decreases, while the horizontal direction shortens. Three stages can be distinguished in the development of a tsunami: the formation of the wave, its free propagation in the open ocean and its propagation in the region of the continental platform[49](see table 3 and figure 13).

[47]Comisión Oceanográfica Intergubernamental,21-26.

[48]"How does tsunami energy travel across the ocean and how far can tsunamis waves reach?" International Tsunami Information Center, accessed March 18, 2018, http://itic.ioc-unesco.org/index.php?option=com_content&view=article&id=1164&Itemid=2031.

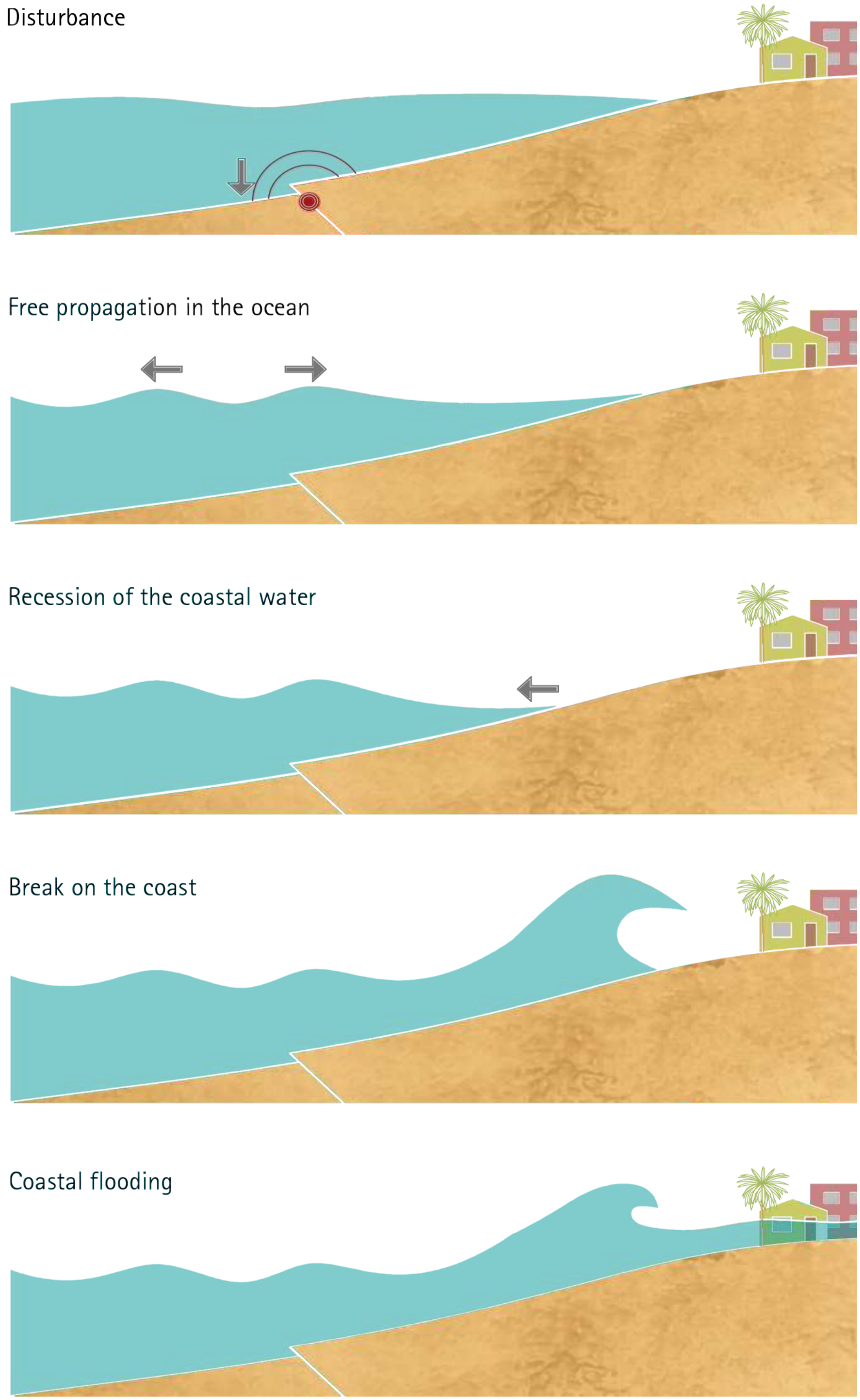
[49]"Algunas definiciones de Tsunami," Sistema Nacional de Alarma de Maremotos Chile, accessed March 18, 2018. http://www.snamchile.cl/index.php?p=gemTsunami.

[50]"Algunas definiciones de tsunami", SNAM Chile, last accessed April 17, 2018, http://www.snamchile.cl/index.php?p=gemTsunami.

[51]"What's a tsunami and how are they monitored?", Julie Ramsden , ABC NEWS, last modified June 21, 2017, http://www.chicagomanualofstyle.org/tools_citationguide/citation-guide-1.html.

PHASE	PROPAGATION	CHARACTERISTICS
I	Formation of the wave	The wave originates due to an earthquake, landslide, volcanic eruption or meteorite impact. From the origin it starts propagating near its source.
II	Free propagation in the open ocean	The wave propagates freely at great depth in the open ocean.
III	Propagation in the region of the continental platform	The wave changes its profile due to the lower depth of the ocean until it breaks on the shore.

Table 3: Propagation phases of a tsunami. Source: SNAM Chile[50].



Fugure 13:
Origin and propagation of a tsunami.
Source:
own elaboration from Julie Ramsden[51].

When a tsunami reaches the shore, it can assume different profiles depending on the size and period of the waves, the bathymetry near the coast, the shape of the coast, the current tide and other factors. A tsunami can approach the coast like a rapid rising tide causing a limited flood of low-lying coastal areas. In other cases, it can reach the coast in the form of a destructive vertical wall of turbulent water with debris. Normally, a tsunami is preceded by the decrease of the sea level which causes the coastal water line to recede a kilometer or more[52] (see figure 14).

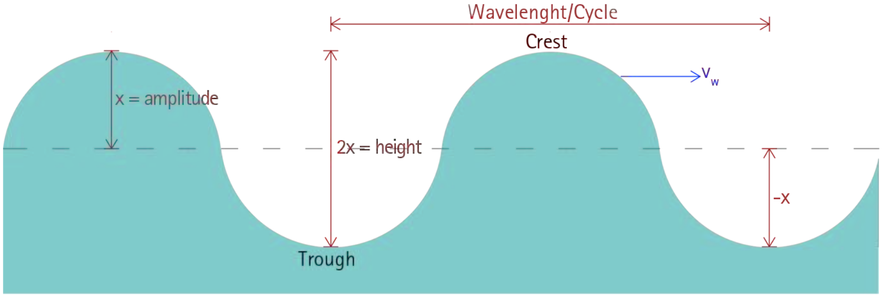


Figure 14:
Waves propagation.
Source:
own elaboration from Lumen Learning[53].

2.2.3. Tsunamis classification

Tsunamis can be classified according to the distance or travel time from their source to their arrival onshore in: local tsunamis, regional tsunamis, tele-tsunamis and meteo-tsunamis. Local tsunamis, due to the closeness of the generating point to the shore and therefore the short arrival time, are the most destructive of all. Most of the deaths and the material damages have been caused by this type of tsunamis. Between 1975 and 2012, 39 local or regional tsunamis were generated, 26 of them in the Pacific Ocean and in its adjacent seas, which caused about 260,000 deaths and caused billions of dollars of material damages.

Local tsunamis are generated within a range shorter than 100kms from the shore or less than one-hour travel time from the shore. Normally, these types of tsunamis are generated by earthquakes, however, they can also be caused by landslides or pyroclastic flows due to volcanic eruptions. Regional tsunamis are tsunamis capable of causing

[52]Comisión Oceanográfica Intergubernamental, 25.

[53]"Wave", Lumen Learning, last accessed April 4, 2018, https://courses.lumenlearning.com/physics/chapter/16-9-waves/.

[54]Unknown Author, "May 1960: Surviving a Tsunami. Lesson from Chile, Hawaii, and Japan", Unknown Author, National Weather Service, last accessed on April 17, 2018, https://www.weather.gov/jetstream/survive (accessed April 1, 2018).

[55]"La intensa marejada que azotó la V región en imágenes," Agencia Uno, acessed April 3, 2018, http://www.theclinic.cl/2015/08/08/galeria-hd-la-intensa-marejada-que-azoto-la-v-region-en-imagenes/.

Fugure 15:
Effects of the 1960 Chilean tsunami on Onagawa, Japan.
Source:
own elaboration Unknown Author, National Weather Service[54].

Fugure 16:
The meteo-tsunami of the 8th of August 2015 striking the coast of Valparaíso.
Source:
Agencia Uno[55].

destruction in a specific geographic region, normally located at a maximum of 1000kms from its origin, or in areas located within 1 to 3 hours travel time. Occasionally, regional tsunamis can have very limited and localized effects in areas outside the region but very restricted compared to the ones of a tele-tsunami.

Tele-tsunamis, also known as far field tsunamis or trans-oceanic tsunamis, are generated from sources very far from the shore, generally further than 1000km or at more than 3 hours of travel time of the waves. This type of tsunami is less frequent than regional tsunamis. Normally, they start as local tsunamis causing great destruction near the source then the waves continue travelling throughout the ocean with enough energy to cause more victims and destruction on coasts located more than 1000km away from their source. The earthquake that in 1960 stroke Valdivia, Chile, generated a tele-tsunami strong enough to cross the Pacific Ocean and cause damages and death not only in Chile but also in Japan, Hawaii, the Philippines and China (see figure 15).

In addition to all the above, meteo-tsunamis, or meteorological tsunamis, are phenomena with the characteristics of a tsunami but generated by meteorological or atmospheric disturbances. These waves can be produced by atmospheric gravity waves, sudden pressure variations, gusts of wind, typhoons, or hurricanes. Meteo-tsunamis' waves have the same temporal and spatial scale as the tsunami waves. They can be equally, especially in bays and coves, where strong amplification can occur[56].

An example of meteo-tsunami, is the one hit coast of Central Chile on the 8th of August 2015, causing the destruction of coastal infrastructure and buildings in several localities of the Valparaíso and Coquimbo region (see figure 16). The meteo-tsunami originated by the simultaneous occurrence of particular meteo-oceanographic conditions together with a violent storm with gusts of winds from the northwest and a historical minimum of atmospheric pressure associated with the frontal system. The astronomical tide as well made its contribution to raising the sea level over which the waves broke violently on the coastal edge[57].

[56] Comisión Oceanográfica Intergubernamental, 8.

[57] Patricio Winckler, et al "El temporal del 8 de agosto de 2015 en las regiones de Valparaíso y Coquimbo, Chile Central," *Latin american journal of aquatic research* 45, no.4 (2017): 622. https://www.researchgate.net/publication/319757644_El_temporal_del_8_de_agosto_de_2015_en_las_regiones_de_Valparaiso_y_Coquimbo_Chile_Central.

2.2.3.1. Tsunamis recurrence

Since scientists cannot predict when an earthquake will occur, they cannot establish exactly when a tsunami will occur. However, by examining historical tsunamis, scientists know where tsunamis will most likely be generated. Past tsunami heights measurements are useful to predict the future impact and flood limits in specific coastal communities. Analyzing tsunamis' historical data records, it isit's possible to suppose tsunamis' recurrence even f with a very big margin of approximation[58].

2.4. Anti-tsunamis measures

Despite the unpredictability of the phenomenon, future losses can be limited through a multiprotection strategy that include a series of preventive measures like hazard mapping, early warning systems, community preparedness, vulnerable infrastructure relocation and coastal protection systems. The hazard mapping of the areas expected to be damaged by a tsunami should be drawn using the available historical data, paying attention especially to the vulnerable areas and the evacuation routes. While the densification of tsunamis warning with the installation of new seismic and sea level stations would improve the monitoring and the warning system. An early warning system allows a rapid evacuation of coastal communities in area at risk.

On receiving of the warning, the community must evacuate the area as established in the evacuation plan. In order for an evacuation plan to be effective, the population has to be aware of the hazard and of the emergency measures that have to be undertaken through the organization of awareness programs. Community preparedness is fundamental in the coastal areas, only if a community is well prepared is able to follow emergency evacuation plans and procedures. A community which choose to ignore warnings may get severely affected if it is not prepared to take immediate measures[59].

[58]Servicio Hidrográfico y Oceanográfico de la Armada de Chile, Tsunami. Las grandes olas (Chile: SHOA, 2000), 7.

[58]Servicio Hidrográfico y Oceanográfico de la Armada de Chile, *Tsunami. Las grandes olas* (Chile: SHOA, 2000), 7.

[59]Anand S. Arya, Karanth Anup and Agarwal Ankush. *"Hazards, disasters and your community: A primer for parliamentarians,"* Government of India, Ministry of Home Affairs, National Disaster Management Division (2005): 16.17. http://www.undp.org/content/dam/india/docs/hazaras_disasters_and_your_community_a_primer_for_parliamentarians.pdf.

2.3. Earthquakes and tsunamis effects

As already mentioned, looking through the historical records, local and regional tsunami proved to be the most destructive among tsunamis. The effort to mitigate their effects has been in vane in most of the cases. The impact of the seismic waves affects especially the most important infrastructures for the occupation of a territory, like transport system, waters distribution, sanitation, communication, energy and dams. The destructions and damages caused by a tsunami are the direct result of three factors: flood, impact of waves on structures and erosion, and they can be classified as direct or indirect effects[60] (see figure 17 and table 4).

[60]Comisión Oceanográfica Intergubernamental, 13.

[61]Unknown Author, "May 1960: Surviving a Tsunami. Lesson from Chile, Hawaii, and Japan", Unknown Author, National Weather Service, last accessed on April 17, 2018, https://www.weather.gov/jetstream/survive (accessed April 1, 2018).

[62]Comisión Oceanográfica Intergubernamental, 13.

Fugure 17: Effects of the Tohoku tsunami in Sendai, Japan (2011). Source: Unknown Author, National Weather Service[61].

	DAMAGES	CHARACTERISTICS
DIRECT	Floods	Flooding of houses, roads, bridges and other areas not normally covered with water.
	Construction damages	Damages to port constructions and most of the constructions and infrastructures settled in low-tide and landfill areas.
	Conduit rupture	Rupture of pipes and conduits due both to the flood impact and the abnormal quantity of water running through them.
	Damage to basic services	Lack of electricity, water, telephone line and other basic services.
	Sinking of structures and buildings	Loss of soil loses its strength and soil deformation causing the sinking of structures and consequent stress.
	Deterioration of underground constructions	Flooding and deterioration of underground construction like parking lots, metro lines, electricity and water lines.
	Damages to urban infrastructure	Damages to urban infrastructure like streets, transport system and other networks.
	Landslides, avalanches or liquefaction	Loss of strength and stiffness of the soil.
	Losses of plants and vegetation	Damages to the local vegetation, submerged and ravished by the strength of the water.
	General panic	Spreading of panic caused firstly by the earthquake and secondly by the tsunami waves on the coast.
INDIRECT	Fires	Fires caused by damages to electricity and gas lines.
	Explosions	They can be caused in fuel tanks unprovided of proper security measures, in addition to gas pipes and gas tanks used for cooking.
	Spillage of hydrocarbons	As the conduction and storage systems are affected, spills may occur.
	Epidemics	The epidemics that may be triggered after a tsunami are due to the decomposition of the bodies that arrive as the days pass and to the consumption of contaminated water.

Table 4: Tsunami effects. Source: own elaboration from Comisión Oceanográfica Intergovernmental[62].

2.5. Earthquakes and tsunamis scales

2.5.1 The Modified Mercalli Intensity Scale (MMI)

The Modified Mercalli Intensity Scale was developed in 1931 by the American seismologists Harry Wood and Frank Neumann on the basis of the Mercalli Intensity Scale drafted by Giuseppe Mercalli between 1884 and 1906. The scale, marked by Roman numerals, is composed of increasing levels of intensity that vary from undetectable shaking to ruinous destruction. It does not have mathematical basis, it is instead an arbitrary ranking based on observed effects.

The lower levels correspond to how an earthquake is perceived by the people. While the higher levels refer to verified structural damages to constructions. Therefore, the contribute of structural engineers is essential for assigning intensity values of VIII or above. The effects of an earthquake have conventionally been resumed and classified to guide an objective identification of the level of intensity[63] (see table 5).

[63]"The Modified Mercalli Intensity Scale," USGS, accessed March 21, 2018. https://earthquake.usgs.gov/learn/topics/mercalli.php.

[64]"The Modified Mercalli Intensity Scale", USGS, last accessed April 17, 2018, https://earthquake.usgs.gov/learn/topics/mercalli.php.

INTENSITY	SHAKING	AVERAGE EARTHQUAKE EFFECTS
I	Not felt	Not felt except by a very few under especially favorable conditions.
II	Weak	Felt only by a few persons at rest, especially on upper floors of buildings.
III	Weak	Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibrations similar to the passing of a truck. Duration estimated.
IV	Light	Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.
V	Moderate	Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.
VI	Strong	Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Slight damages.
VII	Very strong	Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken.
VIII	Severe	Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned.
IX	Violent	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.
X	Extreme	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent.

Table 5: The Modified Mercalli Intensity Scale. Source: USGS[64].

2.5.2. The Richter Magnitude Scale (M_L)

The Richter Magnitude Scale was developed in 1935 by Charles F. Richter, seismologist at the California Institute of Technology, who introduced the concept of earthquake magnitude. As already mentioned, the magnitude (M_L) is calculated as the logarithm of the amplitude of waves recorded by seismographs with adjustments for the variation in the distance between the various seismographs and the epicenter of the earthquakes. On the Richter Scale, magnitude is expressed in whole numbers and decimal fractions (see table 6). Because of the logarithmic basis of the scale, each whole number increase in magnitude represents a tenfold increase in measured amplitude[65].

The Richter Scale is not commonly used anymore, except for small earthquakes, with $M_L<5$, recorded locally, for which M_L and mblg are the only magnitudes that can be measured. Scientists have developed far-more sensitive seismometers that, with faster computers, have enabled them to record and interpret a broader spectrum of seismic signals. The moment magnitude uses seismograms plus what physically occurs during an earthquake, known as the "seismic moment". The seismic moment defines how much force is needed to generate the recorded waves, that information plugged into the moment magnitude scale give us the amount of energy that is released during an earthquake[66].

[65]"Richter scale," USGS, accessed March 21, 2018. https://earthquake.usgs.gov/learn/glossary/?term=Richter%20scale.

[66]"Magnitude Explained: Moment Magnitude vs. Richter Scale," Incorporated Research Institutions for Seismology, accessed April 1, 2018. https://www.iris.edu/hq/inclass/animation/magnitudes_moment_magnitude_explained.

[67]Glen Brown, "2008 U.S. Event Hazards Rating Map", Tulsa Geology Society, last accessed April 17, 2018, www.tulsageology.org/_literature_127154/Glen_Brown.

MAGNITUDE	DESCRIPTION	AVERAGE EARTHQUAKE EFFECTS
1.0 -1.9	Micro	Microearthquakes, not felt, or felt rarely. Recorded by seismographs.
2.0 - 2.9	Minor	Felt slightly by some people. No damage to buildings.
3.0 - 3.9	Minor	Often felt by people, but very rarely causes damage. Shaking of indoor objects can be noticeable.
4.0 - 4.9	Light	Noticeable shaking of indoor objects and rattling noises. Felt by most people in the affected area. Slightly felt outside. Generally, causes none to minimal damage. Moderate to considerable damage very unlikely. Some objects may fall off shelves or be knocked over.
5.0 -5.9	Moderate	Can cause damage of varying severity to poorly constructed buildings. At most, none to slight damage to all other buildings. Felt by everyone.
6.0 – 6.9	Strong	Damage to a moderate number of well-built structures in populated areas. Earthquake-resistant structures survive with slight to moderate damage. Poorly designed structures receive moderate to severe damage. Felt in wider areas; up to hundreds of miles/kilometers from the epicenter. Strong to violent shaking in epicentral area.
7.0 - 7.9	Major	Causes damage to most buildings, some to partially or completely collapse or receive severe damage. Well-designed structures are likely to receive damage. Felt across great distances with major damage mostly limited to 250 km from epicenter.
8.0 - 8.9	Great	Major damage to buildings, structures likely to be destroyed. Will cause moderate to heavy damage to sturdy or earthquake-resistant buildings. Damaging in large areas. Felt in extremely large regions.
9.0 - greater	Great	At or near total destruction – severe damage or collapse to all buildings. Heavy damage and shaking extends to distant locations. Permanent changes in ground topography.

Table 6:
The Richter Scale.
Source:
Glen Brown[67].

2.5.3. Moment Magnitude Scale (M_W)

The Moment Magnitude Scale is a seismic magnitude scale used to measure the size of earthquakes. It was developed in the 70's as successor of the Richter magnitude scale (M_L) to obtain more reliable results in case of very large earthquakes, more specifically with M_L>=7. Since January 2002, the United States Geological Survey started using this scale to calculate and report magnitudes for all modern earthquakes . The scale compares the magnitude released during the earthquake to the energy released by explosive (see table 7).

[68]"USGS Earthquake Magnitude Policy (implemented on January 18, 2002)," USGS, accessed on April 5, 2018, https://web.archive.org/web/20160428095841/http://earthquake.usgs.gov:80/aboutus/docs/020204mag_policy.php.

[69]USGS in "Seismic waves," Earth Science, accessed April 5, 2018, http://earthscience.xyz/SeismicWaves.

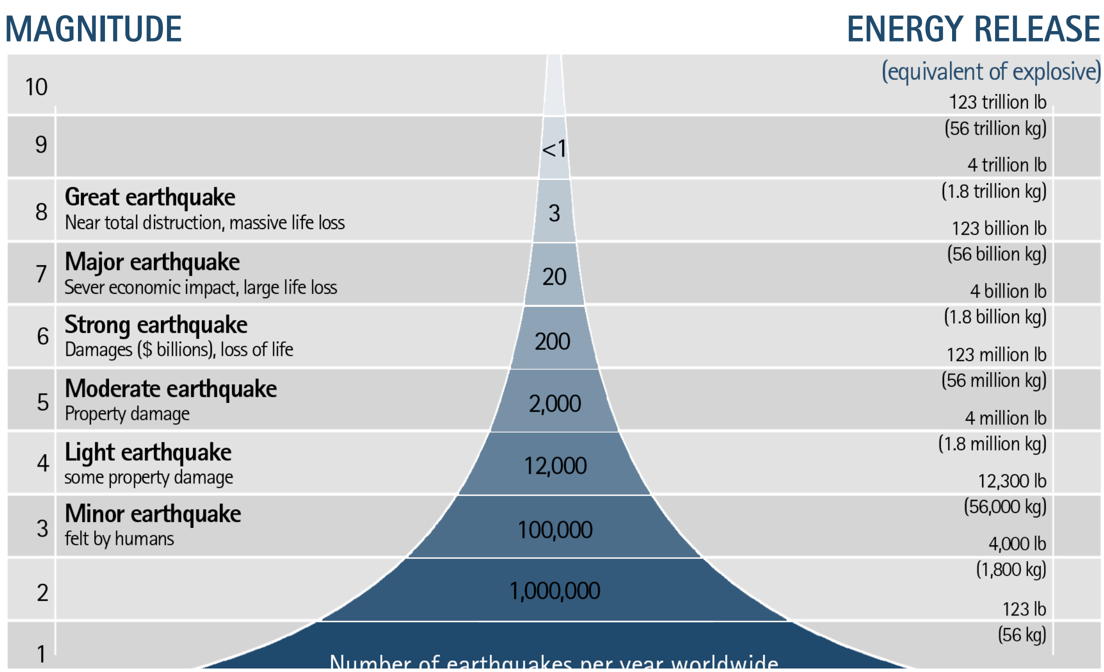


Table 7: Moment Magnitude Scale. Source: own elaboration from USGS[69].

2.5.4. Modified Sieberg Sea-wave Intensity Scale

The Modified Sieberg Sea-wave Intensity Scale is a descriptive tsunami intensity scale elaborated by Sieberg-Ambraseys in 1962 on the basis of the Sieberg scale (1923). It measures the intensity of a tsunami trough the macroscopic observation of a tsunami's effect on humans, objects, and buildings[70] (see table 8).

[70]"Surveys and measurements," International Information Tsunami Center, Accessed March 18, 2018. http://itic.ioc-unesco.org/index.php?option=com_content&view=article&id=1022:8&catid=1142&Itemid=2433.

[71]S.L. Soloviev, "Tsunamis" in *The Assessment and Mitigation of Earthquake Risk*, ed. United Nations Educational, Scientific and Cultural Organization (Paris: NICI, 1978), 131.

INTENSITY	DESCRIPTION	AVERAGE TSUNAMI EFFECTS
I	Very slight	Wave so weak as to be perceptible only on tide-gauge records.
II	Slight	Wave noticed by those living along the shore and familiar with the sea. On very flat shores generally noticed.
III	Rather large	Generally noticed. Flooding of gently sloping coasts. Light sailing vessels or small boats carried away on shore. Slight damage to light structures situated near the coast. In estuaries reversal of the river flow some distance upstream.
IV	Large	Flooding of the shore to some depth. Light scouring on man-made ground. Embankments and dikes damaged. Light structures near the coasts damaged. Solid structures on the coast injured. Big sailing vessels and small ships carried inland or out to sea. Coasts littered with floating debris.
V	Very large	General flooding of the shore to some depth. Breakwater walls and solid structures near the sea damaged. Light structures destroyed. Severe scouring of cultivated land and littering of the coast with floating items and sea animals. Except for big ships all other type of vessels carried inland or out to sea. Big bores in estuary rivers. Harbor works damaged. People drowned. Wave accompanied by strong roar.
VI	Disastrous	Partial or complete destruction of man-made structures for some distance from the shore. Flooding of coasts to great depths. Big ships severely damaged. Trees uprooted or broken. Many casualties.

Table 8: The Modified Sieberg Sea-wave Intensity Scale. Source: S.L. Soloviev[71].

3

GEOGRAPHY AND NATURAL DISASTERS OF CHILE

3.1. Geography of Chile

Chile is located on the western edge of South America. It borders the Pacific Ocean to the west, Peru to the north, Bolivia to the north east, Argentina to the east and the Atlantic Ocean to the south (see figure 19). It stretches from the 17° to the 56° parallel South with a total area of 756,102km^2, including Easter Island (Isla de Pascua) and Isla Sala y Gomez[72]. Chile has a North-South extension of 4,270km (2,653mi), and an East-West average extension of 177km (110mi).

The Nazca Plate borders with two-thirds of Chile and moves about 10cm per year, shifting eastward under the continental plate of South America (see figure 20). The Peru-Chile Trench is the result of this continuous movement, which, with its 150km of width and an average of 5,000m of depth, lies beyond a narrow band of coastal waters off northern Chile and central Peru. It reaches its deepest point of 8,066m a little north from the port of Antofagasta. Even if the mass of water of the ocean hides this fact, most of Chile lies on the edge of a steep cliff.

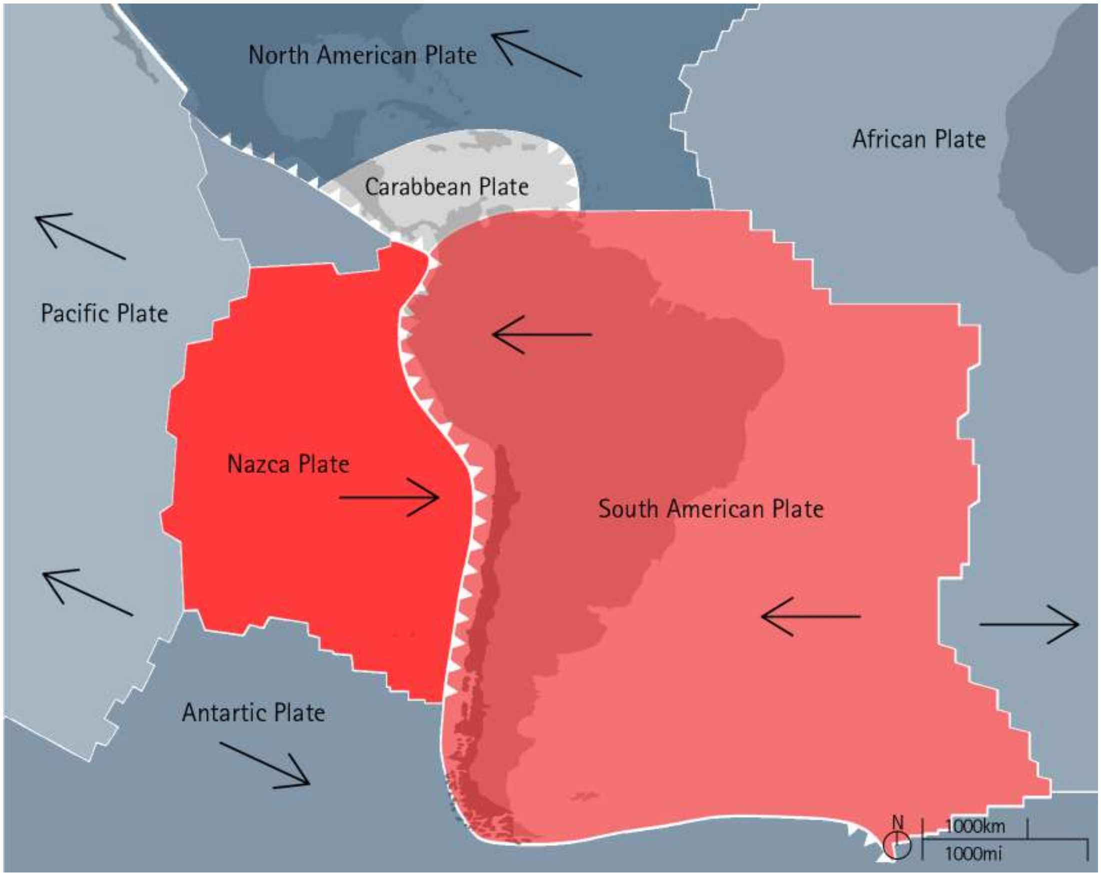
The continuous crash between the Nazca and the South American plate generated the Andes, a geologically young mountain range. Only in Chile, it includes about 620 volcanoes, many of which still active. Almost sixty of them erupted in the 20th century. Therefore, it is not surprising if more than half of Chile's land surface has a volcanic origin and mountains occupy about 80% of it.

The Andes are not the only mountain range in Chile. The non-Andean mountains are part of transverse and coastal ranges. The transverse ranges are mostly located in the Near and Far North, with various shapes and extensions from the Andes to the ocean, creating valleys with an E-W direction. The costal ranges can be found in the center of the country where they form the Central Valley which extends between them and the Andes. In the Far South. At this latitude, the higher elevations of the coastal range

[72] "South America: Chile", Central Intelligence Agency, last modified on April 4, 2018, https://www.cia.gov/library/publications/the-world-factbook/geos/ci.html.

[73] "Chile map reference", Index Mundi, last modified on January 20, 2018, https://www.indexmundi.com/chile/map_references.html.

Figure 19:
Chile in South
America.
Source:
own elaboration from
Index Mundi[73].



▲▲ Destructive margin
Constructive margin
Conservative margin
Plate movement direction

Figure 20:
CTectonic plates of South America
Source:
own elaboration from Humberto Del Busto[74].

turn into a variety of islands, originating channels and fjords.

Most of the Chilean coastline is rugged but still rich in beaches of various lengths and beauty, some of which surrounded by cliffs. The Humboldt current, originated on northwest of the Antarctic Peninsula (in the Bellingshausen Sea), runs up the full length of the coast (see figure 21). This current is the reasons why the ocean's water temperature remains frigid all year around. In the central part of the country, the water does not get warmer than 15° C even in summer[75].

[74]Humberto Del Busto et al., "Análisis de riesgo en el diseño de hospitales en zonas sísmicas." (Organización Panamericana de la Salud, 1989), 36, http://helid.digicollection.org/es/d/J049s/.

[75]Rex A. Hudson, *Chile: A Country Study* (Washington: GPO for the Library of Congress, 1994), http://countrystudies.us/chile/.

[76]Alejandra Mora, "Humboldt Current", Universidad Academia de Humanismo Cristiano, accessed March 23, 2018, http://www.geoacademia.cl/geonuevo/puntos-de-vista/.

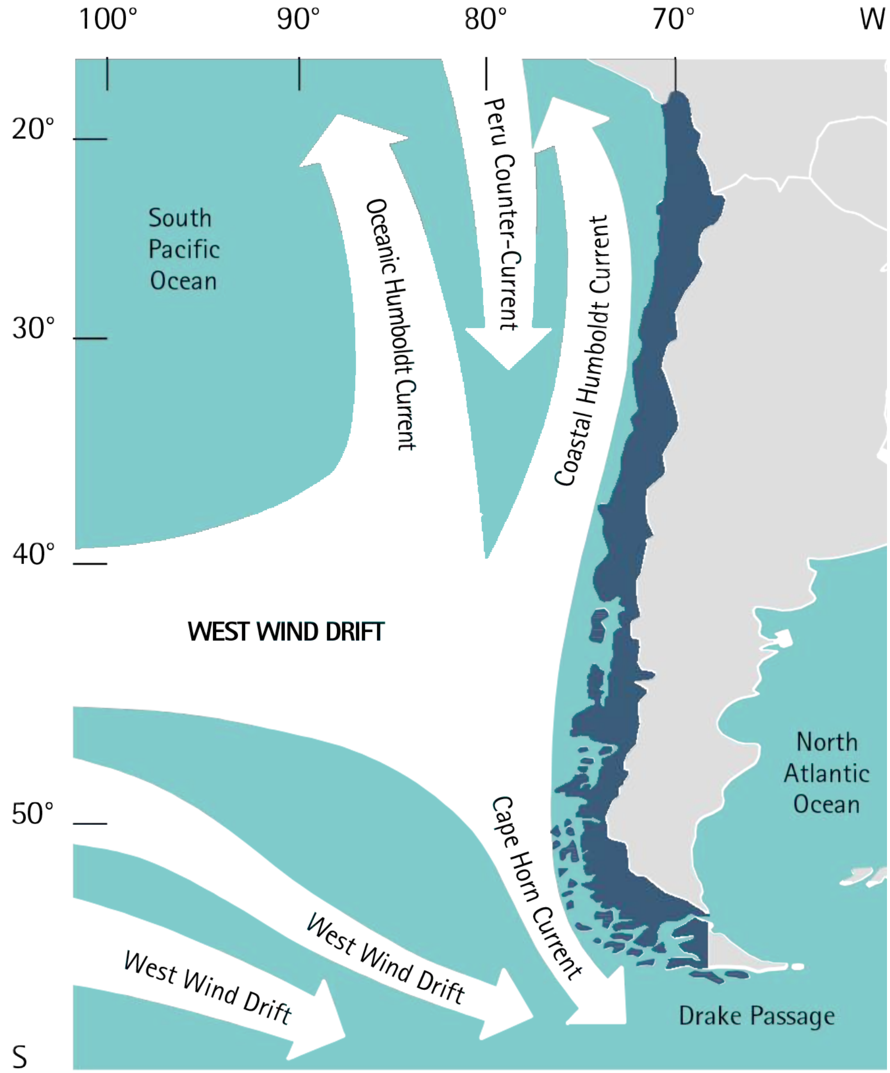


Figure 21: The Humboldt Current. Source: own elaboration from Alejandra Mora[76].

3.1.1. Natural division

Chile extends from approximately 625km North of the Tropic of Capricorn to a 1,400km North of the Antarctic Circle. Its territory hosts a wide diversity of Earth's climates. Geographically it is possible to talk about several different Chiles. The country usually is divided into five geographic regions: The Far North, the Near North, Central Chile, the South, and the Far South (see figure 22). Each region has its own characteristics flora, fauna, climate, and topography (see table 9).

Table 9:
Natural Regions of Chile.
Source:
Own elaboration from Rex A. Hudson[78].

[77]Rex A. Hudson, Chile: A Country Study, (Washington: GPO for the Library of Congress, 1994), http://countrystudies.us/chile/.

[78]Ibid, 8.

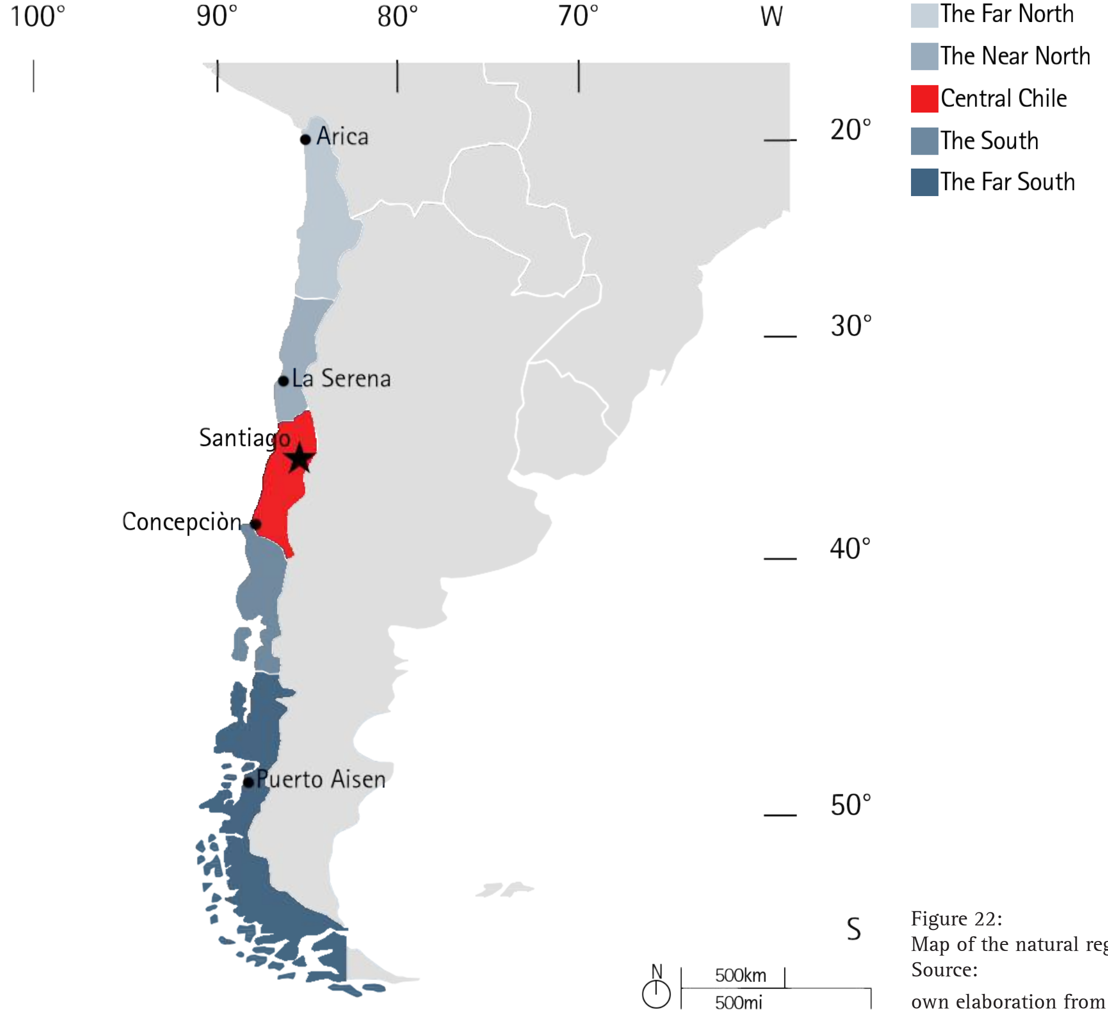


Figure 22:
Map of the natural regions of Chile.
Source:
own elaboration from Rex A. Hudson[77].

GEOGRAPHIC REGIONS	ADMINISTRATIVE REGIONS	GEOGRAPHIC REGIONS
The Far North	I: Arica & Parinacota	The Far North (Norte Grande) extends from the Peruvian border to the Copiapó River. It is an arid region, it hosts the Atacama Desert, one of the driest areas in the world. The average monthly temperatures at sea level is about 20.5° C during summer and 14° C during winter. Most of the population inhabit the coast.
	II: Tarapacá	
	III: Antofagasta	
	IV: North Atacama	
The Near North	IV: South Atacama	The Near North (Norte Chico) extends from the Copiapó River to about the 32° South, just North of Santiago. It is a semiarid region, the central area registers an average rainfall of about 25mm per month during the winter season, therefore it is often subjected to droughts. The temperatures are moderate, with an average temperature at sea level of 18.5° C in summer and 12° C in winter, at sea level.
	V: Coquimbo	
	VI: North Valparaíso	
Central Chile	VI: South Valparaíso	Central Chile (Chile Central) hosts the three major metropolitan areas: Santiago, Valparaíso, and Concepción. It extends from about the 32° parallel South to about the 38° parallel South. Its climate is similar to the Mediterranean climate with a matoral vegetation. The Andes run through the region together with the Coastal range. Between the two ranges takes form a fertile intermediate depression.
	VII: Santiago	
	VIII: O'Higgins	
	IX: Maule	
	X: North Bío-Bío	
The South	X: South Bío-Bío	Southern Chile goes from the Bío-Bío River at about 38° parallel South to below Chiloe Island at the 43.4° parallel South. This is the lake district of Chile, the valley between the Andes and the Coastal range is near to the sea level, the hundreds of rivers that descend from the Andes form lakes of different extensions. It is one of the rainiest areas in the world. With Valdivia being one of the wettest zones, with an average annual rainfall of 2,535.4mm.
	XI: Araucanía	
	XII: Los Ríos	
	XIII: North Los Lagos	
The Far South	XIII: South Los Lagos	The Far South (Chile Austral) extends from the 43° parallel South to Cape Horn at the 44° parallel South. The continental coastline is rich in inlets and fjords. The rest of the regions is made up of thousands of islands forming numerous archipelagos crossed by narrow channels. The northern part of the Far South still registers a lot of precipitations on the contrary of the most southern part.
	XIV: Aisén Region	
	XV: Magallanes	

3.1.1.1. Central Chile

Central Chile hosts the majority of the population split in three main metropolitan areas: Santiago, Valparaíso and Concepción. Due to its latitude, the climate is temperate and similar to the Mediterranean one. The amount of precipitation increases drastically and progressively from a semi desertic North to the rainy South.

In the Santiago area, the average temperature is 19.5°C in the summer months of January and February, and 7.5°C in the winter ones, June and July. The average monthly rainfall is close to 0mm in summer and about 69mm in winter. On the contrary, in Concepción, the average monthly temperatures are lower in summer with an average 17.6°C but higher in winter with an average of 9.3°C, and it receive a greater amount of rain: with a monthly average of 20mm in summer and 253mm in winter. The numerous rivers of the region considerably increase their flow during the winter rains and during spring for the melting of the Andean snows, while they remarkably shrink during summer.

In Central Chile, the Coastal Range runs parallel to the Andes. The Central Valley takes form between the two mountain ranges, it contains some of the most productive agricultural land of the country, especially in the northern area (see figure 23). In the North and the South of Santiago there is a large production of fruits, including the grapes used to produce the best Chilean wines. Another great variety of agricultural lands can be found in the southern part of the region.

Most of the southern lands, today used for agriculture, were originally covered with old-growth forests. After being cleared for agriculture they soon got exhausted of their organic matter and left to deteriorate. Large parts of this worn-out land have been reforested with lumber trees to support the cellulose and paper industries. During the 80s, new investments in the industries drastically transformed the rural economy of this region.

The pre-Andean highlands and some of the highest mountains in the Coastal Range (especially the Cordillera de Nahuelbuta) still host large parts of old-growth forests. Due to their remarkable beauty, some of these forests have been turned into national parks to protect the land from overexploitation. The areas between the Coastal Range and the Ocean, are lower than the Central Valley and generally quite flat (see figure 24). It is in this section that the longest beaches stretch[79].

[79] Ibid, 13.

[80] "Geomorfologia de Chile," last accessed April 14, 2018, http://www.mediateca.cl/900/chile/relieve/region%20de%20valparaiso.htm.

[81] "Mapa físico de Chile 33 - 36 grados", last accessed April 12, 2018, http://ww2.educarchile.cl/Portal.Base/Web/verContenido.aspx?ID=130639.

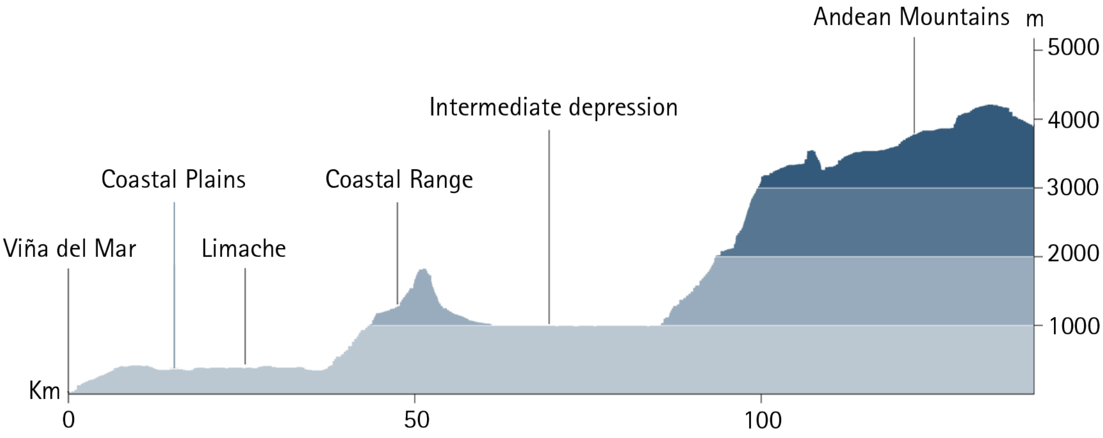


Figure 23: Transverse profile W-E at 33° parallel South. Source: own elaboration from Mediateca[80].

Figure 24: Central Chile physical map. Source: EducarChile[81].

3.2. Natural Hazards in Chile

Natural hazards in Chile are common phenomena due to its geological, climatic, morphologic and topographic characteristics. Together with its localization in the southwestern margin of the South American continent, the country is exposed in all its extension to the catastrophic effects of different kind of natural hazards. It is recognized by the scientific community as one the countries with higher seismicity due to the interaction of the Nazca and South American plates, with an average of a destructive earthquake every ten years.

Together with the seismic hazard, Chile has a significant volcanic activity counting more than three-dozens of active volcanoes along the Andes Range. The Lascar volcano (5,592m) is the most active volcano in Northern Chile and it last erupted in 2007. Among the other most active volcanoes, the Llaima (3,125m) in Central Chile, last erupted in 2009, and the Chaiten in 2008 forced major evacuations of the area. Other notable active volcanoes are Cerro Hudson, Calbuco, Copahue, Guallatiri, Llullaillaco, Nevados de Chillan, Puyehue, San Pedro, and Villarrica[82] (see figure 25).

Droughts represent another hazard affecting the population, especially in the northern regions. These droughts are mostly due to a change of currents known as El Niño and La Niña which are opposite phases of a larger climate cycle called the El Niño-Southern Oscillation (ENSO)[83]. The first one tends to favor cooler, wetter conditions while the second one bring warmer and drier weather. This change is not only the cause of droughts, during the winter months it causes strong storms and high waves along the coast.

[82]"South America: Chile", Central Intelligence Agency, last modified on April 4, 2018, https://www.cia.gov/library/publications/the-world-factbook/geos/ci.html.

[83]"What are El Niño and La Niña?," National Oceonographic and Atmospheric Administration, accessed April 28, 2018, https://oceanservice.noaa.gov/facts/ninonina.html.

[84]"Explain the distribution of Earthquakes and Volcanoes," last accessed April 14, 2018, https://www.tes.com/lessons/T8RW2V9EZsOWqg/explain-the-distribution-of-earthquakes-and-volcanoes.

Figure 25:
Active volcanoes of Chile.
Source:
own elaboration from TesTeach[84].

3.2.1. Earthquakes and tsunamis in Chile

The same telluric displacements of the Nazca Plate that originated the Peru-Chilean Trench is the reason why Chile is highly prone to earthquakes. During the 20th century, it has been struck by twenty-eight major earthquakes, all with a magnitude greater than 6.9 on the Richter scale. The strongest in the Pacific Rim were registered in 1906, with estimated magnitude of 8.4 on the Richter scale, and in 1960 with 9.5 on the Richter scale[85]. Earthquakes are the main mechanism generating tsunamis, therefore Chile is highly exposed to the phenomenon, especially considering the continuous urban and rural growth of coastal towns (see figure 26).

The tendency to urbanize areas very close to the sea, is characterized by its scarce planning and objective ordering in terms of such threat[86]. Local tsunamis, generated close to the coastline, are the main responsible for damages in Chile, and the most dangerous due to the rapidity with which they can reach the shore. Tele-tsunamis, as well, generated in remote regions of the Pacific, have proven to cause significant impact on the national coastline, even if less frequently. It is the case, for example, of the Japan tsunami of 2011 that reached the coast of Dichato, in the Bío-Bío Region, destroying the coastal infrastructures. The concern for the study of tsunamis, in various parts of the world, has been strengthened due to the recent destructive consequences of phenomena of this nature.

During the 90s twelve events of important magnitude were registered in Chile with a balance of 4,347 deaths and more than one billion dollars of property damages[87]. Even if most of the events between 1975 and 2000 occurred along the boundary of the Eastern-Asian coastal regions Asia and Oceania due to the high amount of convergent plates edges existing in the area; the American coasts have not been exempted. The activity generating tsunamis is concentrated in the convergent zone of the Cocos Plate with the North American and Caribbean Plates, affecting

[85]Rex A. Hudson.

[86]Marcelo Lagos López, "Tsunamis de origen cercano a las costas de Chile." Rivista de Geografia Norte Grande, 27, (2000): 94.

[87]Intergovernmental Oceanographic Commission, UNESCO, "Master Plan. Tsunami Warning System in the Pacific", Second Edition, (2000): 32 http://unesdoc.unesco.org/images/0011/001177/117788e.pdf.

[88]"Index of tsunami Peru Pictures," last accessed April 15,2018, http://earthweb.ess.washington.edu/tsunami/Peru/Picture/Smjpg/.

Figure 26:
The cost of
Valparaíso and
Vina del Mar.
Source:
Eleonora F. Serpi

Figure 27:
Tsunami Peru 1996.
Source:
University of
Washington[88].

the coasts of Mexico in 1995 and Nicaragua in 1992. Meanwhile, the subduction zone that involves the Nazca and South American Plates has produced two important events, affecting the coasts of Peru in 1996 (see figure 27) and Colombia in1979.

Since the arrival of the Spanish conquerors 1562, Chile has a written record of the greater tsunamis. Between 1550 and 1800 an average of thirteen events were recorded every fifteen years. Between 1800-1900 the records increased to 21 events every fifteen years, with more than one tsunami per year, while between 1900 and 2000, 68 tsunamis were recorded with minor damages.

This significant increase does not correspond to an increase in frequency of the phenomenon, but it is justified by the development of instruments capable of detecting it. Considering the total of tsunamis, only 3.9% of them had intensity VI on the Modified Sieberg Sea-wave Intensity Scale, represented by the events of 1730, 1868, 1877 and 1960[89]. While the events with magnitude with intensity I on the Modified Sieberg Sea-wave Intensity Scale, represent 64.7% of the tsunamis occurring every 5,6 years. This statistic confirms the low frequency of destructive events compared to the non-destructive one[90].

[89]Marcelo Lagos López, "Tsunamis de origen cercano a las costas de Chile." Rivista de Geografia Norte Grande, 27, (2000): 96-97.

[90]Marcelo Lagos López, 97.

3.2.1.1 The Great Chilean Earthquake, May 22nd, 1960

The strongest earthquakes registered in Chile are dated 1906, with estimated magnitude of ML=8.4 on the Richter scale, and 1960 with ML=9.5 on the Richter scale. The latter one, often referred as the Great Chilean earthquake (Gran terremoto de Chile) occurred on May 22nd, during a larger sequence of strong earthquakes that affected Chile between the 21st May and 6th June of1960. The first one with magnitude of ML=8.1 on the Richter scale struck Concepción while the strongest was recorded in Valdivia[91]. It occurred in the afternoon (19:11 GMT, 15:11 local time), and lasted approximately 10 minutes.

The resulting tsunami affected southern Chile, Hawaii, Japan, the Philippines, eastern New Zealand, southeast Australia and the Aleutian Islands[92]. The epicenter of this megathrust earthquake was registered near Lumaco, approximately 570km (350mi) south of Santiago, with Valdivia being the most affected city of all Chile (see figure 28). Localized tsunamis severely battered the Chilean coast, with waves up to 25m (82 ft). The main tsunami raced across the Pacific Ocean and devastated Hilo, Hawaii. Waves as high as 10.7m (35ft) were recorded 10,000km (6,200mi) from the epicenter, and as far away as Japan and the Philippines.

The Chilean coast was devastated by a tsunami from Mocha Island (38° parallel South) to the Aysén Region (45° parallel South). Across southern Chile the tsunami caused numerous life losses, damages to port infrastructures and boats (see figure 29). The exact death toll and monetary losses arising from this widespread disaster are not certain. Various estimates have been published, ranging between 3,000 and 5,7000 deaths, while the monetary cost ranged between US$417 million to US$800 million .

[91]Rex A. Hudson.

[92]Kenji Satake, and Brian F. Atwater. “Long-term perspectives on giant earthquakes and tsunamis at subduction zones.” *Annual Review of Earth Planetary Sciences* 35, (2007): 349-374. https://doi.org/10.1146/annurev.earth.35.031306.140302.

[93]“1960 Chile Earthquake’s Exponential Effects,” last accessed April 15, 2018, https://history.libraries.wsu.edu/fall2014/2014/08/29/earthquake-disrupts-chile/.

[94]“The Largest Earthquakes in the World,” last modified October 17, 2003, https://web.archive.org/web/20070107005353/http://neic.usgs.gov/neis/eq_depot/world/1960_05_22_articles.html.

Figure 28:
Valdivia Earthquake,
1960.
Source:
University of
Washington[93].

Figure 29: Tsunami in Valdivia, 1960. Source: University of Washington[94].

3.2.1.2. 27F, Earthquake February 27th, 2010

The 2010 Chile Earthquake, commonly referred as 27F, began on February 27th, 2010 at 3:34 am (06:34 UTC). The earthquake originated in the Chilean subduction zone, where the Nazca Plate is subducted under the South American Plate. The epicenter of the 8.8MW earthquake was registered offshore from the Maule Region, approximately 105km (65mi) north-east of Concepción, one of Chile's most populated cities (see figure 30). It is the second strongest earthquake recorded in the history of the country after the Valdivia earthquake in 1960, and one of the ten strongest recorded worldwide.

The section of fault that moved during the earthquake was 450-500km (280-310mi) long and about 100km (60mi) wide. The rupture propagated both north, towards the capital Santiago, and south towards Concepción. The highest intensity, IX on the Modified Mercalli Intensity Scale, was recorded on the coast, at the town of Constitución, in the north of the epicenter. An intensity of VIII on the Modified Mercalli Intensity Scale was registered in Concepción, while an intensity VI on the Modified Mercalli Intensity Scale in Santiago[95].

This earthquake affected areas populated by nearly thirteen million inhabitants, more than 75% of the total population causing hundreds of fatalities. 15,000 jobs were lost and close to 3% of the Chilean population fell below the poverty line. Hundreds of thousands of houses were severely damaged and more than 200,000 families found themselves without a home. In economic terms, the earthquake caused damages for US$30 billion that can be divided into US$10,357 million in private infrastructure, US$10,538 million in public infrastructures and about US$9,000 million of losses in goods and services not due to the earthquake (see table 10). The tsunami generated by the earthquake that reached the shore near the epicenter within minutes from the shake, created waves of 2.3m on the Chilean coast of Talcahuano[96]. The archipelago of Juan Fernandez, about 700km off the coast, was strongly damaged and the Marquises Islands were affected by several waves of 2-4m high[97]. After crossing the Pacific Ocean, waves of 1,2m high were reported in Japan, causing coastal floods. The alert systems

[95] USGS, "Report on the 2010 Chilean Earthquake and Tsunami Response," USGS publications, 2011, https://pubs.usgs.gov/of/2011/1053/of2011-1053.pdf.

[96] "Mw 8.8 Off Shore Maule, Chile on 27/02/2010 at 06:34 UTC", last modified on February 27, 2010 https://www.emsc-csem.org/Earthquake/167/Mw-8-8-Off-Shore-Chile-27-02-2010

[97] Ibid.

[98] "M 8.8 - offshore Bio-Bio, Chile," USGS, last accessed April 5,2018, https://earthquake.usgs.gov/earthquakes/eventpage/official20100227063411530_30#map.

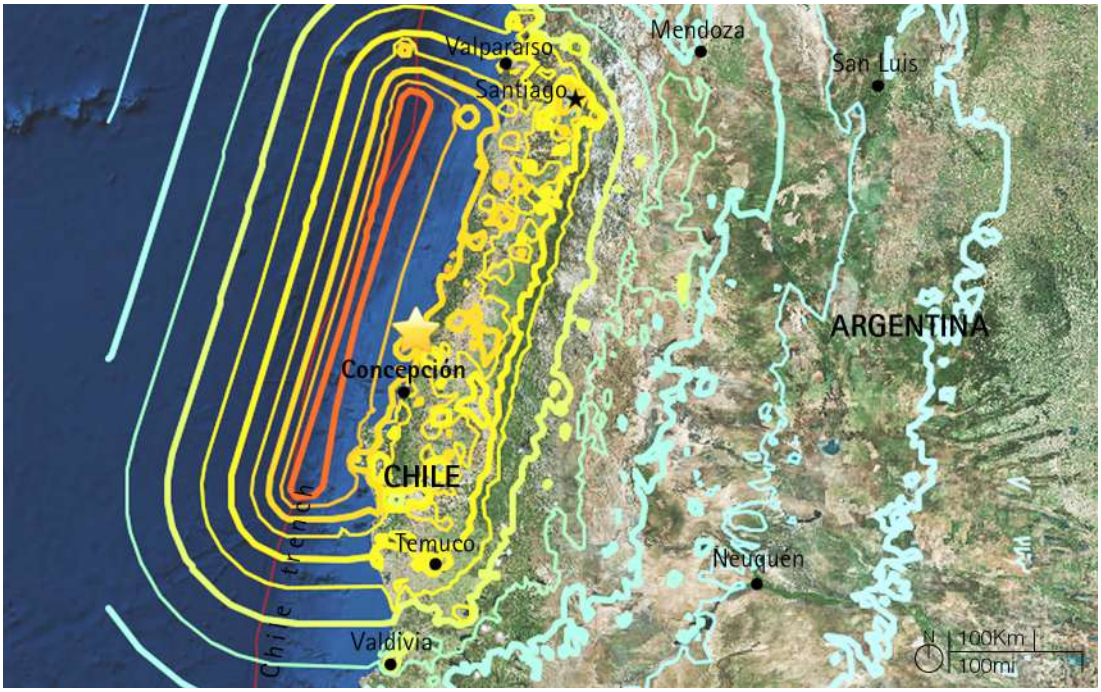


Figure 30:
27F Earthquake Map.
Source:
own elaboration from
USGS[98].

in place provided information for the evacuation of the population in several regions, including Easter Island, Samoa, American Samoa and Japan[99].

The tsunami affected six regions of the country causing the death of 181 people, equivalent to one third of the total life losses[100]. A positive correlation has been found between the runup and the percentage of victims in the affected localities[101]. Scouring damages were recorded at least in 16 points on coastal roads.

It damaged nearly 17,000 homes were and 41 major coastal structures were destroyed. Approximately 3,000 boats were damaged, corresponding to about 20% of the total number of boats registered, with small fishermen boats being the most affected. The impact on the fishing industry was strong enough to cause the reduction of 17% in the tons of landings compared to the previous year[102].

[99]"Mw 8.8 Off Shore Maule, Chile on 27/02/2010 at 06:34 UTC", last modified on February 27, 2010

[100]Manuel Contreras and Patricio Winckler "Pérdidas de vidas, viviendas, infraestructura y embarcaciones por el tsunami del 27 de Febrero de 2010 en la costa central de Chile", Obras y Proyectos, no.14, 2013, http://dx.doi.org/10.4067/S0718-28132013000200001.

[101]Ibid.

[102]Ibid.

[103]USGS, "Report on the 2010 Chilean Earthquake and Tsunami Response."

Deaths	521 people
Missing Persons	56 people
Homes destroyed or damaged	~370,000 (11% of the total in the area)
Hospitals destroyed or damaged	73
Bridges destroyed or damaged	221
Schools destroyed or damaged	3,049 schools, housing 1.25 million students
Coastal communities affected	More than 900
Estimated economic losses	US$30 billion. 17% of GDP

Table 10:
Summary of damages and losses from February 27, 2010.
Source:
USGS[103].

4

TSUNAMI LOAD EFFECTS ON STRUCTURES

4.1. Tsunami loadings

Tsunamis can generate forces strong enough to decrease the structures capacity to withstand failure. These loads can be resumed in: lateral hydrostatic forces, buoyant or vertical hydrostatic forces, hydrodynamic forces, impulsive or surge forces, debris impact forces, debris damming forces, uplift forces, additional gravity loads from retained water on elevated floors and breaking waves[104] (see figure 30). Not all the above loads will affect a particular structure or structural component simultaneously. Different scenarios might occur based on phenomenon siting, structural system and design. Therefore, other parameters have to be considered to evaluate a building capacity, such as tsunami inundation and flow characteristics at the building site, building shape, effect of building water tightness, type and depth of foundations, and soil characteristics[105].

[104]Federal Emergency Management Agency FEMA P-646, Guidelines for design of structures for vertical evacuation from tsunamis, Second Edition (Washington D.C.: U.S. Department of Homeland Security: 2012), 78.

[105]Ibid, 94.

[106]Harry Yeh, Andre R. Barbosa, Harrison Ko, and Jessica Cawley, "Tsunami Loadings on structures: Review and analysis," Coastal Engineering Proceedings 1, no. 34 (2014), 2.

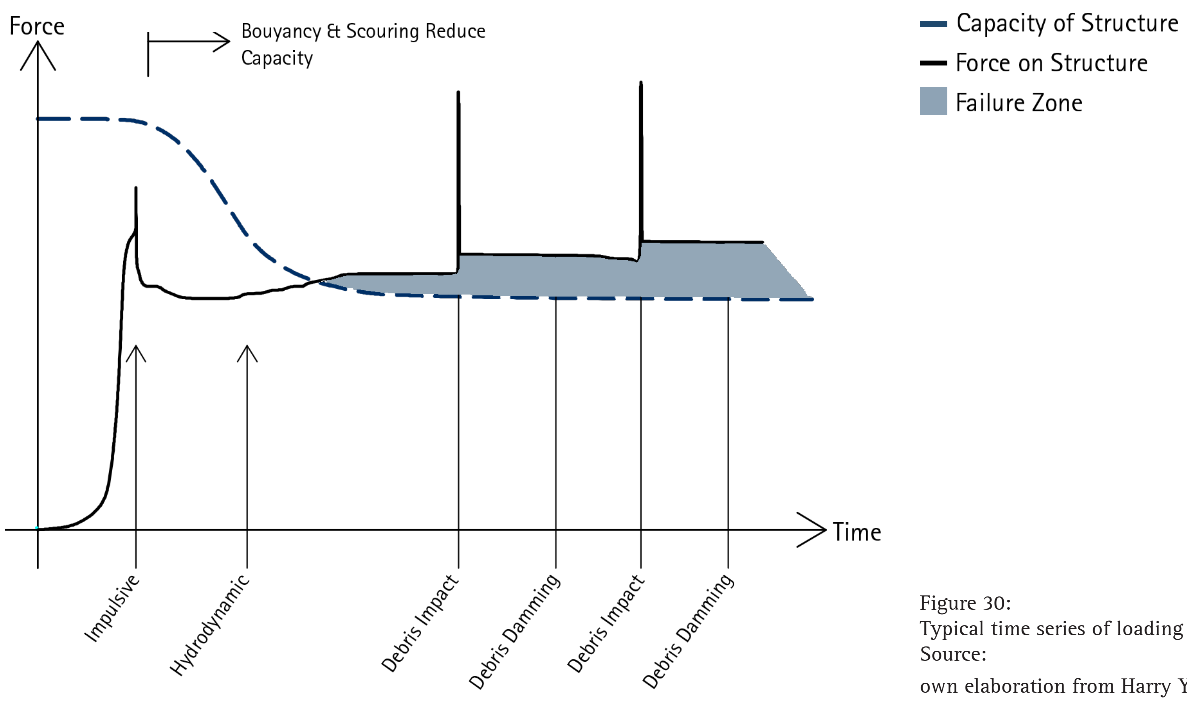


Figure 30:
Typical time series of loading and capacity.
Source:
own elaboration from Harry Yeh, et al.[106].

4.1.1. Lateral hydrostatic forces

Lateral hydrostatic loads are generated by a standing, or slowly moving, mass of water applied to a surface, like a wall or floor slab. These forces are always perpendicular to the affected surface and they are caused by an imbalance of pressure due to different water levels on opposite sides of the structure or component (see figure 31). Hydrostatic forces may not cause significant damages to structures with a limited width, around which the water can easily flow but they have a great effect on long structures like sea walls and dikes, where the water depth on one side is very different from the water depth on the other side. Since the water pressure increases linearly with the water depth, the hydrostatic loads increase with the square of the water depth[107].

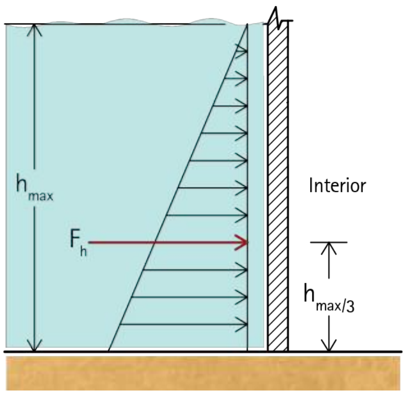


Figure 31:
Hydrostatic force distribution and location of resultant.
Source:
own elaboration from FEMA[108].

4.1.2. Buoyant or vertical hydrostatic forces

Buoyant or vertical hydrostatic forces act vertically on partial or total submerged structures or structural components (see figure 32). The total buoyant force equals the weight of water displaced reducing the net structural body force and any opposing forces resisting flotation. It must be resisted by the weight of the component, therefore has a stronger impact on light structures with minor resistance to upward forces like light wood frame buildings, basements, swimming pools and components designed considering only gravity loads[109](see figure 33). To reduce the hydrostatic forces and potential uplift of the building it is recommended that all nonstructural walls at the lower levels of the building be designed as breakaway walls[110]. The effects of buoyancy forces depend on the duration and depth of a tsunami inundation, and the burial depth of the building[111].

[107]Federal Emergency Management Agency, *FEMA P-646, Guidelines for design of structures for vertical evacuation from tsunamis*, 80-81.

[108]Ibid, 82.

[109]Ibid, 82.

[110]Ibid, 130.

[111]Harry Yeh, Andre R. Barbosa, Harrison Ko, and Jessica Cawley, "Tsunami Loadings on structures: Review and analysis," *Coastal Engineering Proceedings* 1, no. 34 (2014), 1.

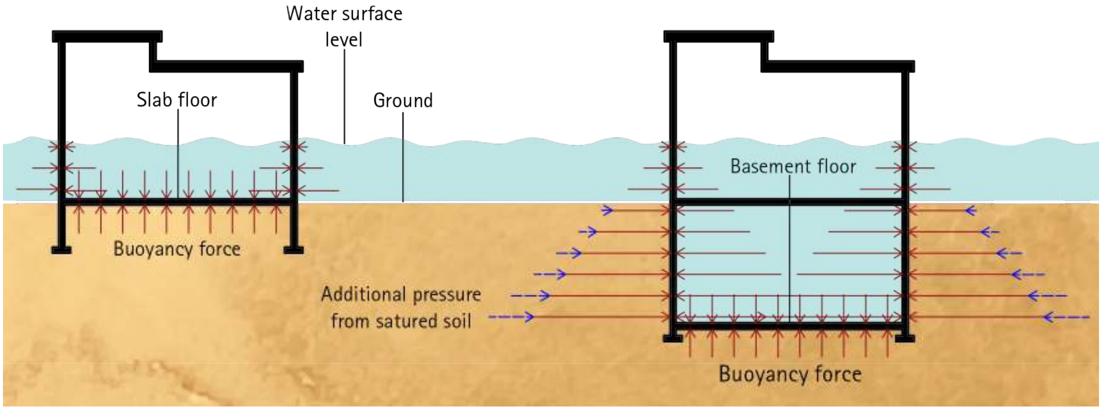


Figure 32:
Lateral and vertical hydrostatic pressure on building.
Source:
own elaboration from FEMA[112]

Figure 33:
Effects of buoyancy forces on a wooden structure house in Jolts, Japan (2011).
Source:
U.S. Air Force / Handout[113].

4.1.3. Hydrodynamic forces

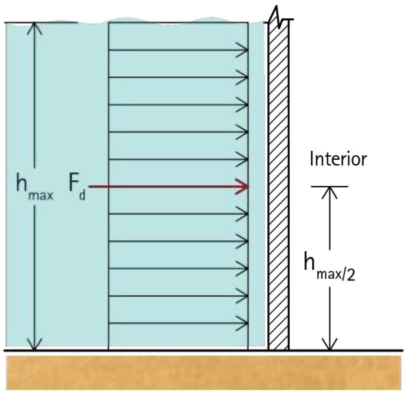


Figure 34:
Hydrodynamic force distribution and location of resultant.
Source:
own elaboration from FEMA[115].

Hydrodynamic forces are generated by the water flowing at moderate and high velocity against and around a structure. They are applied both to the structure, considered as a whole, and to individual structural components, originating positive frontal pressure against the structure, drag effect along the sides, and negative pressure in the downstream side (see figure 34). These forces are the result of a function considering fluid density, flow velocity and structure geometry. They are the compound of the lateral pressure forces, from the moving mass of water, and the friction forces generated as the water flows around the structure or component. The resultant force acts approximately at half the distance of the design still water level[114](see figure 35).

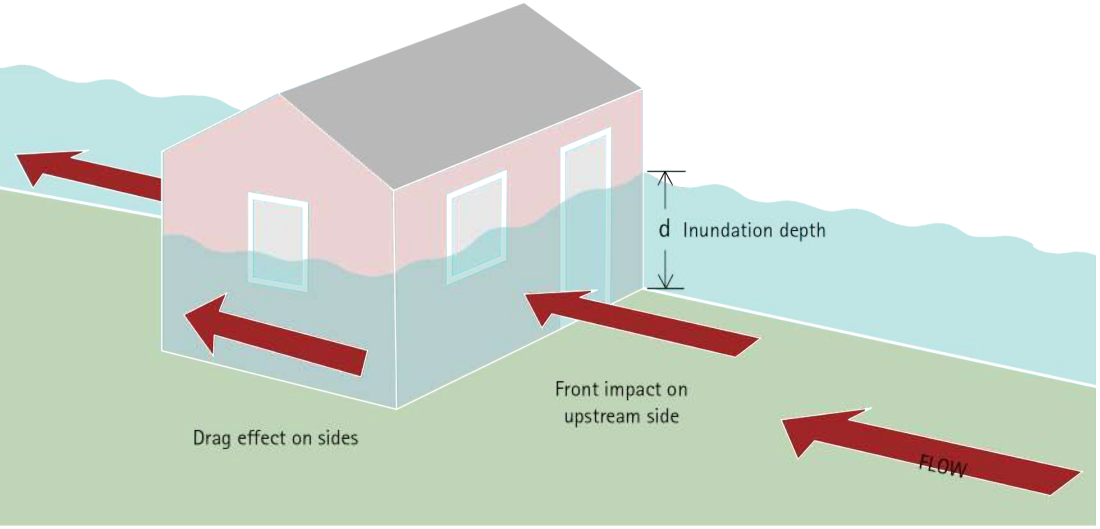


Figure 35:
Hydrodynamic and impact forces.
Source:
own elaboration
from FEMA[116].

4.1.4. Impulsive forces

Impulsive forces are forces impinging against a vertical obstruction subjected to the leading edge of a tsunami during runup, they are also known as "surge forces"[117]. They have very short duration, but they are stronger than any other force generated. As the surge passes through a structure, impulsive forces will be applied sequentially to all structural components, but not at the same time. Once the leading edge of the surge has passed a structural component, it will no longer experience the impulsive force, but rather a sustained hydrodynamic drag force[118]. Therefore, if the runup zone is flooded by an earlier tsunami wave, subsequent waves will impact buildings in the form of a bore[119] (see figure 36).

4.1.5. Floating debris impact forces

Impact forces are generated from the collision of waterborne debris like cars, driftwoods, lumber, boats and shipping containers against structures and structural components. The magnitude of the impact force depends on the debris weight and velocity. Smaller, therefore lighter, debris can easily float and travel faster than larger and heavier debris which need larger depths to float. It is difficult to exactly estimate this force because of the numerous variables that could affect it, it should be evaluated considering the site and the potential debris in the surrounding area. For example, in a small coastal town it is likely that floating debris would consist mainly of driftwood, pier pilings and small boats, while in presence of large ports, the debris would include shipping containers[120] (see figure 37).

[112] Federal Emergency Management Agency, *FEMA P-936, Floodproofing Non-Residential Buildings*, (FEMA: 2013), 2-21.

[113] U.S. Air Force / Handout, "Magnitude 8.9 Strong Earthquake Jolts Northern Japan," Getty Images, accessed April 26, 2018, https://www.gettyimages.com/license/110118353.

[114] Federal Emergency Management Agency, *FEMA P-646, Guidelines for design of structures for vertical evacuation from tsunamis*, 83.

[115] "Hydrodynamic forces," FEMA, accessed April 26, 2018, https://emilms.fema.gov/IS0280/unit4-lesson-summary.htm.

[116] Ibid, 84.

[117] Federal Emergency Management Agency, *FEMA P-646, Guidelines for design of structures for vertical evacuation from tsunamis*, 155.

[118] Ibid, 94.

[119] Ibid, 85.

[120] Ibid, 86-87.

[121] "Tsunami engulfs Natori," ABC News, last modified June 3, 2013, http://www.abc.net.au/news/2013-06-03/tsunami-engulfs-natori/4730828..

[122] Athit Perawongmetha, "Japan Moves Forward In Aftermath Of Earthquake Despite Nuclear Fears," Getty Images, accessed April 26, 2018, https://www.gettyimages.com/license/111481426.

Figure 36: Tsunami engulfs Natori, Japan (2011). Source: Unknown Author, ABC News[121].

Figure 37: Effects of debris impact in Otsuchi, Japan, after the tsunami in 2011. Source: Athit Perawongmetha/Getty Images[122].

4.1.6. Damming of accumulated waterborne debris

The damming effect caused by the accumulation of waterborne debris can be considered as a hydrodynamic force strengthen by the payload of the debris dam against the structure. It is uniformly distributed along the all width of the debris dam. Since the dam consists of a heap of debris across the structural frame, the total debris damming force will likely be withstood by multiple structural components, depending on the framing dimensions and the size of the debris dam[123].

4.1.7. Uplift forces on elevated floors.

The uplift pressure is a vertical hydrostatic force generated by the volume of displaced water under a building, applied to the submerged floor levels. These levels have to be designed not only to resist the standard gravity loads, but they also must resist the uplift generally by the buoyancy and hydrodynamic forces. When considering the buoyant forces on a floor slab, attention must be given to the potential increase of buoyancy due to the extra volume of water displaced by air contained underneath the floor framing system. The presence of structural walls and columns in a building will obstruct the tsunami flow passing through, resulting in significant uplift forces on the floor slab immediately in front of the obstruction. Therefore, it is important that buildings are designed to minimize the obstruction of the lower levels with breakaway door and windows and an open plan[124].

4.1.8. Additional retained water loading on elevated floors

During drawdown, the water retained on the top floors of a building, applies additional gravity loads that can cause the failure of the system. The level of water retained, depends on the maximum inundation depth in situ, and on the lateral strength of the wall system of the elevated floor. Since it is likely that the exterior walls will be compromised at some point, the water will flood the

[123]Federal Emergency Management Agency, *FEMA P-646, Guidelines for design of structures for vertical evacuation from tsunamis*, 90.

[124]Ibid, 91.

[125]Ibid, 93.

[126]Ibid,78.

[127]Federal Emergency Management Agency, *FEMA P-550, Recommended Residential Construction for Coastal Areas: Building on Strong and Safe Foundations, second Edition*, (Washington D.C.: U.S. Department of Homeland Security: 2009), 10-11.

submerged floor levels. For elevated floors without walls like parking lots, the water may remain on elevated floors until it drains off the structure[125].

4.1.9. Breaking waves

When a tsunami wave breaks in a plunging mode, due to the sudden depth change in the ocean floor, the wave front becomes almost vertical and releases with a violent impact an extremely high pressure over a brief duration. Once a tsunami wave has broken, the wavelength increases, and it can be considered as a bore[126]. The most severe damages are normally caused by breaking waves which can reach different height depending on the flood zone. The force, this way generated against a vertical surface, is often ten or more times stronger than the force induced by high winds during a storm[127].

4.2. Loading effects

4.2.1. Scour

Scour consists in the removal of soil or fill material by the flow of floodwaters around pilings and other foundation supports where the obstruction of the flow increases turbulence. There are two primary scour mechanisms that occur during a tsunami event: shear-induced scour and liquefaction-induced scour (see figure 38). The first one is similar to the phenomenon observed during storm surge flooding and consists of soil transport due to the flow velocity. The second one results from rapid drawdown as the water recedes.

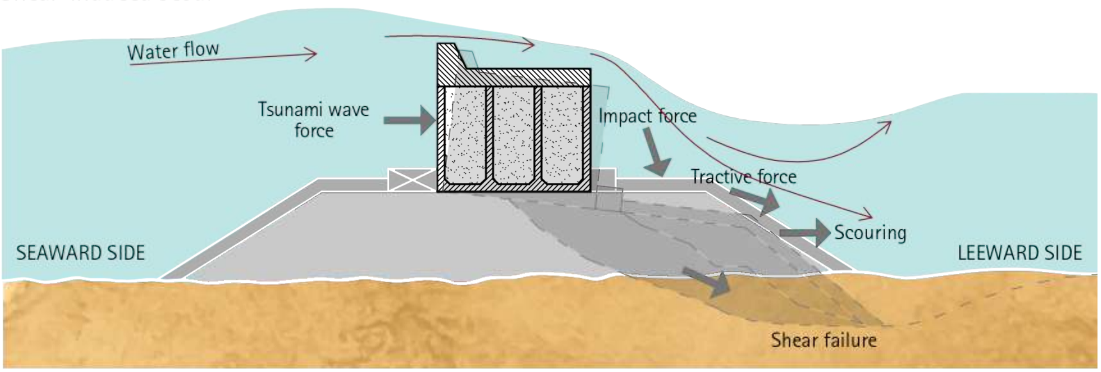
Scour around shallow foundations can lead to failure of the supported structural element. Pilings, pile caps, columns, walls, footings, slabs, and other elements found under a flooded building can lead to localized scour. The effects aggravate with rising flow velocity and turbulence, and they are generally localized. They range from small, shallow conical depressions in the sand around individual piles to larger and deeper depressions around a buil-

ding foundation[128].
To prevent the instability of coastal structures, like seawalls, it is necessary to protect the seabed from scour. The strength of waves and currents is able to erode both granular material and clay. In most cases scour protection can be provided with a rock bed on stone or geotextile filter; or with concrete block and mattress systems specifically designed. Scour protection is usually used at the toe of seawalls and dikes; or around piles and pillars, at the toe of vertical-front breakwaters, and at groin heads[129].

[128]Federal Emergency Management Agency, *FEMA P-646, Guidelines for design of structures for vertical evacuation from tsunamis*, 73.

[129]Ibid, 2.

Shear-induced scour



Liquefaction-induced scour

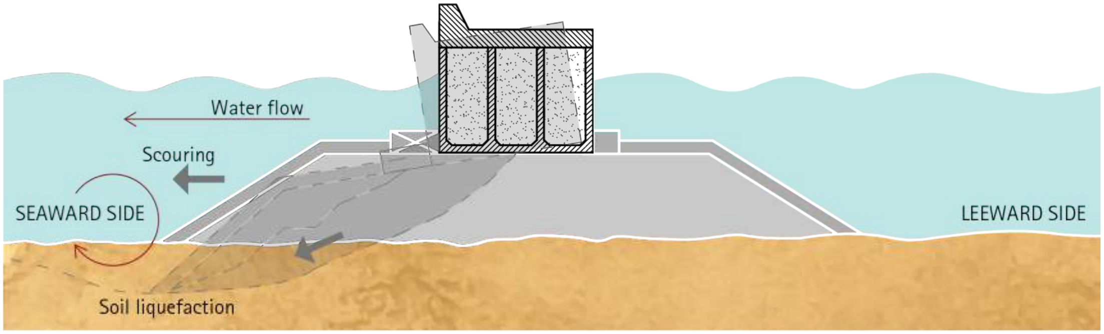


Figure 38: EShear and liquefaction-induced scour mechanism. Source: Athit Perawongown elaboration from Mantripathi Prabath Ravindra Jayaratne, et al.[130].

4.2.3. Erosion

Erosion refers to the wearing and washing away of coastal lands, including sand and soil. It is part of a larger process of shoreline changes. Because of the dynamic nature of erosion, it is one of the most complex hazards to understand and difficult to accurately predict at any given site along coastal areas. Short-term erosion changes are cause by storms, tsunamis and periods of high wave activity. Because of the variability in direction and magnitude, short-term erosion effects have greater magnitude than long-term erosion. The erosion over a large area between a foundation and a flood source exposes the foundation to increased lateral flood loads, both hydrostatic and hydrodynamics reducing their stability (see figure 39)[131].

[130]Mantripathi Prabath Ravindra Jayaratne, et al., "Failure mechanisms and local scour at coastal structures induced by tsunami," *Coastal Engineering Journal* 58, no.4 (2016): 164-170.

[131]Bruce Jaffe, "Scour at Musefau," USGS, accessed April 27, 2018, https://walrus.wr.usgs.gov/news/samoareports.html.

Figure 39: Example of scour effects after the tsunami in Samoa (2009). Source: Bruce Jaffe, USGS[131].

5

COASTAL EROSION

Coastal erosion is a natural process that causes the loss of coastal zone sub aerial land parts like beaches, dunes or cliffs. It results in a consistent sediment imbalance and consequent retreat[132], deteriorating the quality of coastal landscape, and negatively impacting the financial investments for protective structures (see figure 40). Since coastal areas highly contribute to the Gross Domestic Product of a country, this phenomenon is considered an obstacle hindering economic growth. Coastal erosion becomes an issue when there is not enough space to accommodate the changes and, the impact will keep rising, until people will continue settling along the coast[133].

Therefore, coastal erosion is not a problem for high elevated and solid grounds but it is a serious problem for rural and urbanized areas with low elevation[134]. Lately, it has been aggravated by the frequent occurrence of extreme events, whose increasing intensity has been associated with the climate and global environmental changes. Coastal erosion has been having greater effects in areas affected by abnormal storm surges responsible for coastal flooding. The damages caused by coastal flooding are related to atmospheric perturbations, nearshore bathymetry and to the geomorphological characteristics of the coastline[135].

[132]Nelson Rangel-Buitrago, Victor N. de Jonge, and William Neal, "How to make Integrated Coastal Erosion Management a reality," *Ocean & Coastal Management* 156 (2018): 290, https://doi.org/10.1016/j.ocecoaman.2018.01.027.

[133]Allan Williams, Nelson Guillermo Rangel-Buitrago, Enzo Pranzini, and Giorgio Anfuso, "The management of coastal erosion," *Ocean & Coastal Management* (2017): 4-5, https://doi.org/10.1016/j.ocecoaman.2017.03.022.

[134]Nelson Rangel-Buitrago, Victor N. de Jonge, and William Neal, 291.

[135]Carolina Martínez, Manuel Contreras-López, Patricio Winckler, Héctor Hidalgo, Eduardo Godoy, and Roberto Agredano, "Coastal erosion in central Chile: A new hazard?," *Ocean & Coastal Management* 156 (2018): 141, https://doi.org/10.1016/j.ocecoaman.2017.07.011.

[135]Humberto Merino, "Cambio climático: los desafíos de las costas de Chile," Enfoque Chile, last modified November 9, 2017, https://www.revistaenfoque.cl/tsunamis-marejadas-y-el-cambio-climatico-los-desafios-de-la-costa-de-chile.

Figure 40: Coastal erosion in La Serena, Chile, August 2015. Source: Humberto Merino[135].

5.1. Coastal erosion causes

Coastal erosion is the result of both slow shoreline behaviors acting for decades, and rapid processes lasting a time-span of seconds. This natural process can be directly or indirectly related to the human ones, which, with the construction of engineered structures has a strong impact on a limited area but secondary repercussions on other coastal zones. Most processes act simultaneously, therefore the coastal erosion recorded in a given area is the direct or indirect consequence of the interaction of all the processes. These processes are magnified by the global warming resulting in an increase of precipitations together with flooding risk during extreme events.

The causes analysis of coastal erosion must take in consideration all of the spatial and temporal scales at which it works[136]. Two factors have been highly debated recently, the first one about the increasing frequency of severe storms, the second one about the sea level rise. Even if there are records proving that sea levels are rising, there are no clear ones about the amount, only a range, but the experts' shared opinion is that it could be up to 98cm by the end of the XXI century[137]. Despite the undeniable hazard, most of the world coastal zones are very attractive places both for economic and residential developments.

5.2. Coastal erosion management strategy

Until today, most of decision-making within coastal erosion management has been based on economics needs through cost-benefit analysis or on action reaction basis. A Coastal Erosion Management Strategy must be based on a clear awareness of the erosion processes, property rights, legislation and aesthetics. The practices of the current management to strategy include: protection, accommodation, planned retreat, use of ecosystems and sacrifice[138] (see table 11 and figure 41).

Among these approaches, protection through the construction

[136] Nelson Rangel-Buitrago, Victor N. de Jonge, and William Neal, 290.

[137] Allan Williams, Nelson Guillermo Rangel-Buitrago, Enzo Pranzini, and Giorgio Anfuso, 6.

[138] Ibid, 5.

STRATEGY	APPROACH
Protection	It corresponds to the use of hard' and/or 'soft' measures, costly and often temporary. These seaward structures are built to protect the existing shoreline position, or to advance it, claiming further land.
Accommodation	It consists in the use of land at risk without attempting to prevent flooding, allowing the conservation and/or the migration of eco systems. This strategy requests advanced planning and the acceptance that economic values might change, it is the most suitable option for flood-prone areas. When possible, buildings should be elevated, and the land use turn into cultivation of, for example, salt tolerant crops.
Planned retreat	It consists in the change of land use and relocation of existing buildings when cost-effective protection is not a suitable solution, thus allowing flooding of a previously protected area. Structures can be moved inland, demolished or let degrade. This measure, like most of them, tend to be retroactive rather than proactive but enhances adaptability, allowing the shoreline and the sand dunes to freely move back and forth.
Use of ecosystems	It consists in the generation and restoration of coastal ecosystems, such as coastal forests, reefs, wetlands, seagrass beds and dune vegetation. The main limit of this approach is the lack of space where ecosystems can develop, especially in urbanized areas.
Sacrifice	It is considered an "extreme" strategy, and it is mostly applied after extreme-erosion events that leave coastal structures highly damaged. These broken structures, instead of being replaced by new ones, should be removed allowing the natural regeneration of the shorelines.

Table 11: Coastal erosion management practices. Source: own elaboration from Allan Williams, et al.[139], and Nelson Rangel-Buitrago, Victor N. de Jonge, and William Neal[140].

of hard structures is often considered as the best coastal erosion management practice. On the contrary, hard structures are not always the most suitable solution, and their negative effects on the natural processes is a significant problem affecting many coastlines around the world. They are costly and require continuous maintenance, and their dimensions must keep up with the constantly increasing coastal erosion risk. Negative effects overcome the positive ones in the utilization of hard structures as protective

[139]Ibid, 6.

[140]Nelson Rangel-Buitrago, Victor N. de Jonge, and William Neal, 292.

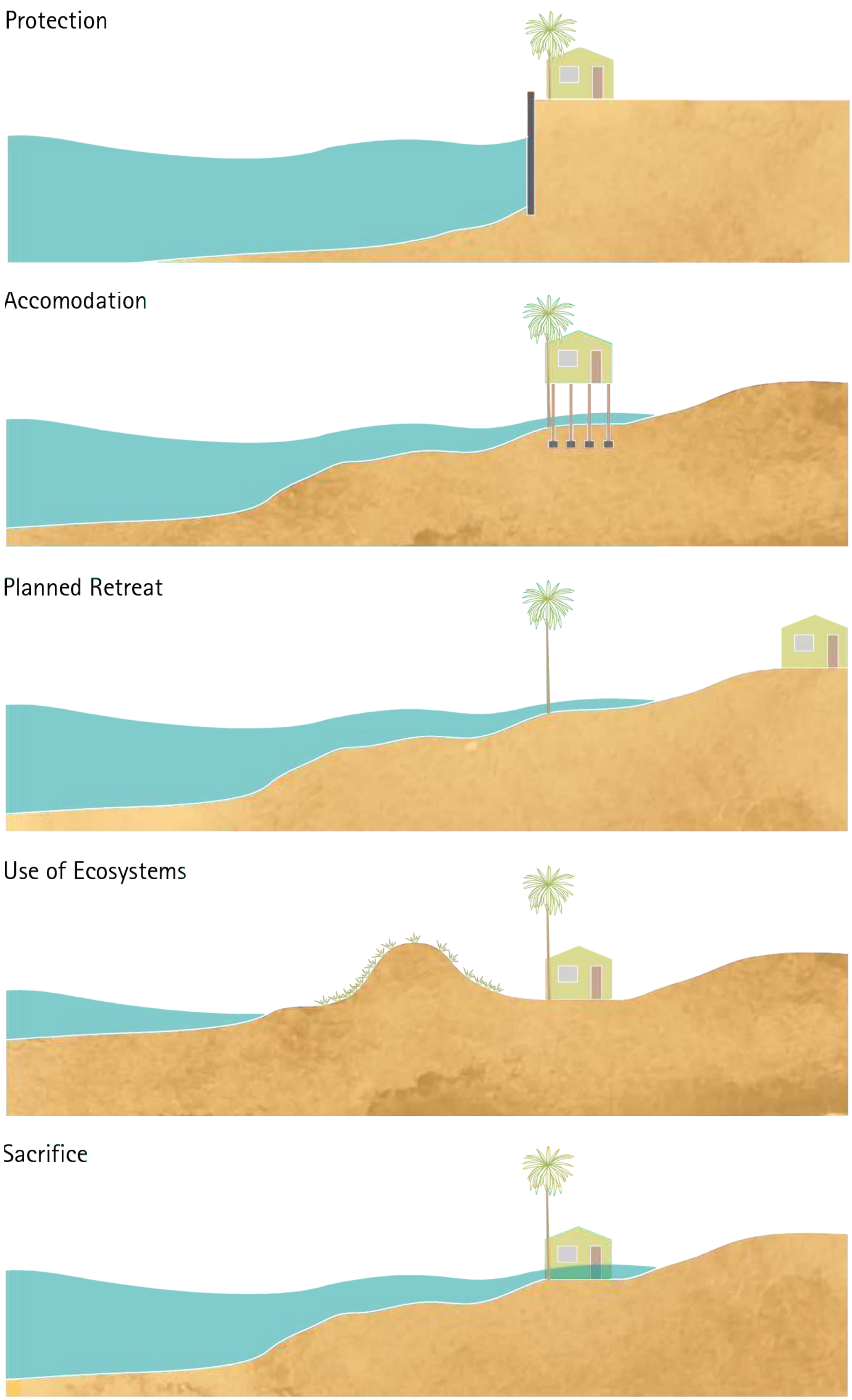


Figure 41:
Coastal Erosion Management Strategies.
Source:
own elaboration from Allan Williams, et al.[141], and Nelson Rangel-Buitrago, Victor N. de Jonge, and William Neal[142].

strategy against coastal erosion because they interfere with the processes operating on wider scales[143](see figure 42).

The use of ecosystems is more cost-effective and sustainable than the hard measure approach. Ecosystems can weaken extreme wave effects. Their growth and reproduction can keep up with the sea-level rise and augment the accretion of sediments when available. This approach not only prevent shore erosion, it also provides other benefits for the inhabitants and for the environment itself, like for example enhancing fishery and tourism[144].

Coastal erosion management must follow a deep knowledge of all the forces and factors involved in the erosion process, both natural and man-originated, and how they affect the coastal resilience. Managers must compare present and future urban development models with the related expected coastal erosion. Thus, the understanding of the local and regional processes is fundamental for an effective coastal management program. No matter what is the approach that will be undertakes, it should always meet the parameters for a "sustainable development," not compromising the future coastal use of the future.

Management plans must consider the land user's necessities and preferences, maintaining and, when possible, even promoting social wellbeing, together with the economic and environmental value. Strategies should be studied to accommodates changes without interfering with the functions of the coastland. Monitoring the response of the environment to the adopted measure is necessary to establish better future coastal erosion management plans[145].

[141]Allan Williams, Nelson Guillermo Rangel-Buitrago, Enzo Pranzini, and Giorgio Anfuso, 6.

[142]Nelson Rangel-Buitrago, Victor N. de Jonge, and William Neal, 292.

[143]Ibid, 292.

[144]C. Adriana Gracia, Nelson Rangel-Buitrago, Judith A. Oakley, and Allan Williams, "Use of ecosystems in coastal erosion management," *Ocean & Coastal Management* (2017): 278, https://doi.org/10.1016/j.ocecoaman.2017.07.009.

[145]CNelson Rangel-Buitrago, Victor N. de Jonge, and William Neal, 295.

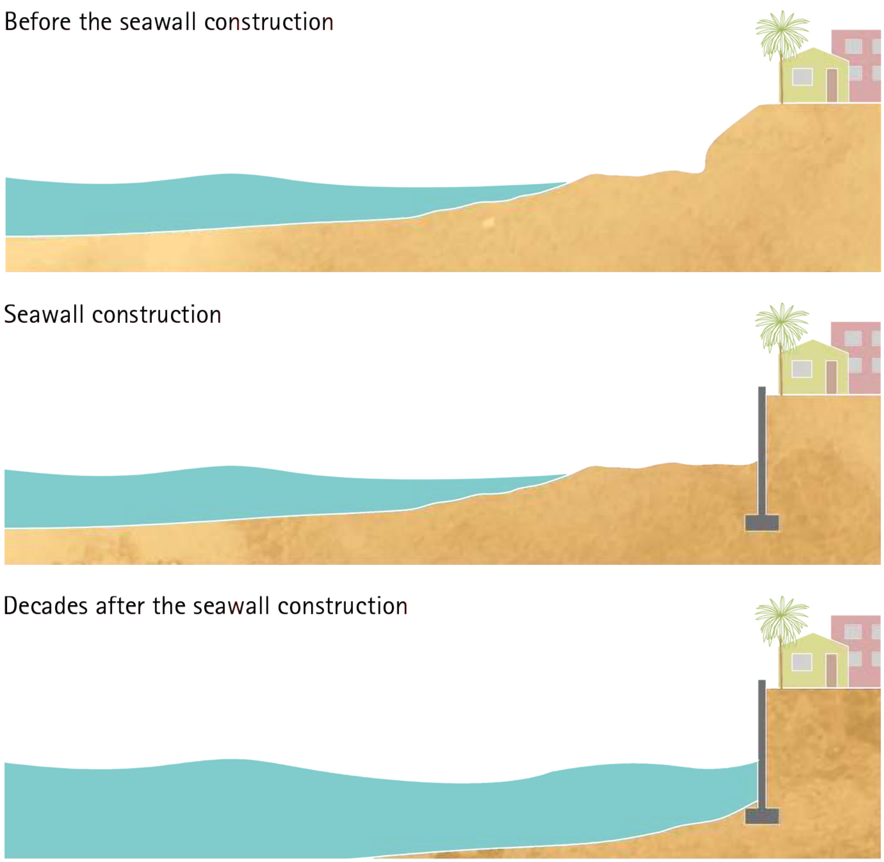


Figure 42:
Negative effects of seawalls on coastal erosion.
Source: own elaboration from Edward A. Keller[146].

5.3. Intervention Concerning the Erosion Causes (ICEC)

The Intervention Concerning the Erosion Causes (ICEC) is a very effective managing strategy but the least used in coastal management. It includes all the previously listed strategies plus the intervention to prevent the erosion causes (see figure 43). ICEC envisages the recovery of natural habitats, and the destruction and/or relocation of the man-made structures that stop the sediment production and its migration to and through coastal systems. Therefore, for an appropriate coastal management, managers must to look in both directions, inland and at the sea.

Eliminating the causes unfortunately is not that easy, for starter, the sea level rise, which is a major cause, cannot be eliminated and neither measures with a strong economic impact, like harbors. This strategy can be applied only if the current economic approaches, cost-benefit and action-reaction, are not considered essential to the management model. ICEC considers both climate-related and non-climate related problems, because is not only about solving an issue, but it is about the future livability of our ecosystem[147].

[146]Edward A. Keller, *Santa Barbara Land of Dynamic Beauty*, in "Coastal Armoring," last accessed July 14, 2018, http://explorebeaches.msi.ucsb.edu/beach-health/coastal-armoring.

[147]Nelson Rangel-Buitrago, Victor N. de Jonge, and William Neal, 295-98.

[148]Ibid, 295.

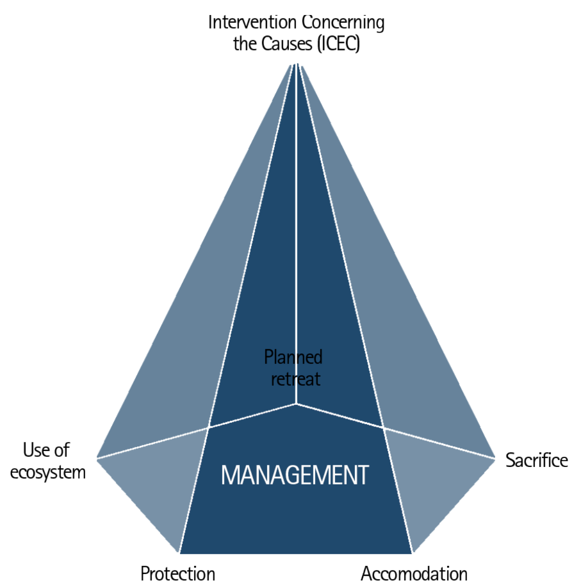


Figure 43: Intervention Concerning the Erosion Causes Approach (ICEC). Source: own elaboration from Nelson Rangel-Buitrago, Victor N. de Jonge, and William Neal[148].

5.4 Management plans and norms

When establishing management plans, flexible proactive strategies should be undertaken instead of reactive measures, ameliorating the coastal environmental quality and its ability to cope with erosion. The most critical issue is normally the definition of clear long-term objectives, which are fundamental to draft suitable strategic plans[149]. Management norms follow analysis, planning and envision implementation and control. Strategic decisions generally include a considerable level of uncertainty and a high monetary cost. The implementation of long-term strategy can encounter many difficulties, a major one is that the time needed to produce results is longer than the life of politician who take the decisions; and who need quick and visible results for their political purposes[150].

5.4.1. Government management tools

Governments have a set of management tools which can help reduce erosion. These tools go further than standard engineering measures, they include monetary resource for scientific research, policies, planning codes, stakeholders support and monitoring/reviews/assessments of instruments[151]. Government institutions can develop effective law reforms by respecting four fundamentals points which include the update of the current environmental legislation focusing on coastal erosion; the implementation of the supportive measures in the decision-making process. Moreover, governments can and must increase public awareness about risks generated by inappropriate short-term management practices and provide efficient and sustainable solutions to coastal erosion issues[152].

[149]Ibid, 298.

[150]Allan Williams, Nelson Guillermo Rangel-Buitrago, Enzo Pranzini, and Giorgio Anfuso, 14.

[151]Ibid, 16-17.

[152]Nelson Rangel-Buitrago, Victor N. de Jonge, and William Neal, 298.

5.4.1.1. Setback zones

The establishment of setback zones and setback lines are part of the planned retreat approach. It is a highly effective measure, it reduces property damage caused by coastal flooding and erosion, by moving the existent structures away from the hazard zone. They can be seen as buffer zones of undeveloped land and they provide an economic and sustainable alternative to common protection works, like seawalls or dikes. Setbacks have two directions, one vertical and one horizontal. The vertical one establishes the height above a sea level while the horizontal one the distance from a seaward benchmark which together protect structures from inundations[153](see figure 44).

5.5. Stakeholders in coastal management

Coastal management programs, to be effective, need an appropriate level of cooperation of all the parts concerned, included the stakeholders. In coastal decision-making the major stakeholders often have interests in conflict with the objectives of coastal management. To ensure the reduction of genuine coastal management plans, politicians need to be informed on how laws will reflect natural variability[154]. Sometimes wealthy owners of beachfront properties can overcome local governments.

It is the case of Southampton, New York, where the community tried to outlaw seawalls by placing a line of 20/25ton boulders on the beach to protect their beachfront houses from flooding. Later a wall construction was permitted by a post-Sandy beach-regulation loophole. Several other house owners also started building seawalls, resulting on a long line of seawalls and causing the erosion of the beach[155](see figure 45).

[153]Ibid, 17.

[154]William J. Neal, et al., "Why coastal regulations fail," *Ocean & Coastal Management* 156 (2017): 32, https://doi.org/10.1016/j.ocecoaman.2017.05.003.

[155]Ibid, 27.

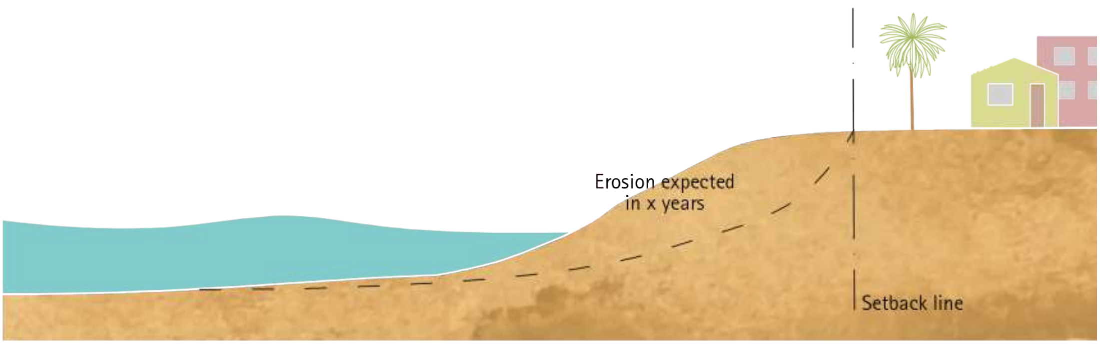


Figure 44:
Set back line.
Source: own elaboration from Allan Williams, Nelson Guillermo Rangel-Buitrago, Enzo Pranzini, and Giorgio Anfuso[156].

Figure 45:
Construction of a seawall in Southampton due to the post-Sandy beach regulation loophole.
Source: Hampton Pix[157].

5.6. Failure in coastal erosion management and regulations

Before analyzing the failures in coastal erosion management, it is important to state that even if appropriate strategies can reduce the causes and the effects and therefore the vulnerability to coastal erosion, a complete elimination of the phenomenon is not possible with the knowledges and instruments we hold today[158]. Failure of coastal regulations is in large part responsible for damages and losses due to coastal hazards. Generalized management principles and approximated decisions, especially regarding short-term solution for limited areas do not take in consideration the impact they have on further areas. Some of these regulations have shorter life the interval between major coastal-hazard events and they fail because they underestimate natural processes and coastal dynamics.

Another significant issues in the regulation-making system that is for every prohibition there are variances that permit exceptions, and then the exception, once is no longer a singular reality, becomes the rule. A similar process happens in case of emergency dispensations, compensatory mitigation, and 'temporary' structures which from 'exceptional' and 'temporary' become permanent solutions. Even where these measures are explicitly prohibited by the law. In some cases, variances are turned into new regulations, proving that any law that allows variances loses its protection purpose[159].

[156]IAllan Williams, Nelson Guillermo Rangel-Buitrago, Enzo Pranzini, and Giorgio Anfuso, 17.

[157]Hampton Pix, "Lawsuit: Post-Sandy bulkheads at Southampton homes a 'time bomb'," Newsday, last modified November 30, 2013, https://www.newsday.com/long-island/towns/lawsuit-post-sandy-bulkheads-at-southampton-homes-a-time-bomb-1.6696559.

[158]Nelson Rangel-Buitrago, Victor N. de Jonge, and William Neal, 296.

[159]William J. Neal, et al., 25.

5.6.1. Approximative mapping of hazard zones

The establishment of hazard zones is based on records and models of past events, but the effects of future storms will depend on a new and different set of variables. Mapping, instead, should be based on predictive models of future events, and focus on local processes that will influence currently predicted water levels, including the erosion rates of the specific zones (see figure 46). High erosion rates will cause potential storm-surge zone to shift landward and allowing waves to reach farther inland during hazard events. If erosion rates are not integrated in flood maps, they will need to be frequently redrawn to be accurate[160].

[160]Ibid, 23

[161]Eurobodalla Shire Council, "Development assessment and Sea Level Rise," last accessed July 14, 2018, http://www.esc.nsw.gov.au/development-and-planning/considerations/coastal-and-flooding-considerations/interim-coastal-hazards-adaptation-code/development-assessment-and-sea-level-rise.

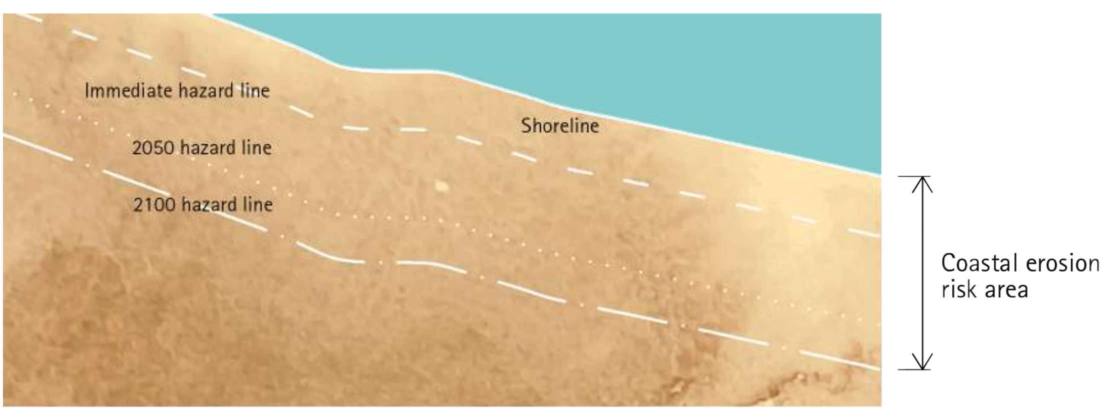


Figure 46: Coastal erosion hazard zone scheme.
Source: own elaboration from Eurobodalla Shire Council[161].

5.6.1.1. Outdated control lines

Control lines are normally imaginary lines used to limit maritime zones, or other areas where urban development is prohibited. Most of the times they establish a distance from the shore based on past long-term erosion rates without taking in consideration possible increases in erosion rates and sea-level, or other impacts caused by anthropogenic activities. Laws and regulations that were established before the acceleration of the sea-level rise rate reduced their already scares effectiveness. An example is Dauphin Island, in Alabama, which has been battered by a series of major hurricanes, like Katrina in 2005, which caused the erosion and shifting of a great amount of sand, leaving the current control lines offshore under water (see figure 47).

Even if these lines become useless, they are still employed ad reference to regulate new construction. The new modeling for predicting storm surge, tsunami inundation, and flood zones, together with new mapping based on recent storms showed that the 'fixed' setback lines and zones are often outdated before they are even published. Therefore, 'flexible' control lines, with periodic adjustments and updates, will better respond to the constant shifting of shorelines, flood zones, storm and tsunami surge zones[162].

[162]G.C. SPIES Coastal Surveyor, *"In Alabama, a Community on Shifting Sands,"* The New Yor Times, last accessed July 20, 2017, https://www.nytimes.com/slideshow/2012/11/19/science/earth/20121119REBUILD/s/20121119REBUILD-slide-0B3U.html, 28.

[163]Ibid, 28.

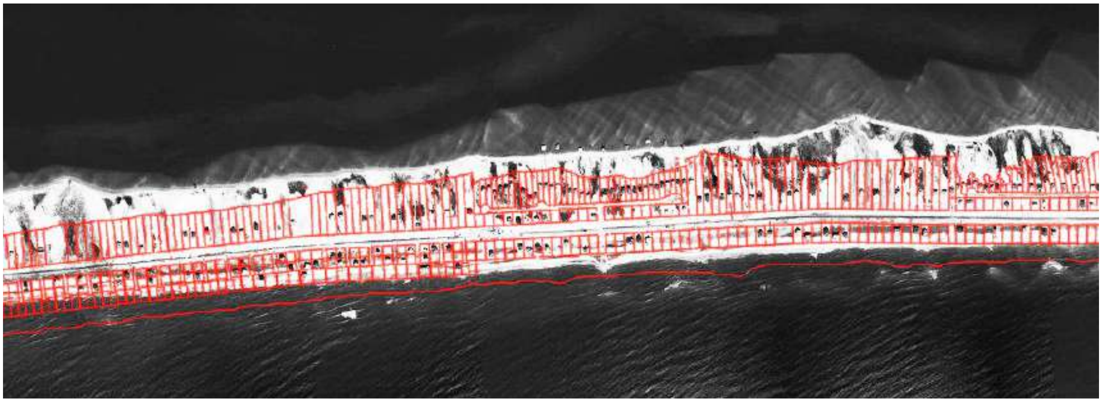


Figure 47: Construction of a seawall in Southampton due to the post-Sandy beach regulation loophole. Source: Hampton Pix[163].

5.6.2. Political-legislative failures

The political-legislative failures are caused by incompatibly between the decisions made by politicians driven by economic interests and the reality of Nature. Regulations are often overridden by emergency dispensations during post-disaster recoveries and small erosion-control projects without interagency approvals. Political-legislative failures consist of: over-generalization of laws which do not reflect the complexity of the coasts; lack of funds destined to regulate monitoring, enforcement and penalties; inability to envision goals far in the future due to economic conflicts of interest for politics[164].

5.6.2.1. The 'one-size-fits-all' regulatory approach

Coastal laws and regulations are often generalized to simplify their codification turning in a 'one-size-fits-all' approach. In the contrary, coastal zones are normally very different in terms of habitat, shore type and forms, sediment, landward slope, land use, and many other parameters which are not in the one general regulation. To be effective, coastal regulatory laws, must take in consideration the complex nature of the shore which requires higher level of detail, allowing micromanaging decisions but no variances. Countries which do not have the resource to establish their own regulatory system, base their approach on the management plans of first world countries. Like Puerto Rico's Maritime Law which comes from Spain, where coastal and socio-economic conditions are very different[165].

5.6.2.2. Buildings codes

Building codes, when existing, establish the minimal safety standards for the construction of structures. Past post-hazard lessons proved that, especially inland building codes, cannot be applied to coastal structures, therefore, buildings codes must be constantly updated and adapted to better respond to costal changes and

[164] William J. Neal, et al., 21.

[165] Ibid, 29.

flooding hazard. However, post-hazard inspections keep revealing inadequate code requirements and code violation: The post-hazard rush to rebuild can results in too few inspectors for the job or inspectors with conflicts of interests[166].

[166]Ibid, 29.

6

SHORE PROTECTION

Shore protection consists in a series of measures that can be taken to protect the coast from erosive forces and inland flooding caused by waves, currents, storm surges and tsunamis. The measure adopted in a given situation depends on the three primary factors: the affecting problem, the morphological conditions and the land use. A prerequisite for a successful shoreline restoration project is the understanding of the coastal morphological processes. Given a particular situation and problem, certain solutions will work, and others will not.

The coastal area is a dynamic natural landscape. Interventions should be made only if the interests of the society are more important than preserving the natural coastal resource. Whenever possible is preferred to destroy old protection schemes to re-establish the natural coastal environment. Giving high priority to the quality of the coast resource[167]. According to the measures taken for shore protection, two major categories of intervention can be distinguished: hard engineering measures and soft engineering measures.

Hard engineering is a coastal management strategy used to protect coasts from erosion and flooding, by absorbing the energy dissipated by the waves. They are easily recognizable man-made structures used to interrupt natural processes (see figures 48-49). Even if this approach is commonly perceived as the best coastal erosion management practice, these structures represent short-term solutions with often a negative impact on the environment. Installing hard engineering structures is expensive due to their continual maintenance requirements and can lead to negative effects on a broad spatial scale, including an increase in coastal erosion[168].

Soft engineering, on the contrary, works together with nature to avoid coastal damages rather than trying to stop natural processes. It is based on ecological and sustainable principles, reducing the negative impact on the natural environment. Soft engineering aim to create long-term sustainable solutions which are less expensive to implement and maintain[169].

[167]Mangor, Karsten and Pilkington, Caitlin, “Shore protection, coast protection and sea defense methods,” accessed April 27, 2108, http://www.coastalwiki.org/wiki/Shore_protection,_coast_protection_and_sea_defence_methods

[168]Nelson Rangel-Buitrago, Victor N. de Jonge, and William Neal, “How to make Integrated Coastal Erosion Management a reality,” Ocean & Coastal Management 156 (2018): 292, https://doi.org/10.1016/j.ocecoaman.2018.01.027.

[169]“Coastal management,” BBC, accessed April 29, 2018, http://www.bbc.co.uk/schools/gcsebitesize/geography/coasts/coastal_management_rev2.shtml.

[170]REUTERS/Kim Kyung-Hoon, “Seven years after tsunami, Japanese live uneasily with seawalls,” Asia One, accessed on April 29, 2018, http://www.asiaone.com/asia/seven-years-after-tsunami-japanese-live-uneasily-seawalls.

[171]Ibid.

Figure 48:
Seawall protecting at a port in Miyako, Iwate Prefecture, Japan (2018).
Source: REUTERS, Kim Kyung-Hoon[170].

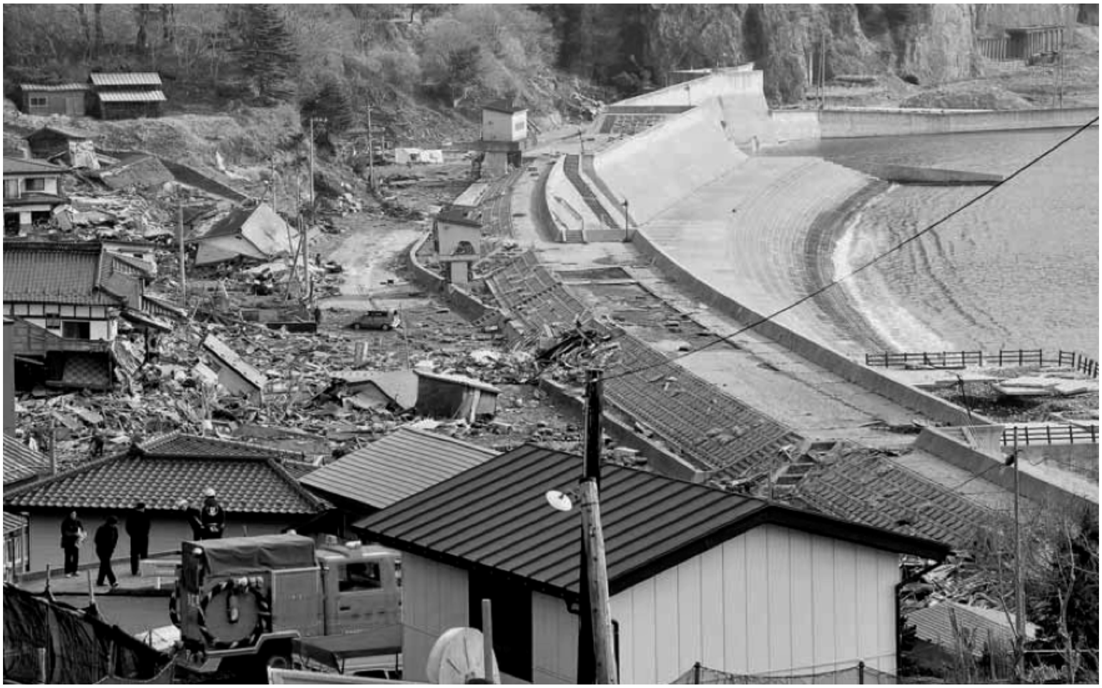


Figure 49:
Seawall protection failure in Noda, Japan, 2011.
Source: REUTERS, Kim Kyung-Hoon[171].

6.1. Conventional defensive coastal structures

Coastal structures, or hard engineering measures, are human-made structures designed to prevent shoreline erosion and flooding of the hinterland, to protect harbor basins and entrances against waves, and to stabilize navigation channels at gulfs and inlets[172]. On the basis of their purpose there are different types of coastal structures (see table 12).

[172]Hans Falk Burcharth and Steven A. Hughes, "Types and Functions of Coastal Structures," in *Coastal Engineering Manual*, Vol. 6 (Vicksburg, Mississippi: Coastal Engineering Research Center, 2013), 2.

[173]Ibid, 2.

STRUCTURE	OBJECTIVE	FUNCTION
Sea dike	Prevent or alleviate flooding by the sea of low-lying land areas.	Separation of shoreline from hinterland by a high impermeable structure.
Seawall	Protect land and structures from flooding and overtopping.	Reinforcement of some part of the beach profile.
Revetment	Protect the shoreline against erosion.	Reinforcement of some part of the beach profile.
Bulkhead	Retain soil and prevent sliding of the land behind.	Reinforcement of the soil bank.
Groin	Prevent beach erosion.	Reduction of longshore transport of sediment.
Detached breakwater	Prevent beach erosion.	Reduction of wave heights in the lee of the structure and reduction of longshore transport of sediment.
Reef breakwater	Prevent beach erosion.	Reduction of wave heights at the shore.
Submerged sill	Prevent beach erosion.	Retard offshore movement of sediment.

Beach drain	Prevent beach erosion.	Accumulation of beach material on the drained portion of beach.
Beach nourishment and dune construction	Prevent beach erosion and protect against flooding.	Artificial infill of beach and dune material to be eroded by waves and currents in lieu of natural supply.
Breakwater	Shelter harbor basins, harbor entrances, and water intakes against waves and currents.	Dissipation of wave energy and/or reflection of wave energy back into the sea.
Floating breakwater	Shelter harbor basins and mooring areas against short-period waves.	Reduction of wave heights by reflection and attenuation.
Jetty	Stabilize navigation channels at river mouths and tidal inlets.	Confine streams and tidal flow. Protect against storm water and crosscurrents.
Training walls	Prevent unwanted sedimentation or erosion and protect moorings against currents.	Direct natural or man-made current flow by forcing water movement along the structure.
Storm surge barrier	Protect estuaries against storm surges.	Separation of estuary from the sea by movable locks or gates.
Pipeline outfall	Transport of fluids.	Gravity-based stability.
Pile structure	Provide deck space for traffic, pipelines, etc., and provide mooring facilities.	Transfer of deck load forces to the seabed.
Scour protection	Protect coastal structures against instability caused by seabed scour.	Provide resistance to erosion caused by waves and current.

Table 12: Types and functions of coastal structures. Source: Hans Falk Burcharth and Steven A. Hughes[173].

6.1.1. Seawalls

Seawalls are built on the cost with the purpose of preventing or mitigating overtopping and flooding, caused by storm surges and tsunami waves. Seawalls are a reinforcement of the coast built parallel to the shoreline. They are mostly used to protect built environments located near the sea. There are different types of seawalls from vertical face structures like heavy concrete walls, tied walls, and stone-filled cribwork to sloping structures with reinforced concrete slabs, concrete armor units, and stone rubble (see figure 50).

Erosion of the beach, landward of a seawall, can be stopped or at least limited. However, the erosion of the seabed right in front of the structure is enhanced from the increased wave reflection generated by the seawall. This phenomenon causes a steeper seabed profile, allowing larger waves to hit the structure. Therefore, seawalls risk instability due to the erosion of the seabed at the bottom of the structure, and by an increase in wave crashing, runup, and overtopping. Due to their vulnerability to toe scour, seawalls are often used together with other system of beach control like groins and beach nourishment[174].

[174]Ibid, 2.

[175]"Seawall structure," last modified January 18, 2007, http://www.coastalwiki.org/wiki/Seawall.

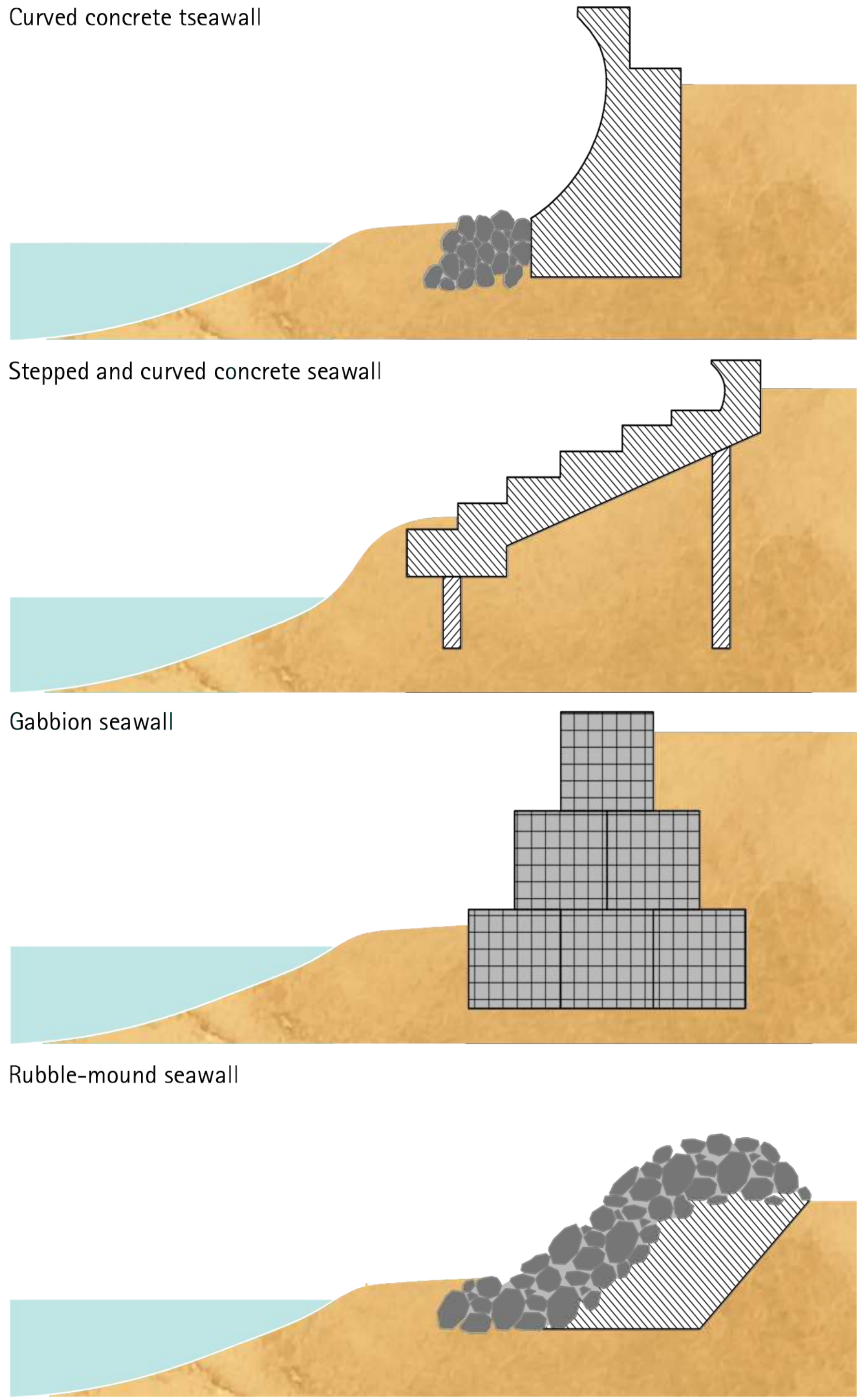


Figure 50:
Examples of Seawall cross sections.Source:
own elaboration from Coastalwiki[175].

6.1.2. Sea Dikes

Sea dikes are onshore structures with the main aim of protecting low-lying areas from flooding. They generally consist in a pile of fine materials like sand and clay with a gentle seaward inclination to reduce the wave runup and erosion. The surface is usually armored with grass, asphalt, stones or with a concrete slab[176] (see figure 51).

6.1.3. Breakwaters

Breakwaters are used to reduce wave impacts, reflecting and dissipating the energy of incoming waves. They can protect harbors and harbor facilities, creating adequately calm waters for safe mooring and loading operations. Breakwaters are also built to improve maneuvering conditions at harbor entrances and small ports. Other applications are regulations of water intakes for power stations and protection of coastlines against tsunami waves.

When meant for shore protection, like detached breakwaters, they are built in a parallel and close position to the shore. The position and design of the breakwaters used depends on the size and shape of the area to be protected, the directions of storm waves, currents and littoral drift. When protecting harbors and channel entrances they can be either detached or shore-connected. Breakwaters can be classified into two main types: sloping-front and vertical-front structures.

Sloping-front structures are usually rubble-mound structures topped with rock or concrete armor units, with or without wave-wall superstructures. Vertical-front structures are mainly built with sand-filled concrete caissons or stacked heavy concrete blocks positioned on a rubble stone bedding layer. When placed in deep water, concrete caissons are normally put on a high mound of quarry rock for economic reasons. These types of breakwaters are referred as composite structures[177] (see figure 52).

[176]Hans Falk Burcharth and Steven A. Hughes, 2.

[177]Ibid,2.

[178]Ibid, 7.

[179]Ibid,7.

Sea dike

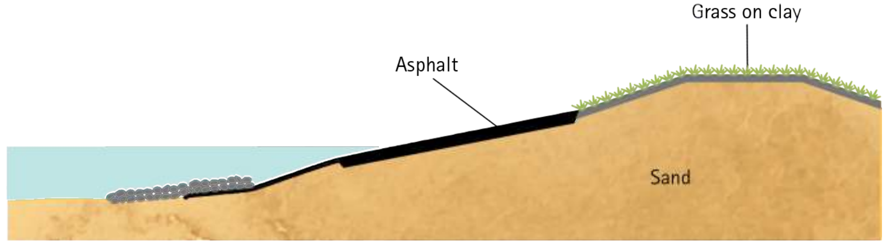
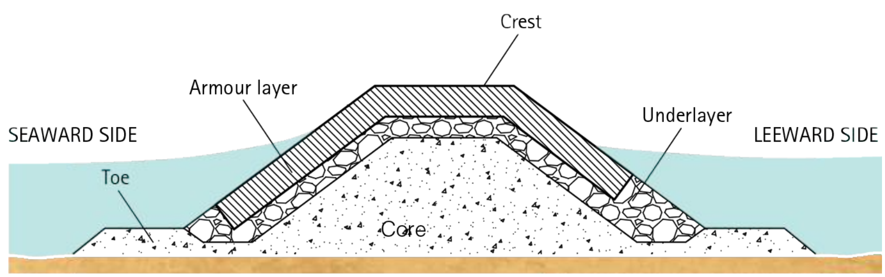


Figure 51:
Example of asphalt-armored sea dike.
Source:
own elaboration from Hans Falk Burcharth and Steven A. Hughes[178].

Sloping front breakwater



Caisson breakwater with vertical front

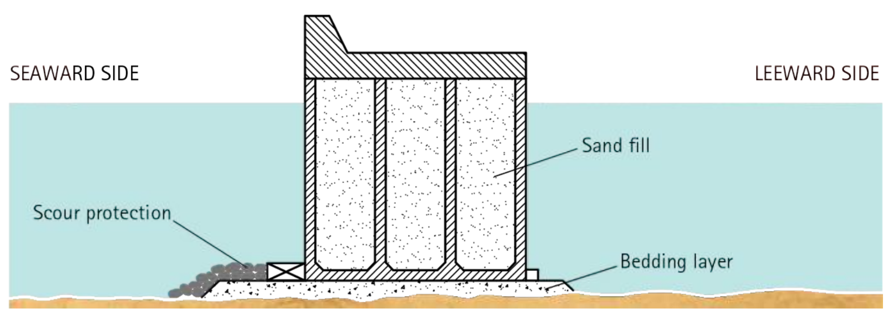


Figure 52:
Conventional multilayer rubble-mound breakwater and caisson breakwater with vertical front cross section.Source:
own elaboration from Falk Burcharth and Steven A. Hughes[179].

6.2. Natural defensive structures

Natural defensive structures, or soft engineering measures, are natural elements used as protective barriers against strong winds, storm surges and other natural hazards, and to enhance the development and protection of the ecosystem (see figure 47). In case of tsunami, they can reduce its energy even if they cannot completely stop it and they are not as effective as coastal structures[180]. Their effectiveness depends on the magnitude of the tsunami and the type of vegetation and natural elements used to mitigate it. The combination of natural barrier with coastal structures represents an optimal solution considering the costs, the ecological impact and the benefits (see figure 53). Among the natural barriers, greenbelts and sand dunes with beach nourishment are the two strategies most used as they necessitate relatively little capital investment and provide human and animal-friendly beach fronts, increasing the inter-relationships among the coastal ecological systems[181].

6.2.1. Green belts

Green belts barriers consist of coastal forests, like mangrove forests in South-East Asia or Pine forests in Japan, whit great mitigation effect in case of small tsunamis, sea winds, sandstorms and high tides, but not against major tsunamis like the one that stroke Japan in March 2011. Green belts weaken the impact of a tsunami, postponing its arrival time and trapping drifting debris. Moreover, the nearby communities can directly benefit from them as they create spaces for recreation and wildlife[182]. Numerous tsunami survey report that coastal forests helped reducing the death toll and damages generated by the Indian Ocean tsunami in 2004[183] (see figure 54).

Many organizations supported and enhanced the reforestation of coastal green belts as natural bio-shield against tsunamis (see figure 55). Since 2006, the International Union for Conservation

[180]Eric Wolanski, “Thematic paper: Synthesis of the protective functions of coastal forests and trees against natural hazards,” *Coastal protection in the aftermath of the Indian Ocean tsunami: What role for forests and trees* (2006): 161.

[181]Norio Tanaka, “Effectiveness and Limitations of Vegetation Bioshield in Coast for Tsunami Disaster Mitigation,” in *The Tsunami Threat-Research and Technology* (InTechOpen, 2011),161, https://www.intechopen.com/download/pdf/13082.

[182]Rajib Shaw, Yusuke Noguchi, and Mikio Ishiwatari, “Green belts and coastal risk management,” (Washington DC: World Bank, 2012), 6. https://openknowledge.worldbank.org/handle/10986/16156.

[183]Alexander M. Kerr and Andrew H. Baird, “Natural barriers to natural disasters,” *BioScience* 57, no. 2 (Oxford University Press: 2007): 102.

[184]IEric Wolanski, 163.

[185]Lori Dengler, “Sumatra tsunami and earthquake impacts,“ accessed May 25, 2018, http://www.groundtruthtrekking.org/photo/mangrove-damage/.

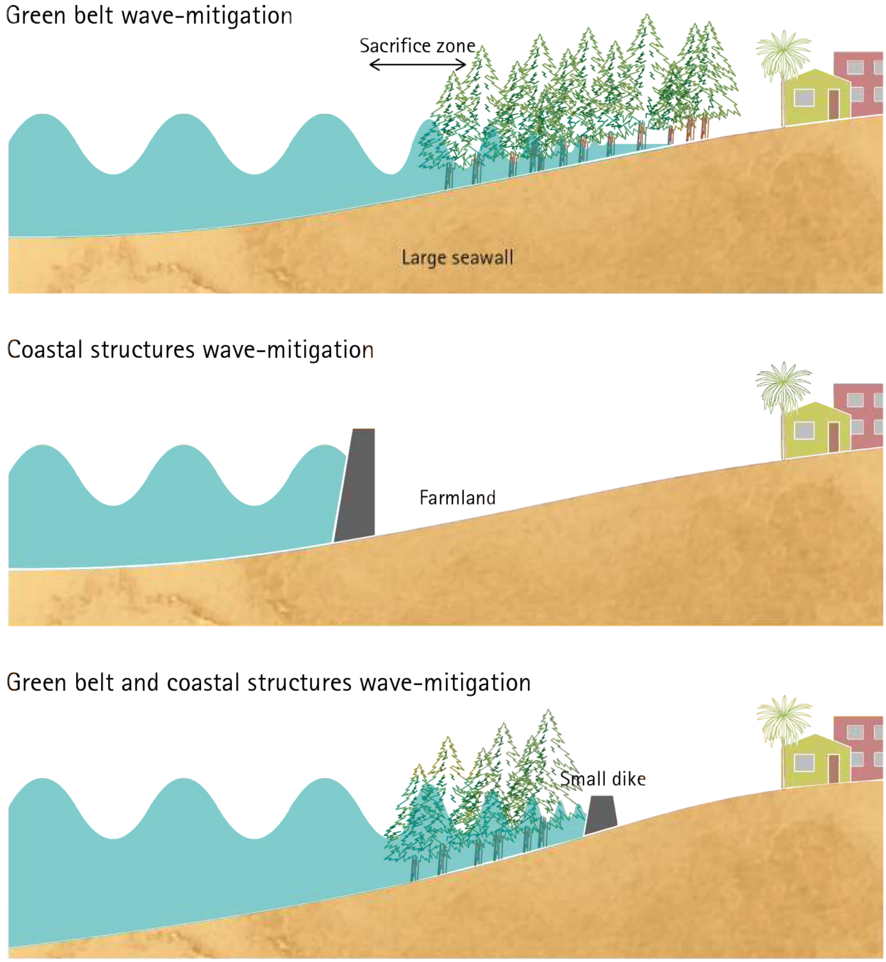


Figure 53:
Role of coastal structures and natural barriers.Source:
own elaboration from Eric Wolanski[184].

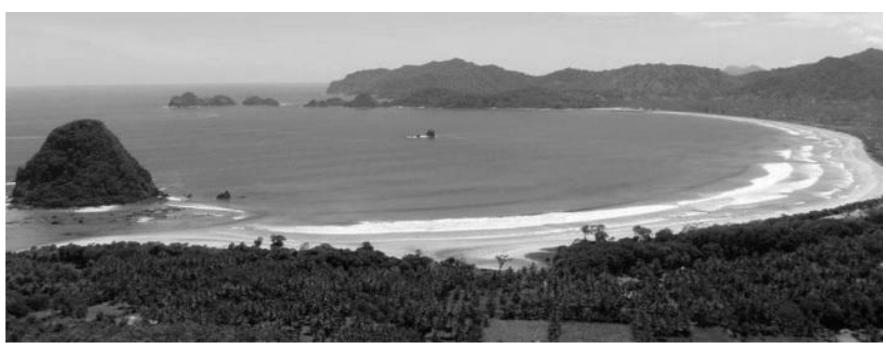


Figure 54:
Coastal forest in Pulau Merah, Indonesia. Source:
unknown author[185].

of Nature (IUCN) is endorsing the project “Mangroves for the Future,” whose objective is constructing mangroves barriers in 12 countries between Asia and Africa[187]. Even if coastal forests cannot assure full protection; they can reduce the menace to an acceptable degree. The right use of vegetation depends on factors like the severity of the expected natural hazards, the local bathymetry, climate, and land use[188].

[186] Alexander M. Kerr and Andrew H. Bair, 102.

[187] Eric Wolanski, 161.

[188] Lori Dengler, “Sumatra tsunami and earthquake impacts,“ accessed May 25, 2018, http://www.groundtruthtrekking.org/photo/mangrove-damage/.

Figure 55: Flooded coastal mangroves after the Indian Ocean tsunami in 2004 at the northwest end of Simeulue Island off Sumatra. Source: Lori Dengler[188].

6.2.1.1. Coastal forests as tsunami barriers

Coastal forests function as a permeable barrier able to absorb impact forces and delay the water flow of large storm waves and tsunamis. While non-permeable coastal structures, like seawalls, reflect waves back to the ocean, permeable structures, like breakwaters and coastal forests, partially reflect and partially transmit the waves. Coastal forests gradually absorb the energy as the water flows through them. Without the forest, the maximum height of the run-up is determined by the magnitude and nature of the tsunami and other local features like coastal profile, bathymetry and beach slope. Once the tsunami gets to the shore, the water depth, velocity, and force decrease depend on the amount of water reflected and energy adsorbed by the coastal forest (see figure 56).

[189]Keith Forbes and Jeremy Broadhead, *The role of coastal forests in the mitigation of tsunami impacts*, (Bangkok: Thammada Press, 2007),7, http://www.fao.org/forestry/14561-09bf06569b748c827dd-df4003076c480c.pdf.

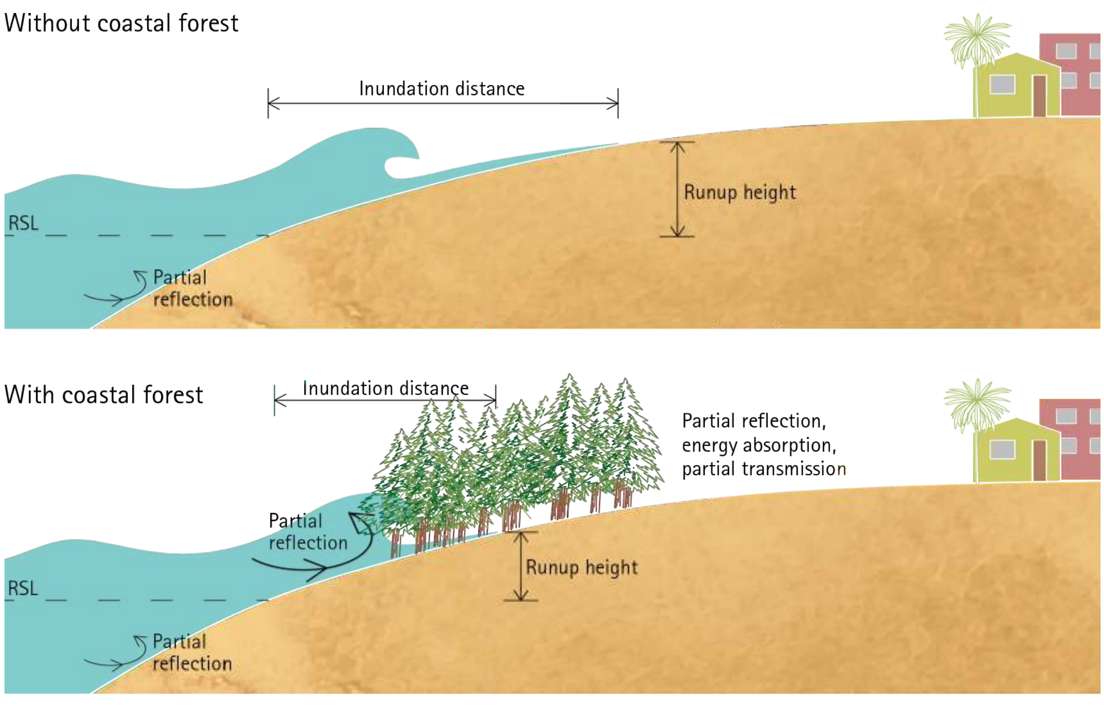


Figure 56: Tsunami wave run-up with and without coastal forest barrier. Source: own elaboration from Keith Forbes[189].

Field observations and laboratory research set the main parameters that affect the coastal forest ability to mitigate a tsunami. These parameters can be resumed in forest width, tree density, tree age and height, trunk diameter and species composition. Each parameter can be adjusted to obtain the necessary degree of mitigation. The relationship among parameters is complex and marked by codependence and interaction.

Forest width is one of the most influent mitigation factors. The energy is gradually dissipated by the hydraulic forces (drag forces) generated by the contact with tree trunks, branches and foliage. Simulations show that forests with a width greater than 100m are able to considerably reduce the transmitted energy of long period waves while forests narrower than 50m suffer a significant loss in hydraulic force. This suggests that the narrower is a forest the higher is the risk from long period waves. Therefore, incrementing forest width will gradually reduce the potential risk due to the impact.

Numerical simulations show that a coastal forest of 200m width can reduce the drag force of a 3m-tsunami by 80%, and its flow velocity by 70%[190]. However, larger waves can cause breakage and the decrease in the percentage reduction, while smaller waves, despite their less significant force and depth, may pass under the canopy, limiting the mitigation effects provided by the forest. As forest width diminish, the importance of undergrowth and lower branches increases, especially in case of near-field tsunamis.

The density of a coastal forest is the factor that determines how much the barrier is permeable. Its overall density or permeability is the sum of the horizontal density which consist of the spacing among the trees, and the vertical density resulting from the configuration of above-ground roots, stem, branches and foliage. Though forest density has a weaker mitigation effect compared to width, it directly influences the forest's ability to reflect a tsunami, as well as absorb its energy. Moderate densities are the most efficient in tsunami mitigation. If too sparse, like most coconut

[190] Keith Forbes and Jeremy Broadhead, 7-9.

groves, waves can easily pass through unmitigated, but if too dense, like some mangroves, a large wave can completely level the forest and pass over unmitigated[191].

The forest age, calculated on the average age of dominant size trees, is linked with both tree height and diameter which help enhancing the mitigation effects of coastal forests. The age increases the breaking strength of trunks and branches, and therefore the resistance of the forest from being tear down. The taller is the forest, the greater its reflective area and the lower the chances of being overtopped by a tsunami. If the forest density is sufficient to resist the wave and the soil cohesion is strong enough to withstand additional leverage from the force generate high in the trees, increasing tree height enhance the resistance against a tsunami[192].

The tree species play an important role in the level of tsunami mitigation. The two most important aspects that have to be considered when choosing the species to plant are the vertical configuration of roots, bole, branches and foliage, and understory development. Drag resistance at the lower layers of the forest is determined primarily by the shade tolerance of plant species in the undergrowth. Tree species with lower branches or stilt rooting allow to reach an appropriate density level at lower layers[193].

6.2.1.2. Effectiveness and limitations of vegetation barriers for tsunami mitigation

Analyzing the historical records of the tsunamis that stroke Japan, it is possible to determine the effects and limitations of coastal forests. After the Indian Ocean tsunami in December 2004, the research aimed at understanding the effectiveness of coastal vegetation to minimize infrastructure damage and protect human lives. The investigations showed that planting or strengthening greenbelts of mangroves and other kind of coastal forests may help reducing the effect of future extreme events[194]. In order to

[191]Ibid, 11.

[192]Ibid, 14.

[193]Ibid, 17.

[194]Norio Tanaka, "Effectiveness and Limitations of Vegetation Bioshield in Coast for Tsunami Disaster Mitigation," in *The Tsunami Threat-Research and Technology*, (InTech, 2011), 162, https://doi.org/ 10.5772/14465.

achieve an effective coastal vegetation planning it is necessary to understand the limitations of coastal forests in relation to the magnitude of a tsunami and the maintenance of forests itself. Demerits of coastal forests have also been exposed but they can be overcome with proper planning and management (see figure 57). For example, an open gap in the forest, like a road or a river, is very dangerous as it can channel and amplify a strong current. Floating debris from broken trees also can be a threat for surrounding buildings and hurt people. Many planting projects that followed the Indian Ocean tsunami present dangerous gaps in the coastal forest. In order for the planting projects to be successful is fundamental the participation and support from local authorities and communities. An integrated coastal vegetation management system that vision the use of the materials produced by the forest together with the community participation and awareness program can guarantee the effectiveness of a sustainable vegetation bio-shield[195] (see figure 58) .

It cannot be ignored that the surveys reported a significant number of cases where coastal forests failed to protect the coastline from a tsunami. These failures can be attributed to the unexpected dimensions of a tsunami or to the inadequacy of one or more forest attributes. If forest width, density, tree diameter, or soil substrate strength are insufficient, a tsunami can uproot trees or break tree trunks and branches, and level the forest. This is mostly the case of degraded or altered forests with scarce density and replaced tree species[196]. When the green belt fails, the broken materials become debris that can be carried inland by the tsunami, like in the case of the coastal areas of Aceh, Indonesia, where after the Indian Ocean tsunami of 2004, mangrove debris were found up to 2-3km inland (see figure 59). The damages caused by the crush of floating debris can exceed the damages caused by water alone due to the greater mass and inertial forces of the objects carried along[197].

[195] Norio Tanaka, 177.

[196] Keith Forbes and Jeremy Broadhead, 4.

[197] Keith Forbes and Jeremy Broadhead, 21.

In Chile, after the tsunami of 2010, researchers studied the benefits of tree barriers as a tsunami mitigation measure in the Bay of Concepción. Possible tree barriers were designed through a physical model with cylindrical wooden sticks, and four different configurations were tested using a recreated scenario based on a numerical model of the 2010 Chilean tsunami (see figure 60). The physical experiment demonstrated that these kinds of barriers can decrease the inundation area and run-up by up to 13%. Finally, the on-field survey showed that the species of pinus radiata and populus alba, with trunk diameters larger than 20cm, are the ones that batter responded to the waves impact in the most affected areas[198].

[198] R. Aránguiz, M. Villagrán, and G. Eyzaguirre, "Use of trees as a tsunami natural barrier for Concepcion, Chile-11th International Coastal Symposium," *Journal of Coastal Research* 64 (2011): 451-453.

Figure 57:
Sendai, Japan,
before and after
the 2011 Tsunami.
Source:
The Telegraph[199].

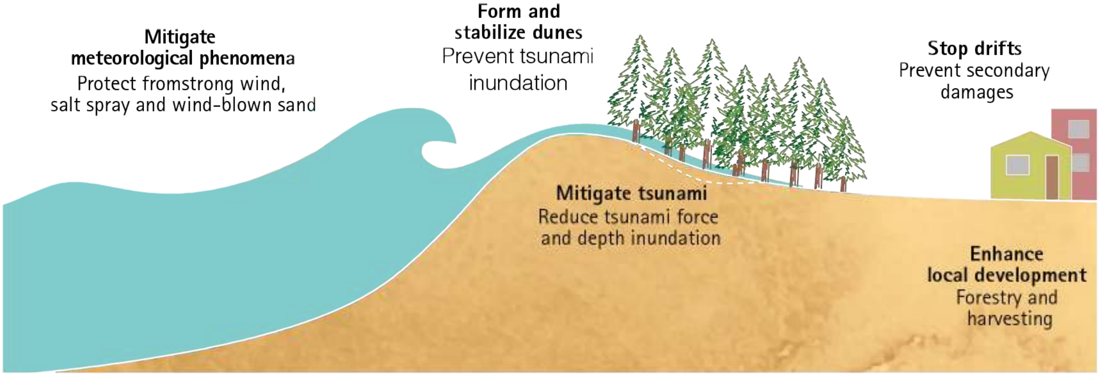


Figure 58:
Tsunami forest
functions.
Source:
own elaboration
from K. Harada and
F. Imamura[200].

Figure 59:
Aceh, Indonesia,
after the Indian
Ocean tsunami in
2004.
Source:
Jean-Luc
Luyssen[201].

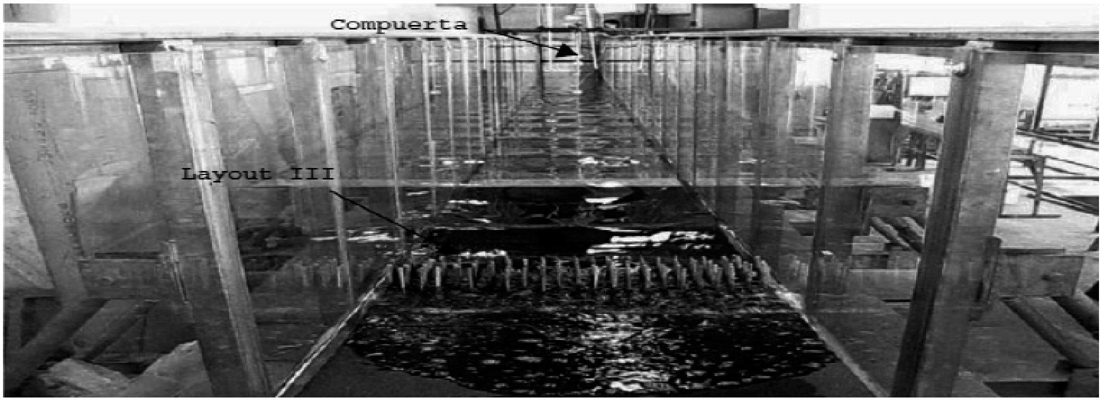


Figure 60:
Tree barrier layouts
tested.
Source:
R. Aránguiz, M.
Villagrán, and G.
Eyzaguirre[202].

6.2.2. Dune construction and beach nourishment

Beach nourishment is a soft engineering approach used in response to shoreline erosion and flood reduction, which involves consists in the artificial addition of sediment of suitable quality to a beach area that suffer a sediment deficit. Nourishment can also be referred to as beach fill, beach replenishment, beach re-nourishment and beach feeding[203]. The projects are designed and engineered to work like natural beaches, allowing sand to freely shift in response to currents, wave and water levels.

Beach fills can be placed as underwater mounds, directly on the beach, as dunes or all three at the same time (see figure 61). After beach nourishment the sand is distributed gradually by the natural processes characterizing the beach system. Wide nourished beach, with gentle slopes and tall sand dunes work as natural buffers protecting the coast. Due to the continuous movement of sand, nourished beaches have to be periodically re-nourished with additional quantities of sand to guarantee the protection and mitigation effects in case of hurricanes and coastal storms (see figure 62).

The sand used to nourish a beach comes from a different source, chosen on compatibility of sand, cost, removal, transportation, and other environmental factors. Beach fill can be dredged from underwater sources such as harbors, navigation channels or from other offshore deposits. Finding an affordable borrow source with sufficient quantities of high-quality beach fill is difficult. Grain size, color, composition, and texture of the material have to be as similar to the native sand as possible to ensure the benefits of the design.

Every beach nourishment project is unique, because different beaches in different areas have different physical, geologic, environmental, and economic characteristics. Since it is impossible to predict with certainty future waves or storm conditions, numerical models are used to help design beach nourishment projects through a range of possible beach behavior and certain types of storms.

[199]Peter Foster, "Japan tsunami: grim tide of death as 2,000 bodies wash up on the shores," The Telegraph, March 14, 2011, https://www.telegraph.co.uk/news/worldnews/asia/japan/8381336/Japan-tsunami-grim-tide-of-death-as-2000-bodies-wash-up-on-the-shores.html.

[200]Harada, K. and F. Imamura, "Effects of Coastal Forest on Tsunami Hazard Mitigation – A Preliminary Investigation," https://doi.org/10.1007/1-4020-3331-1_17.

[201]Jean-Luc Luyssen, "Indonesia Tsunami: Banda Aceh, then and now," Alizul, https://alizul2.blogspot.com/2012/04/indonesia-tsunami-banda-aceh-then-and.html.

[202]R. Aránguiz, M. Villagrán, and G. Eyzaguirre, 451.

[203]Matthew M. Linham and Robert J. Nicholls,"Beach nourishment," ClimateTechWiki, accessed May 25, 2018, http://www.climatetechwiki.org/content/beach-nourishment.

[204]U.S. Army Corps of Engineers and Horry County Government., "Beach Nourishment. How beach nourishment projects work," *Shore Protection Assessment, Horry County Government*, https://www.horrycounty.org/Portals/0/docs/beachrenourishment/HowBeachNourishmentWorks%20(002).pdf.

[205]Town of Duck, "Beach Nourishmnet updates," last modified June 14, 2017, https://www.townofduck.com/beach-nourishment-project/beach-nourishment-update-june-14-2017/.

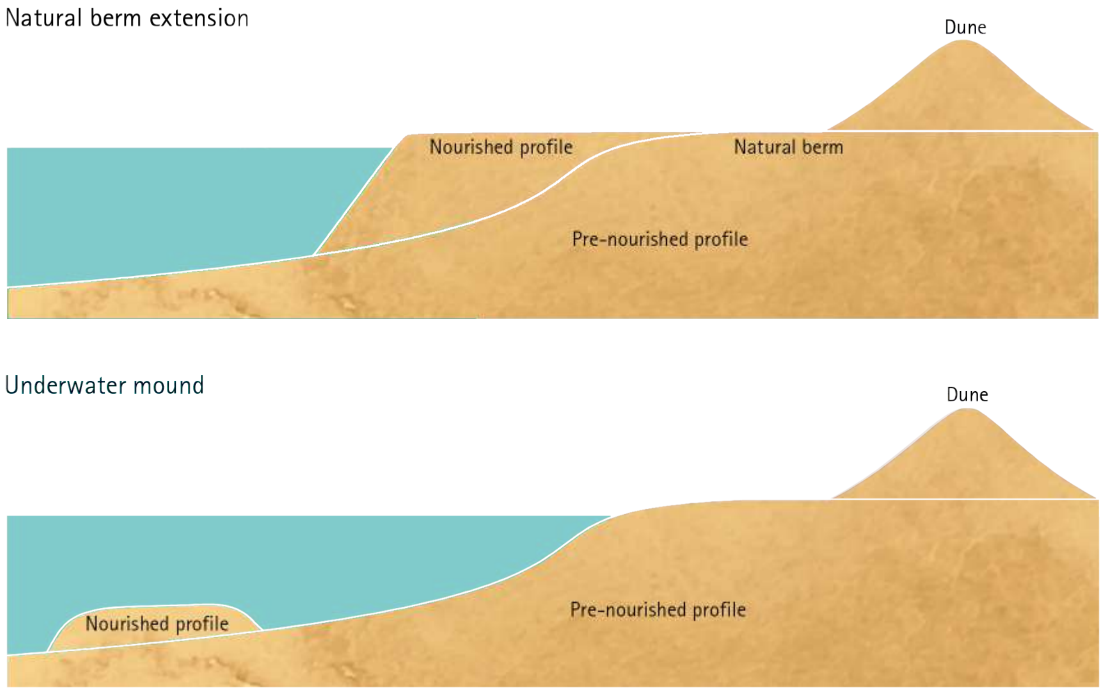


Figure 61: Examples of beach fill.Source: own elaboration from U.S. Army Corps of Engineers[204].

Figure 62: Beach nourishment works at Duck, North Carolina. Source: Town of Duck[205].

The main factors considered by the designs are climatology, beach shape, sand type, volume and rates of sediment transport, erosion patterns and causes, waves and water levels, historical data and previous storms, probability of certain beach behaviors at a given location, existing structures and infrastructure, and earlier engineering activities in the area.

Studying the beach topography above and below the water, it is possible to identify coastal processes, calculate the volume of beach fill needed, and determine how many years the project will last before re-nourishment is needed. Periodic re-nourishments range on average from 2 to 10 years, varying according the initial design, wave climate, use of sand, storm types, and project age, and (see figure 63). Beach nourishment is not an exact science; variables and uncertainties exist. Actual periodic re-nourishment intervals may differ from the planned ones[206].

[206]U.S. Army Corps of Engineers and Horry County Government., "Beach Nourishment. How beach nourishment projects work."

[207]Ibid.

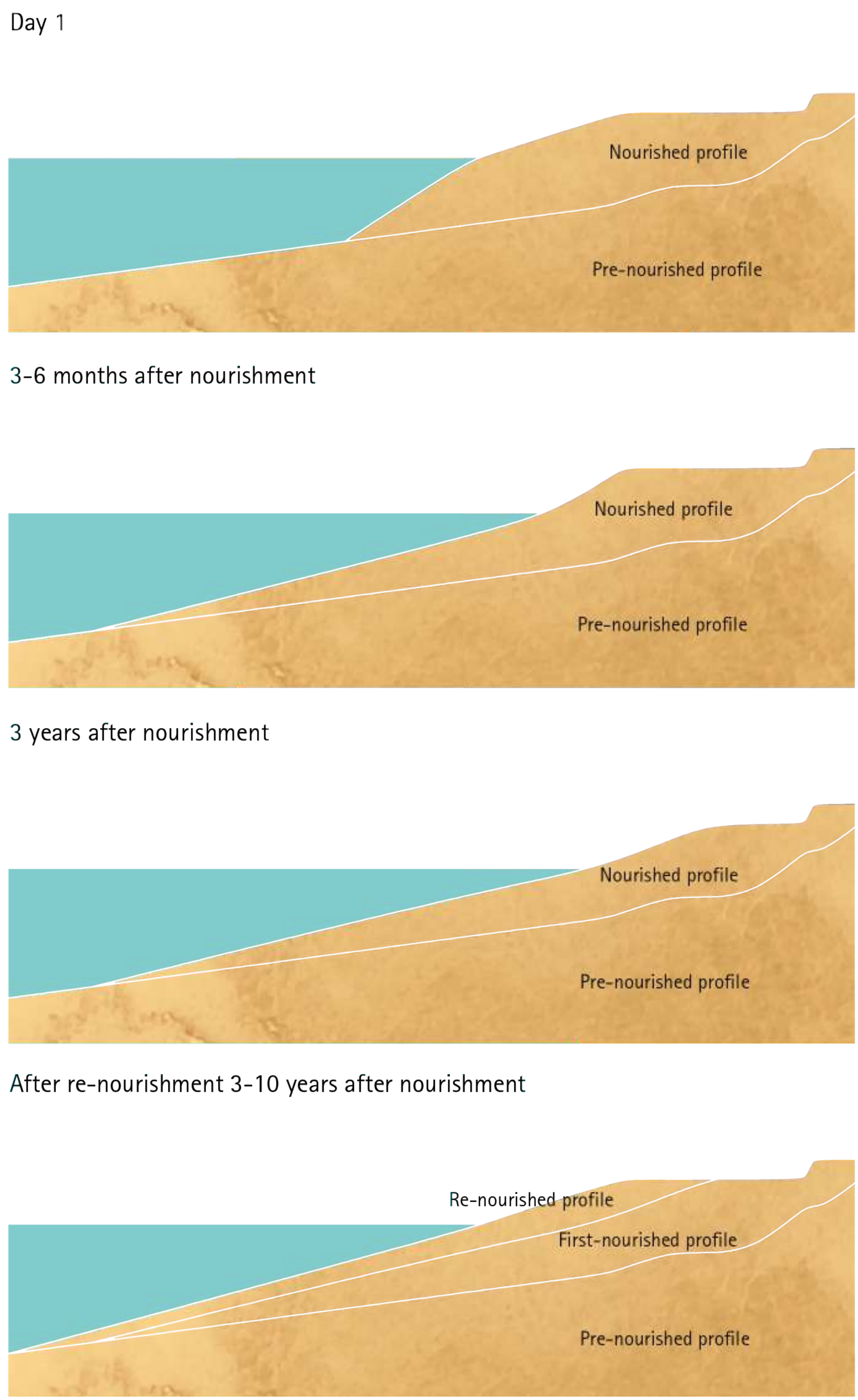


Figure 63:
Hypothesis of a timeline showing coastal changes after a nourishment project.
Source:
own elaboration from U.S. Army Corps of Engineers[207].

6.2.2.1. Sand dunes as tsunami barriers

Beach nourishment is a soft engineering approach used in re6.2.2.1. How beach nourishment works as natural barrier.
High and wide beach berms are designed to reduce wave energy. The gradual slope of a nourished beach force waves to break in shallow waters, dissipating most of the wave energy before reaching the beach. Water currents redistribute sediment, which are deposited in deeper water or moved along the shore. These sediments often create an offshore bar causing the waves to break farther offshore, again dissipating their energy, and thus protecting people and infrastructures behind the beach (see figure 64).

Sand dunes can be constructed, or existing dunes improved, to reduce damage from inundation. They help preventing flooding and storm damage originated by storm surge, wave runup and overtopping, working as a protective shield. Berm height and width, dune height and offshore slope are critical features of a beach nourishment design. Designing a project to protect against any and all kind of storms is not economically feasible. Extreme conditions and severe storms could exceed the capacity of a beach nourishment project to protect people and properties[208].

[208] Ibid.

[209] Ibid.

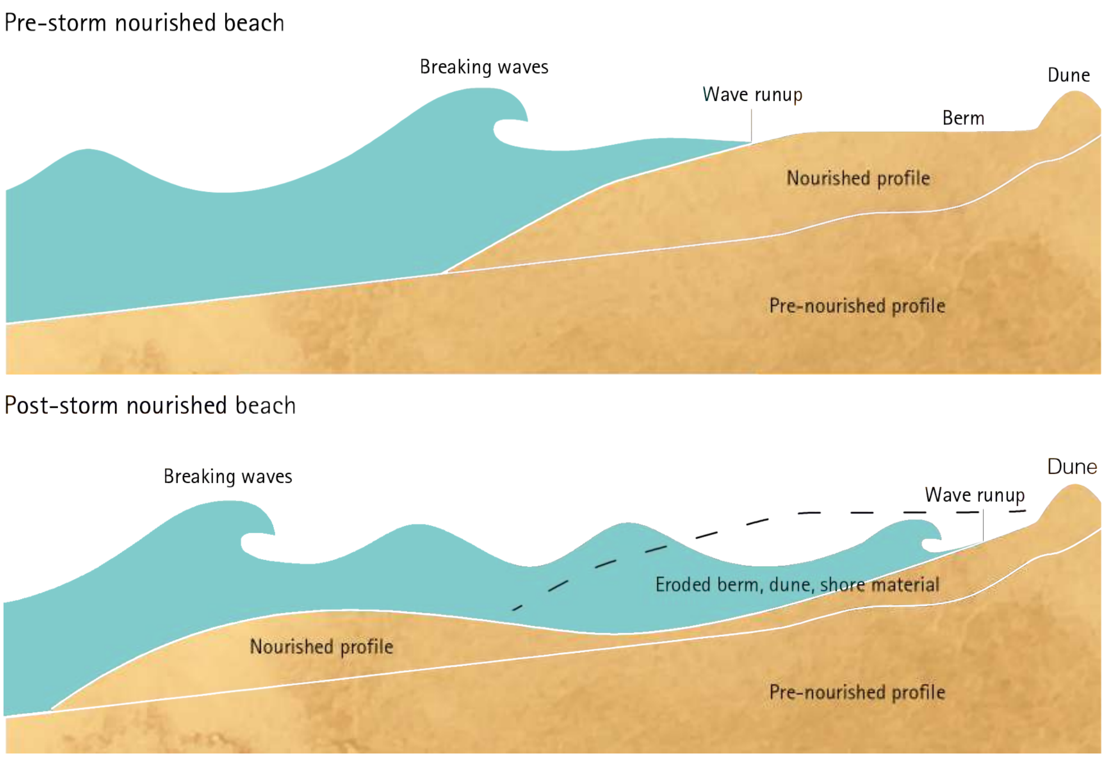


Figure 64: Nourished beach changes after a strong storm or a tsunami. Source: own elaboration from U.S. Army Corps of Engineers[209].

7

COASTAL EROSION IN CENTRAL CHILE

The increasing urbanized coastal areas together with more frequent recurrence of extreme storms in Central Chile, may have originated a new coastal hazard in addition to earthquakes and tsunamis[210], even if, to date, there are no clear evidences regarding shoreline changes in such region. The relationship between coastal erosion and extreme storm events is still not clearly understood because of the insufficiency of long-term wave and sea level records, the absence of high-resolution satellite images dating the 20th century, the lack of long-term beach profile monitoring data and the unawareness of how urbanization influences the sediment supply in urban river basins like the Marga-Marga river in Viña del Mar[211].

The occurrence of other factors, like El Niño–Southern Oscillation (ENSO) and the frequent seismic cycles, originates additional variables which interact uniquely on the coasts of Chile which cannot be ignored. To establish a solid physical background for future coastal development, it is necessary to acquire further oceanographic data and draft long-term beach monitoring plans of urbanized coasts. With the information available today, it is not possible to determine the measure in which coastal erosion represent a new hazard for the coasts of Central Chile[212].

7.1. Coastal erosion in the Valparaiso region

The Greater Valparaíso is the main Chilean coastal metropolitan area with roughly one million of inhabitants. The conurbation includes six growing coastal cities with a built surface area which tripled in the last forty years with great repercussion on the environment. A preliminary morphological changes assessment has been carried out in four urban beaches over a 52-year period from 1964 to 2016. The beaches in questions are: Playa de Reñaca (in Reñaca), Los Marineros and Las Salinas in Viña del Mar (see figure 65) and Caleta Portales in Valparaiso.

The analysis showed that the Playa de Reñaca was subjected to an accretion of 12.6m, while Los Marineros and Las Salinas remai-

[210] Carolina Martínez, et al., “Coastal erosion in central Chile: A new hazard?” *Ocean & Coastal Management* 156 (2018): 141, https://doi.org/10.1016/j.ocecoaman.2017.07.011.

[211] Ibid, 141.

[212] Ibid, 153.

[213] Municipalidad de Viña del Mar, “Cartografía oficial de Viña del Mar,” (2009).

Figure 65: Beaches of Viña del Mar. Source: own elaboration from SECPLA Municipalidad de Viña del Mar[213].

ned stable but experienced slight rotation of the shoreline due to a southward shift in the offshore wave direction. Caleta Portales, in the contrary, receded of 12.6 m between 2004 and 2016[214] (see figures 66-67). The erosion trend of these four beaches increased in the last decade due to a greater incidence of extreme storm surges. Even if historical data show that there are no significant changes in wave height, storms frequency has increased in the last 60 years, from an average of 5 storms per year to 20 per year[215]. If the erosive trend and the urbanization in the contributing basins keep raising, together with the increased storm incidence and intensity, the southward direction shift in offshore wave and the sea level rise are maintained or intensified the coast will deteriorate.

Coastal erosion management, in Central Chile, envisages a combination of protective engineered solutions and integrated coastal management measures, which should focus principally on overseeing the urbanization growth within the coastal zone and promoting a sustainable development. The analysis of the available satellite images and topographic surveys provided the necessary information to determine spatio-temporal changes along the shore which have been later linked to the long-term variables like wave climate and Main Sea Level (MSL). The analysis reported an increase in erosion rates due to the MSL rise during the ENSO warm phases and a frequency increase of extreme storms, suggesting future deterioration of the coast, if such factors will not decrease[216].

[214]Carolina Martínez, et al., 153.

[215]Ibid, 153.

[216]Ibid, 151.

[217]Ibid, 151.

[218]Ibid, 151.

Figure 66: Caleta Portales, Valparaiso, 2014. Source: Carolina Martínez, et al.[217].

Figure 67: Erosion of Caleta Portales, Valparaiso, 2015. Source: Carolina Martínez, et al.[218].

7.1.1. Storm frequency and seasonality

Records analysis shows an intensification in the frequency occurrence of extreme events during the last 60 years. Between 2015 and 2016, 83 events with wave heights greater than 3.0m were recorded[219]. The events of August 2015 (see figure 68) and July 2016 are the one that more affected the coast and were generated by local storms with waves higher than 6.0m which coincided with winter frontal systems. Even if most of these storms arise in the SW, extreme events originated in the North Pacific during the austral summer caused relatively low wave heights but longer wave periods[220].

7.1.2. Sea level and ENSO events

In Chile, the Main Sea Level (MSL) is influenced by the seismic activity originated in the subduction zone between the Nazca and the South American plate. Vertical seismic drop may cause rapid decreases, in the order of meters, in the MSL. The effects of these sudden changes are equivalent to the ones produced during centuries of climate change. Even if multiple studies regarding recent decades did not find any evidence of a substantial increase in the MSL, these results might have been affected by the uplift of the Earth's crust due to tectonic activity[221]. Beside climate change, seismic activity and tsunami effects, the MSL is influenced, on a large-scale, by the cyclical ENSO oscillations, which can cause the MSL to increase up to 30cm during El Niño phase and decrease of the same amount during La Niña phase[222] (see figure 69).

7.2. Control and mitigation schemes

The coast represents the main economic resource in the Great Valparaíso Region, commercial activities are connected both with its seaport and with coastal tourism. Moreover, estate developments occupy the coastal zone in an unrestrained manner, with negative environmental consequences, like the degradation of beaches, wetlands and dune fields. From a mitigation perspective, different approaches can

[219] Ibid,150.

[220] Ibid, 150.

[221] Ibid, 153.

[222] Ibid, 152.

[223] Agencia Uno, "La intensa marejada que azotó la V región en imágenes," The Clinic, last modified August 8, 2015, http://www.theclinic.cl/2015/08/08/galeria-hd-la-intensa-marejada-que-azoto-la-v-region-en-imagenes/.

[224] Ibid, 155.

Figure 68:
Storm surge hits the coast of Valparaiso, August 2015.
Source:
Agencia Uno[223].

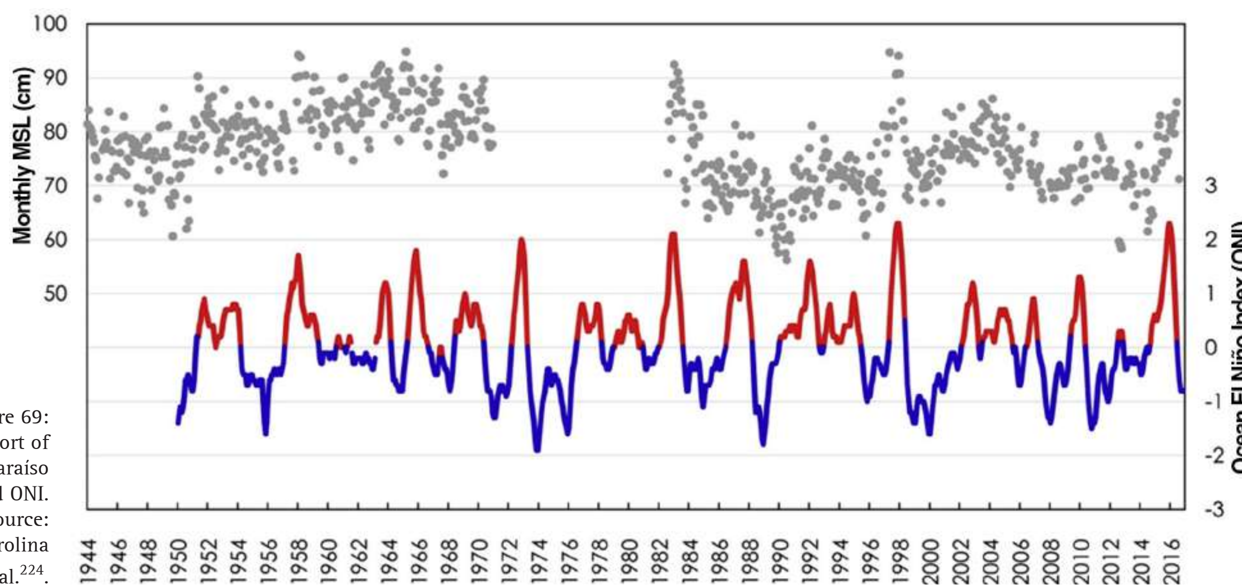


Figure 69:
MSL in the port of Valparaíso (1944-2016) and ONI.
Source:
Carolina Martínez, et al.[224].

be undertaken, from doing nothing to beach nourishment or the construction of hard engendered structures.

The 'doing nothing' approach is not an option when the coast is highly urbanized like in the Great Valparaiso region, often threatened by storm surges and has already experienced remarkable damages and sand loss in the past. The protective approach through hard structures is the primary response to coastal erosion in this area (see figures 70-71). The prediction of collateral damages generated by the modification of the natural sedimentary dynamics is fundamental for this approach to be affective. Due to exposure of the Chilean coasts to seisms and tsunamis, hard structures should be able to both stabilize coastal erosion and protect from tsunami hazard.

Beach nourishment is mostly used in tourist destinations with high erosion rates to restore spaces for recreation. Chile has not experienced this approach yet, and future use would need the adaptation of the already well-established methods and the formation of new skilled professionals. Planned retreat is another interesting option, but not a possible solution due to economic reasons. Anyway, shoreline retreat alone wouldn't be able to prevent or stop erosion processes[2256].

7.3. Improvement of monitoring schemes and modeling tools

Shoreline modeling together with long-term monitoring is a very helpful tool to determine erosion rates on different scales and times and therefore a very valuable instrument to plan land use in coastal zones. However, the lack of long-term oceanographic records regarding beach profiles and waves height in the Great Valparaiso or elsewhere in Chile, causes serious limitations. There are no monitoring data of either nearshore processes nor beach morpho-dynamics in the country. A methodical acquisition of oceanographic variables, could supply the needed information on the frequency and intensity of ENSO events, ameliorate the prediction schemes of climate changes and evaluate the natural uncertainty of such factors on different time scales[226].

[225]Ibid,154.

[226]Ibid, 153.

[227]Secretaria Comunal de Planificación, Municipalidad de Viña del Mar, "Relación armónica del entorno para una propuesta de protección en borde costero."

Figure 70: Breakwaters along the Av. Perù in Viña del Mar, 2018. Source: Eleonora F. Serpi.

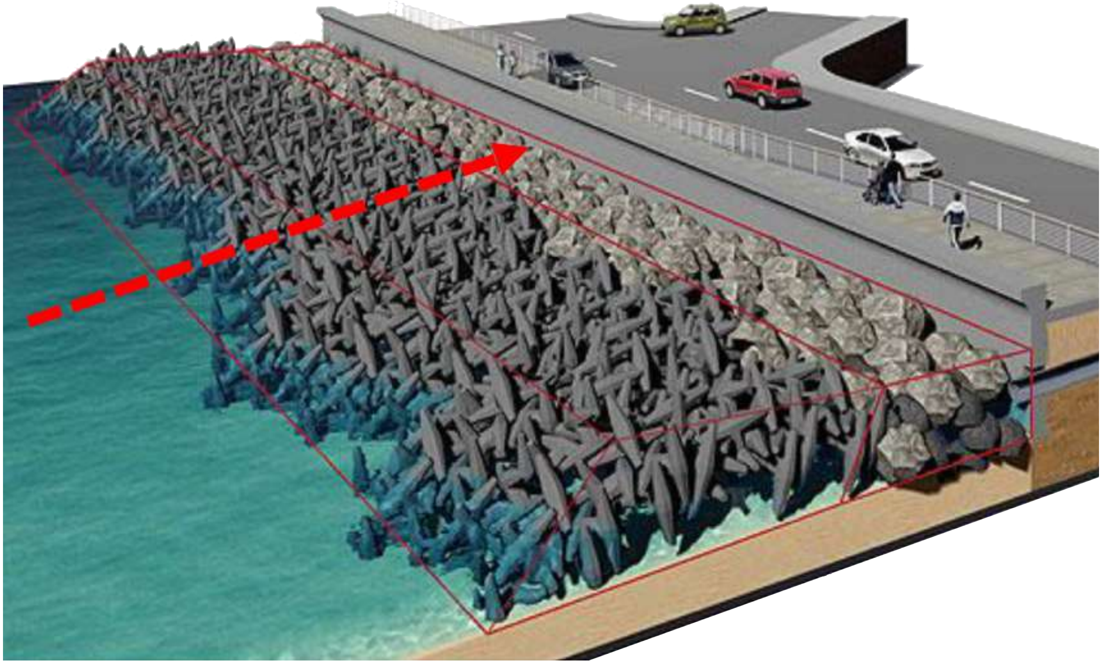


Figure 71: Breakwaters proposal for the Av. Perù in Viña del Mar. Source: Secretaria Comunal de Planificación, Municipalidad de Viña del Mar[227].

8

VIÑA DEL MAR

Viña del Mar (33.0153° S, 71.5500° W) is a city located on the Pacific coast of the Valparaíso Region, Central Chile, about 120km from the capital Santiago (see figure 72). It is the fourth largest city of the country with an area of 122km2 and a population of 334.248[228], which considerably increases in the summer season and during the rest of the year, especially on weekends and holidays, with a monthly floating population that exceeds 100,000 people[229]. Together with Valparaíso, Concón, Quilpué, and Villa Alemana, it is part of the Greater Valparaíso[230], Chile's third largest metropolitan area, with a population of 951.311[231], after the metropolitan areas of Santiago and Concepción[232]. Given its geography and residential character, it has historically maintained the status of a holiday-escape city and it is today considered the tourist capital of Chile, receiving more than one million tourists per year[233].

Viña del Mar is also known as the "Garden City" because of the green areas surrounding it and for the beautiful gardens preserved within the urban center with varied floral and arboreal native and exotic species. The beauty offered by its urban aesthetic is harmoniously combined with its thirteen beaches spread along the 8km of coastline (see figure 73-76). The city is also characterized by an intense cultural and artistic life, gastronomy and entertainment with important and prominent venues, like for example the Municipal Casino[234].

[228]INE, "Cenus 2017," accessed April 22, 2018, http://www.inevalparaiso.cl/contenido.aspx?id_contenido=13.

[229]INE, "Cifras turísticas mensuales," accessed July 23, 2018, http://historico.ine.cl/canales/chile_estadistico/estadisticas_economicas/turismo/cifras_turis_mens_historicas.php.

[230]Hector Santibañez Frey, *La memoria de los barrios. Síntesis de cinco historias locales de Viña del Mar contadas por adultos mayores* (CEME: 2015), 9. http://www.archivochile.com/Mov_sociales/mov_pobla/MSmovpobla0010.pdf.

[231]INE, 2017.

[232]Hector Santibañez Frey, 9.

[233]INE, "Cifras turísticas mensuales."

[234]"Nuestra Ciudad," Ilustre municipalidad de Viña del Mar, accessed April 22, 2018, http://www.vinadelmarchile.cl/seccion/2/nuestra-ciudad.html.

Figure 72:
The Valparaíso Region.
Source:
Eleonora Francesca Serpi.

Figure 73:
View over the coast of
Viña del Mar, 2018.
Source:
Eleonora F. Serpi.

Figure 74:
Playa Los Marineros,
Viña del Mar, 2018.
Source:
Eleonora F. Serpi.

Figure 75:
Playa Acapulco,
Viña del Mar, 2018.
Source:
Eleonora F. Serpi.

Figure 76:
Plaza Mexico in
Viña del Mar, 2018.
Source:
Eleonora F. Serpi.

8.1. Territory morphology

The morphology of the territory is characterized mainly by the Coastal Range, which runs along the Chilean coast defining the beaches, the cliffs, the slopes and the plains. The Coastal Range withdraws to from the plain where Viña del Mar is located, originally known as the 'arenal', 'sandy area'. The plain contains two important geographical elements for the urban definition: the Marga-Marga estuary, and the Cerro Castillo (see figures 77). The last one is a hill isolated from the plain level that defines the limit of the plain together with the Coastal Range.

[235] Municipalidad de Viña del Mar, "Cartografía oficial de Viña del Mar," (2009).

Figure 77:
Topography and
hydrography of
Viña del Mar.
Source:
own elaboration
from SECPLA Municipalidad de
Viña del Mar[235].

8.2. Urban layout

The urban layout developed in the plain has a regular structure based on orthogonal blocks, while the layout on the hills is sinuous, influenced by the slopes produced by the gorges (see figure 78). The blocks, or ‘manzanas’, have been gradually subdivided along the centuries into smaller and smaller parcels until, since 1960 the need to provide access to all the parcels led to the division the blocks in two or more parts.

[236] Ibid.

Figure 78:
Urban layout of
Viña del Mar.
Source:
own elaboration
from SECPLA Municipalidad de
Viña del Mar[236].

8.3. Climate

The City of Viña del Mar has a temperate-Mediterranean climate with long dry season and winter rains influenced by the coastal location and the influence of the cold Humboldt current which produce a cyclonic-orographic rainfall regime. The precipitations concentrate in the colder months, with values that can reach 120mm per month. The annual precipitations oscillate between 250 and 400mm, with an average maximum daily rainfall of 60mm in 24 hours. The thermal influence of the water affects the temperatures through the air that enters the continent from the sea, regulating the daily and seasonal temperatures variation. The annual variations fluctuate between 12°C and 20°C.

The lowest temperatures are registered in the months from May to August with an average of 11.4°C, while the highest temperatures are registered in January with an average of 17.7°C. Due to the influence of the sea there is a wide coverage of low morning cloud and a high relative humidity throughout the year. The winds are predominantly anticyclonic from the south and southwest, with oceanic characteristics. The rain winds have north or northwest direction with maritime influence. Seasonal differences exist in the predominance of southwest winds, in the colder months the direction is north, northeast and northwest[237] (see figure 79).

[237]Ilustre Municipalidad de Viña del Mar, "Declaration de impacto ambiental. Modificación de Plan Regulador Comunal de Viña del Mar. Sector Petroleras Las Salinas".

[238]"Clima: Viña del Mar," Climate-data, accessed April 22, 2018, https://es.climate-data.org/location/941/.

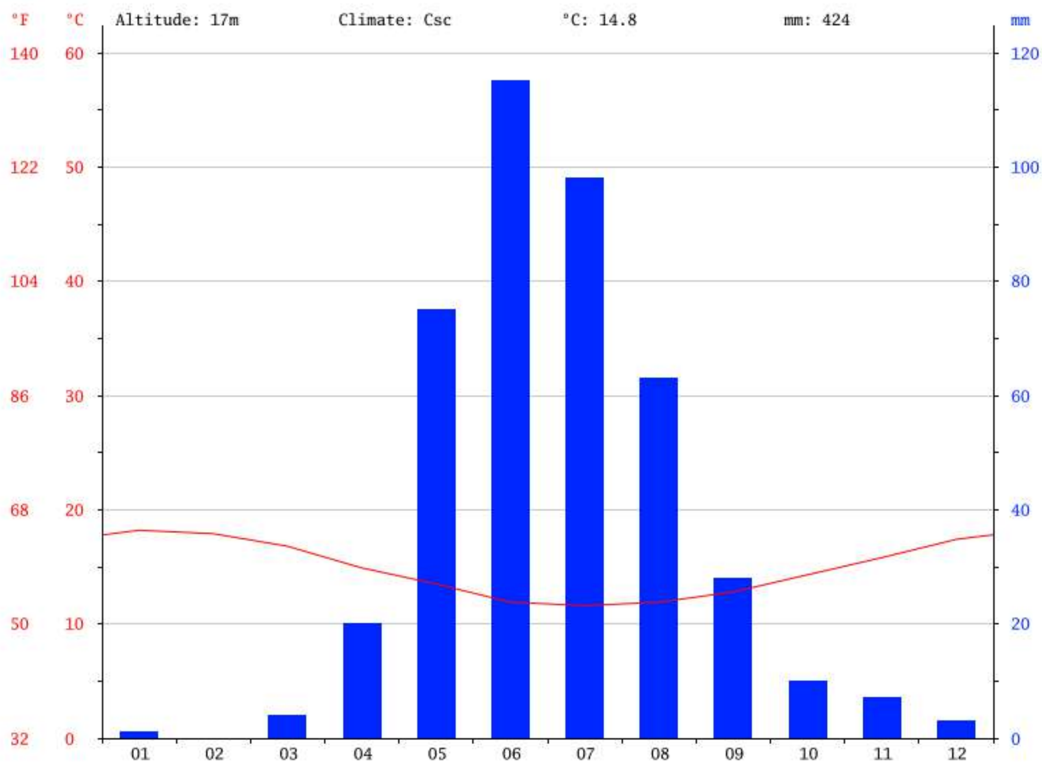


Figure 79: Climogram Viña del Mar. Source: Climate-Data[238].

8.4. History of Viña de la Mar

Historical records from the end of the 15th century report that the area was originally inhabited by the Incas who were extracting gold from the bottom of the Marga-Marga River. In 1536, an expedition under the guide of Diego de Almagro, the first European to discover Chile, travelled along the Marga-Marga River until the Pacific Ocean looking for the gold described by the natives[239]. In 1543, the haciendas "La Viña de la Mar" and "Las Sietes Hermanas" were respectively ceded by Pedro de Valdivia to the Portuguese navigator Mr. Pedro Omepezoa and to the Captain Diego García[240]. For the following three centuries, these haciendas were constantly subdivided and reunited according to personal whims and commercial vagaries.

In 1840, Francisco Alvarez, perhaps the richest man in Chile at that time, bought both of the haciendas to turn them into vineyards and cultivable land, refusing to build any house or shop[241]. According to the explicit will of his widow, he built a huge park with plants and trees original from various points of the globe, which in part are still preserved in the Quinta Vergara district, earning for the city the name of "Garden City" still in use today (see figure 80). With the construction of the railroad between Santiago and the port of Valparaíso in 1863, new advances and inhabitants arrived to Viña del Mar, among them, José Francisco Vergara, a young engineer, husband to Mercedes Alvarez, and heiress of all the lands that extend from the Almendral ravine (current sector Baron) up to the Reñaca estuary. It will be the same José Francisco Vergara to fund the city of Viña del Mar in 1874[242].

The development of Viña del Mar can be resumed in three main stages: the period of the Gran Hacienda (1543-1855), the Foundation (1855-1927) and the Transformation period towards Modernity (1927 onwards)[243]. The first period corresponds to the history of the hacienda "La Viña del Mar" and ends with the con-

[239] Hector Santibañez Frey, 7.

[240] Ibid, 7.

[241] Ibid, 7.

[242] Ibid, 7.

[243] Ibid, 7-8.

struction of the railroad in 1855[244]. The second one begins with the construction of the railroad and sees the prosperous town struggling to become an autonomous city with an incipient industrial development (see figure 81). This period ends around 1927, when innovative ideas emerge in the scheme of the functioning and development of the city[245].

The third period begins with the purpose of transforming Viña del Mar into an attractive seaside resort, one of the first in Latin America. From 1927, the transformation process of the city becomes fully effective even if the initiative dates back to the beginning of the century when there were already the premises of making Viña del Mar a first-class tourist resort with a casino. It is only when Mr. Gastón Hamel becomes mayor that this decisive stage for the progress of the city begins[246].

Fourteen million Chilean pesos were invested in the construction of a large hotel, a swimming pool, terraces and baths along the Miramar walk and in the completion of the Casino and the Municipal Theater[247] (see figure 82-83). The fund was also spent in the construction of a new bridge along Av. Libertad and other urban improvement like paving, sewers and the installation of public lighting in various neighborhoods of the city. Great importance was given to the realization of squares, gardens and public walks. The municipal services were organized to improve the cleaning system, the decoration and the urbanization giving to the city the initial shape of what Viña del Mar is today.

Most of the population was composed of proletarian families, arrived during the first half of the 20th century. This massive arrival significantly changed the social structure of the city, determining the new settlement pattern and life style. When the settlement in the main working-class districts existing in the city could not respond to the large housing demand, the families saw in the hills of the city an opportunity to have their own land where they could build their homes, building a new history[248].

[244]Ibid, 8.

[245]Ibid, 8.

[246]Ibid, 8.

[247]Ibid, 8.

[248]Ibid, 7-8.

Figure 80:
Viña del Mar, the Garden City.
Source:
Ramón Subercaseux[249].

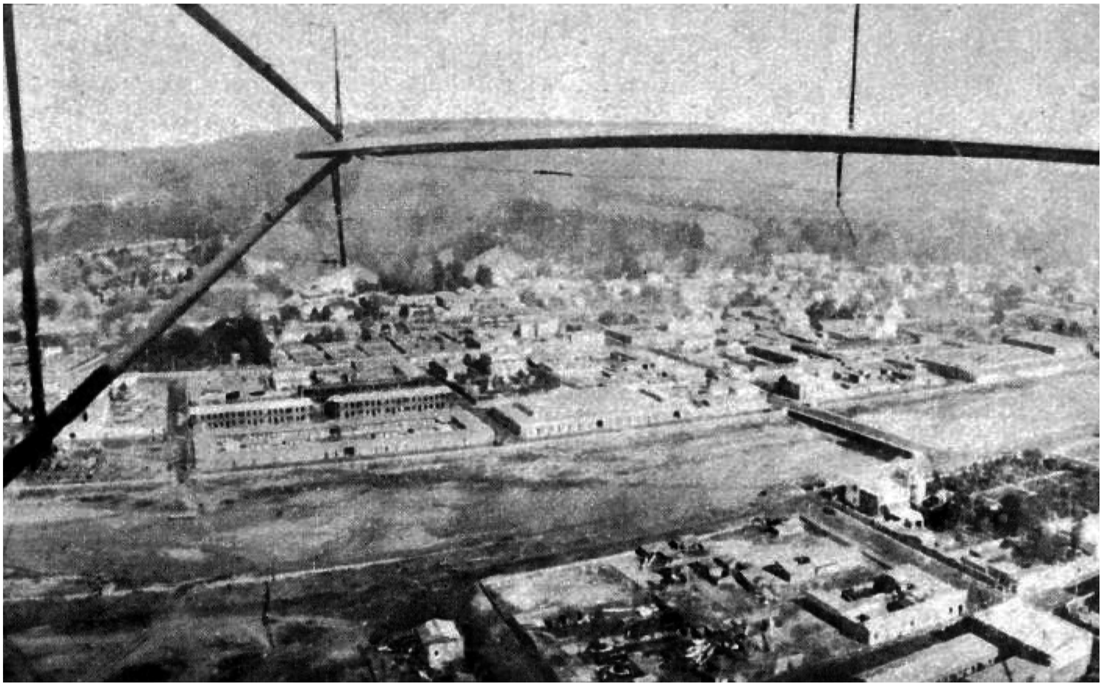


Figure 81:
Aerial view of Viña del Mar, 1913.
Source:
Álbum de Viña del Mar[250].

Figure 82:
Casino of
Viña del Mar, ca. 1940.
Source:
Jacques Cori[251].

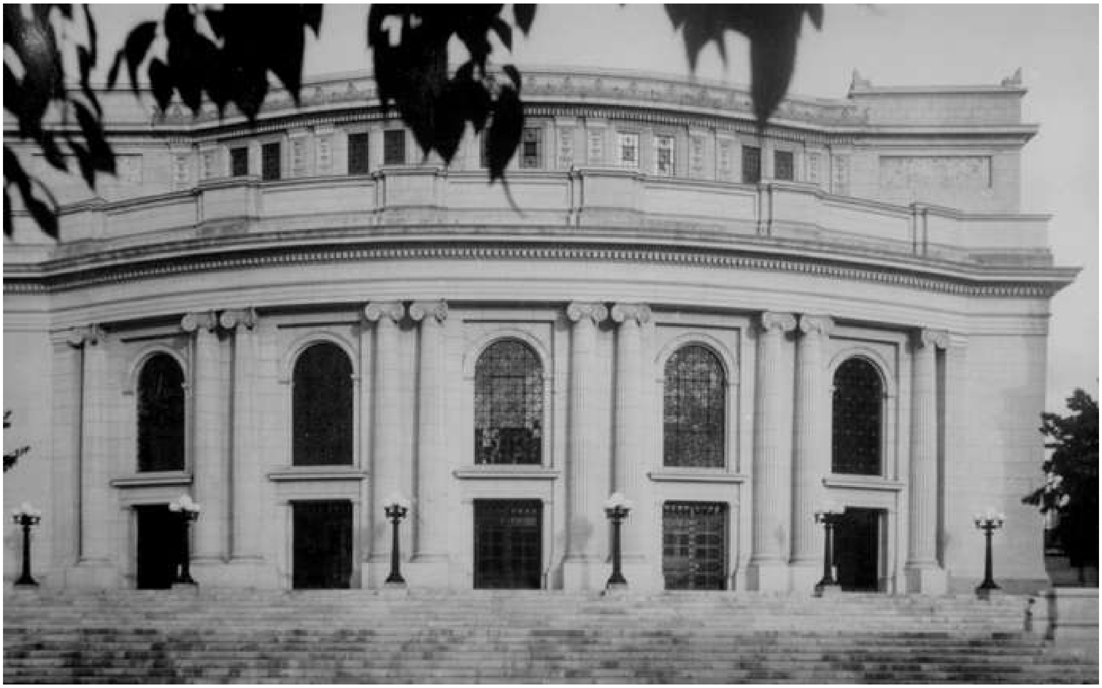


Figure 83:
Theather of Viña
del Mar, ca. 1940.
Source:
Jacques Cori[252].

8.5. Population

Viña del Mar is the city with the least rural population and the highest density in the Valparaíso Region. Most of its current population is the result of the migratory flows originated by the great attraction exercised by the city. Its growth in the last 30 years has generated a set of complex and diverse problems due to a demand that exceeds the availability of basic infrastructure, urban equipment and services. This situation will become even more complex considering the future growth of inhabitants and floating population due to tourism activity.

Since the 60s, the city started experiencing a great urban expansion, developing vast population sectors, mainly in the southern periphery and in the northern part of the commune. The oldest sectors, the Población Vergara, Chorrillos, Recreo and Agua Santa, there have been undergoing a process of consolidation and densification. Currently, the sectors forming the commune are clearly delimited, each with particular characteristics and a certain identity differing them from each other, even if in their interior they present certain degrees of heterogeneity (see figure 84).

The territorial conformation of the commune is characterized by a central zone or plain, which corresponds to the oldest sector of the city. Most of the services and commercial activities are located there, as well as an important residential sector of the richest population. The other part of the population lives in the sectors located on the surrounding hills (see figure 85). They have the residential characteristics of medium and low social strata, except for the areas of Recreo-Agua Santa and Reñaca Bajo, where medium and high economic groups predominate.

The popular sectors, where more than half of the population reside, are: Nueva Aurora, Forestal, Chorrillos in the southern area; Santa Inés, Miraflores, Achupallas, Santa Julia, Gómez

[249]Ramón Subercaseux, 1934. In Maino, Hernán, Pintura Chilena del Siglo XIX. Ramón Subercaseux: *Multifacético Itinerario de un Artista Diplomático* (Santiagio: Origo, 2008), 27.

[250]*Álbum de Viña del Mar: recuerdos fotográficos de esta ciudad y breves reseñas de su progreso, recursos, clima, sociabilidad, edificios, etc* (Valparaíso: Sociedad Imprenta y Litografía Universo, 1913).

[251]Jacques Cori, "Jacques Cori," Ciudades & Lugares de Chile, accessed 23 July, 2018, http://ciudades-lugares.blogspot.com/p/jacques-cori.html.

[252]Ibid.

[253]Municipalidad de Viña del Mar, "Modificacion al Plan Regulador Comunal de Viña del Mar. Sector Población Vergara. Memoria Explicativa," (May 2016), 31.

[254]Servicio Fotogramétrico del Fuerza Armada de Chile, Aerophotometric Relief of Viña del Mar, 2009.

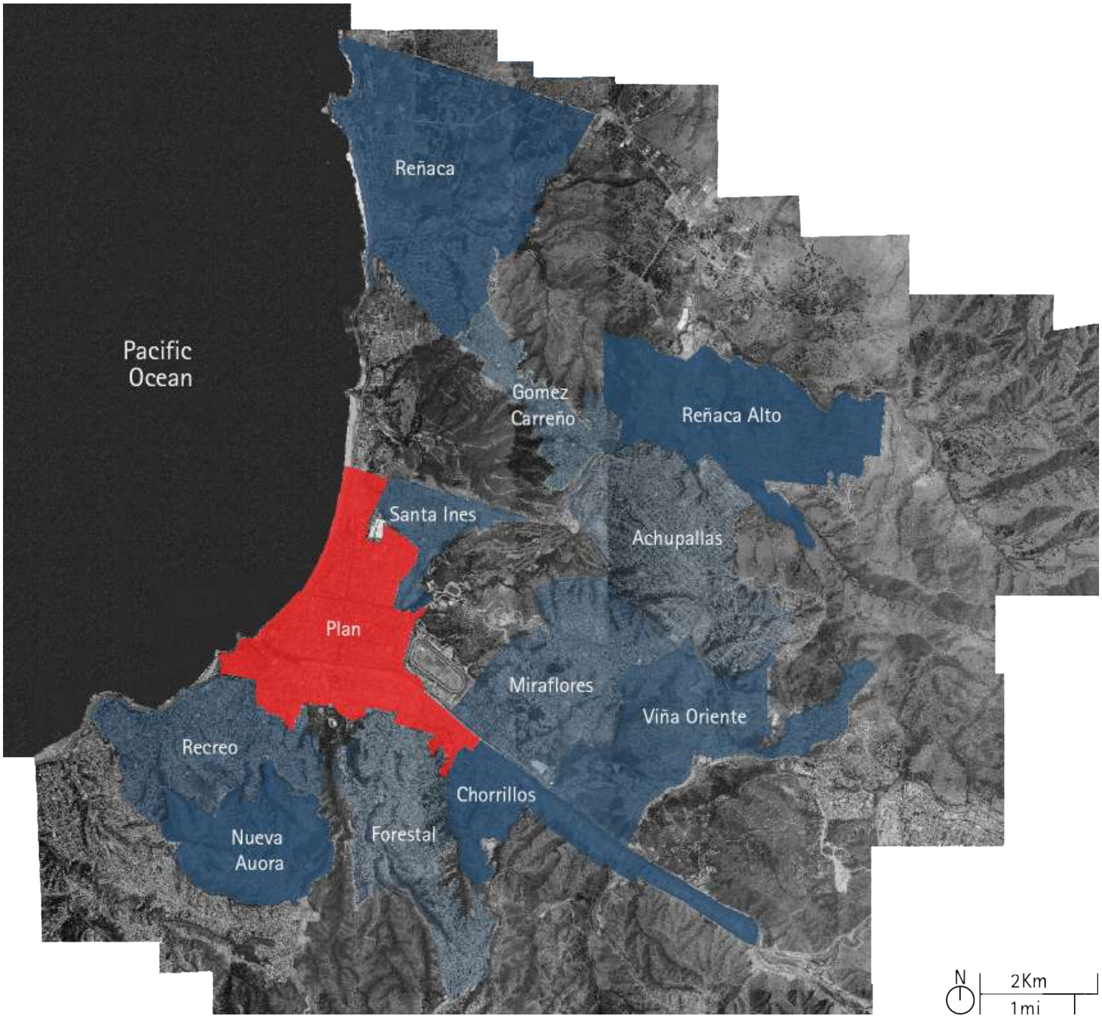


Figure 84: Sectors of Viña del Mar. Source: own elaboration from SAF[253] and Municipalidad de Viña del Mar[254].

Carreño, Glorias Navales and Reñaca Alto, in the northern area; Limonares, Beagle Channel, Villa Dulce, El Olivar and Villa Hermosa, in the eastern area. Each of these sectors presents particular features in terms of its geographical characteristics, history, the socioeconomic status of its population, community facilities and the degree of organization of its community, all of which developed in its inhabitants a marked sense of belonging and territorial identity[255].

[255]Hector Santibañez Frey, 8-9.

[256]Municipalidad de Viña del Mar, "Cartografía oficial de Viña del Mar," (2009).

[257]María Darrigrande, "El balneario y la conquista formalizada del borde costero: Continuidades y fragmentos en Viña del Mar 1928 – 1963" (PhD diss, Pontificia Universidad Católica de Chile, 2010), 154.

Figure 85:
Population distribution in
Viña del Mar.
Source:
own elaboration
from SECPLA Municipalidad de
Viña del Mar[256] and
María
Darrigrande[257].

8.6. Urban development of Viña del Mar

8.6.1. The foundation of Viña del Mar

As previously mentioned, Viña del Mar was founded by Francisco Vergara, who requested and obtained the permission to create a town on his property. The fist decisive conditions for the urban conformation were set in Foundation Decree in 1874[258]. It established an orthogonal grid development in the plain limited by the Cerro Castillo and the train line to the west, the Marga-Marga estuary to the north and the hills to the south. The resultant city was far from the sea and had a traditional regular checkerboard structure parallel to the railway.

The morphological conformation of Viña del Mar was determined by two concrete actions. The first one is its foundation, with the plan proposed by Francisco Vergara, and the second one is the development of the train line that joined Viña del Mar with Valparaíso and later continued to Santiago (see figure 86). Viña del Mar was not born as a seaside town but as a projection of the port of Valparaíso, which found in this place greater space for industrial development and for the residence of the well-offs. Its future connotation is considered as a

> *"condition achieved by this sort of satellite city which mixes the port dormitory, the aristocratic holiday escape and the industrial core"[259].*

In the beginning, the occupation of the coastal border consisted merely of the necessary road and rail infrastructure that connected the port of Valparaíso with the new-born town. This network generated a continuity along the coast, and configurated the present infrastructure system. This infrastructure had two different incompatible purposes: it permitted the access to the beaches, thus constituting the first seaside and residential areas and, at the same time, allowed the establishment of industrial zones with their respective docks on the sea[260].

[258] Carolina Miranda, "Antecedentes sobre la configuración urbana de Viña del Mar, 1874 -1892". *Archivum*, Revista del Archivo Histórico Patrimonial de la I. Municipalidad de Viña del Mar, no.4 (2002):196.

[259] Nolberto Alarcón Eduardo and Marcel Brito, *Patrimonio Arquitectónico de Viña del Mar Antiguo: 1880 - 1930*, Seminario de Investigación, Universidad Católica de Valparaíso, Facultad de Filosofía y Educación, Instituto de Historia (Viña del Mar, 1999): 56.

[260] C. Benavides, M. Pizzi and M. P. Valenzuela, Ciudades y arquitectura portuaria, Los puertos mayores del litoral chileno (Santiago: Editorial Universitaria, 1998): 59.

8.6.2. The role of the infrastructures in the urbanization process

The first significant initiative for the appropriation of the coast was the construction of the railway between Valparaíso (Barón station) and Viña del Mar in 1855 and ten its extension to Santiago in 1863, generating a rapid connectivity with the city[261]. The lines were used both for the transport of people and merchandise. Viña del Mar was born as part of the development fostered by the train line, which expand the territorial needs of Valparaíso, solving the lack of space for the industrial and residential site of the port.

The train traveled along the coast between Valparaíso and Viña del Mar, and then entered the agricultural valleys. The stations of Miramar and Recreo opened at the end of the 19th century allowing the access to the beaches. The construction of the flat junction road (Av. España) between the port and Viña del Mar, in 1901, contributed to the consolidation of the residential areas at the edge of the sea, specifically in the areas of Cerro Castillo and Recreo. The opening of connecting roads, like Av. Libertad and its respective bridge over the Marga-Marga estuary in 1892, Av. Perù in 1914, Av. Marina in 1915, was decisive in the urban development of the city. It not only improves the connectivity of the city but it also makes possible the parceling of land in the Población Vergara and Cerro Castillo[262] (see figure 87).

In 1930, the paving of the road to Concón gave the access to new beaches in the north of the city, continuing the development of road infrastructure along the coast. Finally, the opening of variant of the road between Santiago and Viña del Mar in 1931 enhances the arrival of visitors, no more only by train but also by car[263].

[261]Rodrigo Booth, "El Estado Ausente: la paradójica configuración balnearia del Gran Valparaíso (1850-1925)," Eure, no.83 (May2002): 110, http://dx.doi.org/10.4067/S0250-71612002008300007.

[262]María Darrigrande, 162-163.

[263]José Miguel Gil Zabala, "Historia General de Viña del Mar," Archivio Historico Patrimonial Municipalidad de Viña del Mar, accessed May 8, 2018, https://sites.google.com/site/archivohistoricopatrimonial/historia-general-de-via-del-mar.

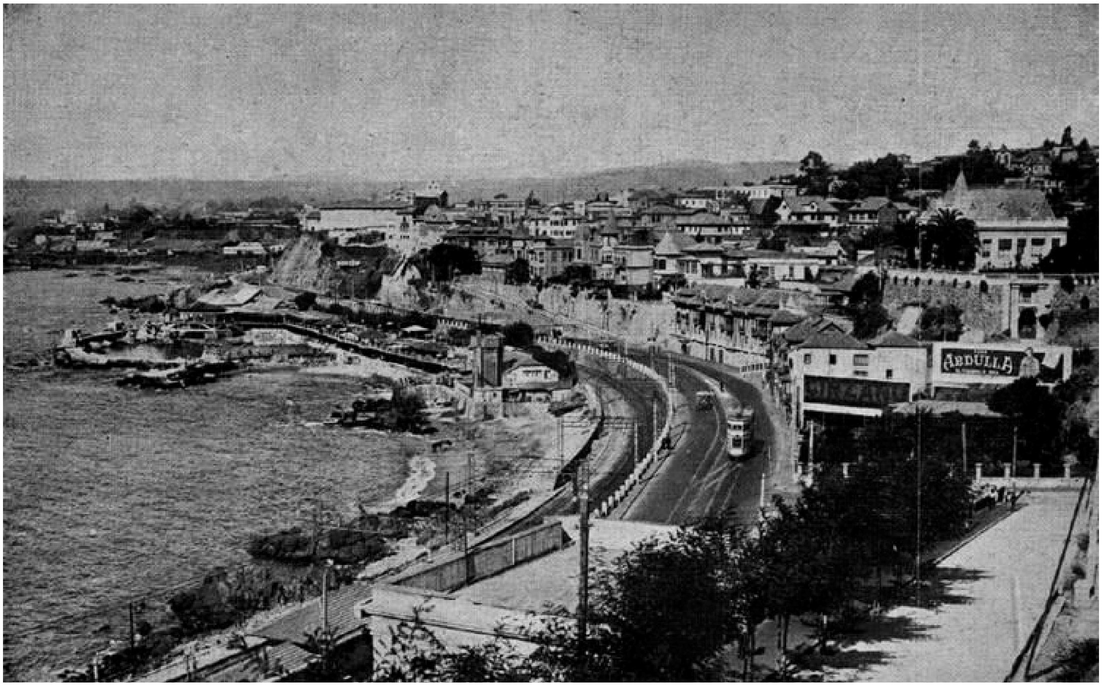


Figure 86: Valparaíso-Viña del Mar railway line, Recreo, 1930. Source: Archivo fotográfico de la Biblioteca Nacional de Chile[264].

Figure 87: Libertad Bridge over the Marga-Marga River, 1925. Source: Unknown Author[265].

8.6.3. From a residential and industrial suburb of Valparaíso to seaside resort town

At the beginning of the 20th century the city as the mere consequence of the expansion of the port and considered as a suburb of Valparaíso[266]. Only after the earthquake of 1906, a new stage for the city began, producing an opportunity for building and urbanizing. The approach of the city to the coastal edge was enhanced, and so its status of aristocratic Villa. An example is the Cerro Castillo that looked over the first equipped beach in the area; the Miramar beach, where interesting Castles and Chalets were located. This beach hosted the first Viñamarinos baths and after the earthquake, born after the cleaning the fallen where the bathrooms and a restaurant were then located[267] (see figure 88).

> *"It is possible to think that the original intention of the wealthy inhabitants of Valparaíso for opting for Viña del Mar as their second or first residence, was to live in a place exclusively residential, socially homogeneous and where the use of green had an ornamental orientation"[268].*

The tourist aspirations of the city were hold back due to the industrial exploitation of the beaches near the city center and those that functioned as such were far from the city center, such as Las Salinas, Montemar and Concón. With the opening of the bridge of Av. Libertad the city started growing in the northern side of the Marga-Marga estuary, where the Vergara Population was established on the initiative of the Sociedad Anónima Población Vergara (see figure 89). This residential area will coexist with the port activities of Vergara dock.

The Vergara dock provided services to the industries in the area, live as the Sugar Refinery (see figure 90). At the beginning of the 20th century most of the industries were located from the north of the Marga-Marga estuary to Las Salinas beach, making it difficult to turn the area into a residential district. Despite the original

[264]"Panorama del Balneario del Recreo, Viña del Mar, hacia 1930," Memoria Chilena, Biblioteca Nacional de Chile, accessed on May 5, 2018, http://www.memoriachilena.cl/602/w3-article-99918.html.

[265]"Puente San Martín y el Estero Marga Marga de Viña del Mar en 1933 ," Enterreno Chile, last modified November 15, 2016, https://www.enterreno.com/moments/puente-san-martin-y-el-estero-marga-marga-de-vina-del-mar-en-1933.

[266]Booth, 1.

[267]Ibid, 6.

[268]Ibid, 6.

[269]Darrigrande, 173.

claim to parceling the land for residential purposes, this was only achieved after 1912, when the Anonymous Resort Association of Viña del Mar was formed[269].

In 1912, the land near the sea was acquired by the Anonymous Resort Association of Viña del Mar. In 1913, the Association published the "Album of Viña del Mar"[270], a small book which presented an urban project proposed for the coastal area of the Población Vergara, based on a "Plano de Conjunto" (see figure 90). A combination of images of the area and texts explained the proposal and the works to be undertaken. This is the first formal initiative to populate the north of the estuary with residential buildings and beach facilities, recognizing the value of the coastline.

> *"The Población Vergara district, near the sea, is the only one that Viña del Mar can use to form the true resort city that has an extensive beach for recreation, with a large avenue on the edge of the ocean for the ride of vehicles and pedestrians, and with contiguous flat lands necessary to contain Hotels, Casino and buildings that elevate their facades to the sea"*[271].

The text explained the infrastructure works that the Society would carry out to enhance the district as an elite seaside resort escape. It was intended both to sell land to private companies and to engage the companies to build hotels, casinos and chalets. Special emphasis was placed on the construction of the seafront between the Marga-Marga estuary and the Vergara dock. The esplanade, corresponding to Av. Perù, was the first to be built and represents the first way to gain ground on the sand (see figure 96). The creation of Av. Perú, as a large public waterfront, served to widen the blocks closer to the sea, while the beach became narrower and narrower. This situation determined the subsequent construction of the protection wall, to reduce the risk of natural floods[272].

[269] Darrigrande, 173.

[270] *Álbum de Viña del Mar: recuerdos fotográficos de esta ciudad y breves reseñas de su progreso, recursos, clima, sociabilidad, edificios, etc.*

[271] Ibid.

[272] Darrigrande, 185.

The law of 1928, emanated from the Central Government, authorized the Municipality to contract a loan of $14 million of Chilean pesos to carry out the works and established the creation of the "Pro-Balneario" board, responsible for contracting, directing, supervising and managing the construction sites. Among the most important works carried out, there is the Casino, built to complement the summer activities and generate a strong inflow of money for the municipality, the O'Higgins Hotel, for accommodating tourists with maximum comfort, the Municipal Theater, as a center of entertainment, and finally, as an initiative of the government, the Palace of the Presidents of Chile, inaugurated by the President Carlos Ibáñez del Campo, honoring the city of Viña del Mar. These projects were exhibited in the first issue of the magazine "Nuestra Ciudad" (October 1930), through a map drawn by the architects Italo Sasso and Agostino Bastiancig (see figure 92). After the Plano Conjunto, no other plan was approved, until the Valparaíso Intercommunal Regulatory Plan of 1965. Both the law, and the plan that supported it, were presented to the community through the editions of the "Nuestra Ciudad" magazine, published between October 1930 and July 1931.

The works carried out during the 1930s maintained the duality of a city that seeks to conquer its coast, but whose center is still located inland. Only from the promotion and habilitation of the beaches Las Salinas and Caleta Abarca, and the creation of the municipal pools in 8 Norte and Recreo, that there is a clear occupation of the coast (see figure 91). Built as form of occupation of the coastal landscape, they were shaped as public spaces, generating access to the beach and service areas, such as dressing rooms, restaurants, kiosks, thus responding to the spatial needs of the activities that accompany the use of the beaches[273].

[273] Ibid, 189-195.

[274] "Playa de Miramar Viña del Mar, hacia 1930," Memoria Chilena, Biblioteca Nacional de Chile, accessed on May 5, 2018, http://www.memoriachilena.cl/602/w3-article-98869.html.

[275] *Darrigrande, 40.*

[276] "Refinería de azúcar de Viña del Mar. Vista exterior, Viña del Mar, 1902," Memoria Chilena, Biblioteca Nacional de Chile, accessed on May 5, 2018, http://www.memoriachilena.cl/602/w3-article-71103.html.

[277] Archivo Museo Histórico Nacional, in "La gran Piscina de Recreo," Enterreno Chile, last modified December 20, 2017, https://www.enterreno.com/blogs/la-gran-piscina-de-recreo.

[278] Órgano Oficial de la Municipalidad de Viña del Mar, "Plano general de Urbanización," *Nuestra Ciudad*, no. 1 (October 1930).

[279] *Álbum de Viña del Mar: recuerdos fotográficos de esta ciudad y breves reseñas de su progreso, recursos, clima, sociabilidad, edificios, etc.*

Figure 88:
Playa de Miramar, 1930.
Source:
Archivo fotográfico de la Biblioteca Nacional de Chile[274].

Figure 89:
View of the Marga-Marga estuary and the Población Vergara, 1930. Source:
María Darrigrande[275].

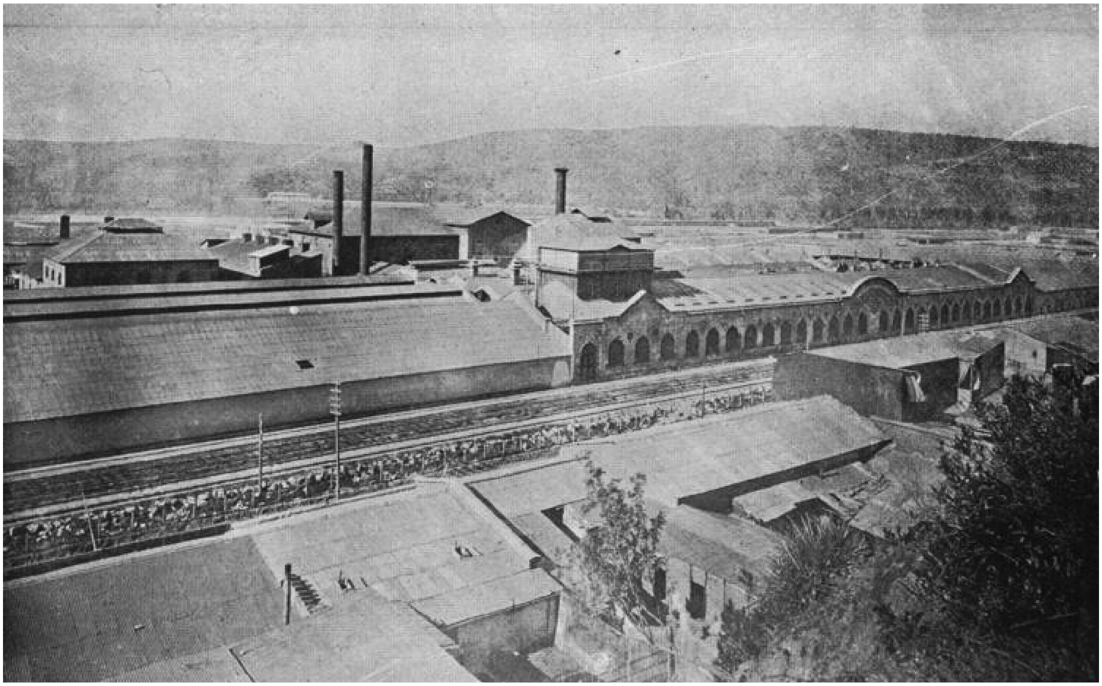


Figure 90: Sugar Refinery in Población Vergara, 1902.Source: Archivo fotográfico de la Biblioteca Nacional de Chile[276].

Figure 91: Swimming pool in Recreo, 1931.Source: Archivo Museo Histórico Nacional[277].

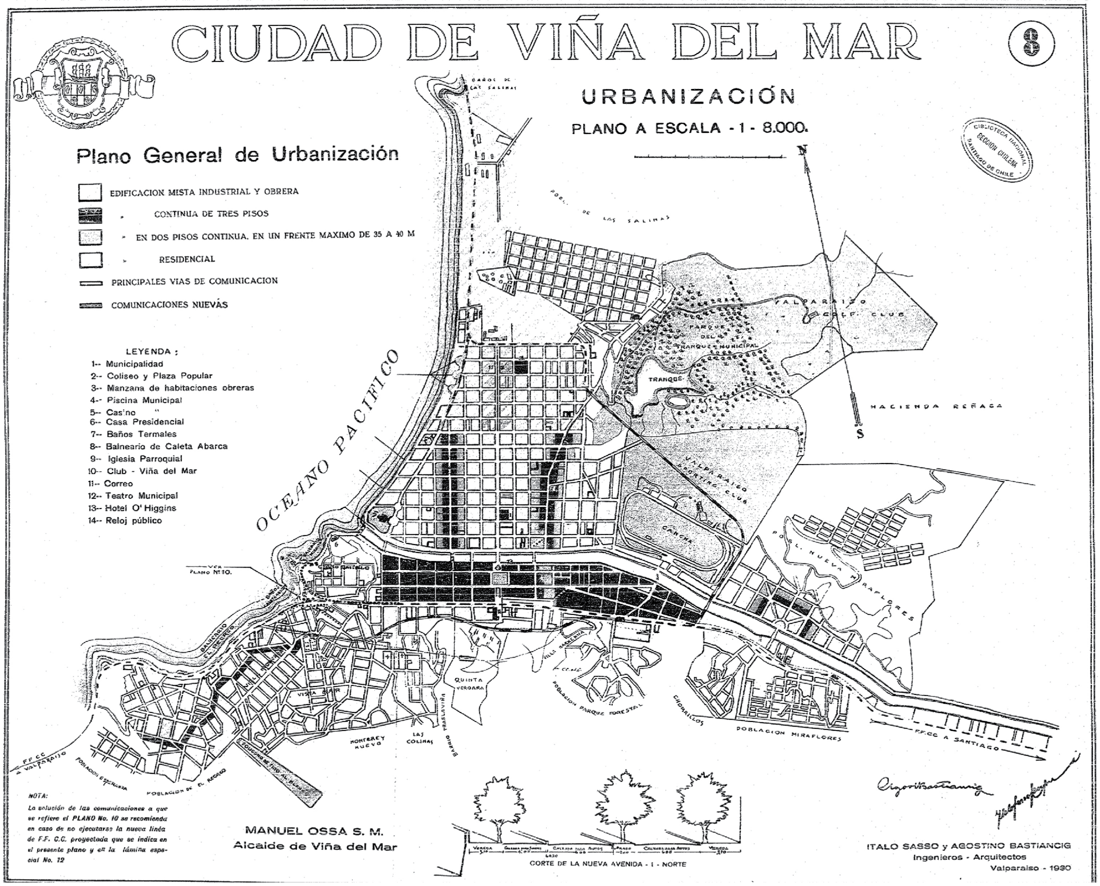


Figure 92:
Plano general de Urbanización, 1930.
Source:
Nuestra Ciudad[278].

Figure 93:
Plano de Conjunto presented by the Sociedad Balneario de Viña del Mar, 1913.
Source:
Álbum de Viña del Mar[279].

8.6.3.1. The protection of Av. Perù from floodings

The creation of the protecting wall of Av. Perú between 1937 and 1944 consisted firstly in the destruction of the existing wall and boardwalk, followed by the construction of the a 6m tall parapet wall. After the construction of the parapet wall, the filling boulders were placed, and finally the rocks that faces the sea. The already narrow beach was buried under the rocks (see figures 96-98). This work turned out to be only a work of maritime defense and not an improvement of the Av. Perù as a public walk side. An impressive infrastructure work for the technology of the time, which destroyed almost a kilometer of beach between Av. 1 and 8 Norte. The protection work configured Av. Perú as remains until today[280].

[280]Darrigrande, 220-221.

[281]"Informe Técnico de la Dirección de Obras Portuarias de Valparaíso", Archivo Histórico Patrimonial de Viña del Mar, 1944.

[282]"Ibid.

[283]"Fotos de 1940 muestra como cambiaron las marejadas Viña del Mar," Unknown Author, Informador Chile, accessed May 9, 2018, https://www.elinformadorchile.com/2017/06/fotos-de-1940-muestra-como-cambiaron.html.

[284]Darrigrande, 141.

Figure 94:
Excavation for the wall foundation in Av. Perù.
Source:
Ramón
Informe Técnico de la Dirección de Obras Portuarias de Valparaíso[281].

Figure 95:
Construction of the protection wall in Av. Perù.
Source:
Informe Técnico de la Dirección de Obras Portuarias de Valparaíso[282].

Figure 96:
View over the
Av. Perù, ca. 1930.
Source:
Unknow Author[283].

Figure 97:
View over the
Av. Perù, ca. 1950.
Source:
Unknow Author[284].

8.6.4. The densification of the waterfront

Projects for apartment buildings started being developed as real estate investments between 1950s and 1960s. Tourism proved to be an economic engine, which involved the consumption of land. In fact, tourism needs not only beach infrastructures, hotels and casino, but also a large quantity of second homes. Thus, Viña del Mar will go from an aristocratic seaside town to a massive tourist city. During the 20th century the public architecture associated with the resort town, was initially based on the social conceptions of welfare, health and democratization of the modern man, while in the recent years it took the opposite direction and the resort town became a good of consumption associated with tourism. Although there is a legislation regulating the waterfront, it is still exposed to the interests of its economic potential, above its capacity to constitute public one space. In this sense, the private interest has prevailed over the public and the coastline has developed an undoubted fragility due to the pressure of the economic exploitation[285].

Once the city started speculating on its territory, it has to face the complicated relation among communication networks, means of transport, occupation of the territory and massification of the services associated with the sun and the beach (see figures 98-99). Apartment buildings become the massive solution to the popularization of beach tourism, used mostly as second homes and preferably located on the waterfront. The correspondence between economic development and massification of the of the seaside, together with the primacy that private interventions acquire over the public ones are central at this stage. It establishes the basis of the future development of the city waterfront; strongly linked to consumption, seasonal conditions and real estate speculation[286].

[285]Darrigrande, 299-300.

[286]Ibid, 296.

[287]"Guía del Veraneante," *Guía anual de turismo de la República de Chile* (Santiago: 1950), in María Darrigrande, 289.

[288]Ibid.

Figure 98: Advertisement of Viña del Mar, 1950. Source: Guía del Veraneante[287].

Figure 99: Advertisement of Viña del Mar, 1950. Source: Guía del Veraneante[288].

8.6.5. Tentative of recuperation and protection of the wat5rfront

Under the mayor Gustavo Lorca, the urban development of Viña del Mar was influenced by the 'Lorca Law'. This law, Law 13,364 of 1959, allowed the Municipality to expropriate properties located between the Avenues 8 Norte to the south, General San Martín and Jorge Montt to the north and the Pacific Ocean to the west; the ones located in Miramar beach except for the Maritime Sanitary. The law expropriates the lands of various industries located on the seafront, many of which had already ceased their activities[289]. Through the Lorca Law, the Municipality expropriated 31,789m^2 to the Dock Company of the Population Vergara in order to build a promenade.

The expropriations were conditioned by an agreement signed between the Dock Company of the Población Vergara and the Municipality of Viña del Mar which established the construction, in the expropriated area, of six high-rise apartment buildings, maintaining a 16m wide promenade for public use. Out of the six that were supposed to be built according to the plan "Conjunto Muelle Población Vergara," only three towers were realized. The first was the Acapulco Building (see figure 100), the second the Hanga-Roa Building, and the last one was built between the Acapulco building and the end of Av. Perú, where the swimming pool of 8 Norte was formerly located. The reason for the paralysis of the project "Conjunto Muelle Vergara" and in part the frustration of the Lorca Law, might have been due to the difficulties encountered in the occupation of the coast considered as a National Good for public use[290].

Nowadays, the Lorca Law still norms the construction of the waterfront of Viña del Mar and Concón, from the Av. España to the Estuary of the Aconcagua River. It has two main purposes, protecting the waterfront from the construction of high-rise buildings which might affect the coastal landscape and block the

[289]Marcelo Ruiz Fernandez, interviewd by Eleonora Francesca Serpi, May 11, 2018.

[290]Ibid.

view to the ocean, and promoting the construction of tourist infrastructures. The Lorca Law does not forbid the construction of new buildings, but it requests the approbation of each new project by at least two thirds of the members of the Municipal Council of Viña del Mar[291].

In 1963, the newspaper El Mercurio de Valparaíso published "The Forbidden Zone of Viña del Mar". It established the prohibition of building affordable housing (DFL) in the area evidenced by the map (see figure 101). The zone was defined by railway to the south, 15 Norte to the north, Av. Libertad to the east, and Av. Perù and San Martin to the west. This way, the city center, the Población Vergara district and the banks of the Marga-Marga River, were restricted areas. The DFL Nº2, promulgated in 1959, established that homes of less than 140m2 could be excluded from paying the corresponding taxes, therefore promoting the construction of small departments while Decree No. 2411intended to protect the area from low-quality real estate speculation and standards. It limited the construction and made the towers and apartment buildings in the area unprofitable, which only re-emerged in 1978, with the so-called Torres de Miramar located on the east side of San Martín Street[292].

[291]Claudia Campos and Carlos Valencia, "La Ley Lorca en el banquillo," El Mercurio de Valparaíso, June 13, 2003, http://www.mercuriovalpo.cl/site/edic/20030613000317/pags/20030613014004.html.

[292]Darrigrande, 279.

[293]*El Mercurio de Valparaíso,* March 4, 1962, 27.

[294]*El Mercurio de Valparaíso*, January 1, 1963, 19.

Figure 100: Advertisement of the Acapulco Building, 1962. Source: El Mercurio[294].

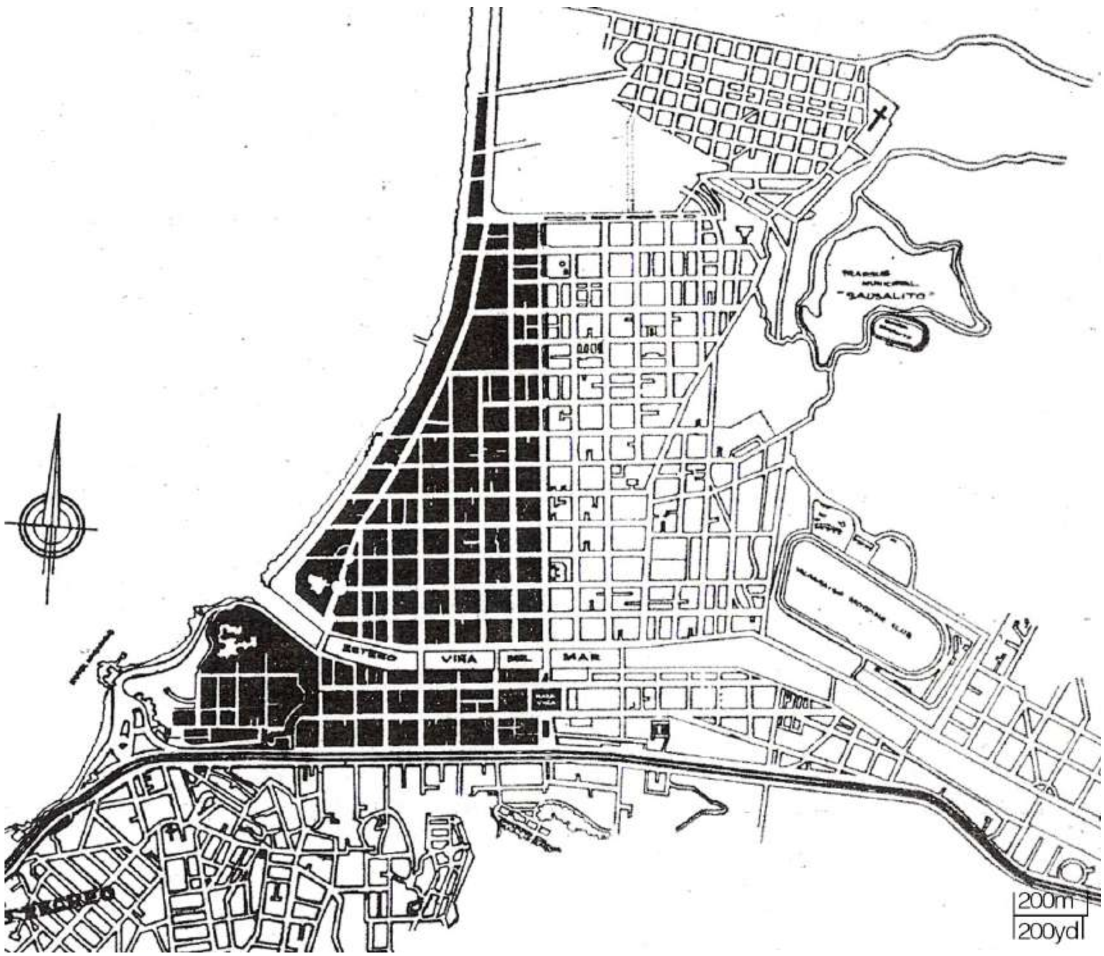


Figure 101:
The prohibited zone
of Viña del Mar
1963.
Source:
El Mercurio[293].

8.6.6. Viña del Mar in the 21st century

Today Viña del Mar is a modern urban city, the biggest coastal city of Chile and the main tourist destination. Its growth is the result of the economic speculation started in the second half of the 20th century which did not consider the importance of a sustainable development capable of guaranteeing both the wellbeing of its inhabitants and the preservation of the natural environment. As the economy is the most influent factor regulating the urban development, today the city suffers of an overdeveloped and overpopulated littoral with high-rise buildings which block the view to the ocean and project long shadows on the adjacent construction and on the few open spaces. The real estate market pushed to a model that aim at the maximum constructability and efficiency of buildings to large profits in the short term.

The over-densification generates overcrowding, traffic problems, worse quality of life and affect the coastal landscape, ultimately leading to the depreciation of the land in the long term. Moreover, residential areas are deteriorating due to changes in land use patterns, densifying intensely the use of private spaces leaving scarce green areas within the blocks. The large concentration of equipment and services in the plan area which serve both the resident population, as well as the floating or tourist one has a strong urban and mobility impact. Due to the same concentration of services and touristic attractions, the coast is suffering of high traffic congestion both pedestrian and vehicular which cause lack of parking, lack of access to the edge, visual and natural space obstruction. The increasing deterioration of the functioning of the communal road network, due to insufficiencies of roads and/or road sections impede the use of the network as a system capable of ordering intercommunal, communal and local flows with fluidity, uniformly irrigating the city.

Moreover, the city is highly exposed to different natural hazards, from earthquake which effects are aggravated by the sandy soil where the Población Vergara is built, to inundation risks. Storm surges annually affect the city, causing structural and economic damages to the building and infrastructures on the waterfront especially along Av. España and Av. Perù. These phenomena together with the climate change are aggravating the coastal erosion which is affecting the urban beaches, high attraction for the city. The proximity to the waterfront together with the low elevation of the Población Vergara, and the gradual degradation of the beaches Vina del Mar is highly exposed to tsunami risk which does not seem to influence or slow down the overdevelopment of the coast

9

TSUNAMI RISK IN VIÑA DEL MAR

The city of Viña del Mar is highly exposed to tsunami hazard due to its proximity to the Pacific Ocean and the Nazca subduction zone and its development on the large plain area corresponding to the delta of the Marga-Marga River, with a roughly elevation of 20m above sea level. Since the arrival of the Spanish conquerors, at the beginning of the 16th century, there have been records of earthquakes and tsunamis striking the area, more precisely the earthquakes of 1575, 1647, 1730, 1822, 1906, 1985 and the tsunamis originated by the last four of them. The latest destructive tsunami in the area has been recorded on 8 July 1730, originated by an earthquake of a $M_L = 8.4$ on the Richter Scale with epicenter offshore city of Valparaíso[295]. At the time Viña del Mar had not been found yet so there are no records about damages, but the cyclic nature of these events and the large temporal gap between the last tsunamis and nowadays suggests that a new devastating tsunami might occur soon with complete different and more catastrophic impact on the city[296].

[295] Chilean Navy Hydrographic and Oceanographic Center, "Registro de los principales tsunamis que han afectado la costa de Chile," accessed may, 8, 2018, http://www.shoa.cl/s3/servicios/tsunami/data/tsunamis_historico.pdf.

[296] M. Carvajal, M. Cisternas, and P. A. Catalán, "Source of the 1730 Chilean earthquake from historical records: Implications for the future tsunami hazard on the coast of Metropolitan Chile," Journal of Geophysical Research: Solid Earth 122, no.5 (Spring 2017): 3648, https://doi.org/10.1002/2017JB014063.

9.1. Inundation map

In order to be aware of the tsunami risk that might affect the coastal cities of Chile, since 1997, the Chilean Navy Hydrographic and Oceanographic Center (SHOA) elaborated tsunami inundation maps of the Chilean coastal cities and towns, considering the worst-known case scenario recorded in each region (see figures 102-103). For the elaboration of these maps, the SHOA utilizes numerical simulations based on topographic, bathymetric and seismic data. The current inundation map of the cities of Valparaiso and Viña del Mar was published in March 2012 based on the earthquake of 1730, which represent a more catastrophic scenario than the previous one based on the event of 1906. In case of the occurrence of a real tsunami, the inundation level might not correspond to the one expected due to the different characteristics of the earthquake generating it which might differ from the one used for the numeric simulation.

Flooding maps are used for urban planning to prevent and mitigate the impact of tsunamis. The municipal authorities employ them in the preparation of evacuation and civil protection plans. These tasks are supervised by the National Emergency Office of the Ministry of the Interior (ONEMI), through the Regional Civil Protection and Emergency Offices (OREMI), and the Local Emergency Committees, according to the Basic Methodology for the Preparation of a Communal Plan of Tsunami Response[297].

As visible in figure 105, considering the worst-known case scenario, the entire plain of the city of Viña del Mar would be flooded with an inundation level that ranges from 6m to 1m with the Población Vergara District as the most affected area. Especially, the blocks between Av. Perú and Av. San Martín due to the absence of appropriate mitigation system and infrastructures, and the proximity to the coast line (see figures 104-105). In case of tsunami alert, the entire area at-risk must be evacuated. For the Valparaiso Region the security height, in case of tsunami, is 30m above sea level[298], therefore the population has to reach the closest hills or, if not possible, the security height on top buildings or climbing on natural elements like trees.

[297] Chilean Navy Hydrographic and Oceanographic Center, "Cartas de Inundación por Tsunami (CITSU). Valparaíso - Viña del Mar," accessed May 8, 2018, http://www.shoa.cl/php/citsu.php.

[298] Department of Housing and Urban Planning, National Office of Emergency of the Interior Ministry and National Investigation Centre for the Integrated Management of Natural Disasters, Vol.6 Guía de Referencia para Sistemas de Evacuación Comunales por Tsunami. Manual Práctico de Planificación e implementación (Santiago de Chile: Department of Housing and Urban Planning. Gobierno de Chile, 2017), 36, http://repositoriodigitalonemi.cl/web/handle/2012/1766.

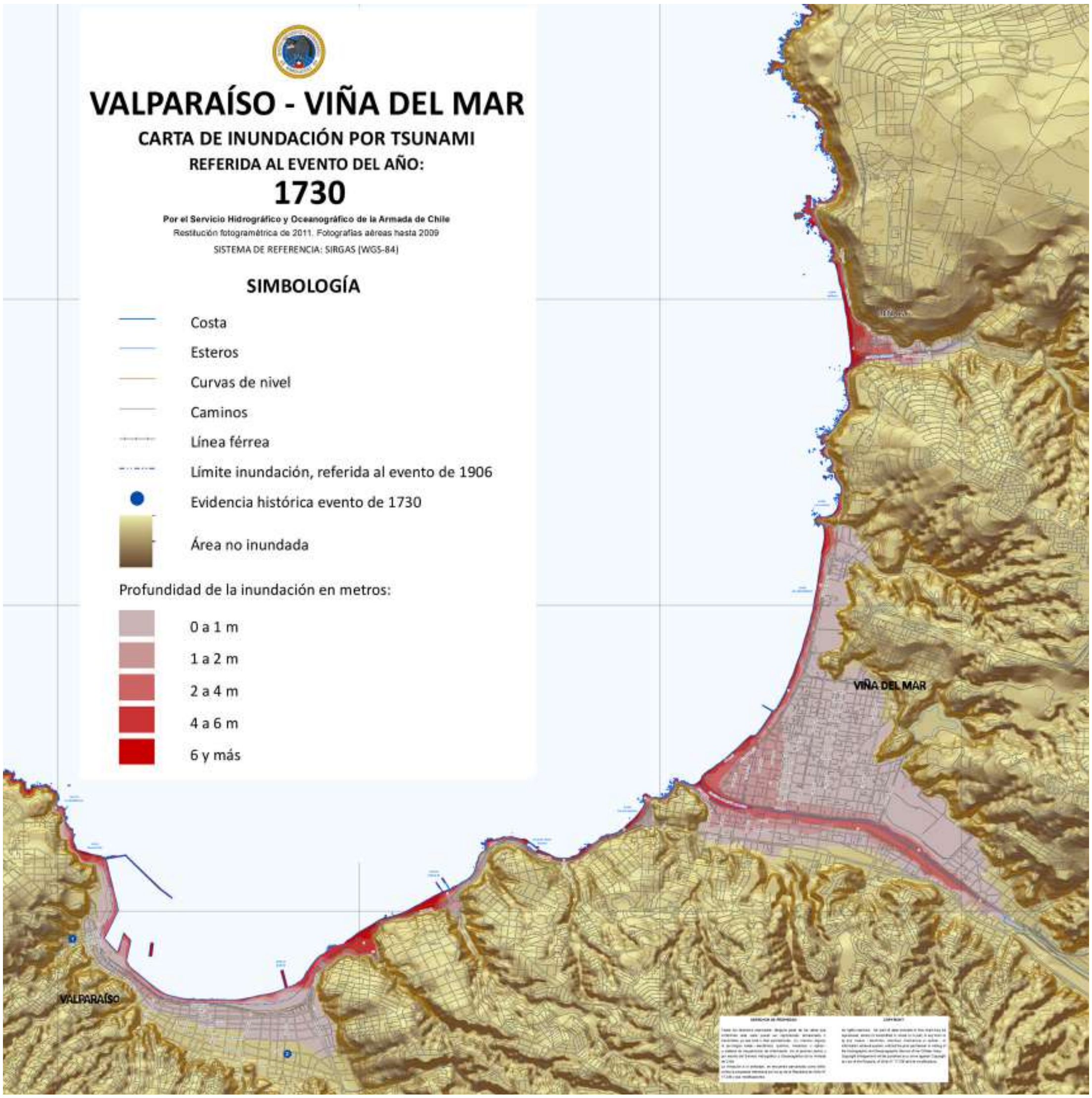


Figure 102: Valparaiso and Viña del Mar Inundation Map (CITSU 2012). Source: SHOA[299].

Figure 103: Inundation Map of Viña del Mar. Source: SHOA[300] and Google Earth[301].

Figure 104:
Av. Perù,
Viña del Mar, 2018.
Source:
Eleonora F. Serpi.

Figure 105:
Av. San Martín,
Viña del Mar, 2018.
Source:
Eleonora F. Serpi.

9.2. Tsunami warning system

Since 1966, the Chilean Navy Hydrographic and Oceanographic Center (SHOA) operates the National Tsunami Warning System (SNAM) and officially represents Chile in the International Pacific Tsunami Warning System of the National Oceanic and Atmospheric Administration (NOAA), operating the Pacific Tsunami Warning Center (PTWC) located in Hawaii. The SNAM and PTWC constantly interact through a series of technological elements that monitor the indicative factors of a tsunami threat[302]. The PTWC issues different types of bulletin (see table 13) to ensure the monitoring of the Pacific Ocean depending on the registered seismic data and, in case of tsunami, the warning computing the Initial Estimated Arrival Time (ETA) of the tsunami in the affected areas[303].

Tsunami Information Bulletin	It informs the PTWS participants of the occurrence of a major earthquake in or near the Pacific Ocean, generating a) no widespread tsunami threat but a small possibility of a local tsunami or b) no tsunami threat at all.
Regional Fixed Tsunami Warning Bulletin	It alerts all PTWS participants of the possibility of a regional tsunami based initially on only seismic information. Tsunami Warning status concern the coastal regions within 1000 km of the earthquake epicenter.
Regional Expanding Tsunami Warning and Watch Bulletin	It informs all PTWS participants of the possibility of a widely destructive tsunami, based initially on only seismic information.
Pacific-Wide Tsunami Warning Bulletin	A warning issued to all PTWS participants after the confirmation of tsunami waves capable of causing destruction beyond the local area.
Tsunami Communication Test Dummy Message	A test message issued by PTWC at unannounced times to test the operation of the warning system.

Table 13: Typologies of international bulletins issued by the PTWC. Source: own elaboration from UNESCO/IOC[304].

[299]Chilean Navy Hydrographic and Oceanographic Center, "Cartas de Inundación por Tsunami (CITSU). Valparaíso - Viña del Mar," accessed May 8, 2018, http://www.shoa.cl/php/citsu.php.

[300]Ibid.

[301]"Viña del Mar," 33°00'38.00"S and 71°33'28.29"W, Google Earth, Google, last modified December 3, 2018.

[302]National Tsunami Warning System, "Sistema Nacional de Alarma Maremotos," accessed may 13, 2018, http://www.snamchile.cl/index.php?p=snam&tenl=3.

[303]UNESCO, Intergovernmental Oceanographic Commission, "Operational users guide for the Pacific Tsunami Warning and Mitigation System (PTWS)," in Technical Series, vol. 87 (Paris: UNESCO/IOC, 2011), 21, http://unesdoc.unesco.org/images/0018/001800/180097e.pdf.

[304]Ibid, 11.

9.2.1. Integrated System of Tsunami Prediction and Alarm (SIPAT)

The current evacuation alarm system in Vina del Mar, known as SIPAT (Integrated System of Tsunami Prediction and Alarm), is operating since May 2016 in the offices of the SHOA in Valparaiso. It was developed by a collaboration of Japan with the Universidad Técnica Federico Santa María, the Pontificia Universidad Católica and the SHOA, using different scenarios based on the earthquakes that stroke Chile since 1960[305]. The SIPAT receives information from the Seismic Center of the University of Chile and takes decisions according to the worst-known case scenario reproducing the physical process of a tsunami along the coast of the country. The model uses basic information about the earthquake to start its evaluation.

The basic information is later detailed to have a better prediction of the characteristics of the tsunami. It is a process with multiple stages, the first one, very fast but with a high margin of approximation, is based on numerical models. The second uses the information detected by the sensors to known what actually appended to obtain details that might help improve the alert. Chile also has tsunami monitoring devices (Sea Level Stations), but they are installed on the coast, and therefore they cannot be used as predictive systems[306]. Moreover, SIPAT divides the country into 21 blocks which allow to evacuate only the directly affected areas, and not all the Chilean territory[307] (see figure 106).

9.2.2. Deep Ocean Assessment and Reporting of Tsunamis (DART)

Buoys are used to identify and monitor tsunamis in the Pacific Ocean. The DART-II buoys (Deep Ocean Assessment and Reporting of Tsunami) is a system combining a buoy and a hydrostatic pressure sensor positioned on the sea floor. The sensor constantly measures the sea level and is able to recognize the variations

[305]Armada de Chile, "Nuevo sistema del SHOA permitirá segmentar las evacuaciones en caso de amenaza de tsunami," last modified June 10, 2016, https://www.armada.cl/armada/noticias-navales/nuevo-sistema-del-shoa-permitira-segmentar-las-evacuaciones-en-caso-de-amenaza-de-tsunami/2016-06-10/143627.html.

[306]Patricio Catalán," El sistema de predicción de tsunamis en tiempo real que Chile podría importar de Japón." Interviewed by Progama Asia Pcifico, Biblioteca del Congreso Naciónal de Chile, December 26, 2016. https://www.bcn.cl/observatorio/asiapacifico/noticias/sistema-prediccion-tsunamis-tiempo-real.l

[307]Armada de Chile, "Nuevo sistema del SHOA permitirá segmentar las evacuaciones en caso de amenaza de tsunami."

[308]Ibid.

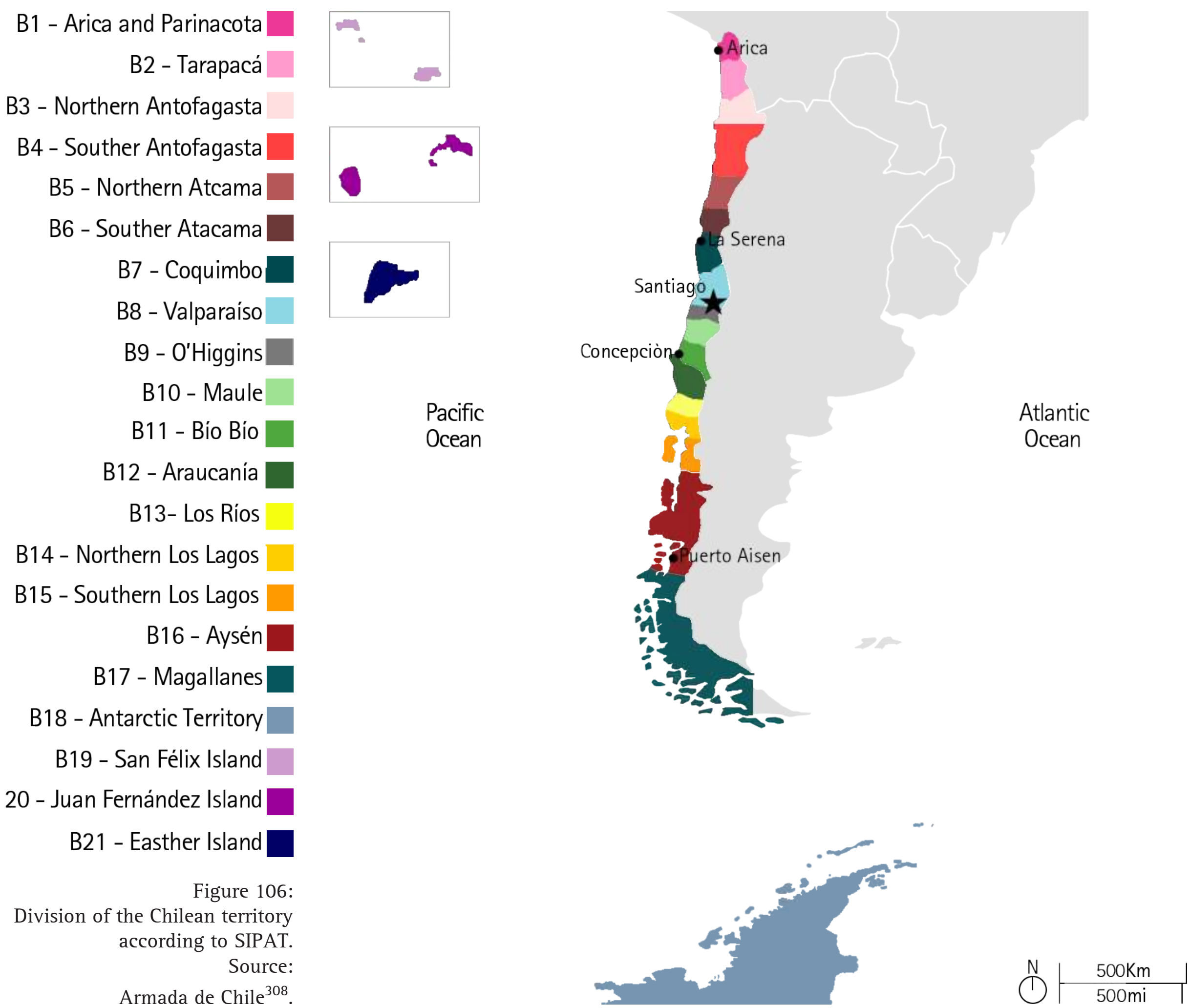


Figure 106:
Division of the Chilean territory according to SIPAT.
Source:
Armada de Chile[308].

generated by the passage of a tsunami, discriminating through the wave period, thanks to the great wavelength of tsunamis. The data is collected by the National Data Center of Buoys (NDBC) and by the SHOA. The National Tsunami Warning System (SNAM) currently has two DART II buoys located off the coast of Iquique and Caldera and three 4G DART buoys off the coast of Mejillones, Pichidangui and Constitución, as part of a cooperation program between SHOA and the NOAA (National Oceanic and Atmospheric Administration) of the United States of America[309].

9.2.3. Network of Sea Level Stations

The Network of Sea Level Stations, is currently composed of 42 digital satellite platforms installed on the coast of Chile and island territories, allowing to monitor the spread and evolution of a tsunami in an effective and timely manner. All stations have redundant systems for data transmission. Regarding the measurement of sea level variations caused by the tsunami, the stations have two sea level sensors for monitoring of the phenomenon. The monitoring carried out through this network of stations is fundamental to establish when the sea level variations caused by the Tsunami have passed and the situation has returned to normal[310].

9.2.4. Diffusion of the tsunami alert

Once the imminent occurrence of a tsunami has been confirmed, the National Tsunami Warning System (SNAM) sends information about the earthquake and the tsunami estimated arrival time (ETA) to the civil organizations in charge of notifying the population. Likewise, it shares with the Pacific Tsunami Warning Center (PTWC) all information related to tidal waves originating in the Chilean coast, which may affect other countries on the Pacific Ocean[311]. For a more immediate response and evacuation, the Chilean population is aware that in case of a strong earthquake it is necessary to take measures even before the alert of the

[309] National Tsunami Warning System, "Sistema DART (Deep ocean Assessment and reporting of Tsunamis)," accessed May 8, 2018, http://www.snamchile.cl/index.php?p=-snam&enl=3.

[310] 0Ibid.

[311] Armada de Chile, "Nuevo sistema del SHOA permitirá segmentar las evacuaciones en caso de amenaza de tsunami."

authorities. Therefore, the commonly adopted rule is that if an earthquake last long and/or does not allow you to stand still, it can generate a tsunami[312].

In case of tsunami warning, the alert is given about 8/10 minutes after the originating earthquake. The population in Viña del Mar is informed through 39 official megaphones, distributed in different sector in the city. The police officers, the fireman and the Navy are the one appointed to spread the alarm since equipped with megaphones. The speakers inform the people to evacuate the area towards the tsunami shelters as a preventive measure. Other cities might adopt different alarm systems, like in the Region of Arica and Parinacota where sirens have been installed by the National Emergency Office of the Ministry of the Interior (ONEMI). Moreover, Subtel developed the Emergency Alert System (SAE) operated by ONEMI, that allows to send alert messages directly to mobile phones[313].

9.2.4.1. Emergency Alarm System (SAE)

The Emergency Alert System (SAE) allow to send written information to compatible mobile phones. These messages are issued in case of tsunami hazards, strong earthquakes, volcanic eruptions and wildfires threatening homes. The alert, which is automatically sent via text to a georeferenced location, is affected by the congestion of cellular networks, since it uses different frequency channels. The alert message is defined by the ONEMI and has "Emergency Alert" as title. The message, which can have up to 90 characters, includes the date and time in its header and can only be interrupted by the user. The SAE emit a sound signal different from any usual notification, with vibration and at the maximum audible level. The signal cannot have a duration shorter than 3 minutes, unless interrupted by the user[314].

[312] National Tsunami Warning System, "Difusión e intercambio de información," accessed May 8, 2018, http://www.snamchile.cl/index.php?p=snam&enl=3.

[313] Catalán, interview.

[314] D. Astudillo and C. Mardones, "¿Por qué Viña del Mar no tiene sirenas de evacuación para tsunami?," LATERCERA, last modified April 4, 2018, http://www2.latercera.com/noticia/vina-del-mar-no-sirenas-evacuacion-t-sunami/.

9.3. Evacuation plan

The emergency evacuation plan of Viña del Mar, drawn and diffused by National Emergency Office of the Ministry of the Interior (ONEMI), is based on the Tsunami Inundation Map of the city (CITSU) by the Chilean Navy Hydrographic and Oceanographic Service (SHOA). It shows how to reach the security height and the evacuation shelters from the area at risk[315] (see figures 107-108). The evacuation plan also includes the positioning of 250 signs in the areas susceptible to flooding. The signs are designed according to the signage established by the Permanent Commission of the South Pacific (CPPS). These signs indicate the evacuation route to follow in case of danger, and the distance from the security area[316].

The analysis of the current evacuation plan of Viña del Mar shows that in case of a near-field tsunami, the vulnerable population who has a very short time before the first tsunami wave reach the shore, about 12min, does not have the time enough time to undertake effective disaster-response activities and reach a secure zone. The most affected areas, on the south-west side of the Población Vergara, are the same who need longer evacuation time (see figure 109 and 110). Recent studies carried out with the support of a PARI-AGENT software, proved that the death toll in the most affected area, the Población Vergara, can exceed the 800 people during day time[317]. This number is influenced not only by the long distance, up to 3km with starting point from the Casino, that has to be covered to reach a security zone, but it is slowed down by the obstacles that cover about 28.4% of the pedestrian area along the main evacuation routes[318], which might cause bottlenecks, falls and panic.

The analysis focuses on the pedestrian-only available escape areas (sidewalks, squares, parks, etc.), as the road is likely to be blocked by traffic jams during a real emergency. It also highlights that some of the particularly at-risk routes are the same that allow escaping the Población Vergara's most vulnerable zones. Due to the impossibility to guarantee the evacuation in less than 15min, which is the maximum acceptable evacuation time established by ONEMI, the use of existing high-rise buildings as vertical evacuation structures is currently suggested as an alternative to horizontal evacuation. Some potential buildings can be identified but they are not designed or to allow a safe ingress and sheltering of people.

[315] Claudia Campos, "El Plan de Viña para tsunamis," El Mercurio, October 28, 2006, http://www.mercuriovalpo.cl/prontus4_noticias/site/artic/20061028/pags/20061028000751.html.

[316] National Tsunami Warning System, "Señaletica de Tsunami," accessed May 8, 2018, http://www.snamchile.cl/index.php?p=senaTsunami&tenl=5.

[317] Jorge León, et al., "Examining the role of urban form in supporting rapid and safe tsunami evacuations: a multi-scalar analysis in Viña del Mar, Chile," Procedia engineering 212 (2018): 635.

[318] Ibid, 635.

[319] Gustavo Alvarado, "Simulacro de tsunami en la Quinta Región: una de las sirenas de Valparaíso falló y sonó con 9 minutos de atraso," SoyChile, last modified November 3, 2016, http://www.soychile.cl/Valparaiso/Sociedad/2016/11/03/427411/Simulacro-de-tsunami-en-Valparaiso-comenzo-a-la-evacuacion-del-borde-costero.aspx.

[320] Ibid.

[321] National Emergency Office of the Ministry of the Interior, "Planos de Evacuación. Viña del Mar," accessed May 13, 2018, http://www.onemi.cl/mapas/region/valparaiso/.

[322] Servicio Fotogramétrico del Fuerza Armada de Chile, Aerophotometric Relief of Viña del Mar, 2009.

Figure 107:
Simulation of a
tsunami evacuation
in Viña del Mar, 3rd of
November 2016.
Source:
Gustavo Alvarado[319].

Figure 108:
Simulation of a
tsunami evacuation
in Valparaiso, 3rd of
November 2016.
Source:
Gustavo Alvarado[320].

Figure 109: Evacuation map of Viña del Mar. Source: ONEMI[321].

Figure 110: Estimated tsunami evacuation time in the Pobacion Vergara. Source: own elaboration from SAF[322].

10

THE POBLACIÓN VERGARA

The Población Vergara sector is located to the north of the Marga-Marga estuary and is delimitated to the west by the Pacific Ocean, to the north by the Av. 15 Norte and to the east by Av. Los Castaños and the Sausalito hill (see figure 111). It is a flat area of about 240 hectares with a rough elevation of 20m above sea level. It constitutes the heart of the city together with the historical sector, located in the south of the estuary. It converges all the traffic flows of the macro commune, thus concentrating great real estate pressure for the installation of equipment and housing.

[323]Servicio Fotogramétrico del Fuerza Armada de Chile, Aerophotometric Relief of Viña del Mar, 2009.

[324]Asesoría Urbana de la Municipalidad de Viña del Mar, "Plano Modificación al P.R.C. Sector Población Vergara," (May 2016).

Figure 111: Delimitation of the Población Vergara. Source: own elaboration from SAF[323] and Municipalidad de Viña del Mar[324].

10.1. Urban evolution

The sector, as the rest of the city, is undergoing a continuous transformation process. Starting from its residential origin to the current role as reference pole for the Great Valparaiso that has driven a strong pressure to replace the old building typologies for the development of vertical collective housing and new structures to provide equipment and services. Analyzing the transformation process, the main changes of the urban settlement can be resumed as showed in table 14.

The urban development, more precisely the housing densification (see figure 112) and increase in the density of equipment and services caused the rising in parking demand and vehicular congestion. This results in the saturation of public spaces cars especially along public roads, subtracting space for other functions, whether pedestrian or transit affecting the landscape and the image of the district. Insufficiency of green public spaces and green areas in relation to population growth.

[325]Municipalidad de Viña del Mar, "Modificación al Plan Regulador Comunal de Viña del Mar. Sector Población Vergara. Memoria Explicativa," (May 2016), 32-33.

[326]Ibid, 24.

Table 14:
Urban transformation characteristics.
Source:
own elaboration from the Municipalidad de Viña del Mar[325].

Construction of new collective housing buildings of 3 and 4 floors.	1960 – today	Building verticalization
Increase of the vertical and collective housing typologies.	1878 – today	Housing densification
Replacement of single-family housing typology, associated with medium-sized farm plot, are replaced by new real estate initiatives.	1960 – today	Replacement of the original typologies
Increase in commercial uses associated with the adaptation or reuse of existing buildings.	1980 – today	Increase in commercial uses
Discard of the ground floors for housing of the new high-rise buildings, either for service use of the building or for commercial equipment and reuse of existing housing for commercial purposes.	1980 – today	Disuse of the groundfloor as housing space
The new high-rise buildings allocate a portion of the ground level to solve the area of pedestrian access and front garden, while most of the rest of the floor is destined as patio, parking lots and warehouses.	1980 – today	Service spaces of residual character at ground level
Replacement of garden areas for hard parking lots and car access ramps, generating a soil waterproofing process.	1980 – today	Replacement of garden areas
Replacement of trees in the public roads to face the high parking demand.	1980 – today	Loss of trees

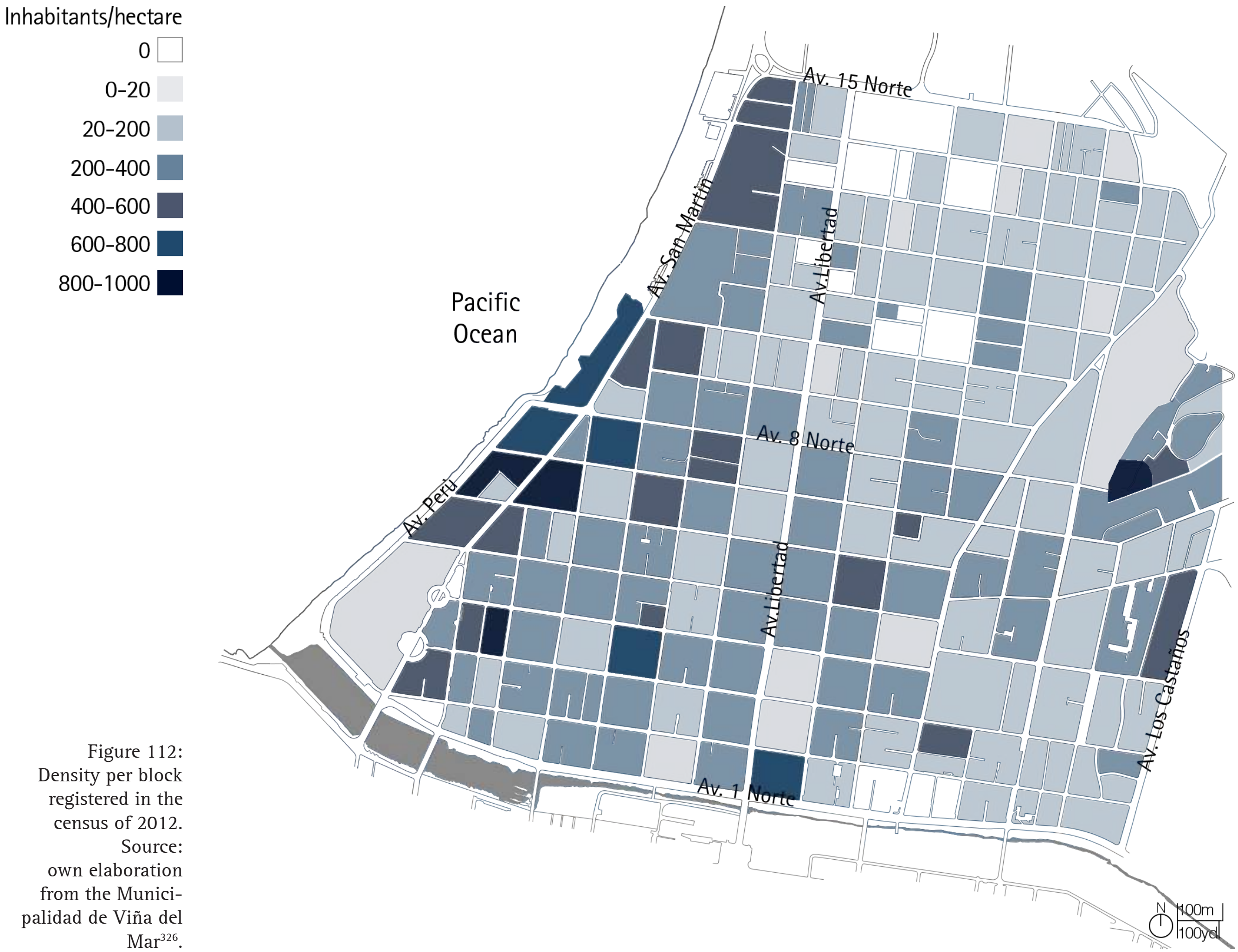


Figure 112: Density per block registered in the census of 2012. Source: own elaboration from the Municipalidad de Viña del Mar[326].

10.2. Urban morphology

The configuration of this sector presents an orthogonal and regular disposition of approximately 140 blocks, which are aligned to the foundation grid. With a shape similar to a trapeze, it covers an extension of about 1600m from north to south and 1800m from east to west. The two main distributing axes are the Av. Libertad and the street 8 Norte which meet forming a cross. Thanks to these two axes it is possible to divide the sector in four sub-sectors (see figure 113) and identify which are the most representative characteristics of each of them.

10.2.1. Subsectors

The South-West sector is one of the most representative sectors for its buildings and public spaces. It consists of a set of emblematic buildings of great heritage value, green areas, coastal edge and Marga-Marga estuary. It is recognized as the urban image of the city. It is the sector of greater recreational activity, with the Municipal Casino, restaurants, cafeterias, bars and entertainment venues, as well as hotels. The South-East sub-sector is one of the most residential sectors, with less presence of commerce and services. The North-West subsector was consolidated during the decades from 1960 to 1980. It is constituted as an almost exclusively residential sector with high-rise residential buildings along the Av. San Martin. The North-East subsector is distinguished by the conversion process of the industrial buildings originally settled in the area.

[327] Ibid, 30.

Figure 113: Subsector division of the Población Vergara. Source: own elaboration from the Municipalidad de Viña del Mar[327].

10.3. Mobility

This area and its road system are determined by its geographical configuration delimitated by edges (estuary, coastal, edge hill and park edge), which establishes strong accessibility restrictions between certain sectors. The Población Vergara suffers of high traffic congestion due to the intercommunal flows crossing it, in addition to those related to the supply of equipment and services, work places, as well as the resident population. Moreover, this sector is crossed by long distance routes that connect the sectors of Reñaca, Concón, Valparaíso and Santiago, as well as the interior communes of Quilpué and Villa Alemana with Valparaíso (see figure 114). From the operational point of view, the edge restrictions conform and configure connectivity difficulties that affect the capacity of the road system, especially when crossing the estuary.

[328] Ibid, 30.

[329] "Viña del Mar," 32°58'41.54"S and 71°19'49.35"W, Google Earth, Google, last modified December 3, 2018.

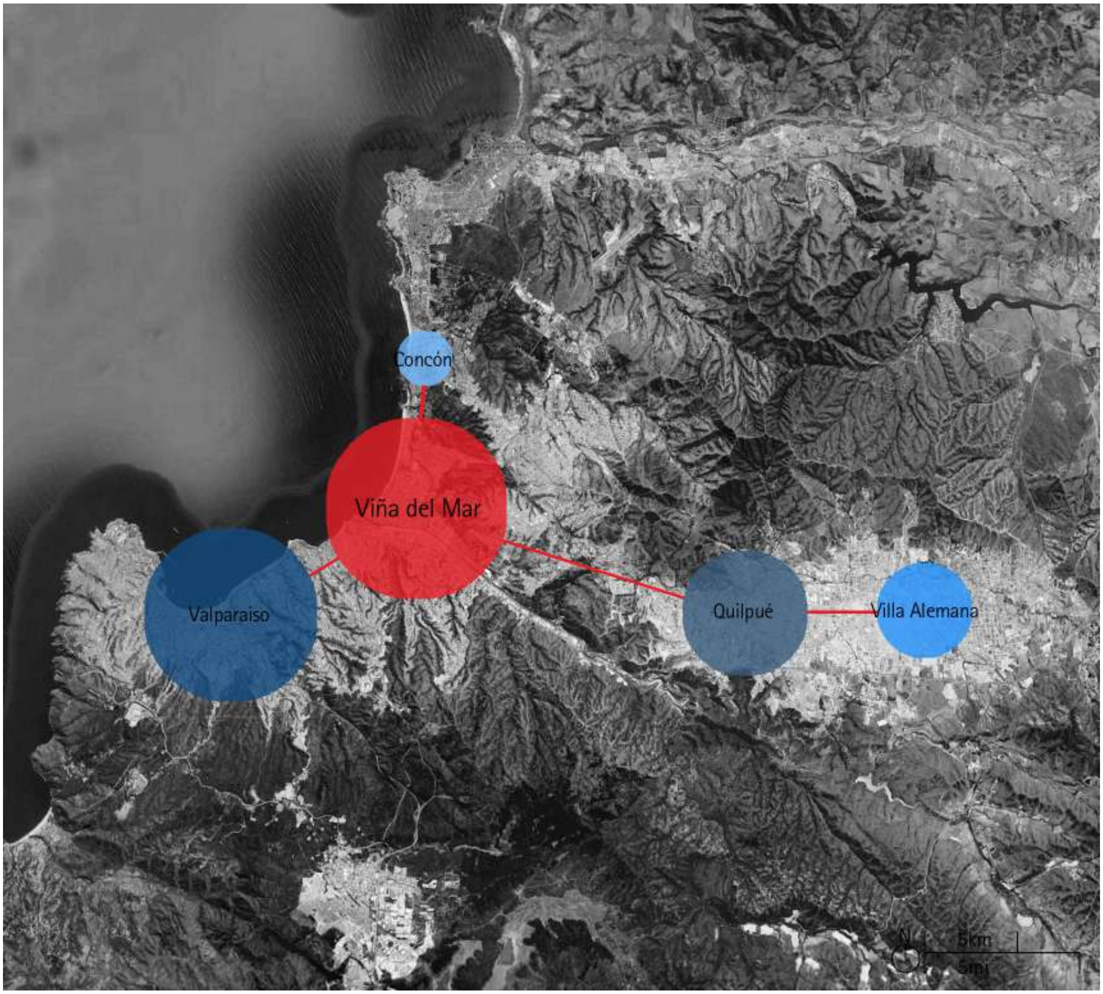


Figure 114: Intercommunal traffic flows. Source: own elaboration from the Municipalidad de Viña del Mar[328] and Google Earth[329].

10.4. Urban analysis

The following analysis of the Población Vergara gather information, reported by the Illustre Municipalidad de Viña del Mar[330], regarding the following variables:

- land use;
- types of construction;
- building heights;
- buildings of patrimonial value;
- green areas and arborization.

10.4.1. Land use

The sector presents a great homogeneity and continuity thanks to its streets layout and offers a large diversity of uses of equipment, but the residential use still prevails for old and new buildings. It is remarkable the level of homogeneity of the characteristics and spatial attributes of the sector, which allows a homogeneous development of the activities. Different scales of equipment can be identified, from the neighborhood one, with services and artisanal products, to the offer of national and international services related to tourism. Similarly, the commercial pole of the northern sector between the streets14 and 15 Norte concentrates a commercial offer of metropolitan scale (see figure 115).

10.4.2. Building heights

Out of a total of 3,783 registered lots, 78% of them host buildings of 1 to 2 floors, 9% buildings of 3 and 4 floors, proving that low-elevation typologies predominate (see figure 116). However, the buildings in height are more noticeable, given their size and the predominant distribution along the coast.

10.4.3. Buildings of Patrimonial Value

The municipality of Viña del Mar hosts several properties protected by the Law of National Monuments and the by the tools

[330]Municipalidad de Viña del Mar, "Modificación al Plan Regulador Comunal de Viña del Mar. Sector Población Vergara. Memoria Explicativa," (May 2016), 24.

[331]Ibid, 38.

[332]Ibid, 39.

[333]Ibid, 43.

[334]Ibid, 31.

provided by the General Law of Urban Planning and Construction through the PRC. More specifically, the city counts 6 National Monuments, protected by the Law 17, 288. Among them, two are considered Natural Sanctuaries and the remaining Historical Monuments. The Población Vergara hosts the Carrasco Palace and the Rioja Palace, both of them Historical Monuments. The former, protected since 1986, is located in Av. Libertad 250; the latter, protected since 1985, is located in Quillota street at the corner with 3 Norte Street. The Población Vergara also hosts three Historic Conservation Buildings: Muelle Población Vergara, in Av, San Martín, Casa Astoreca, in Pje. La Paz 1301, and Casa Losa 702 (see figure 117).

10.4.4. Open spaces and green areas

Viña del Mar presents an organized system of green areas and tree-lined avenues. These two features are fundamental to preserve the identity of the city as "garden city". The sector is ich in trees especially along al the most important axes of but does not compensate to the relative scarcity of parks or squares (see figure 118). Today the sector is suffering for the replacement of green areas for hard parking lots and car access ramps which started a soil waterproofing process.

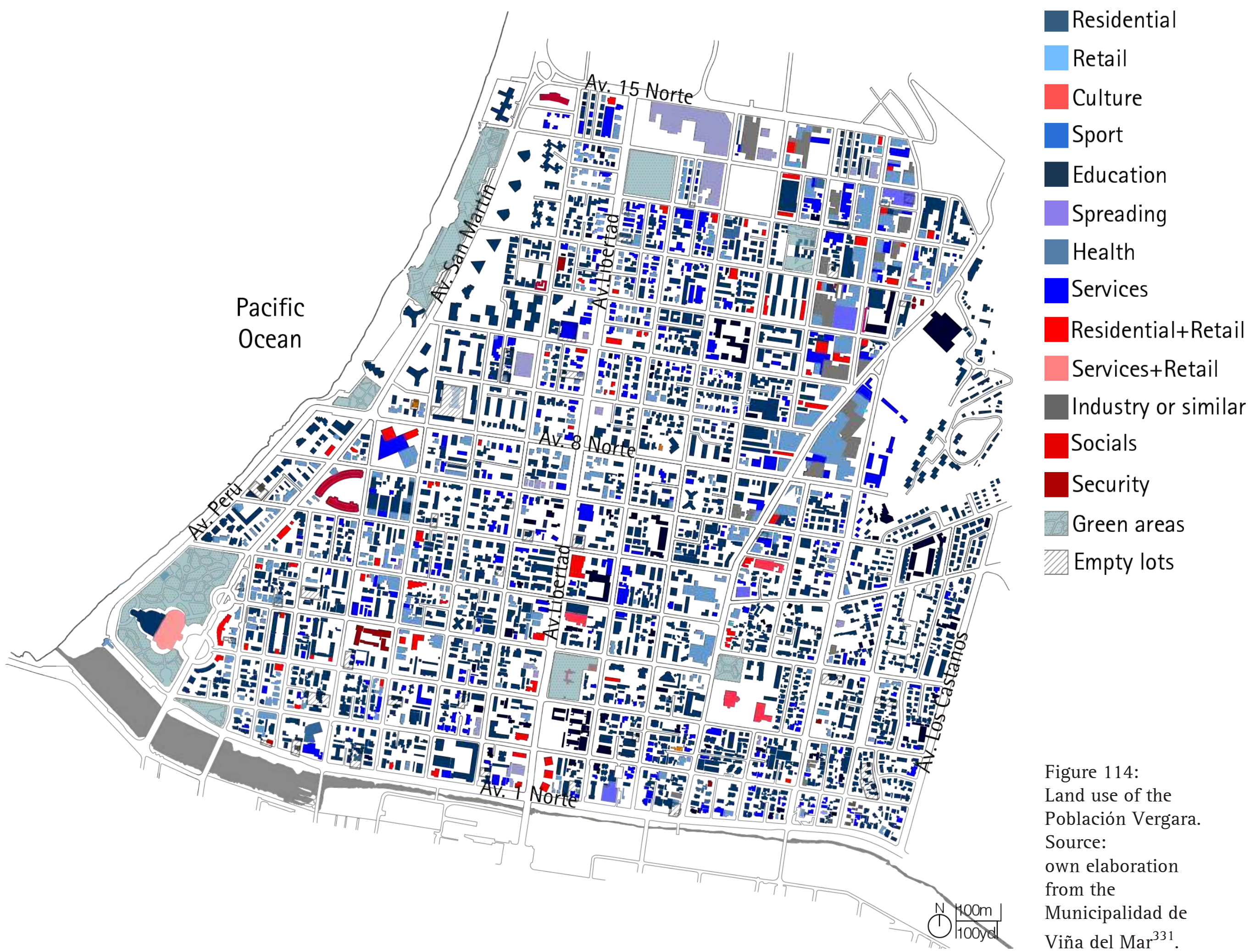


Figure 114:
Land use of the Población Vergara.
Source:
own elaboration from the Municipalidad de Viña del Mar[331].

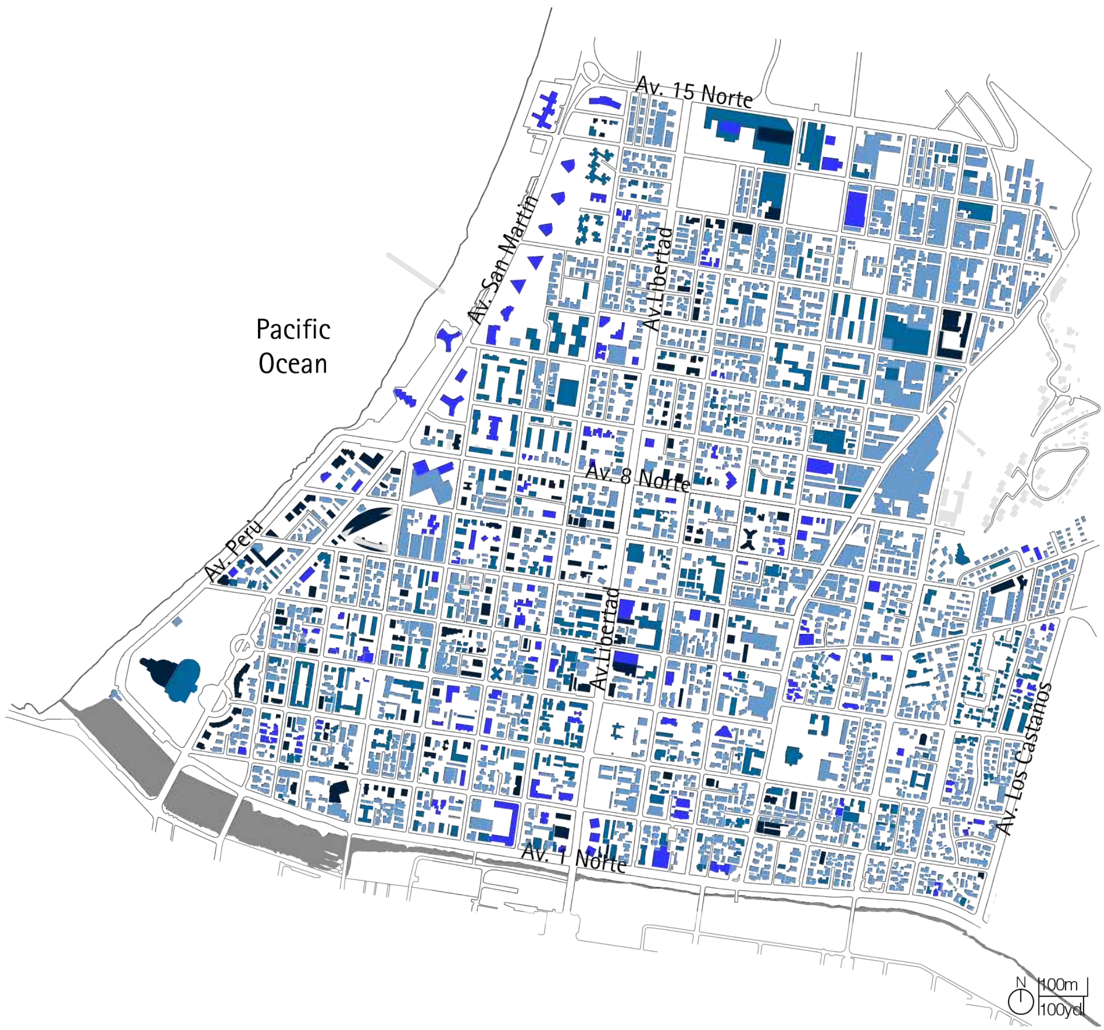


Figure 115: Buildings heights in the Población Vergara. Source: own elaboration from the Municipalidad de Viña del Mar[332].

Historical Monuments

Historic Conservation Buildings

Figure 116: The Historical Monuments in the Población Vergara. Source: own elaboration from the Municipalidad de Viña del Mar[333].

Figure 117: Green areas in the Población Vergara. Source: own elaboration from the Municipalidad de Viña del Mar[334].

10.5. Municipal regulator plan (PRC)

The General Urban Planning and Construction Ordinance (OGUC) defines the Instruments of Territorial Planning (IPT) which regulate the urban occupation and development through a plan, referred as "Plan Regulator Communal" or simply "PRC". The PRC of the city of Viña del Mar can be divided according to the various sectors of the city. For the development of the project, it will be considered the PRC of the Población Vergara. The current main objectives of the PRC of the Población Vergara can be resumed as follow:

- regulate the densification process;
- regulate the verticalization process of large buildings;
- promote the improvement of the current environmental conditions and urban quality;
- protect the historical heritage;
- promote the enhancement and harmonization of the historical heritage of the neighborhood;
- incorporate the environmental regulation corresponding to the seismic behavior.

10.5.1. Zoning proposed by the PRC

In order to simplify the regulation process it is possible to divide the sector into homogeneous areas, zoning. The current PRC approved in 2016, propose a zoning plan based on the actual dominant uses and building development capacity. It tries to balance the characteristics of each neighborhood, considering the fragility of the heritage, aspects of quality of life and habitability and the carrying capacity of the roads towards a more sustainable scenario. It also aims at consolidating the sector image more consistent and coherent with its historical development. The restrictions in terms of land use, buildings height, building and population density, public spaces and green areas are explicated in the Ordinance of the 11th May 2016 (see figure 118).

[335] Asesoría Urbana de la Municipalidad de Viña del Mar, "Plano Modificación al P.R.C. Sector Población Vergara," (May 2016).

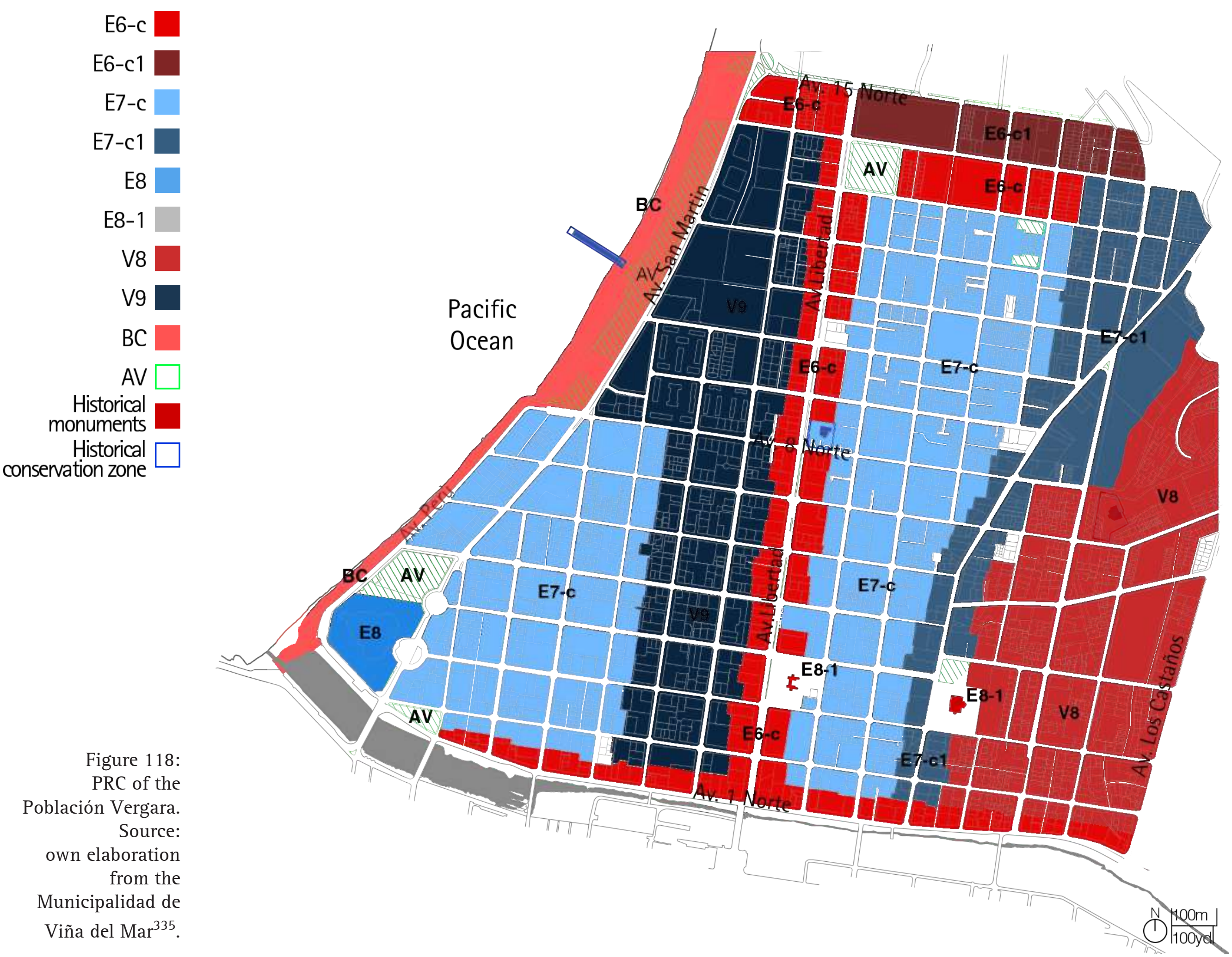


Figure 118: PRC of the Población Vergara. Source: own elaboration from the Municipalidad de Viña del Mar[335].

10.5.1.1. Zoning according to buildings height

Figure 119 shows the zoning distribution for the Población Vergara regarding the height of the existing buildings to establish a regulating plan for vertical development. For this zoning, a range of values divided in 4 categories has been established: A, A+, M, B. The A zone (high) corresponds to the sector to the west of Av. Libertad, where an important part of the collective residential buildings is concentrated. It includes buildings that reach more than 20 floors.

The A + zone (high with high development) refers to the major road corridors, characterized by a larger public space. In this sector building do not overcome 14 floors. The M zone (medium) is composed of two sectors: the first corresponds to the foundational area of the Casino, with buildings from 3 to 10 floors; the second to the area east of Av. Libertad, with a lower concentration of buildings, where the typology of isolated and paired houses still strongly prevails. And last, the B zone (low), located east of Quillota Street, up to its limit with Av. Los Castaños represents one of the most residential and unitary sectors of the Vergara Population and the main residential reserve.

10.5.1.2. Zoning according to dominant uses

Figure 123 shows the zoning distribution of the Población Vergara regarding land use and dominant activities. It divided the district in five areas:

- equipment and services;
- retail - tourism (sector 1 and 2);
- retail and automotive Service;
- large-scale commercial equipment;
- mixed area (sector 1 and 2);
- residential (sector 1 and 2).

The Población Vergara presents mixed uses but the specialization of some sectors is evident. In this regard, the sectors of 'equipment and services' are associated with the major avenues, Av. Libertad, 1 Norte and 15 Norte (see figure 121). The 'retail–tourism 1' sector is located nearby the Casino, with an offer aimed at tourism, with restaurants, cafeterias, bars and hotels (see

[336] Municialidad de Viña del Mar, "Modificacion al Plan Regulador Comunal de Viña del Mar. Sector Población Vergara. Memoria Explicativa," (May 2016), 64.

[337] Ibid, 65.

figure 122). The most representative axes are Av. San Martin and Av. Perú. The 'retail-tourism 2' area is located adjacent to the previous one in the central or interior sector of the south-west quadrant, around the 4th and 5th North axes. It registers a greater diversification of services and commerce, with an important offer of gastronomic services. The 'commercial and automotive service' area is located mainly in the north-east quadrant. This neighborhood, heir to the industrial era of the city and associated with the development of Santa Inés, concentrates a large number of automotive-type services.

The 'large-scale commercial equipment' area is located on the axis of 15 Norte, the development of large commercial establishments has transformed the neighborhood based on the remnants of the industrial occupation. Nowadays, the sector is undergoing a renovation process with a strong increase in pedestrian flows attracted from the commercial servuces of intercommunal scale. The 'residential areas' correspond to those with the highest residential concentration (see figure 123), although they include other types of equipment, and therefore lack a dominant activity with respect to residential use (see figure 124). These areas are clearly concentrated towards the eastern edge of the Población of Vergara, adjacent to the Sporting Club, and in the north-west area, towards the coastal edge facing Av. San Martín.

Figure 119:
Height building development in the Población Vergara.
Source:
own elaboration from the Municipalidad de Viña del Mar[333].

Large retail
Retail - Car service
Retail - Tourism 1
Retail - Tourism 2
Services
Mixed zone 1
Mixed zone 2
Residential 1
Residential 2

Figure 120: Land use in the Población Vergara. Source: own elaboration from the Municipalidad de Viña del Mar[334].

Figure 121:
Av. Libertad, zone
'equipment and services'.
Source:
Eleonora F. Serpi.

Figure 122: Plaza
Colombia, zone
'retail–tourism 1'.
Source:
Eleonora F. Serpi.

Figure 123:
Zone 'residential 2'.
Source:
Eleonora F. Serpi.

Figure 124:
Equipment associated
with the zone
"residential 2".
Source:
Eleonora F. Serpi.

10.5.1.4. Zoning according seismic risk

Various studies on soil quality and morphology have been carried out in relation to the Viña del Mar Commune over time. Particularly for the area of the basin of Estero Marga-Marga and Población Vergara, demonstrating the risk associated with the constructions that are located in these sectors in correspondence with the seismic behavior. In this area, the Study of “Micro Zoning Seismic - urban sectors of the municipalities of Valparaiso and Viña del Mar”, coordinated by the Secretary of Regional Ministerial of Housing and Urban Planning (MINVU), develops background planimeters and conclusions with respect to establishing conditions for certain areas of the aforementioned study. In accordance with Art. 2.1.17 of the OGUC, the “Seismic Risk Area” is defined as the area mapped according to “Zone I + 2” of the Seismic Microzoning Study for the municipality of Viña del Mar (see figure 125).

10.5.1.4.1. Land use in relation to seismic risk

It is important to point out that the risk study that was incorporated containes, as part of its recommendations, the restriction of certain uses considered essential and strategic, such as those referred to some destinations of the health, safety and education uses. Even if the recommendation stands, it is not incorporated in the PRC. On the other hand, the coverage area of the risk study is larger and of a communal nature, therefore, it should be addressed within a larger scope, updating the complete Regulatory Plan of the Commune, which will allow for a more coherent and comprehensive vision in this regard. Today, the sector already hosts the equipment of the type indicated, such as security, education and health, which cover the needs of the sector, and in the case of new facilities, the application of the Art.2.1.17, established by the O.G.U.C., discourages their incorporation. Finally, one of the uses of greatest concern for the case, hospital, remains restricted by the new proposed areas, not incorporating it, in correspondence with the recommendation of the risk study.

[338]Ibid, 73.

Zone 1+2
Zone 3
Zone 4

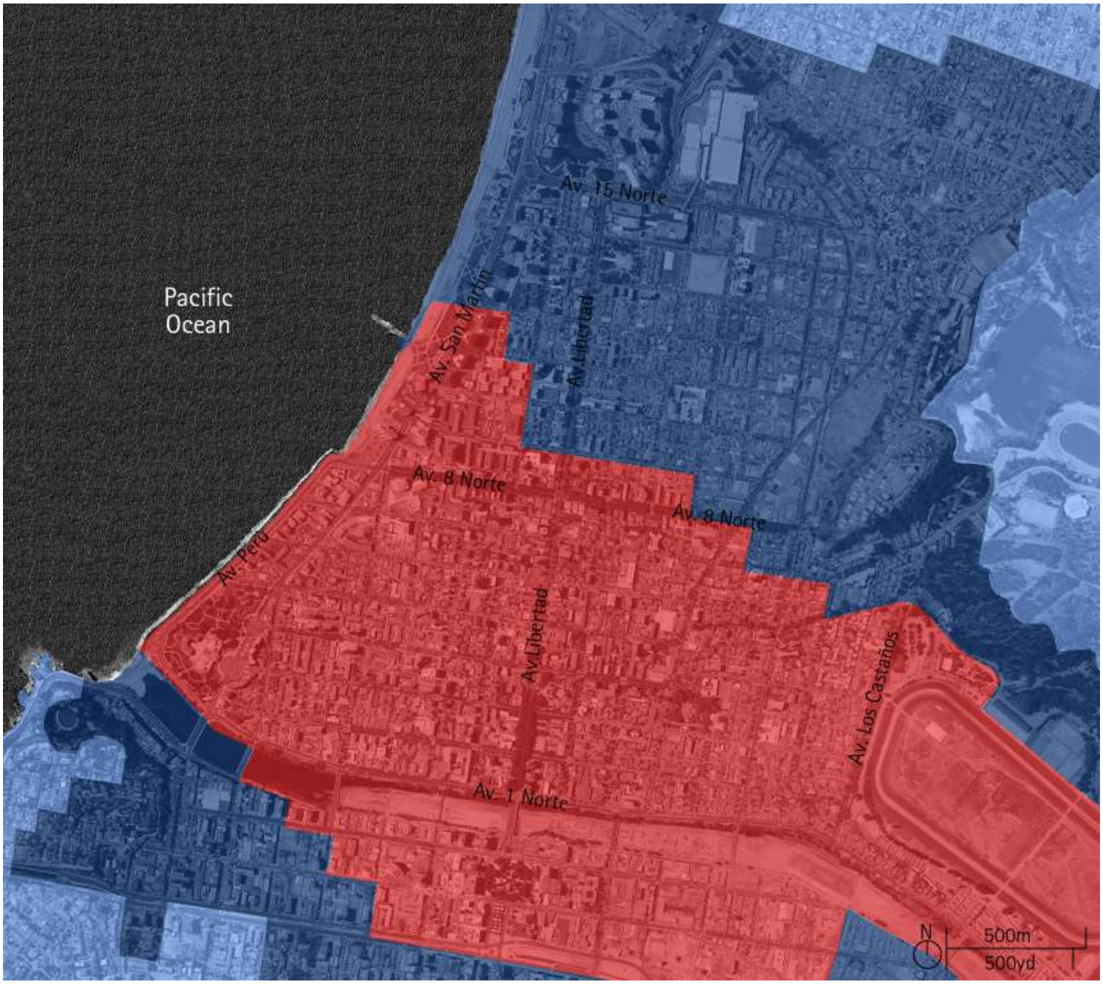


Figure 125:
Seismic Risk areas.
Source:
own elaboration
from the
Municipalidad de
Viña del Mar[338].

11

TSUNAMI VERTICAL EVACUATION SYSTEMS

A Tsunami Vertical Evacuation system (TVE) is a network of one or more evacuation structures designed to be ground-elevated temporary shelters, able to receive a large number of evacuees in a short time window, with a minimum expected occupancy duration of 8 hours up to a maximum of 24 hours. A TVE is meant to be an integration of the Horizontal Evacuation system (HE) when the last one alone is not able to guarantee in-time evacuation of all the inhabitants of a certain area. Evacuation structures include artificial berms, towers, buildings, and platforms within the inundated area providing shelter on the superior levels, which must be higher than the expected inundation height. A TVE must not be considered as a substitution of the horizontal evacuation plan, whenever possible the areas subjected to inundation risk must be evacuated according the HE plan towards natural high ground elevation out of the inundation zone.

Japan was the first country to embrace the concept of 'vertical evacuation' after the 2004 Indian Ocean tsunami. Post-disaster reports showed convincing evidence that seeking shelter in multistory reinforced concrete buildings saved thousands of lives during the 2011 Tohoku tsunami[339]. Today the advantages of vertical evacuation are being evaluated in the countries most exposed to the threat, but the example of vertical evacuation structures are still limited and mostly ubicated in Japan. Few other examples can be found on the west coast of U.S.A. and in South East-Asia.

Chile, even if recent studies demonstrated that vertical evacuation would help avoiding life losses[340], does not legally recognize vertical evacuation as an emergency measure even if suggested in the recently published guide for tsunami evacuation planning[341]. An efficient vertical evacuation system must guarantee the safety of the evacuees with tsunami and earthquake-resistant structures, open and expedited access roads (free of elements that can collapse and block the passage) with easy and visible access from the street, and circulation designed for people with reduced mobility. Travel time must be taken in consideration during the plan-

[339]Michael MacRae, "Tsunami Forces Debate over Vertical Evacuation," American Society of Mechanical Engineers, last modified April 2011, https://www.asme.org/engineering-topics/articles/manufacturing-processing/tsunami-forces-debate-over-vertical-evacuation.

[340]Jorge León, et al., 629-636.

[341]Ministerio de Vivienda y Urbanismo, Ministerio del Interior y Seguridad, Pública, Ministerio de Energía, Oficina Nacional de Emergencias, Centro Nacional de Investigación para la Gestión Integrada de Desastres Naturales, "Vol. 6 Guía de Referencia para Sistemas de Evacuación Comunales por Tsunami," (Santiago de Chile: Ministerio de Vivienda y Urbanismo. Gobierno de Chile, 2017), 53-54.

ning phase, which include not only the time need to reach the structure and its internal vertical circulation but also the interval of time between the triggering event and the warning alert[342], until reaching the minimum safe level above the ground. The design tsunami inundation height must take into consideration the estimation uncertainty of the tsunami runup, the possible splash-up during the waves impact, and the panic of evacuees seeking refuge in the structure[343].

11.1. TVEB main features

As already established, a tsunami vertical evacuation structure must be able to withstand both the inertial loads generated by a major earthquake, and the forces associated with the tsunami waves[344]. The U.S. Federal Emergency Management Agency (FEMA) provides the guidelines, FEMA P646, to design tsunami-resistant structures. The guidelines state that TVEBs must have:

- strong systems able to withstand extreme forces;
- open systems to generate minimal resistance to water flowing;
- ductile systems that withstand extreme forces without failure;
- redundant systems that can resist partial failure without collapsing.

They also specify that a TVEB must be located well above the maximum tsunami inundation level expected at a site. The recommended minimum elevation is the maximum tsunami runup elevation (at a site), plus 30%, plus 3m, of freeboard[345]. Being TVEBs short-term refuges, FEMA recommend a minimum square footage of 0,9m2 (10 square feet) per occupant, guaranteeing evacuees the room to sit down without feeling overly crowded. The footage should be adjusted depending on the specific occupancy needs, this number would not be considered appropriate for longer stays that included sleeping arrangements[346].

[342]Federal Emergency Management Agency, *FEMA P-646, Guidelines for design of structures for vertical evacuation from tsunamis*, 59.

[343]Federal Emergency Management Agency, HMGP-DR-WA-4056, "Tsunami Safe Haven Vertical Evacuation Project, City of Long Beach, Washington," (Bothell: Department of Homeland Security, 2016), https://www.fema.gov/media-library-data/1480599644890-808b8f9520e-e4fdf6c8c989532e89998/LongBeach-DraftEA112916508.pdf, 13.

[344]Federal Emergency Management Agency, *FEMA P-646, Guidelines for design of structures for vertical evacuation from tsunamis*, 68.

[345]Ibid, 67.

11.2. Strategies and typologies

TVEBs can take a variety of forms: buildings, elevated platforms, or artificial berms. Both new or existing structures can serve as TVEBs, but in general, retrofitting an existing structure is more complex than building a new one. TVEBs can be 'stand-alone' structures or integrated in larger facilities and they can have a single-purpose refuge use, or they can be multi-purpose facilities with multiple different uses when not occupied as refuge. Japan is the country with the most developed network of tsunami shelters which includes structures built exclusively for that purpose, along with renovated schools and other public buildings capable of providing temporary shelter for large numbers of people[346].

11.2.1. Elevated platforms

Elevated platform are steel or reinforced concrete structures designed to shelter from few tens of evacuee to more than a thousand. Japan hosts many examples of elevated platforms, most of them were born with the only purpose of being evacuation structures and therefore unused for the 99,9% of their expected life span. It is the case of the Tasukaru (Life-Saving) Tower in the Mie Prefecture, developed by the Fujiwara Industries Co., which consist of a basic steel platform, able to host about 50 people at 5.8 m above ground level[347](see figure 127). Other examples are the Shirahama Beach Resort Shelter, in Shirahama, Tokushima Prefecture, Japan (see figure 128), a reinforced concrete platform of 700m^2, able to host about 700 evacuees at 11,5m above the ground[348]; and the crosswalk bridge In Yoshida-cho, Shizuoka Prefecture, Japan (see figure 130) able to accommodate 1200 people[349].

Evacuation structures can be provided with other features face or escape the tsunami inundation, like the evacuation tower near the coast of Nankoku, Japan (see figure 131). The tower, designed to house about 362 people distributed in two floors at 20m above the ground, is flanked by a floating capsule intended to escape tsunamis[350].

[346] Michael MacRae, "Tsunami Forces Debate over Vertical Evacuation."

[347] Ibid.

[348] Geophysical Institute of The University of Alaska Fairbanks, "Structural countermeasures," accessed August 14, 2018, http://www.aktsunami.org/lessons/58/unit8/atep_58_StructuralCountermeasures_VA.pdf.

[349] "About Tsunami evacuation tower in Nankoku City and Konan City," Nifty Cocorog, accessed August 14, 2018,

http://futaba-bousai.cocolog-nifty.com/blog/2015/05/post-aa51.html.

[350] Marta O. Craviotto, "Japón se acoraza para hacer frente a un tsunami de más de 30 metros," last modified November 18, 2016, https://www.efe.com/efe/america/portada/japon-se-acoraza-para-hacer-frente-a-un-tsunami-de-mas-30-metros/20000064-3100441.

[351] Ibid.

[352] Marta O. Craviotto, "Japón se acoraza para hacer frente a un tsunami de más de 30 metros."

[353] Geophysical Institute of The University of Alaska Fairbanks, "Structural countermeasures."

[354] "About Tsunami evacuation tower in Nankoku City and Konan City," Nifty Cocorog.

[355] "About Tsunami evacuation tower in Nankoku City and Konan City," Nifty Cocorog.

[356] Marta O. Craviotto, "Japón se acoraza para hacer frente a un tsunami de más de 30 metros."

Figure 126: vertical evacuation structure in Japan- Source: Agencia EFE[351].

Figure 127: Tasukaru (Life-Saving) Tower in the Mie Prefecture, Japan. Source: Japan Products[352].

Figure 128: Shirahama Beach Resort Shelter, in Shirahama, Tokushima Prefecture, Japan. Source: Geophysical Institute of the University of Alaska Fairbanks[353].

Figure 129: Elevated Platform in Okushiri Island, Japan. Source: International Tsunami Information Center[355].

Figure 130:
Crosswalk bridge
In Yoshida-cho,
Shizuoka Prefecture,
Japan.
Source:
Futaba Town
Disaster Prevention
Newspaper[355].

Figure 131:
Evacuation tower
near the coast of
Nankoku, Japan.
Source:
Agencia EFE[357].

11.2.2. Buildings

Different typologies of buildings meet the requirements to be designed as TVEB. Their use should consider co-location of evacuation facilities with other uses which allow immediate possibility for a return on investment, like business or commercial use, or that strengthen the identity of the city or produce services to ameliorate quality of life of the population. Among them parking garages, community facilities, recreational facilities like sports complexes, libraries, museums, commercial facilities including multi-level hotels, restaurants, or retail establishments are suitable potential TVEB. Private buildings with residential use shouldn't be consider for evacuation since in case of hazard they are usually locked down for security reasons.

Parking garages are great candidates as TVEB because of the open space at the lower levels which allow water to flow through with minimal resistance; the wide car ramps allow easy and rapid internal circulation to higher levels and the rooftop can be used as rescue helicopter landing site. The main disadvantage of using a parking garage is that cars can become debris that can damage the structure and block the public access during a tsunami event. Community facilities are a great option because in addition to providing a daily service and generating a revenue, also provide protection against meteorological perturbations and room for first aid and water/food storage. The main disadvantage of using a community facility as a shelter is that the normal community activity can hinder and slow down the vertical evacuation. For example, in case of a library, fallen books and shelves after a triggering earthquake can obstacle the circulation inside the building.

Commercial facilities can be financed through private-sector funding and discounted by tax incentives. Generally, these facilities are either located within very vulnerable areas, like hotels in front of the beach, or in the central areas of a city like retail establishments which daily attract lots of residents and tourists. This kind of facilities already proved to be a good option during the 2004

Indian Ocean tsunami where many survivors found rescue on upper floors of tourist hotels[358]. School facilities have great potential as they would not only provide shelter to the members of the community but also guarantee the safety of the children attending the school, which are one of the most vulnerable population.

Choosing school as TVEB means that many people, within the local community, are already familiar with their location, moreover it would potential funding for co-locating tsunami vertical evacuation structures. A disadvantage is that, as for all the structures with co-located uses, the daily use can interfere with the vertical evacuation process[359]. Ocosta Elementary School, in Grays Harbor County, Washington, is the first TVEB built in the U.S.A. The shelter, located on the roof of the gym, was inaugurated in 2016 and can provide refuge to approximately 1,000 people at 16m above sea level[360] (see figures 132-133).

The Nishiki Tower, in Nishiki, Mie Prefecture, Japan, is a five-story, 22m high reinforced concrete structure. On daily basis, the first-floor hosts public toilets and storage space for fire equipment; the second floor a meeting room; and the third floor an archival library for natural disasters. The fourth and fifth floors have 73m2 for evacuees, at 6m above sea level (see figure 134). Rawa Indah, a village of about 2500 inhabitants in the Bengkulu Province, Indonesia, hosts another example of tsunami shelter, born as part of a larger tsunami awareness community project (see figure 135). Rawa Indah is located on the wide coastal plain of Seluma and where there is no natural high ground suitable for tsunami evacuation. The shelter, built in 2014, by the National Emergency Management Agency, together with the assistance of international development aid and the National Public Works, is a 16m high run by the local emergency management agency, Seluma BPBD. Unfortunately, the Seluma BPBD does not have the capacity to maintain the shelter and in 2018 its condition has deteriorated, and new tsunami awareness program have recently been carried out to sensitize the local community[361].

[358]Federal Emergency Management Agency, *FEMA P-646, Guidelines for design of structures for vertical evacuation from tsunamis*, 31.

[359]Ibid, 32.

[360]Geophysical Institute of The University of Alaska Fairbanks, "Structural countermeasures."

[361]StIRRRD, "Initiating tsunami awareness community engagement, Rawa Indah, Seluma," last modified March 5, 2018, https://stirrrd.org/tag/vertical-evacuation-shelter/.

[362]TFC Architecture, "Leading edge disaster preparedness. Ocosta Elementary School, Westport, WA," accessed August 14, 2018, https://www.tcfarchitecture.com/project/ocosta-elementary-school/.

[363]Ibid.

[364]ICHARM, "Tsunami countermeasures in Kii Peninsula," accessed August 14, 2018, http://www.icharm.pwri.go.jp/publication/newsletter/newsletter6_oct07_e.html.

[365]StIRRRD, "Initiating tsunami awareness community engagement, Rawa Indah, Seluma."

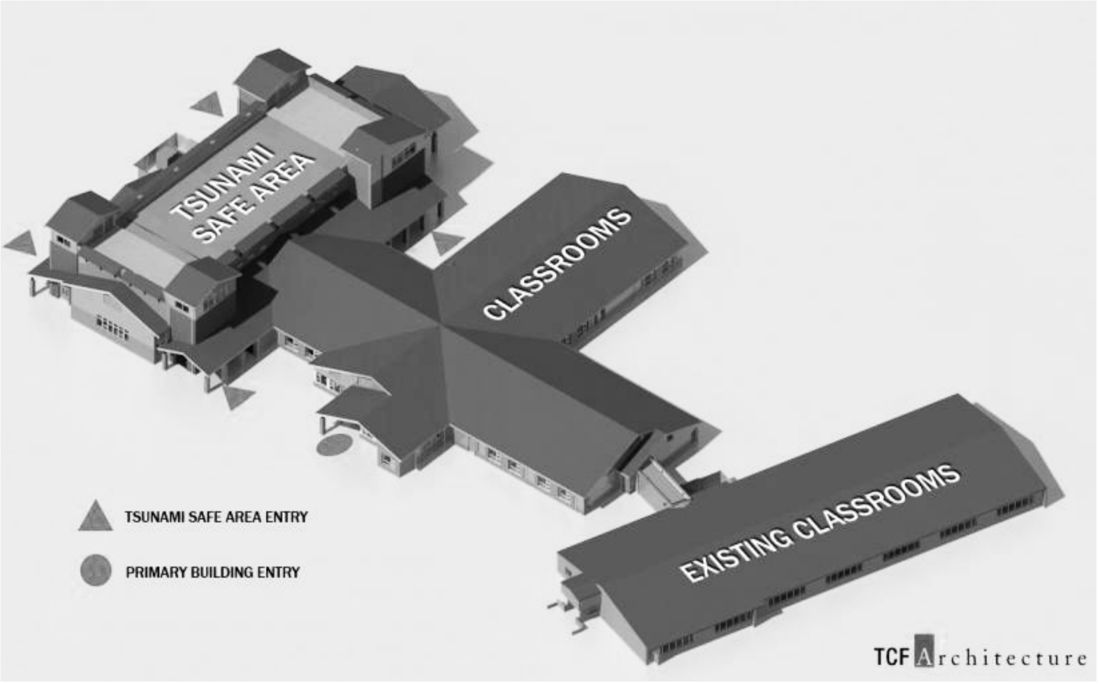


Figure 132: Ocosta Elementary School, in Grays Harbor County, Washington. Source: TFC Architecture[362].

Figure 133: Tsunami shelter, Ocosta Elementary School, Washington. Source: TFC Architecture[363].

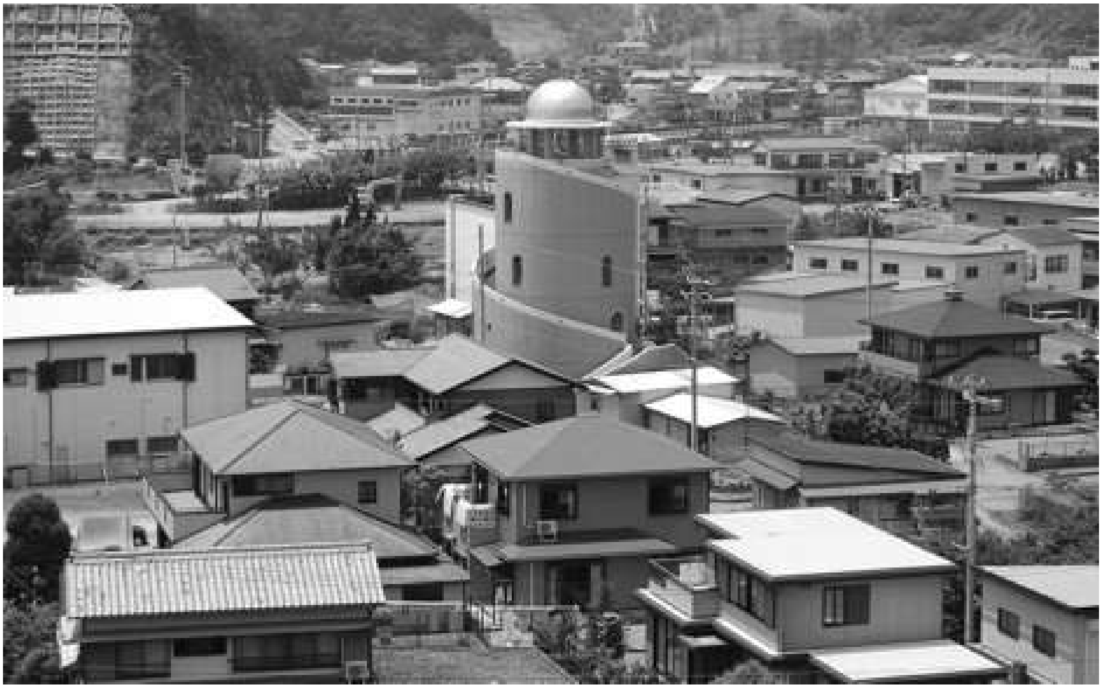


Figure 134: Nishiki Tower, in Nishiki, Mie Prefecture, Japan. Source: ICHARM[364].

Figure 135: Tsunami shelter in Rawa Indah, Bengkulu Province, Indonesia. Source: StIRRRD[365].

11.2.3. Engineered high grounds

Existing high ground areas can be used for vertical evacuation. To ensure the safety of the evacuation adjustments may need for the high ground to be completely above the inundation level and to resist potential damage from wave runup or erosion. When there is no natural high ground, artificial soil berms can be constructed (see figure 136). In either case, the side slopes must be designed or modified to guarantee both efficient ingress and water drainage and to be protected against scour.

Using high ground areas for vertical evacuation has many advantages:

- they provide easy access to a large number of people at the same time;
- they meet the natural human instinct to move towards higher grounds in response to tsunami events, especially after a major earthquake which causes people to be reluctant to enter a structure;
- they can be used as public spaces like squares and parks;
- the sloped sides provide easy access for people with limited mobility.

Some disadvantages also should be taken in consideration:

- they do not provide protection from meteorological perturbations like wind and rain;
- people might panic seeing the waves approaching;
- slopes would need to be armored to prevent scour and ramping[366].

An example of artificial berm is the project designed for the city of Long Beach, Washington (see figure 137). The project known as “Safe Heaven” proposes an armored, hardened earth berm with an access ramp behind the Long Beach Elementary School. The berm with its 10m height and a sheltering area of $800m^2$ would provide refuge to approximately 850 people between residents and visitors. The perimeter of the berm will be covered of earthen side slopes, while the armored inner core will include concrete footings, mechanically stabilized earth, and structural fill to prevent wall failure during a major earthquake and subsequent tsunami. The berm form should prevent the ramping generated by the run-up and scatter any floating debris in the water[367].

[366]Federal Emergency Management Agency, *FEMA P-646, Guidelines for design of structures for vertical evacuation from tsunamis*, 28.

[367]Federal Emergency Management Agency, HMGP-DR-WA-4056, “Tsunami Safe Haven Vertical Evacuation Project, City of Long Beach, Washington,” (Bothell: Department of Homeland Security, 2016), 3-2, https://www.fema.gov/media-library-data/1480599644890-808b8f9520e-e4fdf6c8c989532e89998/LongBeach-DraftEA112916508.pdf.

[368]Federal Emergency Management Agency, *FEMA P-646, Guidelines for design of structures for vertical evacuation from tsunamis*, 95-96.

[369]Ibid, 3-6.

Figure 136:
Artificial berm in Aonae, on Okushiri Island, Japan. Source: FEMA[368].

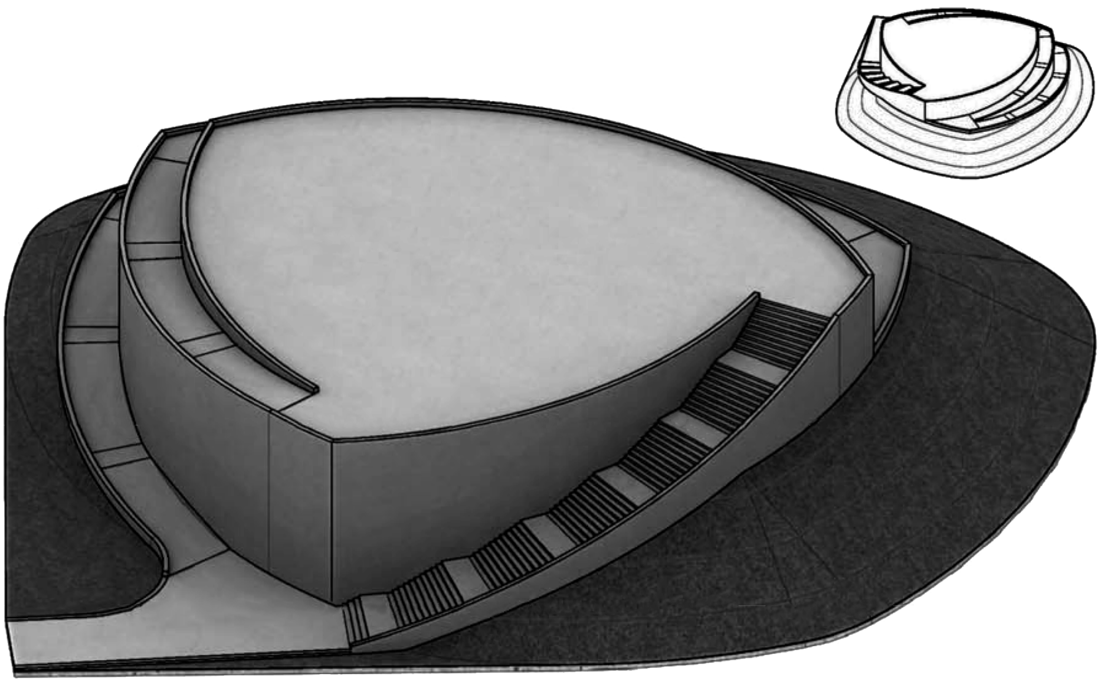


Figure 137:
Safe Heaven project, Long Beach, Washington. Source: FEMA[368].

11.3. Operating a TVEB

A tsunami waves cycle usually ends within the first 12 hours after the first wave reached the shore, in exceptional cases high tides and coastal flooding can last up to 24 hours. Therefore, TVES should be provided with the basic supplies necessary during the first 24 hours of the emergency (see figure 138), stocked in apposite storage areas included in the structure design without compromising the evacuee's security. The availability of supplies means that they have to be protected during non-emergency times while made accessible during emergencies. A vertical evacuation structure should provide the following minimum supplies:

- enough water and food for the occupants during the entire length of the emergency use;
- one flashlight with continuously charging batteries (solar or mechanical charging) every 10 estimated occupants;
- an appropriate number of fire extinguishers;
- first-aid kits;
- supply of extra batteries ensures the functionality of radios and flashlights;
- audible sounding device with continuously charging batteries (solar or mechanical charging) or operating without a power source (e.g., canned air horn);
- on-site sanitation facilities functioning without power and water supply, and possibly waste disposal;
- means of backup to telephone communication like satellite phones, ham radios, cellular telephones, citizen band radios, or emergency radios, should be provided to guarantee on going communication with police, fire, or other emergency personnel;
- a weather radio with continuously charging batteries (solar or mechanical charging);
- a radio transmitter with continuously charging batteries (solar or mechanical charging) to signal the location of the facility[370].

[370] Ibid, 42-44.
[371] Ibid, 42-44.

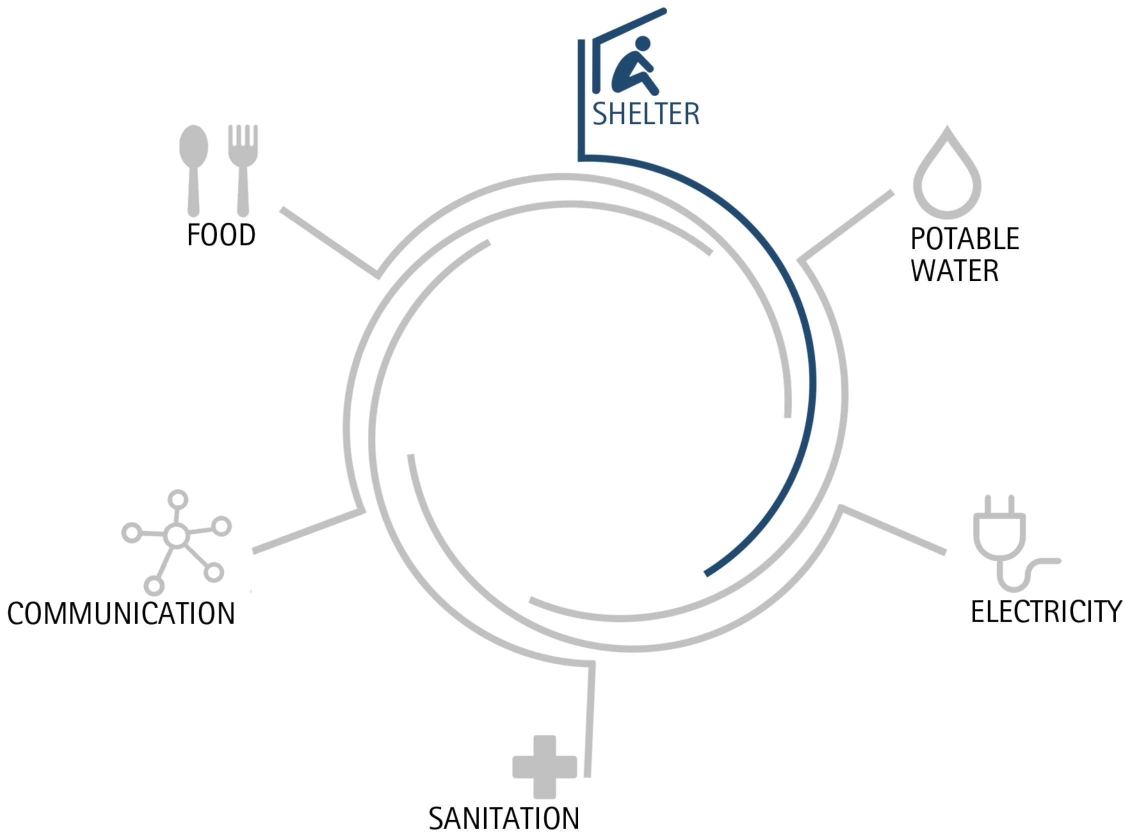


Figure 138:
TVEB features.
Source:
own elaboration
from FEMA[352].

11.4. Cost considerations

Due to the structural requirements of a TVEB, the expected construction costs are higher than the ones for other normal-use structures. A recent study carried by the National Institute of Standards and Technology (NIST)[372], showed that a tsunami-resistant structure, including both seismic-resistant and progressive collapse-resistant design features, is between 10% and 20% more expensive than structures for regular-use buildings, which means an increase of 1% to 8% of the total construction costs. Therefore, even if each project is unique, and the relative costs depend on the specific characteristics of the site, they are not prohibitive[373].

[372] National Institute of Standards and Technology, "Engineering Design and Cost Data for Reinforced Concrete Buildings for Next Generation Design and Economic Standards for Structural Integrity," (NIST, 2007).

[373] Federal Emergency Management Agency, *FEMA P-646, Guidelines for design of structures for vertical evacuation from tsunamis*, 111.

12

NEW TSUNAMI EVACUATION PLAN FOR THE POBLACIÓN VERGARA

The design of the new evacuation system for the Población Vergara is the result of a process that can be resumed in three phases: the draft of an assessment model for potential Tsunami Vertical Evacuation Building's sites, the design of a vertical evacuation system composed of 22 tsunami shelters and finally the drawing of the new evacuation plan resulting from the implementation of the existing horizontal system with the new vertical one.

1 SITES ASSESSMENT

2 TVEBS DESIGN

3 NEW EVACUATION PLAN

12.1. Assessment model for TVES's potential sites

12.1.1. Premises

The model has been developed as a first assessment tool for planning a Tsunami Vertical Evacuation System (TVES). Planning an efficient TVES means choosing potential sites and structures located in the urban area such that the population exposed to the threat of tsunami hazard can reach the designated shelters within the time available between tsunami warning and tsunami inundation. Tsunami evacuation must take in account not only the time needed to reach the structure and attending a safe position, but also the delay of the evacuation alarm after the triggering event[374].

For the case study of Viña del Mar, the maximum travelling time is estimated in 15min as established by the ONEMI[375], 8min reaching the shelter plus 7min to enter the structure up to an appropriate security level. The estimated horizontal ambulatory speed of the population can be calculated according to the parameters reported in table 15, taking into consideration the slope grade of the evacuation route.. In case of restricted ambulatory capability due to age, health, or disability, the average ambulatory speed can be reduced of 50%[376]. For this study, only ambulatory speed of healthy and autonomous population is taken into account.

To guarantee a responsive and rapid evacuation, the routes to the structures should be well marked and easily recognizable as well as the evacuation structures themselves. The location of vertical evacuation structures within the built environment must take into consideration potential hazards in nearby sites that could jeopardize the safety of the structure. Moreover, it must consider the natural tendency for evacuees to migrate away from the shore to avoid coastal flooding, locating the TVEB on the inland side of evacuation zones[377].

12.1.1. 1. Weighting coefficients considerations

The weighting coefficients assigned to the characteristics used to evaluate the categories 'open spaces (OP)', 'vacant lots (VL)' and 'potential existing TVEB ((P) TVEB)' derive from the hypothesis based on

SLOPE	SPEED
< 5%	1,22m/s
10%	0,74m/s
15%	0,53m/s
20%	0,37m/s
30%	0,22m/s

Table 15: Ambulatory speed for healthy and autonomous population. Source: MINVU, et al.[378].

[374]Federal Emergency Management Agency, *FEMA P-646, Guidelines for design of structures for vertical evacuation from tsunamis*, 59.

[375]Ministerio de Vivienda y Urbanismo, Ministerio del Interior y Seguridad, Pública, Ministerio de Energía, Oficina Nacional de Emergencias, Centro Nacional de Investigación para la Gestión Integrada de Desastres Naturales, "Vol. 6 Guía de Referencia para Sistemas de Evacuación Comunales por Tsunami," 50.

[376]Federal Emergency Management Agency, *FEMA P-646, Guidelines for design of structures for vertical evacuation from tsunamis*, 60.

[377]Ibid, 59-61.

[378]Ministerio de Vivienda y Urbanismo, Ministerio del Interior y Seguridad, Pública, Ministerio de Energía, Oficina Nacional de Emergencias, Centro Nacional de Investigación para la Gestión Integrada de Desastres Naturales, 51.

the previous literary review and from a careful study of the tsunami risk in Viña del Mar, carried out through the analysis of the inundation maps and the morphology of the city. Their weights have been successively calibrated on the comparison of the results obtained from a series of previous tests applied to the case study.

In particular, for the 'open spaces (OS)' category, I assumed that the parameter 'location (L)' is predominant on the 'geometry (G)' parameter because it contains all the factors deriving from the exposure of the city to the inundation risk and, therefore, it strongly influences the evacuation process, while the second parameter evaluates the predisposition of the lot to accommodate an evacuation structure. For the 'vacant lots (VL)' category, in addition to the considerations expressed for the previous category, a new parameter, 'land use (U),' has been introduced, but it has a marginal influence in the equation as it depends mainly on the communal regulatory plan which can be modified to promote the functioning of the evacuation system.

Finally, in the category 'potential existing TVEB ((P)TVEB)', the parameters 'location (L)' and 'vulnerability (V)', have the predominant weights in the equation deriving from the tsunami risk exposure. I assumed that the vulnerability of the buildings to flooding has a slightly lower weight because it does not keep in consideration the evacuation time. The factors 'vertical evacuation potential (E)' and 'accessibility and circulation (AC)' have a less incisive weight on the result as they evaluate the characteristics of the building that, through appropriate retrofit work, can be modified and improved.

12.1.2. Sites

The model considers three category of sites, 'open spaces', such as squares and green areas, 'existing buildings with potential as TVEB' and 'vacant lots' which includes empty lots, dismissed and abandoned buildings/houses, buildings and houses for sale. Each category is evaluated through a series of attributes weighted using a multi criteria decision analysis. The aim of the model is to provide an objective evaluation of each site and/or building, to be incorporated in the decision-making process of the evacuation planning.

12.1.2.1. Sites pre-requirements

In the process of selecting the most suitable candidates as potential sites for the development of the vertical evacuation system, only the open spaces and vacant lots situated 200m away from the coastline have been considered as suggested by ONEMI[379] and FEMA[380], to avoid the uncertainty regarding the wave-breaking zone predicted through numerical models. Moreover, coastal structures (e.g., breakwaters, seawalls, jetties), have been proven to be often subjected to failure when exposed to critical wave forces originated from breaking waves. Therefore, even if generally tsunamis break offshore, in case of very steep terrain they can break right at the shoreline, generating strong and uncertain forces. The location of vertical evacuation structures within the tsunami wave-breaking zone results in unknown additional risk to the structure[381]. If located near a harbor or container terminal, the structure would suffer of great impact forces from large waterborne debris.

The other considered parameter refers to the estimated 'evacuation time zone' in which the site is located. As already established, TVES must be used as an integration of the horizontal evacuation plan when the last one alone cannot guarantee in time evacuation of all the sectors of the city. Therefore, buildings located in areas with an evacuation time inferior to 10min have not been considered.

Exception to these pre-requirements should be made if the structures that can serve as evacuation systems are vulnerable infrastructures. Due to the difficulties in evacuating a venerable population in time, the most effective solution would be to guarantee a vertical evacuation of the people who already find themselves within the buildings. This preventive measure would not only guarantee the safety of the people inside, but also help reducing road congestion generated by vehicular and pedestrian traffic, speeding up the evacuation process.

[379]Ibid, 54.

[380]Federal Emergency Management Agency, *FEMA P-646, Guidelines for design of structures for vertical evacuation from tsunamis*, 62.

[381]Ibid, 62.

The 'open spaces' category considers squares and green areas not subjected to environmental conservation programs and squares not subjected to patrimonial or historical conservation programs. Gardens and park adjacent to historical or patrimonial building should be excluded too.

The 'potential existing Tsunami Vertical Evacuation Buildings' are those not subjected to any historical and/or patrimonial conservation program that meet the following minimum requirements:

- a reinforced concrete and steel moment frame systems able to resist extreme forces including the forces caused by the triggering event (e.g. near-source earthquake);
- an open system that allow water to flow through with minimal resistance;
- a ductile system that resist extreme forces without failure;
- a redundant system that can experience partial failure without progressive collapse;
- a height of 30m or at least 8 stories;
- open access for people (at least during business hours);
- adequate capacity (considering a required space for each evacuee of $0.9m^2$)[382].

12.1.2.2. The evaluation tables

The proposed model consists of three evaluation tables, one for each site category: 'open spaces', 'potential existing TVEB' and 'vacant lots'. In absence of one or more category, the model can still be applied to compare the available solutions. The result is a score index, in the range of 1 and 5, with 5 representing the most suitable site for the design of the system and 3.5 being the minimum score for the site to be eligible for hosting a vertical evacuation shelter. The parameters have been chosen to allow the model to be universally applied within a built environment. The results shouldn't be considered as an exclusive solution but as a guide of an effective planning.

[382] Federal Emergency Management Agency, *FEMA P-646, Guidelines for design of structures for vertical evacuation from tsunamis*, 95-96.

12.1.2.2.1. Open spaces assessment table

The open spaces are evaluated according to their location (L) and geometry (G) (see table 16).

$$OS = L \cdot 0{,}70 + G \cdot 0{,}30$$

Location (L): this parameter considers the location of the potential TVEB within the built environment, evaluating site accessibility (SA), the evacuation time zone (TZ), the expected inundation height (h), the closeness to vulnerable infrastructures (VI) and to potential hazards (H) through the following expression:

$$L = SA \cdot 0{,}25 + TZ \cdot 0{,}35 + h \cdot 0{,}05 + VI \cdot 0{,}20 + H \cdot 0{,}15$$

Geometry (G): this parameter considers the site size (S) to evaluate the capacity of the area in fostering potential evacuees and its shape (SH). Giving the difficulty of guiding the population to multiple different shelters, a single site with high foresting capacity should be predilected to multiple smaller shelters to avoid overcrowding and uneven repartition. Areas smaller than $500m^2$ should be excluded with the possibility to be reintroduced if the proposed system will prove to be not efficient Regular shapes facilitate the following design process and allow a better exploitation of the available surface. The geometry parameter is computed as:

$$G = D \cdot 0{,}70 + SH \cdot 0{,}30$$

Table 16:
Open spaces
assessment table.
Source:
Eleonora F.Serpi.

	5	4	3	2	1
SA (site accessibility)	Accessible from the designated horizontal evacuation roads	Accessible from a main two-ways road	Accessible from more than two sides along a one-way road	Accessible from two or less sides along one-way roads	Accessible only through pedestrian passage
TZ (evacuation time zone)	>30min	25-30min	20-25min	15-20min	10-15min
h (expected inundation height m)	<1m	-	1-2m	-	>2m
VI (closeness to vulnerable infrastructures)	<100m	100-200m	200-300m	300-500m	>500m
H (potential hazards exposure)	Far from the site block	-	Limited traffic area, absence of parking lots and gas station	-	High traffic congestion areas, close to parking lots or gas station
S (size)	>10,000m2	7000-10,000m2	5000-7000m2	2000-5000m2	<2000m2
SH (shape)	Circular, Squared/rectangular	-	Triangular, trapezoidal	-	Irregular

12.1.2.2.2. Vacant lots assessment table

The potential of the vacant lots is evaluated according to their location (L), geometry (G), and land use (U) (see table 17).

$$VC = L \cdot 0{,}70 + G \cdot 0{,}20 + U \cdot 0{,}10$$

Location (L): this parameter considers the location of the potential TVEB within the built environment, evaluating the site accessibility (SA), the evacuation time zone (TZ), the expected inundation height (h), the closeness to vulnerable infrastructures (VI) and to potential hazards (H) through the following expression:

$$L = SA \cdot 0{,}25 + TZ \cdot 0{,}35 + h \cdot 0{,}05 + VI \cdot 0{,}20 + H \cdot 0{,}15$$

Geometry (G): this parameter considers the site size (S) to evaluate the capacity of the area in fostering potential evacuees and the shape (SH) of the site considering the necessity of designing a new structure as:

$$G = S \cdot 0{,}70 + SH \cdot 0{,}30$$

Land use (U): this parameter considers the current program (PGM), whether the lot is empty or there is a preexistence; the potential program (PPGM) evaluating the future uses of the new TVEB and the maximum building height (Bh_{max}) in a specific site. Regarding the PGM, empty lots are preferred because there are no costs associated with demolition works. The potential program should consider co-location of evacuation facilities with other uses, allow ing immediate possibility for a return on investment, like business or commercial use, or strengthening the identity of the city, producing services to ameliorate the quality of life of the population. The compatibility of a program in fostering evacuees is also considered in considered in this category. It results:

$$U = PGM \cdot 0{,}20 + PPGM \cdot 0{,}30 + Bh_{max} \cdot 0{,}50$$

Table 17: Vacant lots assessment table. Source: Eleonora F. Serpi.

	5	4	3	2	1
SA (site accessibility)	Accessible from the designated horizontal evacuation roads	Accessible from a main two-ways road	Accessible from more than two sides along a one-way road	Accessible from two or less sides along one-way roads	Accessible only through pede-strian passage
TZ (evacuation time zone)	>30min	25-30min	20-25min	15-20min	10-15min
h (expected inundation height m)	<1m	-	1-2m	-	>2m
VI (closeness to vulne-rable infrastructures)	<100m	100-200m	200-300m	300-500m	>500m
H (potential hazards exposure)	Far from the site block	-	Limited traffic area, absence of parking lots and gas station	-	High traffic congestion areas, close to parking lots or gas station
S (size)	>10,000m2	7000-10,000m2	5000-7000m2	2000-5000m2	<2000m2
SH (shape)	Circular, Squared/rectan-gular	-	Triangular, trape-zoidal	-	Irregular
PGM (current program)	Empty lot	-	Dismissed/ aban-doned/nonfunctio-nal buildings	-	Functional buil-dings for sale
PPGM (potential program)	Educational, com-mercial, parking garage, recreatio-nal, cultural	-	Offices, health	-	Residential
Bh_{max} (max building height)	≥20 floors	16-19 floors	11-15 floor	9-10 floors	< 8 floors

12.1.2.2.3. Potential existing TVEB assessment table

Potential existing Tsunami Vertical Evacuation Buildings are evaluated according to their location (L), vulnerability (V), vertical evacuation potential (E), and building accessibility and internal circulation (AC) (see table 18).

$$(E)TVEB = L \cdot 0,40 + V \cdot 0,30 + E \cdot 0,20 + AC \cdot 0,10$$

Location (L): this parameter considers the location of the potential TVEB within the built environment, evaluating the site accessibility (SA), the evacuation time zone (TZ) and the closeness to vulnerable infrastructures (VI) through the following expression:

$$L = SA \cdot 0,30 + TZ \cdot 0,50 + VI \cdot 0,20$$

Vulnerability (V): it takes in account the Relative Vulnerability Index (RVI) calculated through the PVTA-4[383] model and the current program (PGM) which considers the actual use associated with the building. The vulnerability is computated as:

$$V = RVI \cdot 0,70 + PGM \cdot 0,30$$

Vertical Evacuation Potential (E): this parameter takes into account the building capacity (C) which must guarantee 0,9m^2 per person and the current emergency protocol (EP) as:

$$E = C \cdot 0,60 + EP \cdot 0,40$$

The capacity of the buildings is calculated considering the total area of the rooftop and the 10% of the gross area of each floor above the inundation level.

Building accessibility and internal circulation (AC): this factor considers geometric parameters like emergency stairs width (SW), corridors width (CW); door opening direction (DD) associated with the vertical internal evacuation, and the habilitation and accessibility to the rooftop (RT). this parameter is computed as:

$$AC = SW \cdot 0,30 + CW \cdot 0,30 + DD \cdot 0,15 + RT \cdot 0,25$$

Table 18:
Potential existing TVEB assessment table.
Source:
Eleonora F. Serpi.

[383] F. Dall'Osso, et al.

	5	4	3	2	1
SA (site accessibility)	Accessible from the designated horizontal evacuation roads	Accessible from a main two-ways road	Accessible from more than two sides along a one-way road	Accessible from two or less sides along one-way roads	Accessible only thrurgh pede-strian passage
TZ (evacuation time zone)	>30min	25-30min	20-25min	15-20min	10-15min
VI (closeness to vulne-rable infrastructures)	<100m	100-200m	200-300m	300-500m	>500m
RVI (Relative Vulnerability Index)	Minor	-	Moderate	-	≥Avarage
PGM (current program)	Educational, com-mercial, cultural, recreational	-	Offices, health	-	Residential
C (building capacity)	>5000 pp	5000-4000 pp	2000-4000 pp	1000-2000 pp	<1000 pp
EP (current emergency protocol	Vertical evacua-tion, opening to external public	-	Vertical evacua-tion, closing to external public	-	Evacuation of the building, closing of the building
SW (emergency stairs width)	>1,2m	1,2-1,5m	1-1,2m	1,1m	<1,1m
CW (corridors width)	>3	3-2m	2-1,5m	1,5-1,2m	<1,2m
DD (door opening di-rection)	All towards the inside	-	Towards the inside but the main entrance	-	Towards the outside
RT (rooftop accessibility)	Accessible and habilitad for the public	-	Accessible but not habilitated for the public	-	Not accessible

12.1.2.3. Final considerations

Local regulation plans and building codes must be considered when available. In case these urban planning instruments become an obstacle to an efficient and successful vertical evacuation planning, they should be modified, or exception should be made, to not jeopardize the outcome. Therefore, in case of absence of suitable areas for the development of an efficient TVES, possible alternative strategies include land expropriation, redefinition of parameters established by the local regulation plan or exclusion from such parameters especially when regarding buildings height. Even the preventive measure of locating buildings 200m away from the coast should be ignored if there is no alternative locations available to serve a particular area of the community. In this eventuality, the structure must be designed to resist great impact forces from potential impact of shipping containers and boats and other waterborne debris likely to be present during tsunami inundation[384].

12.1.3. Case study: the Población Vergara, Viña del Mar

11.1.3.1. Potential sites mapping

The three categories of sites have been mapped through an on-field survey which led to the identification of 12 consolidated public spaces, 36 vacant lots and 12 existing buildings eligible for becoming tsunami shelters (see figure 139). Together with the potential sites, the survey highlighted the vulnerable infrastructure and the potential hazard in the district (see figures 140-141). The analysis will strat evaluating whether the sites meet the pre-requirements explained at the paragraph 12.1.2.1 followed by the exclusions of the ones which do not meet such requirements (see figure 142 and 143).

[384] Federal Emergency Management Agency, FEMA P-646, Guidelines for design of structures for vertical evacuation from tsunamis, 64.

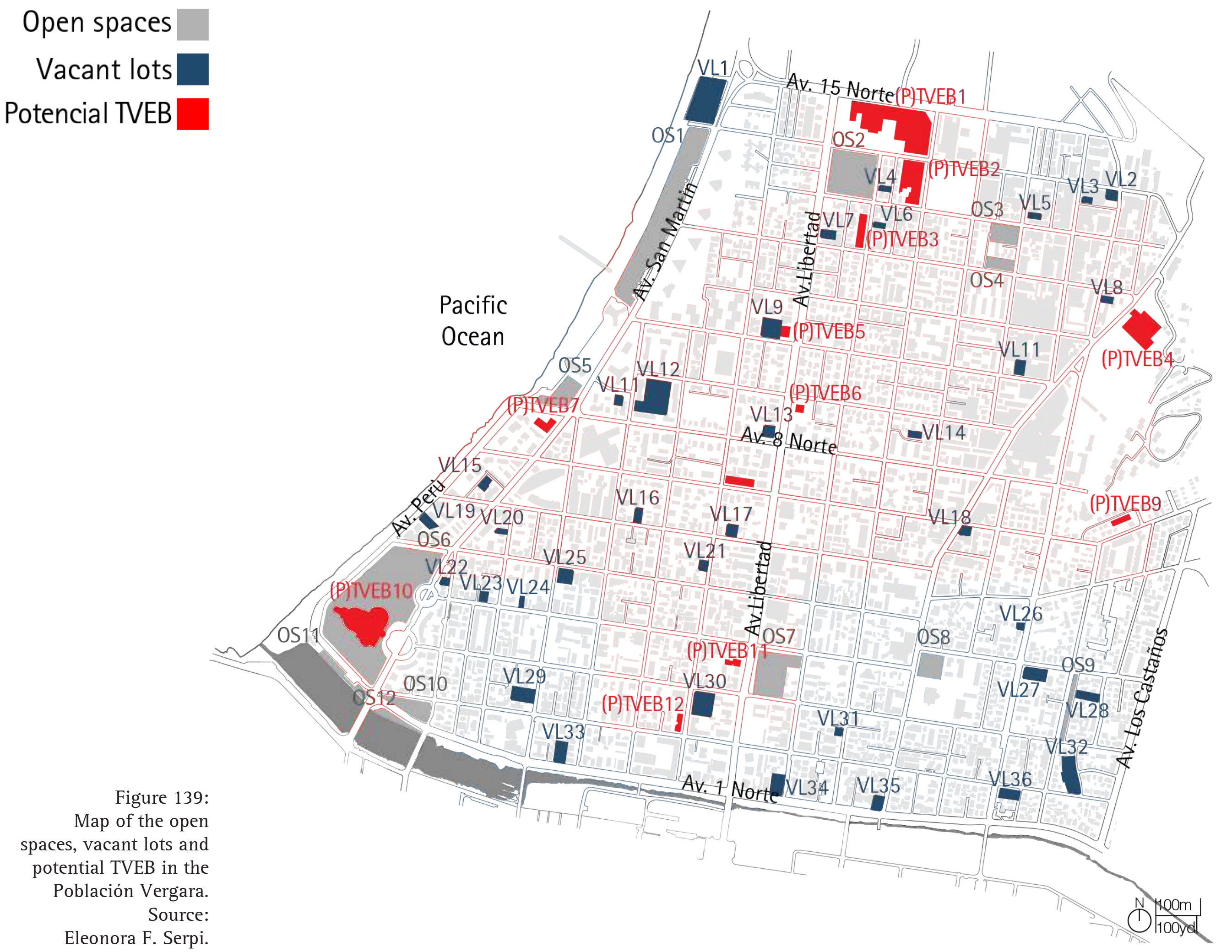


Figure 139:
Map of the open
spaces, vacant lots and
potential TVEB in the
Población Vergara.
Source:
Eleonora F. Serpi.

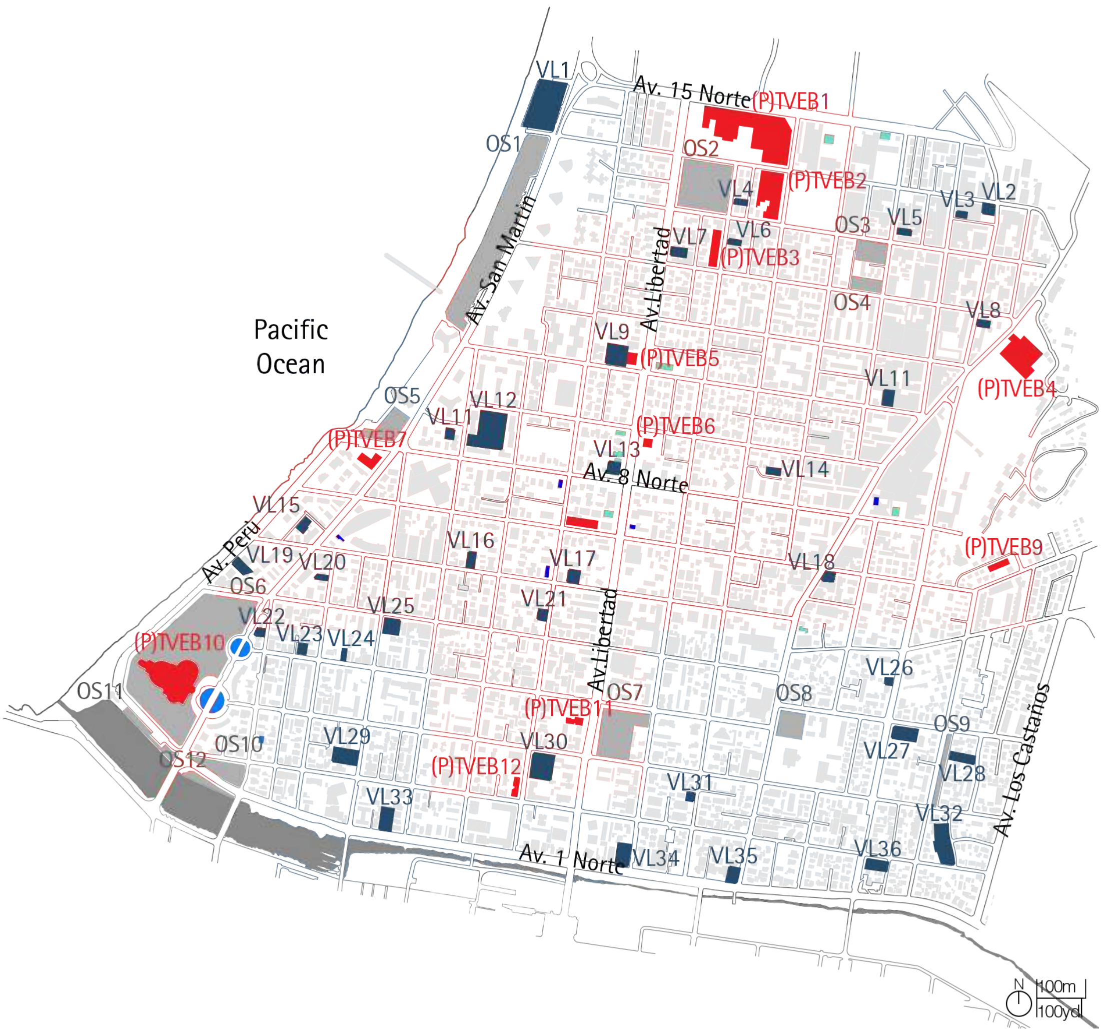


Figure 140:
Map of the TVE sites
and the potential
hazards in the
Población Vergara.
Source:
Eleonora F. Serpi.

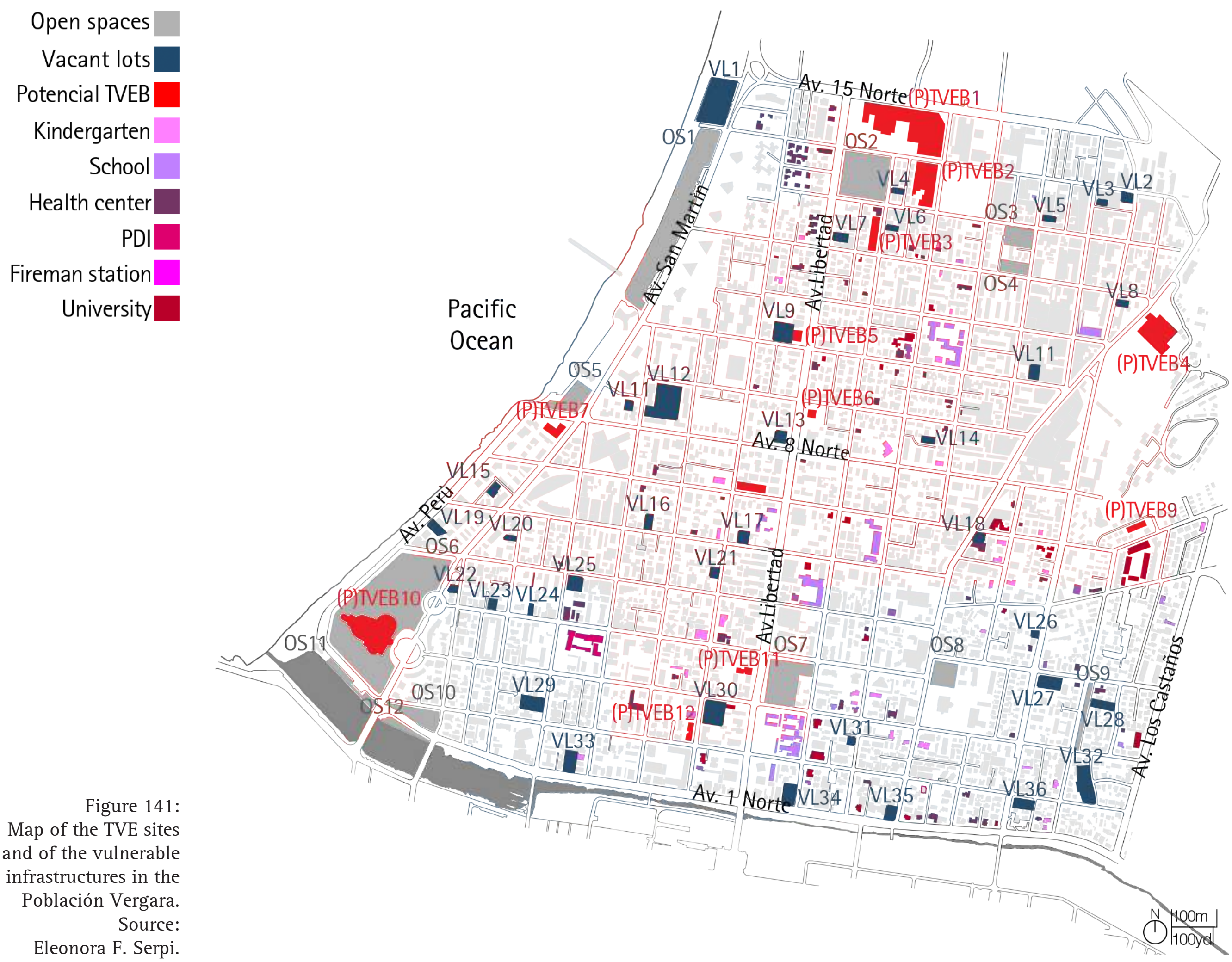


Figure 141:
Map of the TVE sites
and of the vulnerable
infrastructures in the
Población Vergara.
Source:
Eleonora F. Serpi.

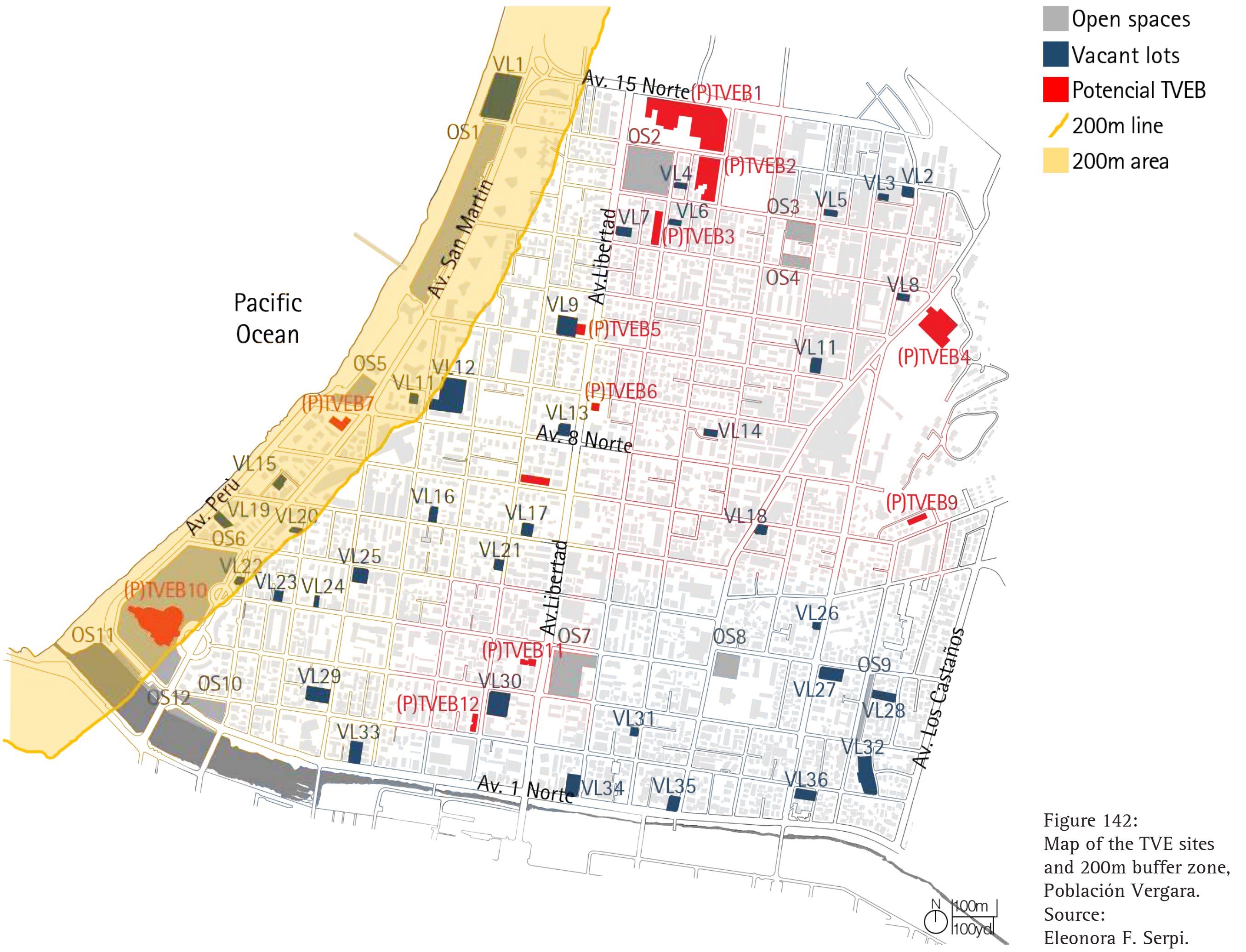


Figure 142:
Map of the TVE sites
and 200m buffer zone,
Población Vergara.
Source:
Eleonora F. Serpi.

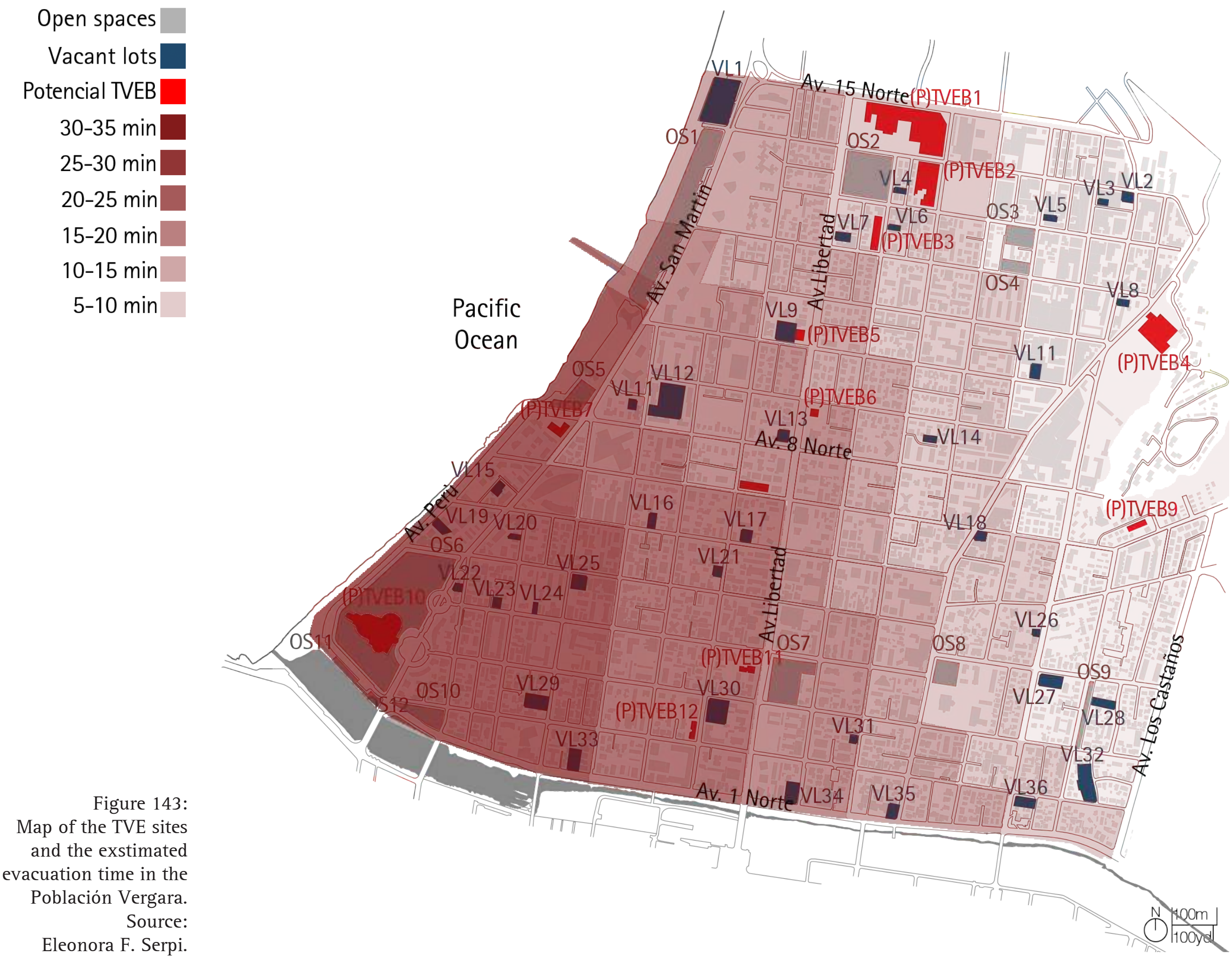


Figure 143:
Map of the TVE sites
and the exstimated
evacuation time in the
Población Vergara.
Source:
Eleonora F. Serpi.

11.1.3.2. Sites assessment

12.1.3.2.1. Open spaces assessment

Among the 12 open spaces (see figure 144) found within the Población Vergara, PS1, OP6 and OP11 were excluded for being located less than 200m away from the coast; OP3, OP4 and OP9 were excluded for being within an evacuation time zone estimated between 5-10 min while PS7 is excluded for being the garden surrounding the historical monument Carrasco Palace. The remaining consolidated public spaces have been evaluated as follow in table 19.

From the evaluation, only OP2, located between Av. Libertad and Av. 3 and 14 Norte, resulted eligible for hosting TVEB (see figure 145).

		OP2	OP8	OP10	OP12
70%	SA 25%	5	5	5	5
	TZ 35%	1	1	5	5
	h 5%	5	5	1	1
	VI 20%	5	2	1	1
	H 30%	5	5	3	3
30%	D 70%	5	2	2	1
	SH 30%	5	5	2	1
	SCORE	4,0	3,0	3,2	2,9

Table 19:
Open spaces
evaluation table.
Source:
Eleonora F. Serpi.

Figure 144:
Map of open spaces in the Población Vergara.
Source:
Eleonora F. Serpi.

Figure 145:
Map of the resulting
spaces in the Población
Vergara.
Source:
Eleonora F. Serpi.

12.1.3.2.2. Vacant lots assessment

Among the 36 vacant lots found within the Población Vergara (see figure 146), VL1, VL11, VL15, VL19, VL20 and VL22 were excluded for being located less than 200m away from the coast; VL2, VL3, VL5, VL8, VL11, VL27, VL28 and VL32 were excluded for being within an evacuation time zone estimated between 5-10 min. The remaining vacant lots have been evaluated as follow in table 20.

From the evaluation, 14 vacant lots have been identified as suitable for hosting new TVEB (see figure 147). The sum of the areas from which it is possible to reach a shelter in less than 8min covers almost the entire Población Vergara but due to the high density of population especially during day time it is necessary to continue evaluating also the potential existing TVEBs to guarantee the minimum footage necessary to evacuate the entire population at risk.

		VL4	VL6	VL7	VL9	VL12	VL13	VL14	VL16
70%	SA 25%	3	2	5	2	3	5	1	2
	TZ 35%	1	1	1	2	3	3	1	4
	h 5%	5	5	5	5	3	5	5	3
	VI 20%	4	5	5	5	2	5	5	4
	H 15%	5	5	5	5	5	2	5	5
20%	D 70%	1	1	2	2	5	2	1	1
	SH 30%	5	5	5	5	5	5	5	5
10%	PGM 20%	5	5	3	3	5	3	5	1
	PPGM 30%	5	5	5	5	5	5	5	5
	Bh_{max} 30%	3	1	3	2	2	3	1	1
	SCORE	3,3	3,2	$\boxed{3,7}$	$\boxed{3,8}$	$\boxed{3,9}$	$\boxed{3,9}$	3,0	3,3

		VL17	VL18	vL20	VL21	VL22	VL23	VL24	VL25
70%	SA 25%	2	5	2	2	3	5	2	3
	TZ 35%	4	1	5	4	5	5	5	5
	h 5%	5	5	3	5	3	3	3	3
	VI 20%	5	5	3	3	3	3	4	5
	H 15%	5	5	3	3	1	3	3	5
20%	D 70%	2	1	1	1	1	1	1	2
	SH 30%	51	5	3	2	5	5	3	5
10%	PGM 20%	1	5	1	5	3	3	3	3
	PPGM 30%	5	5	5	1	5	5	5	5
	Bh_{max} 30%	2	1	1	2	1	1	1	1
	SCORE	3,7	3,7	3,1	2,9	3,3	3,9	3,4	4,2

VL29	VL30	VL31	VL33	VL34	VL35	VL36
2	3	2	4	5	5	5
5	4	3	5	3	2	1
3	5	5	3	3	3	5
3	5	4	5	5	5	5
4	5	5	5	5	5	5
4	4	1	3	3	2	3
5	5	5	5	5	5	5
1	1	3	5	3	3	3
5	5	5	5	5	5	1
1	2	1	3	3	1	1
3,7	4,1	3,3	4,8	4,3	3,8	3,6

Table 20:
Vacant lots
evaluation table.
Source:
Eleonora F. Serpi.

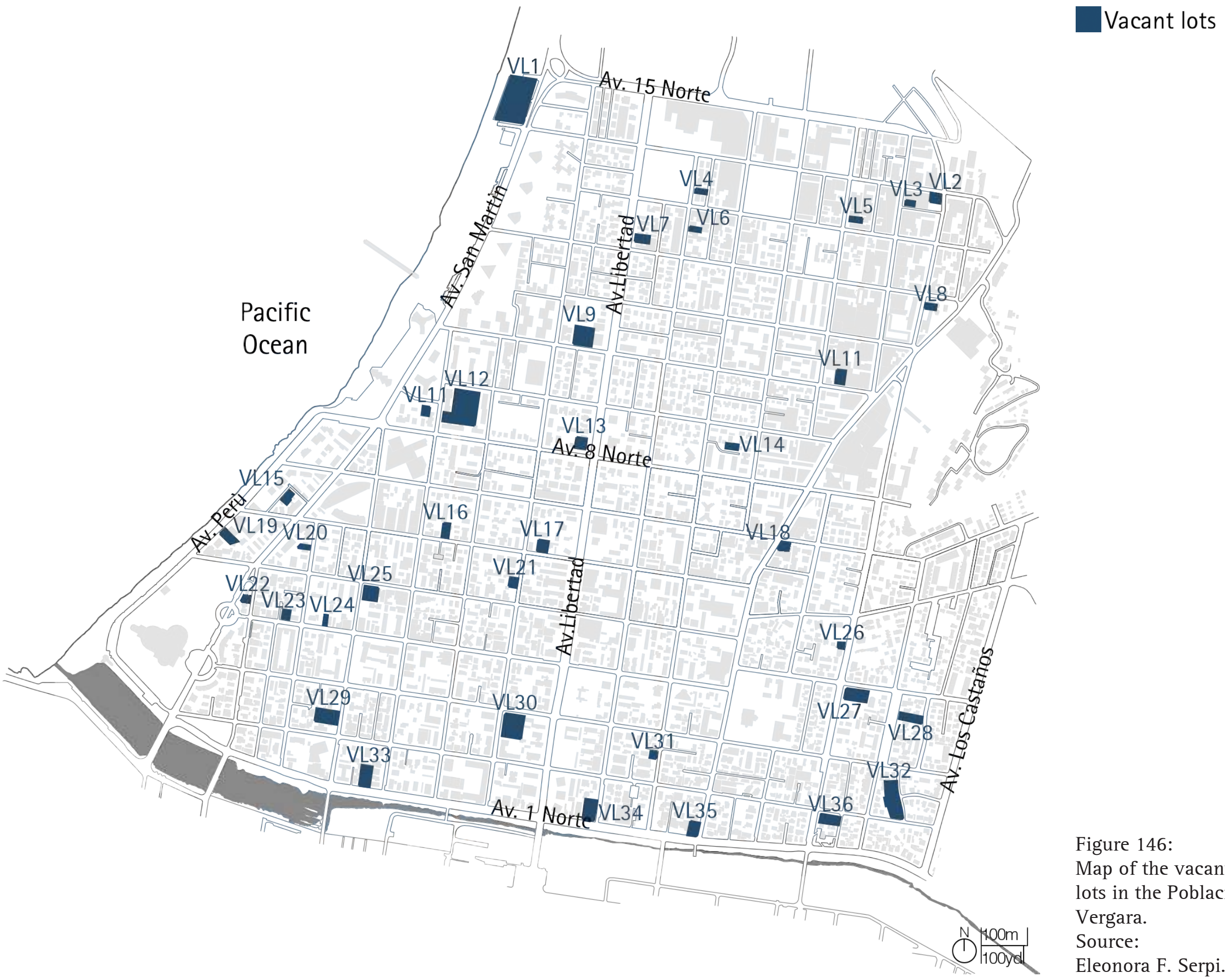


Figure 146:
Map of the vacant lots in the Población Vergara.
Source:
Eleonora F. Serpi.

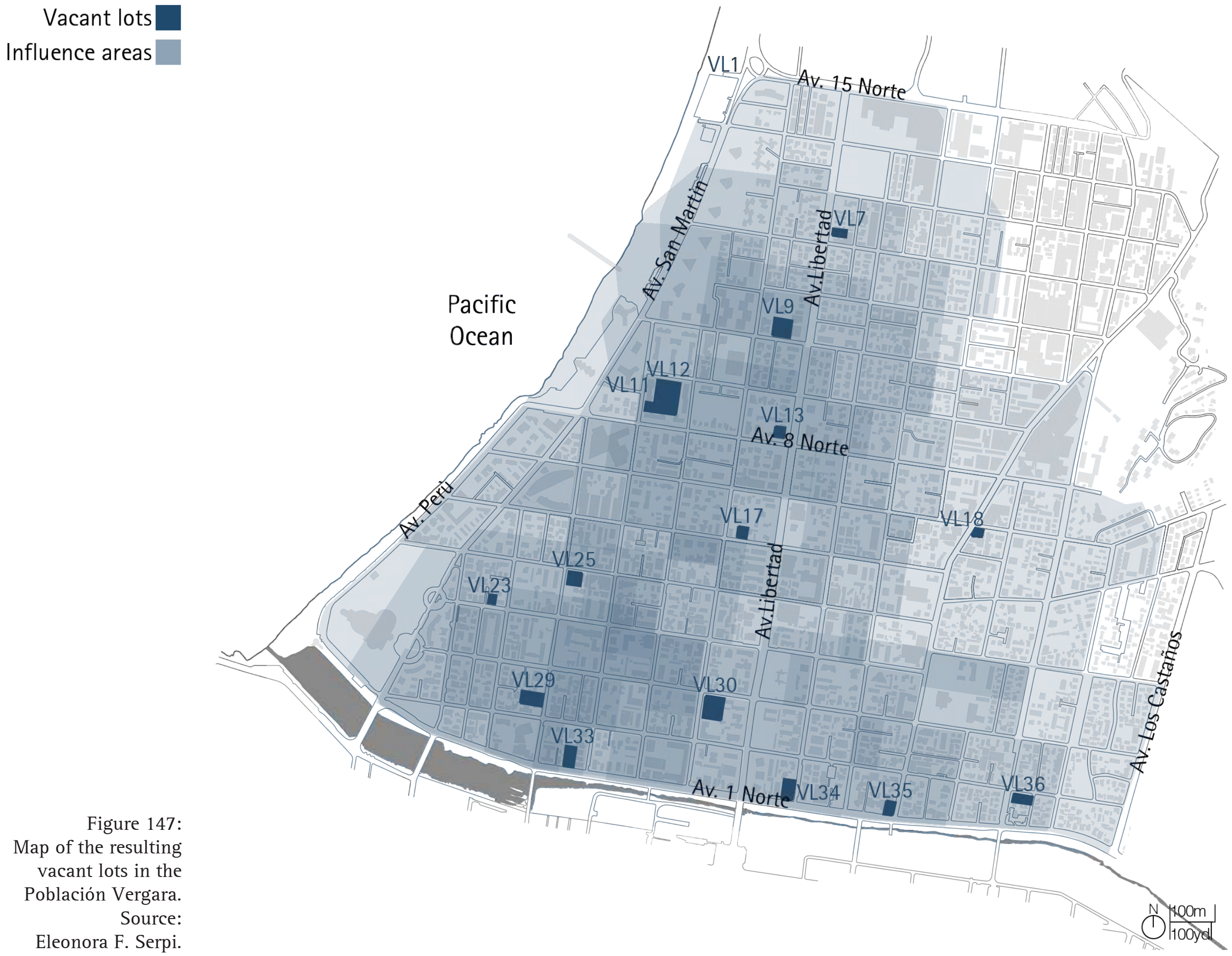


Figure 147:
Map of the resulting
vacant lots in the
Población Vergara.
Source:
Eleonora F. Serpi.

12.1.3.2.3. Potential existing TVEB assessment

Among the 12 buildings that meet the minimum requirements for being considered as potential existing TVEB within the Población Vergara (see figure 148), (P)TVEB7 and (P)TVEB10 are located less than 200m away from the coast and therefore they should be excluded from the evaluation process. Due to the high number of visitors, especially vulnerable population with elders and young children, that daily visit and walk along Av. Perù, the presence of a playground next to the (P)TVEB10, corresponding to the Casino, the two buildings will not be excluded from the evaluation. (P)TVEB4 and (P)TVEB9 were excluded for being within an evacuation time zone estimated between 5-10 min. The remaining potential existing TVEB have been evaluated as reported in table 21.

Most of the eligible (P)TVEB are found along or close to the Av. Libertad, one of the main distributing axes of the Población Vergara (see figure 149) were most of the services are located. This configuartion allows the evacuation of the commuters that daily attend the district for work. The two buildings on the coast (i.e. the Casino and Hotel Enjoy, (P)TVEB10, and the Hotel Atton San Martin, (P)TVEB7), will need to be protected by filters to avoid the direct impact of debris and to mitigate the strength of the waves as the first reach to the shore.

Table 21:
Potentential existing
TVEB evaluation table.
Source:
Eleonora F. Serpi.

		(P)TVEB 1	(P)TVEB 2	(P)TVEB 3	(P)TVEB 5	(P)TVEB 6	(P)TVEB 8	(P)TVEB 11	(P)TVEB 12
40%	SA 30%	5	3	3	5	5	5	5	1
	TZ 50%	1	1	1	2	3	3	4	4
	VI 20%	5	4	5	4	3	5	4	5
30%	RVI 70%	5	5	5	5	5	5	5	5
	PGM 30%	5	5	3	3	3	3	3	3
20%	C 60%	5	4	5	5	3	5	5	3
	EP 40%	1	1	1	1	1	3	3	5
10%	SW 30%	1	2	2	2	1	4	5	2
	CW 30%	2	2	2	2	2	3	3	2
	DD 15%	5	3	3	5	5	5	5	5
	RT 25%	5	3	3	3	3	5	3	5
	SCORE	3,7	3,2	3,2	3,6	3,4	4,2	4,3	4,0

Figure 148:
Map of the potential existing TVEB in the Población Vergara.
Source:
Eleonora F. Serpi.

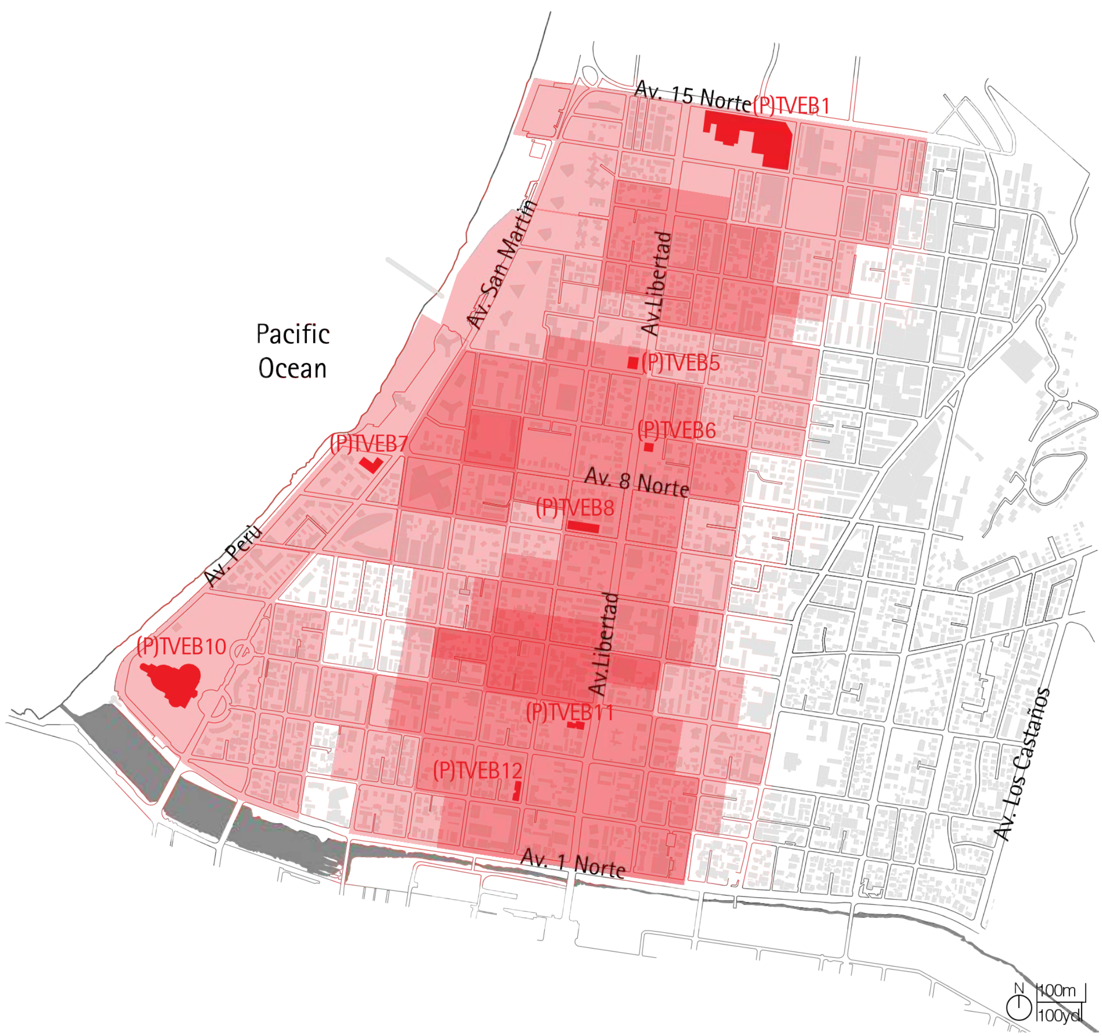


Figure 149:
Map of the resulting potential existing TVEB in the Población Vergara.
Source:
Eleonora F. Serpi.

12.1.3.3. Results

The evaluation highlighted 23 potential sites, that include 1 consolidated public space corresponding to Plaza O'Higgins, 14 vacant lots spread through the district and 8 existing potential TVEB mostly located in the proximity or along Av. Libertad with exception of the Casino and the Hotel Miramar located between Av. Perù and Av. San Martin. Analyzing the influence areas (see figure 150) of each site, corresponding to the area within which evacuees can reach a shelter in less than 8 min, at walking speed of 1,22m/s, superposed to the inundation level corresponding to the event of 1730 used as reference for the inundation map elaborated by the SHOA[384] and to the estimated evacuation time zones (see figure 151), it is proven that the system has a complete coverage of the area that cannot be evacuated with the existing horizontal evacuation plan. The area has proven to be covered, the next step will be the design of the evacuation system composed of 8 existing buildings to be retrofitted to become TVEB and 15 prototypes of TVEB in order to establish whether the system can shelter the entirety of the population at risk found within this area.

[384] Chilean Navy Hydrographic and Oceanographic Center, "Cartas de Inundación por Tsunami (CITSU). Valparaíso - Viña del Mar."

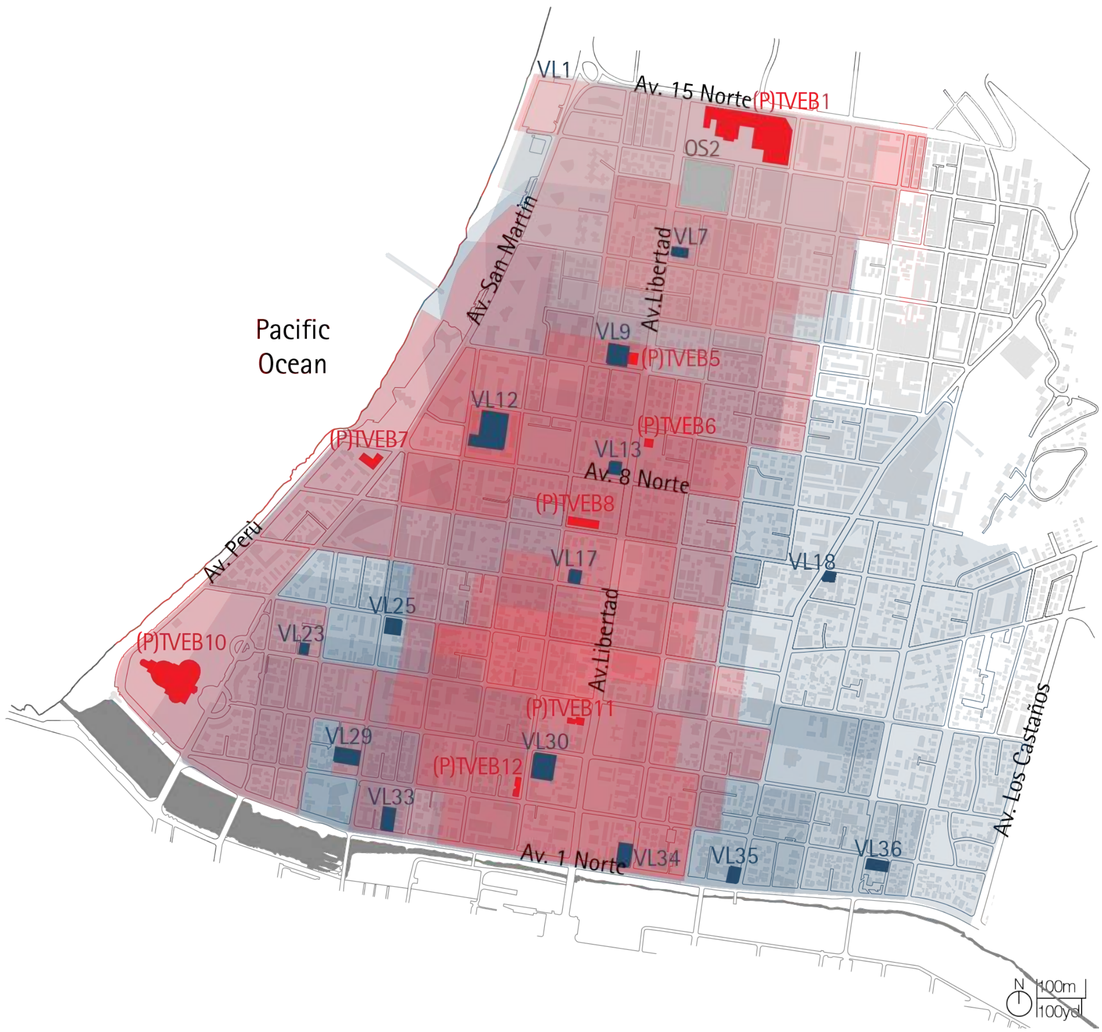


Figure 150:
Map of all the resulting sites with their influence area.
Source:
Eleonora F. Serpi.

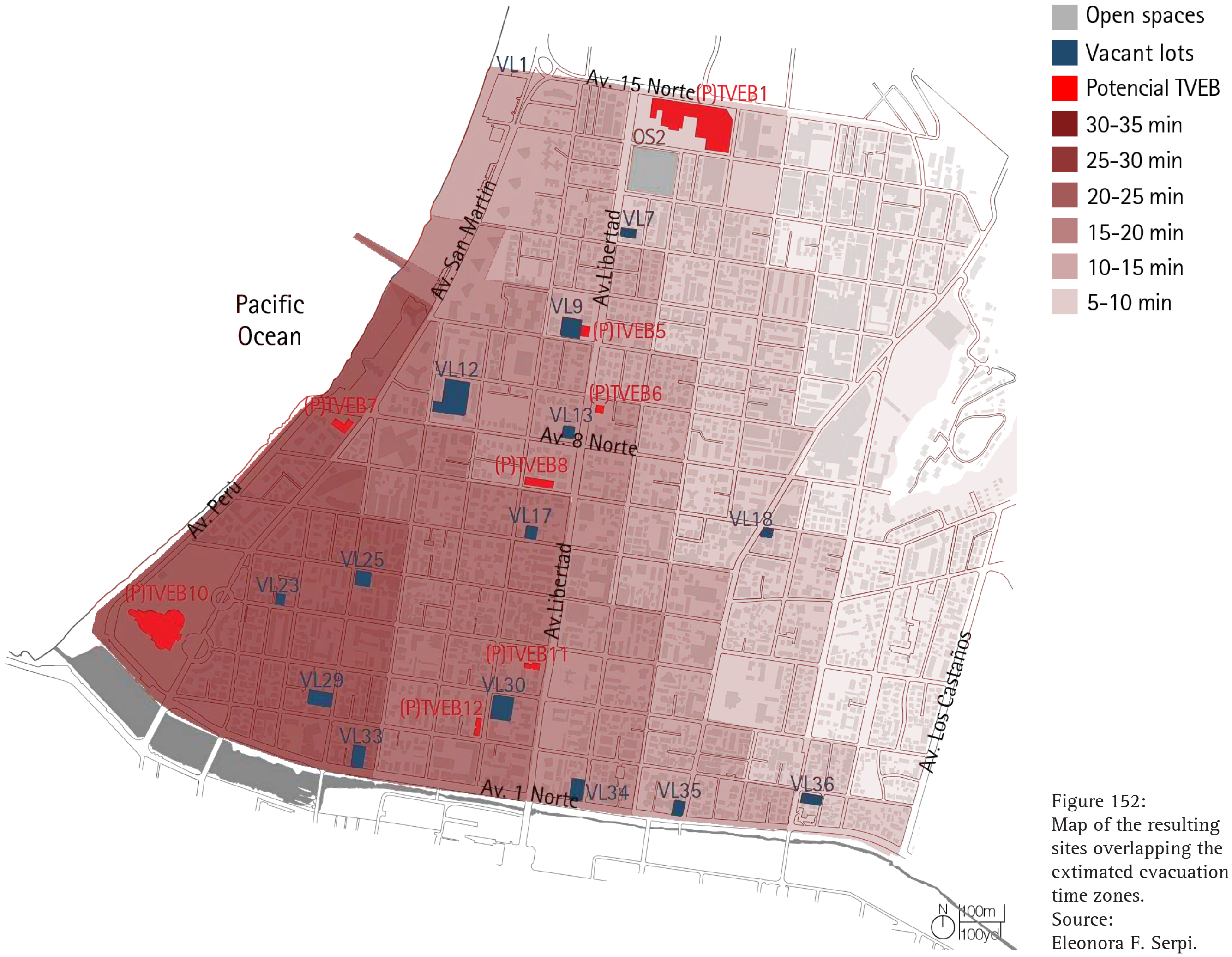


Figure 152:
Map of the resulting sites overlapping the extimated evacuation time zones.
Source:
Eleonora F. Serpi.

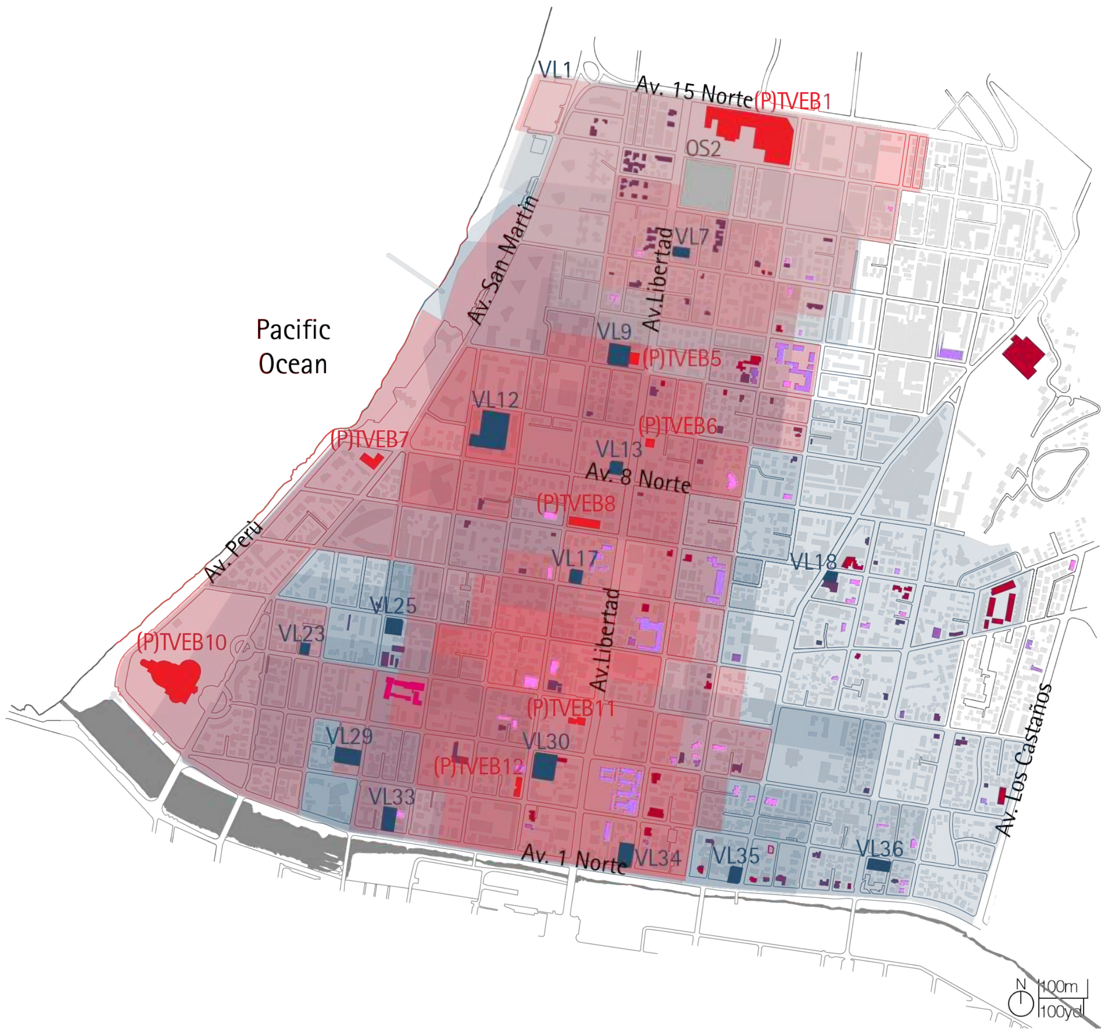


Figure 153:
Map of the vulnerable infrastructures overlapping the resulting sites' influence area.
Source:
Eleonora F. Serpi.

11.2. Tsunami Vertical Evacuation Buildings (TVEBs)

The new Tsunami Vertical Evacuation System will be composed of 23 TVEBs (see figure 154), 8 of which correspond to existing buildings (P)TVEB and 15 of them will be explored through the help of prototypes highlighting the access to the structure and the evacuation path inside the building up to the security level where the shelter will be located.

Figure 154:
Map of the (P)TVEB and of the TEVEB prototypes in the Población Vergara.
Source:
Eleonora F. Serpi.

11.2.1. Existing potential TVEB

11.2.1. 1. Retrofit guidelines

The assessment model for TVES's potential sites, positively evaluated 8 of the 12 potential existing TVEBs individuated during the on-field survey of the Población Vergara (see figure 155-162). During the evaluation process, the physical vulnerability of the buildings has been assessed through the PTVA-4 model[385] which considered different parameters such as numbers of floors, structural material, shape and orientation, plan typology, foundations, presence or absence of mitigation barriers and construction year of the building establishing the Relative Vulnerability Index (RVI) for each one of them. All the buildings resulted having a 'minor' RVI which makes them great candidates to be retrofitted as TVEB.

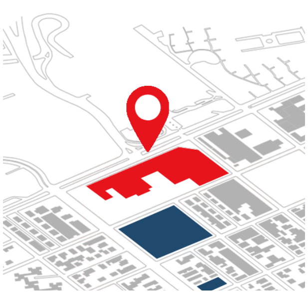
After carrying out more accurate structural studies to establish the real resistance of the building to tsunami loads, the retrofitting of the buildings should focus on the roof system, wall system, access and protection from potential waterborne debris. The rooftop of the buildings which are not accessible will need to be upgraded to support additional live loads generated by the refuge occupancy. Protective barrier, such parapets, will have to be installed to prevent falls and if the roof hosts mechanical equipment they should be relocated on other levels or protected. The access and the internal vertical circulation should be improved with new wide ramps and stairs to allow an easy and rapid circulation to the safe levels of the building.

At the lower levels, subjected to inundation, the wall system should be modified to perform as breakaway walls, limiting the tsunami hydrostatic, hydrodynamic, and surge forces on the building. If the building host functions that might become potential water-borne debris, these functions should be relocated to higher levels or removed. Finally, protective measures should be taken, like the construction of mitigation barriers, in order to protect the structure from waterborne debris and mitigate the strength of the waves, especially for the buildings located close to shore where the impact of the wave will be stronger and debris from the ocean could reach the shore.

[385] F. Dall'Osso, et al., 1229-1256.

(P)TVEB 1: Mall Marina Arauco

Figure 155:
Mall Marina Arauco,
2018.
Source:
Eleonora F. Serpi.



1348, Av. Libertad

10000 people

(P)TVEB 2: Office building Alicahue

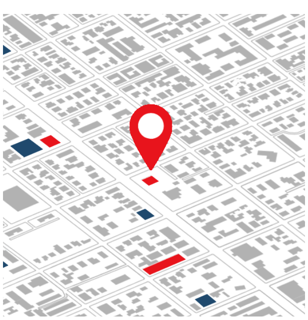
Figure 156: Office building Alicahue, 2018. Source: Eleonora F. Serpi.

Corner Av. Libertad and 10 Norte

1000 people

(P)TVEB 3: Office building Libertad

Figure 157:
Office building
Libertad, 2018.
Source:
Eleonora F. Serpi.



Corner Av. Libertad and 9 Norte

700 people

(P)TVEB 4: Office building Centro Libertad

Figure 158:
Office building
Centro Libertad, 2018.
Source:
Eleonora F. Serpi.

Corner Av. 7 Norte and 1 Poniente

2000 people

(P)TVEB 5: Hotel Atton San Martin

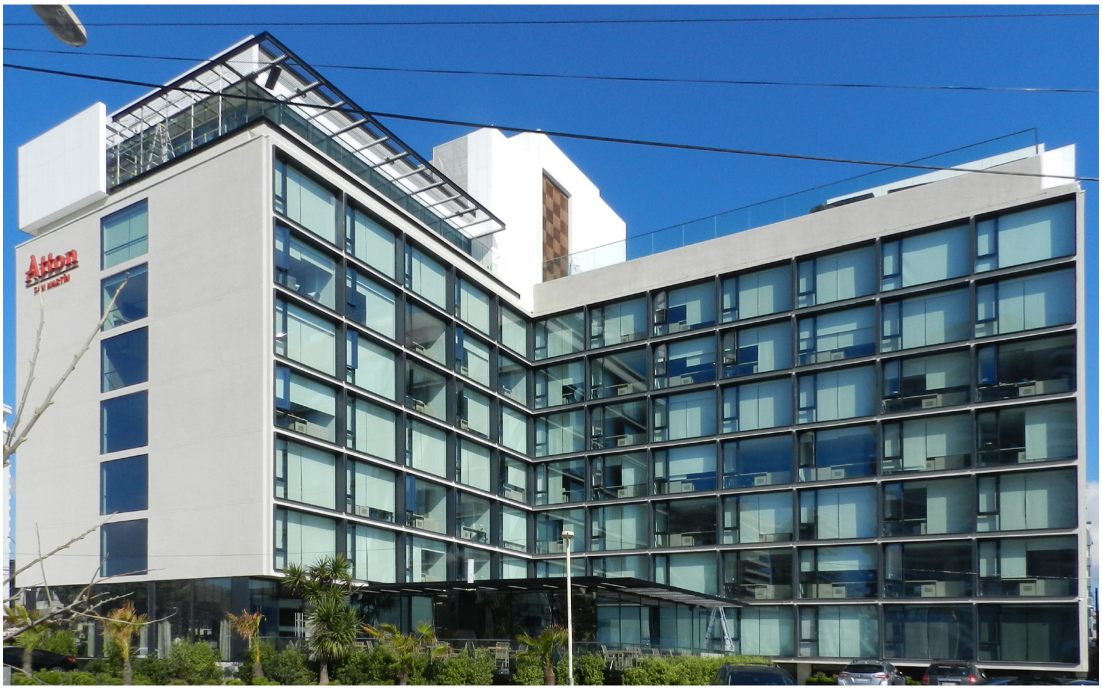


Figure 159:
Hotel Atton
San Martin, 2018.
Source:
Eleonora F. Serpi.

Corner Av. San Martín and 8 Norte

1000 people

(P)TVEB 6: Casino and Hotel Enjoy

Figure 160: Casino and Hotel Enjoy, 2018. Source: Eleonora F. Serpi.

1348, Av. Libertad

3000 people

(P)TVEB 7: Bci Bank office building

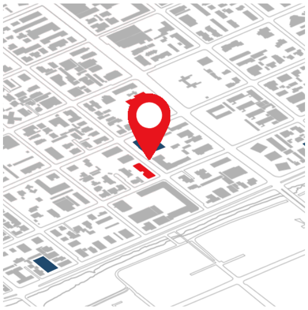
Figure 161:
Bci Bank office building,
2018.
Source:
Eleonora F. Serpi.

705, Av. Libertad

800 people

(P)TVEB 8: Office building Piedra Azul

Figure 162: Office building Piedra Azul, 2018. Source: Eleonora F. Serpi.



Corner Av. 2 Norte with 1 Poniente

800 people

11.2.2. Designing TVEBs

The design phase has the purpose to understand the forms that are the most suitable to host the new infrastructure which combines both an everyday program with and emergency vertical evacuation plan.

11.2.2.1. TVEB Prototype #0

The shape of the structure is strongly linked to the vertical evacuation function, combining elements that guarantee easy access from the outside to the inside and rapid circulation from the ground floor to the upper security levels, proposing an evacuation direction opposite to the common one, in case of fire.

A first phase of brainstorming led to the design of a TVEB prototype #0 (see figure 163) that summarizes the main characteristics that a building must have to guarantee a safe and rapid vertical evacuation:

- universal access and free from obstructions;
- pedestrian access ramp that leads to the security levels;
- open plan at the floodable floors for limiting the tsunami hydrostatic, hydrodynamic, and surge forces on the building;
- circular structures to reduce water friction;
- emergency stairs leading to the rooftop;
- access to the ramp and stairs easily visible and recognizable from the road.

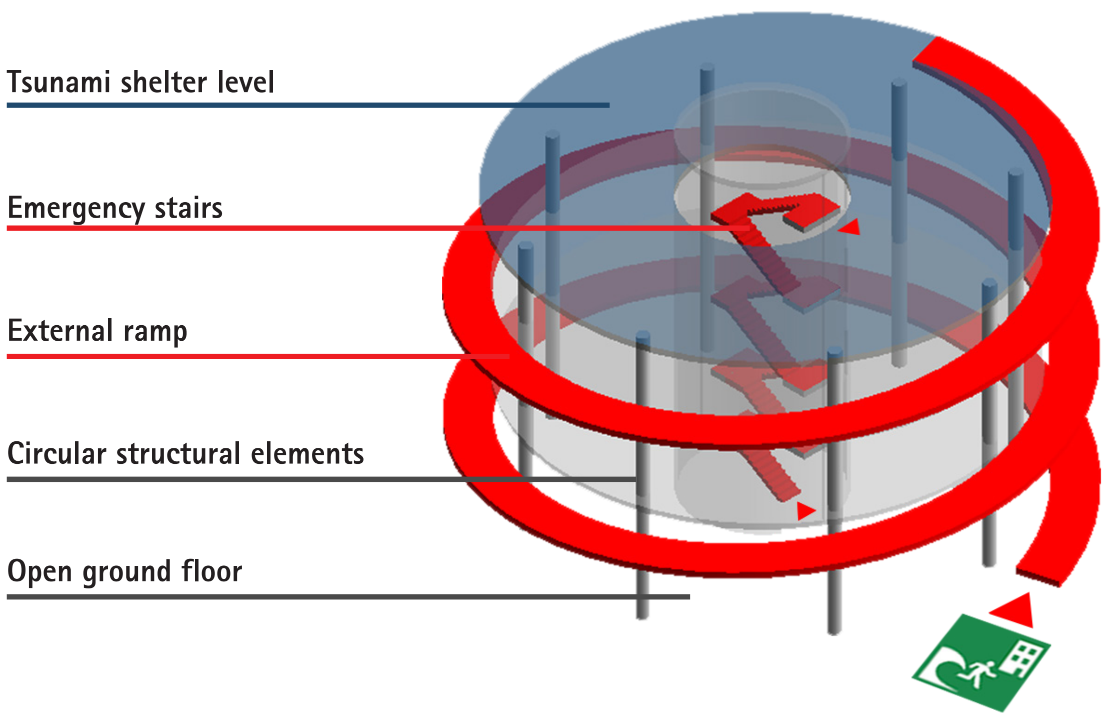


Figure 163:
Concept prototype #0
Source:
Eleonora F. Serpi.

11.2.2.2. TVEBs program

A TVEB will not serve as evacuation structure for the 99.9% of its design life, but it must guarantee the functioning of the evacuation system throughout the time. Therefore, each TVEB must have an associated program to allow a return of investment for owners and/or operators, and to ensure the periodic maintenance of the structure. Moreover, it rapresents an oppurtunity to provide new services for the community while serving as tsunami risk-awareness tools. The program associated to each TVEB prototype (see figure 164) is the result of a careful survey of the Población Vergara, and analysis of the city PRC.

Figure 164:
TVEB associated
program.
Source:
Eleonora F. Serpi.

11.2.2.3. TVEB prototypes

The prototype, once inserted into the lots chosen with the previously presented site assessment model, has been adapted according to the associated program established for each site and according to its characteristics. Contrary to the program, which originates from the need of integrating the structures in the city, creating continuity, the shape is born from a purely functional need and wants to differentiate from the other buildings to create a break, facilitating their recognition within the urban fabric.

The height of the first safe level of each TVEB prototype is calculated considering the estimation of uncertainty of the tsunami runup height shown in the inundation map of the city[385], allowing a freeboard for possible splash-up during the waves' impact, and to create a gap from the inundation to reduce the panic of evacuees sheltered in the structure. To account for this uncertainty, FEMA[386] suggests to increase the maximum tsunami runup elevation of 30% with respect to the values reported by tsunami inundation maps and the first safe level has ben been placed 3m (10 feet) above it:

$$H_{min} = Rmax + (Rmax \cdot 0{,}30) + 3m$$

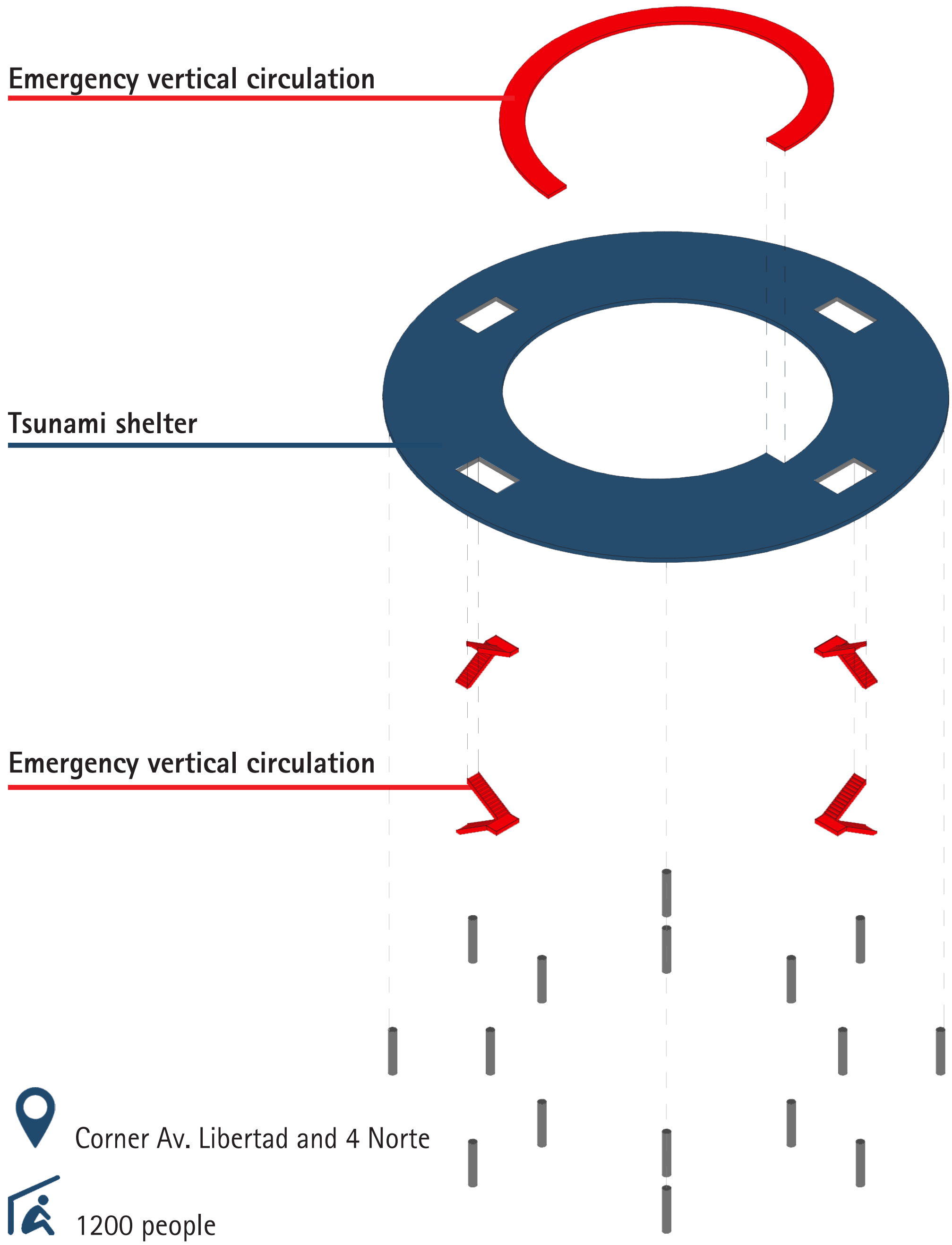
In case of a tsunami alert, these structures will receive a large number of people that need to simultaneously seek shelter above the inundation height. To speed up the circulation process, the traditional methods of entrance and vertical circulation within the buildings, stairs and elevators, are combined with ramps. Ramps can allow evacuees people to rapidly and safely move up towards the upper levels of the TVEB reducing also the probability of accidents caused by tripping over the steps. The ramp also allows disabled users to autonomously move within the structure, even if, very likely, in the case of an emergency they will need to be assisted to not slow down the

[385] Chilean Navy Hydrographic and Oceanographic Center, "Cartas de Inundación por Tsunami (CITSU). Valparaíso - Viña del Mar."

[286] Federal Emergency Management Agency, *FEMA P-646, Guidelines for design of structures for vertical evacuation from tsunamis*, 68.

evacuation process. More specifically, helicoidal ramps represents the best solution guaranteeing the continuity of the flux of people which would be slowed down by the angular landing of traditional linear ramps.

SHELTER 1: The market



Corner Av. Libertad and 4 Norte

1200 people

Figure 165:
Exploded axonometry
Source:
Eleonora F. Serpi.

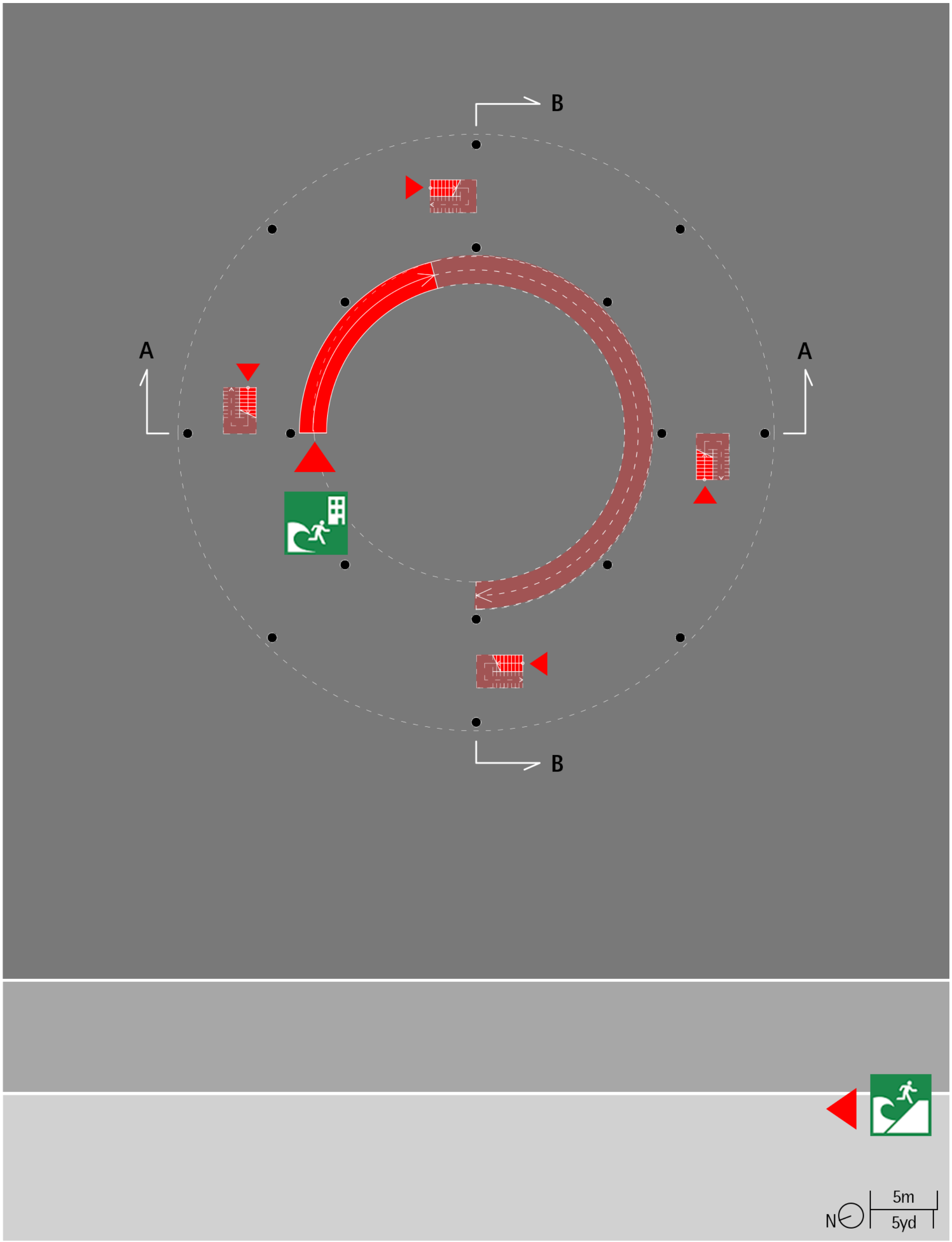
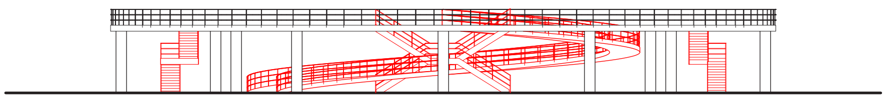
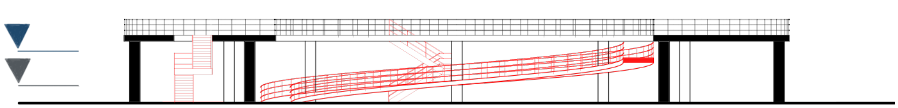


Figure 166:
Groundfloor plan
Source:
Eleonora F. Serpi.



Scale 1:500

Figure 167:
West elevation
Source:
Eleonora F. Serpi.



Scale 1:500

Figure 168:
Cut AA
Source:
Eleonora F. Serpi.

Figure 169:
North elevation
Source:
Eleonora F. Serpi.

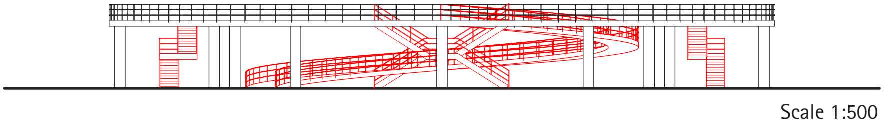
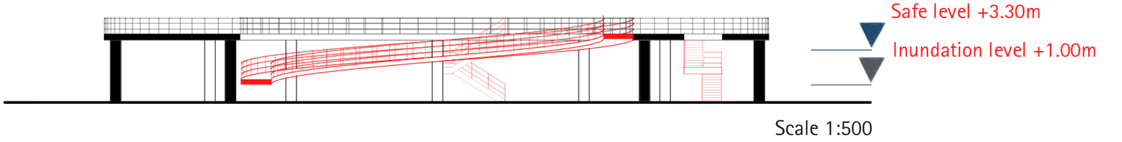
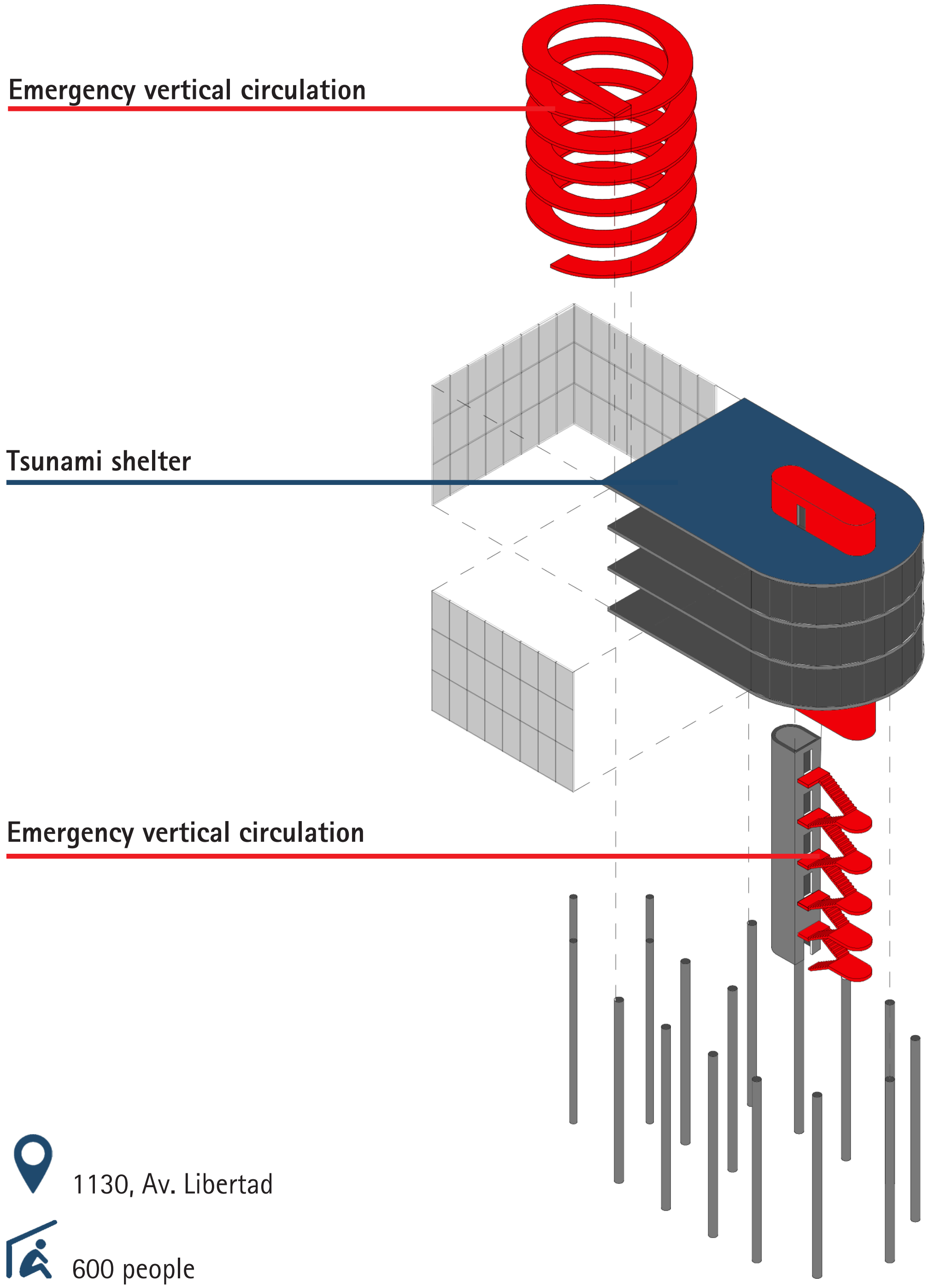
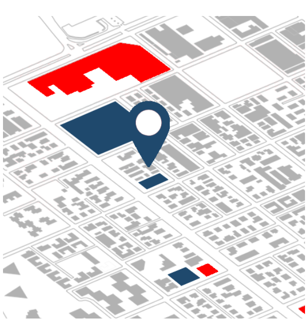


Figure 170:
Cut BB
Source:
Eleonora F. Serpi.



SHELTER 2: The studyroom





1130, Av. Libertad

600 people

Figure 171:
Exploded axonometry
Source:
Eleonora F. Serpi.

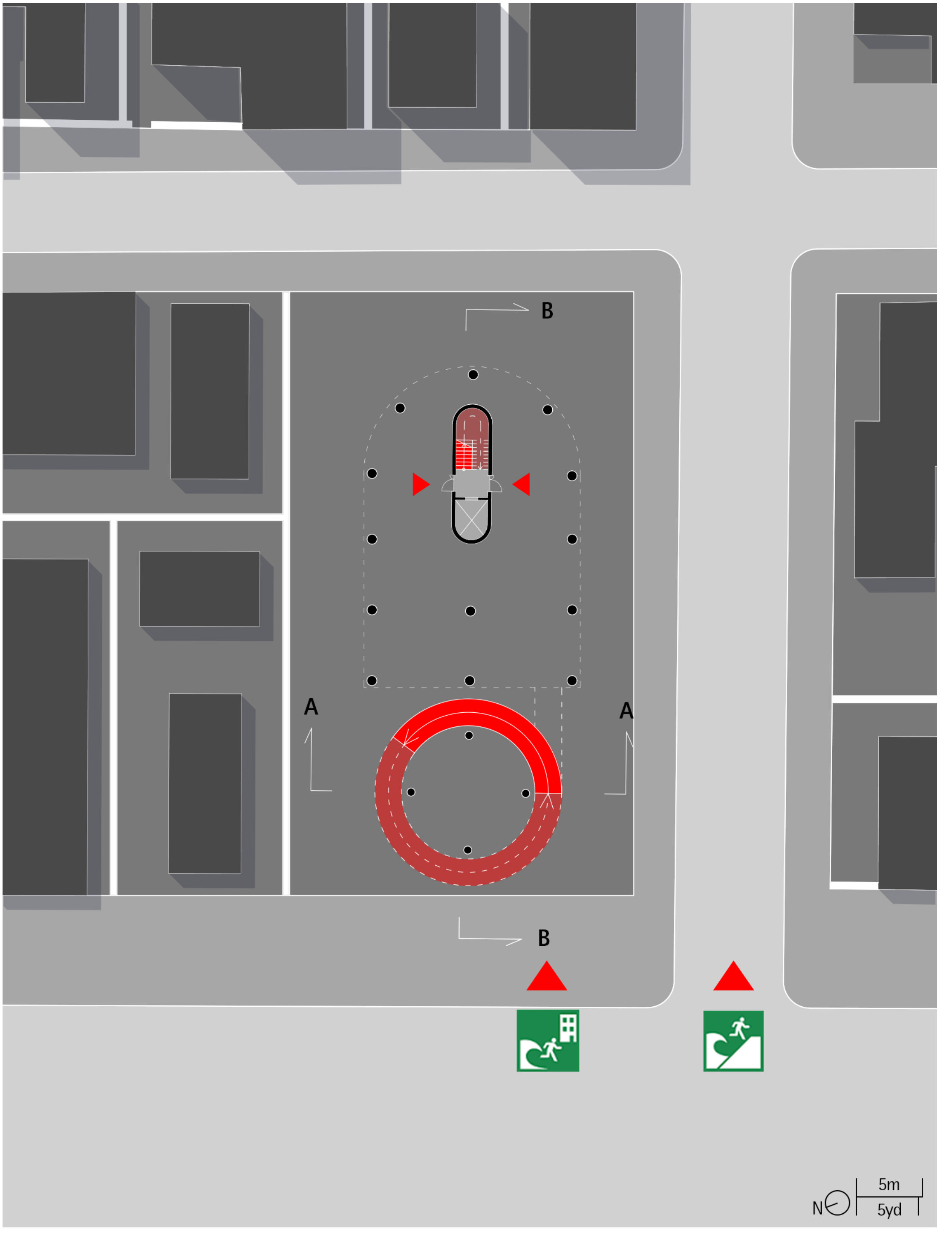
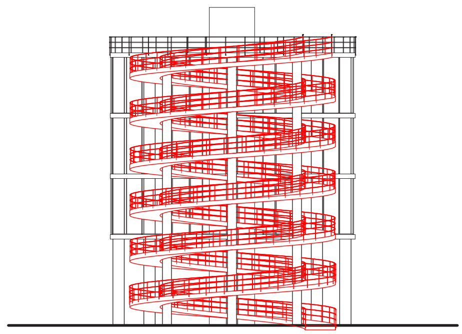
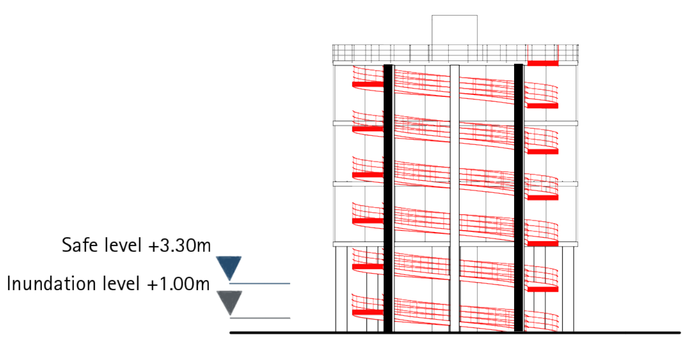


Figure 172:
Groundfloor plan
Source:
Eleonora F. Serpi.



Scale 1:500

Figure 173:
West elevation
Source:
Eleonora F. Serpi.



Scale 1:500

Figure 174:
Cut AA
Source:
Eleonora F. Serpi.

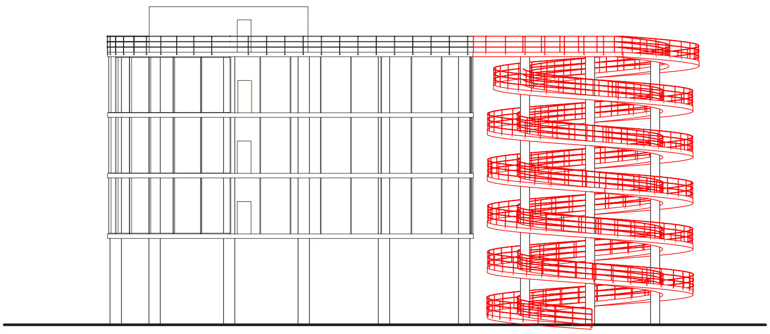


Figure 175:
North elevation
Source:
Eleonora F. Serpi.

Scale 1:500

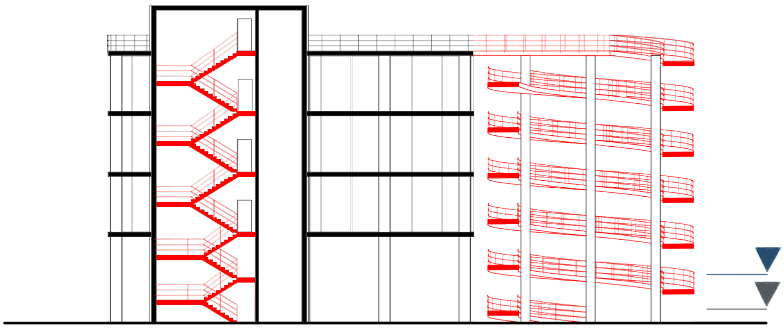
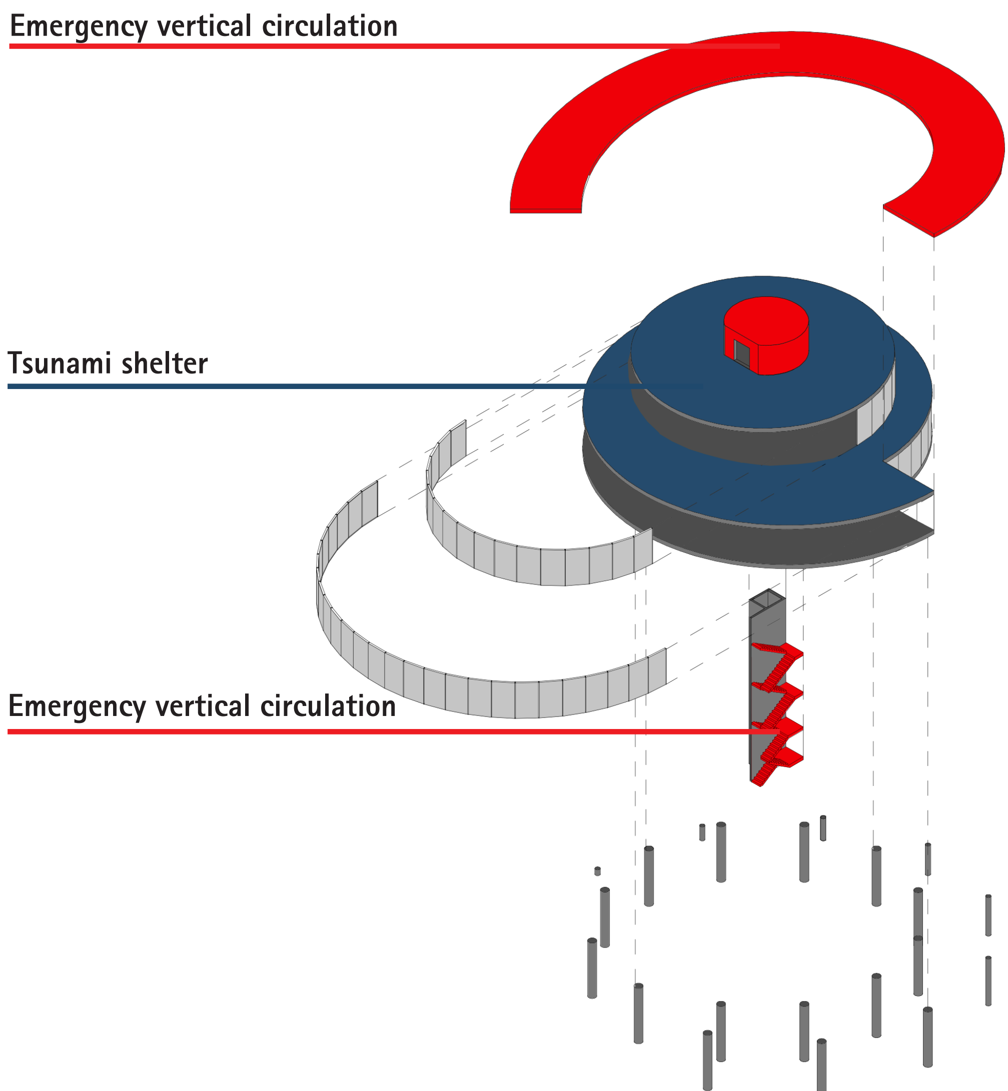


Figure 176:
Cut BB
Source:
Eleonora F. Serpi.

Scale 1:500

SHELTER 3: The gym



665, Av. 10 Norte

900 people

Figure 177:
Exploded axonometry
Source:
Eleonora F. Serpi.

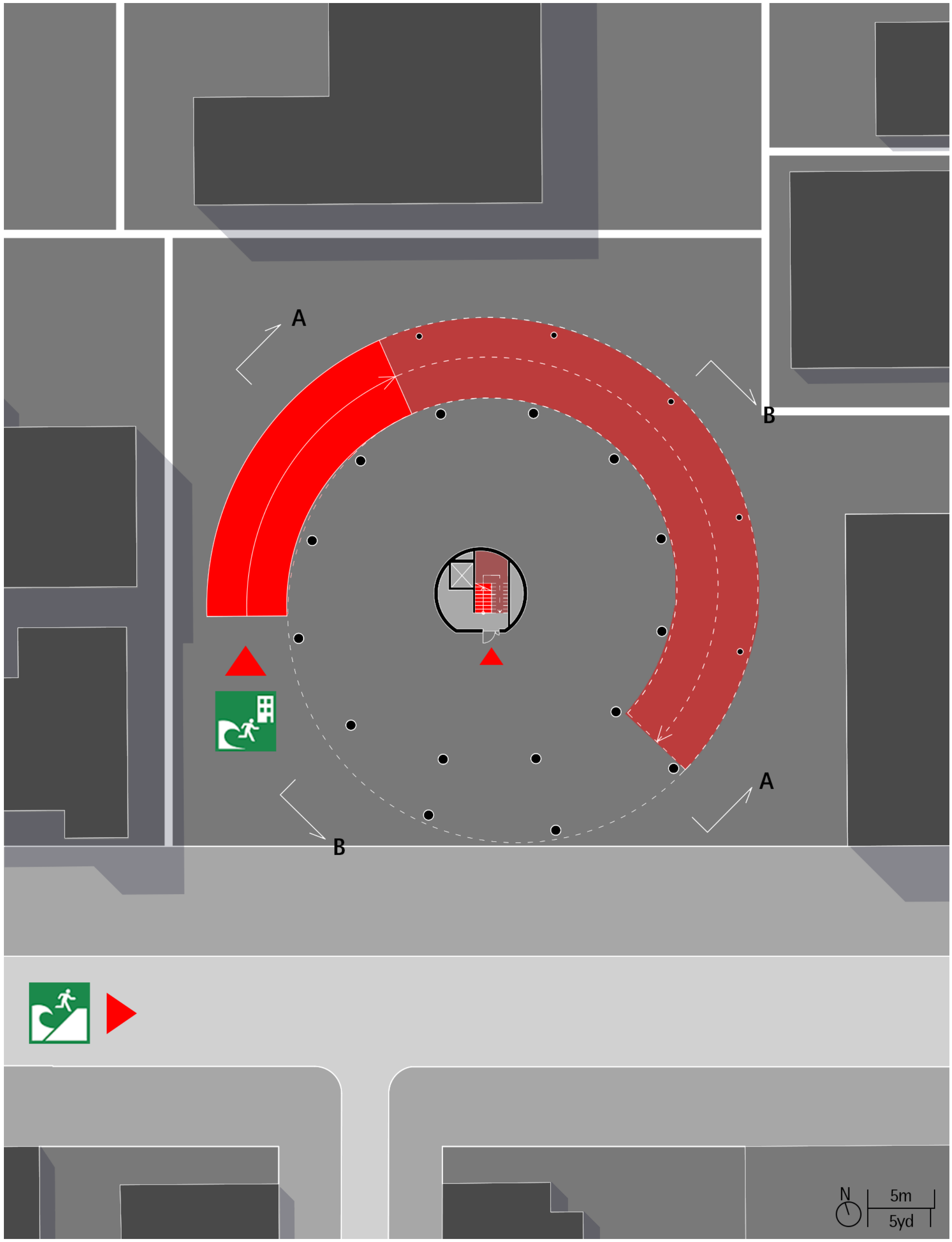


Figure 178:
Groundfloor plan
Source:
Eleonora F. Serpi.

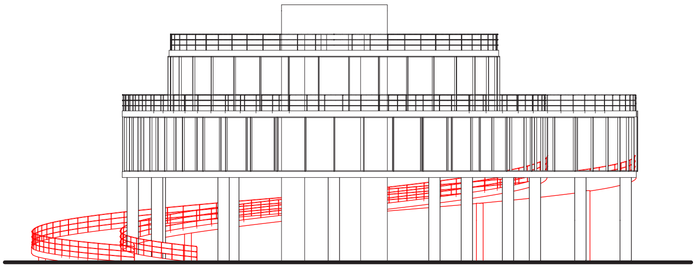


Figure 179:
South elevation
Source:
Eleonora F. Serpi.

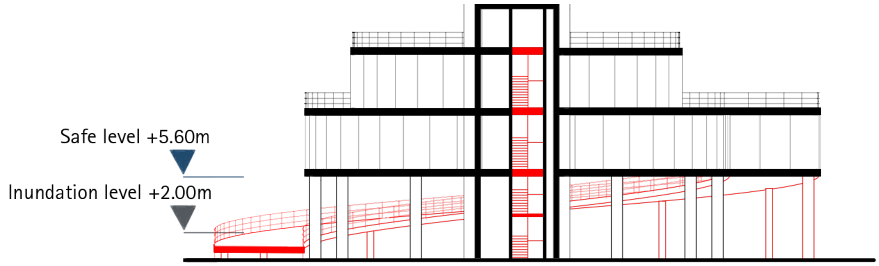


Figure 180:
Cut AA
Source:
Eleonora F. Serpi.

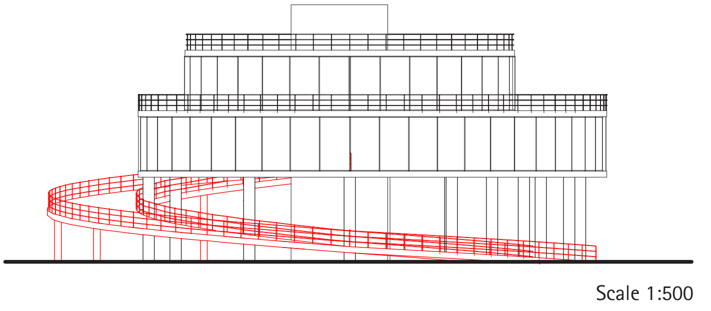


Figure 181:
West elevation
Source:
Eleonora F. Serpi.

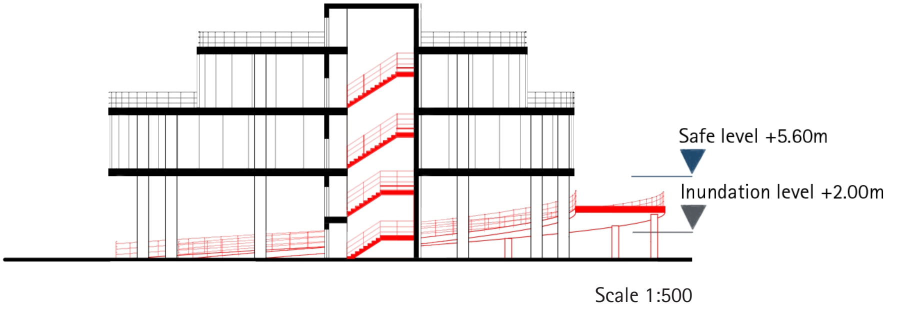
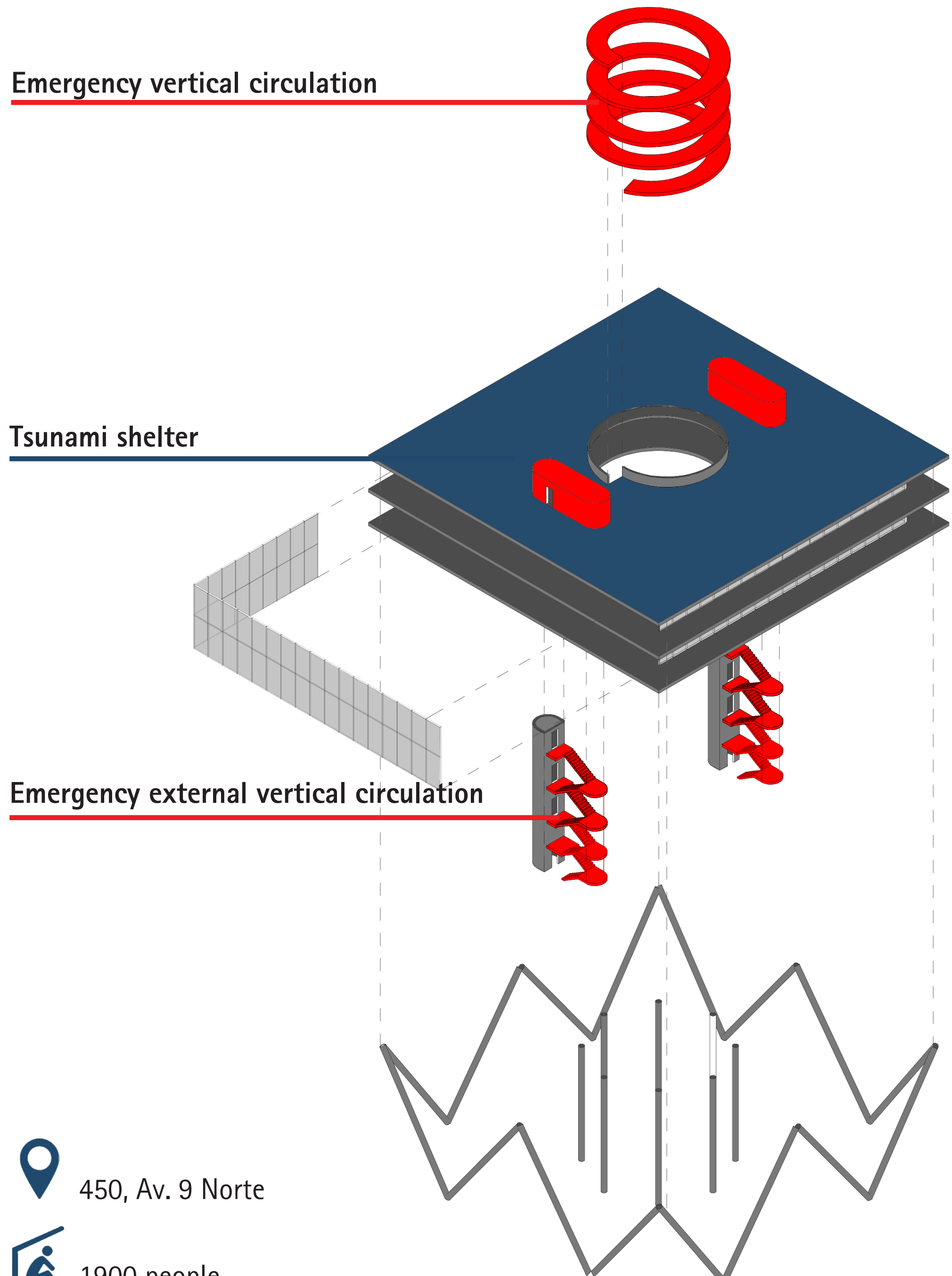


Figure 182:
Cut BB
Source:
Eleonora F. Serpi.

SHELTER 4: The atelier



450, Av. 9 Norte

1900 people

Figure 183:
Exploded axonometry
Source:
Eleonora F. Serpi.

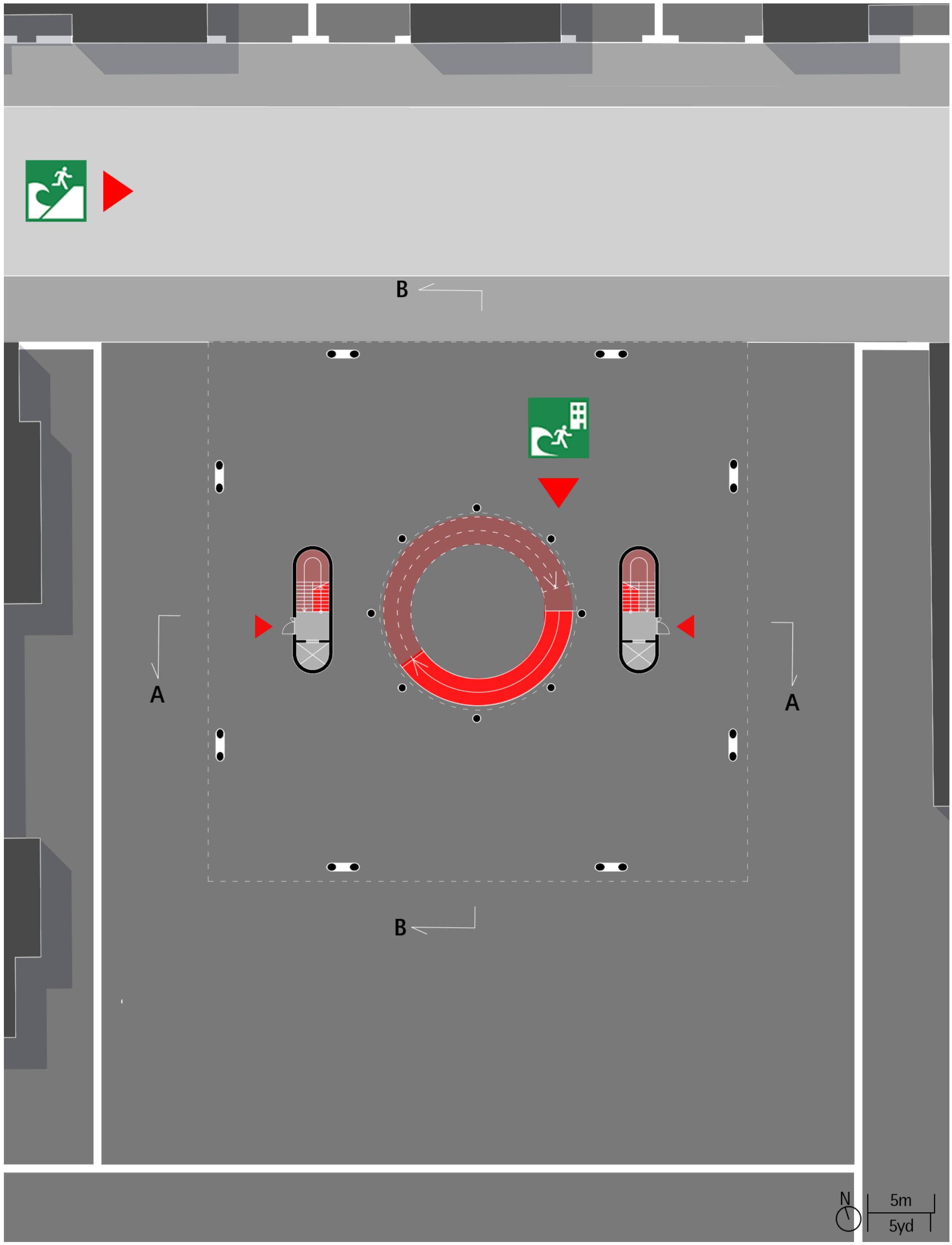


Figure 184:
Groundfloor plan
Source:
Eleonora F. Serpi.

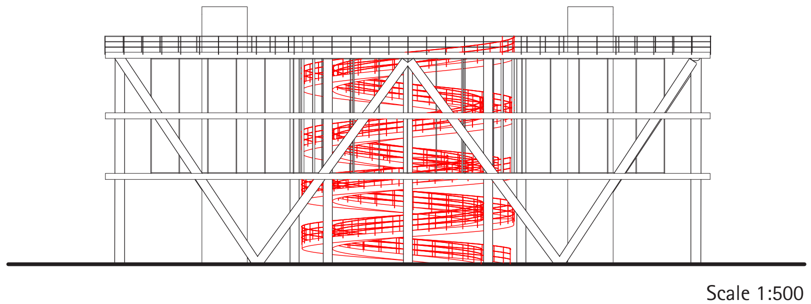


Figure 185:
North elevation
Source:
Eleonora F. Serpi.

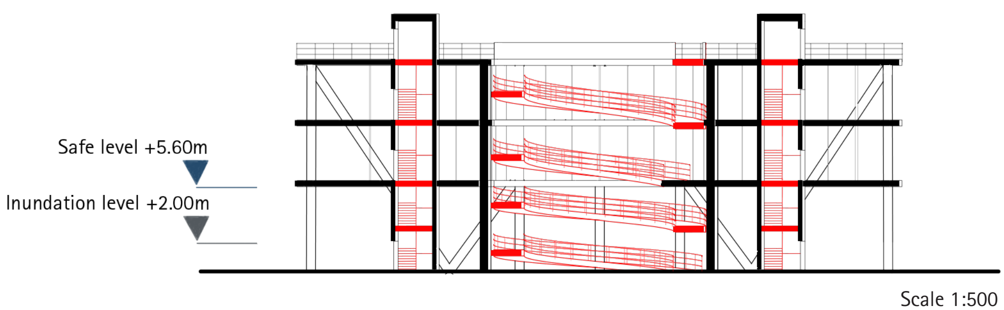


Figure 186:
Cut AA
Source:
Eleonora F. Serpi.

Figure 187:
West elevation
Source:
Eleonora F. Serpi.

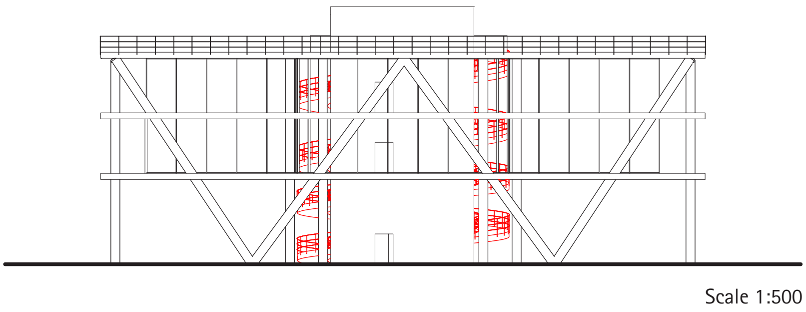
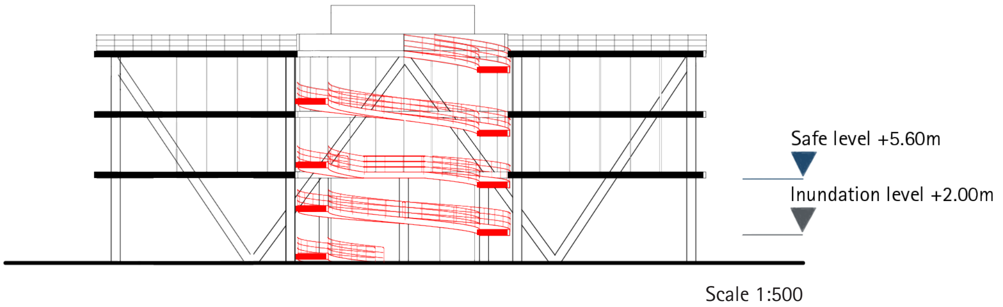
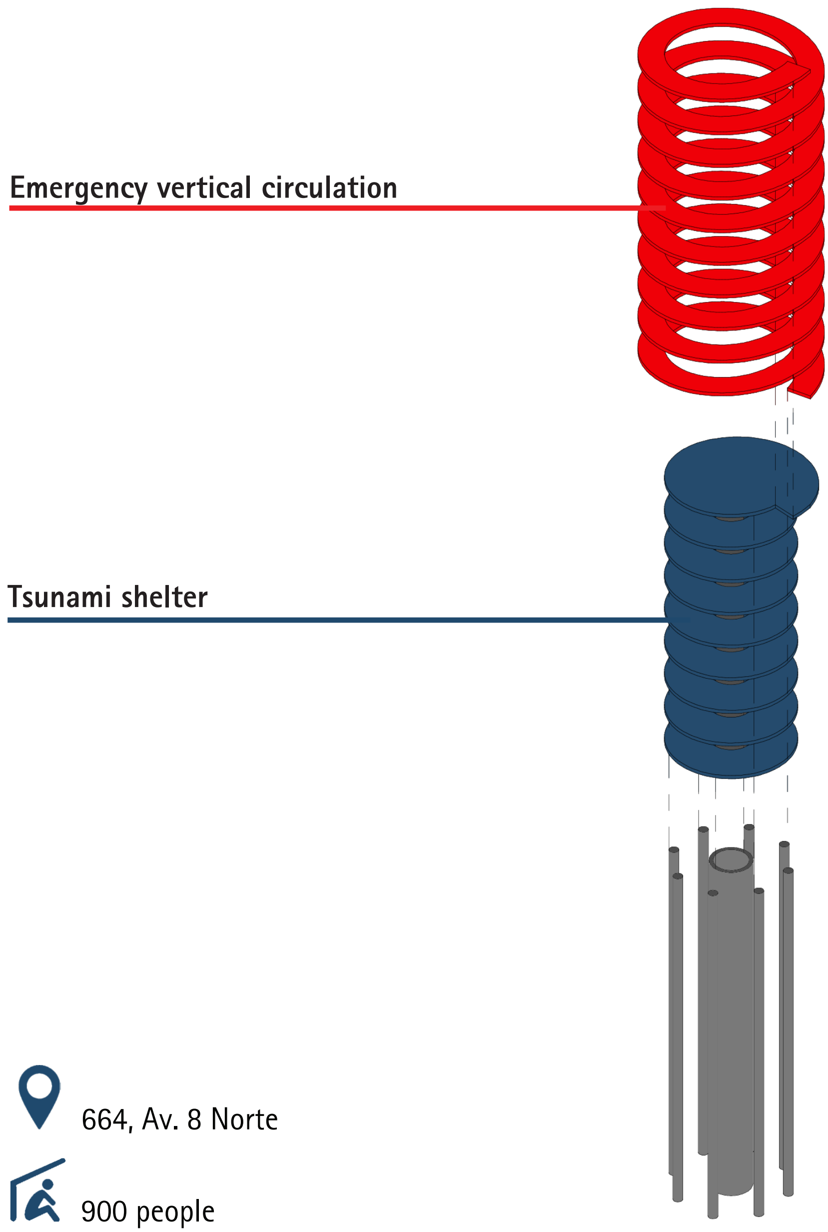
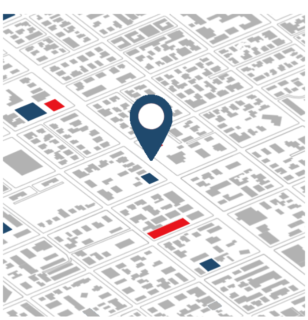


Figure 188:
Cut BB
Source:
Eleonora F. Serpi.



SHELTER 5: The watching tower





664, Av. 8 Norte

900 people

Figure 189:
Exploded axonometry
Source:
Eleonora F. Serpi.

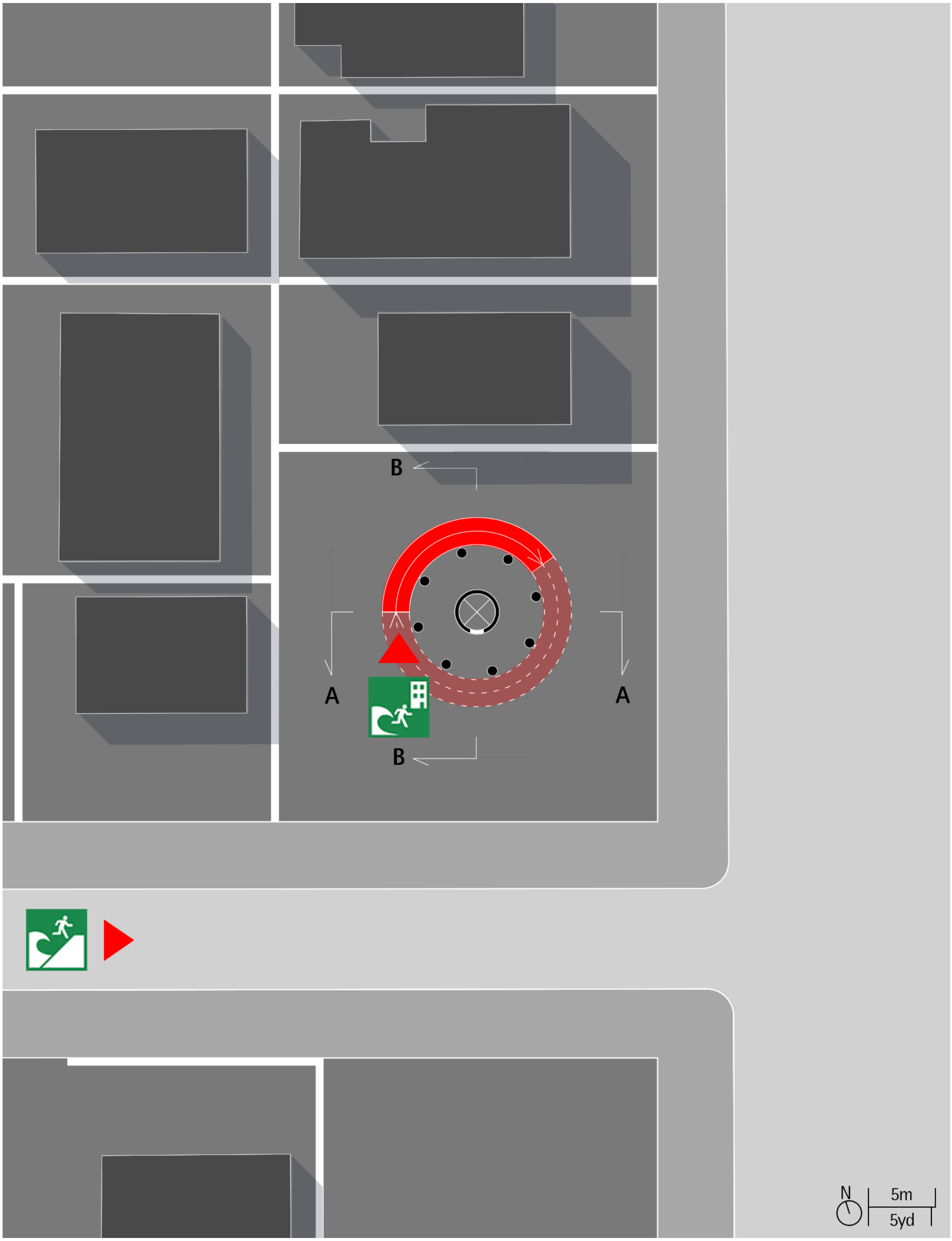


Figure 190:
Groundfloor plan
Source:
Eleonora F. Serpi.

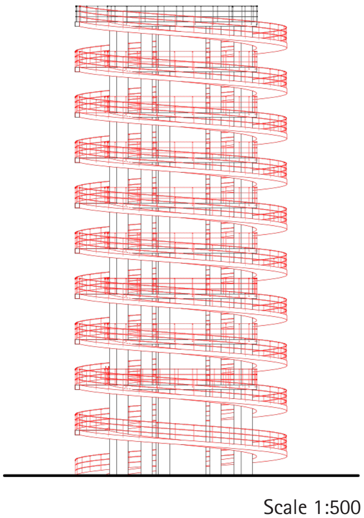


Figure 191:
South elevation
Source:
Eleonora F. Serpi.

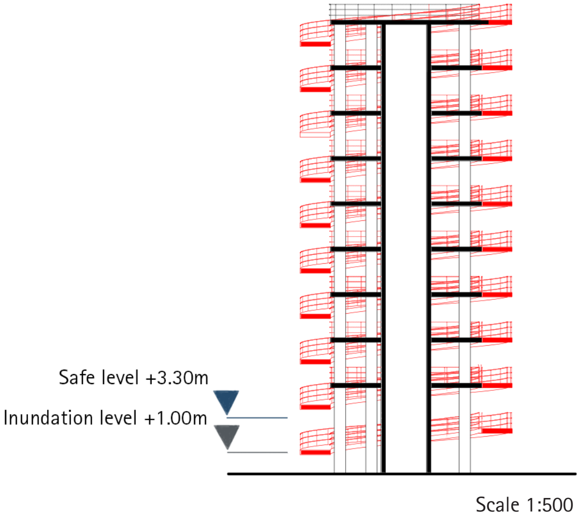


Figure 192:
Cut AA
Source:
Eleonora F. Serpi.

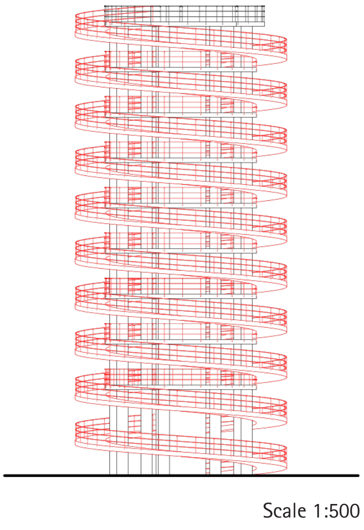


Figure 193:
East elevation
Source:
Eleonora F. Serpi.

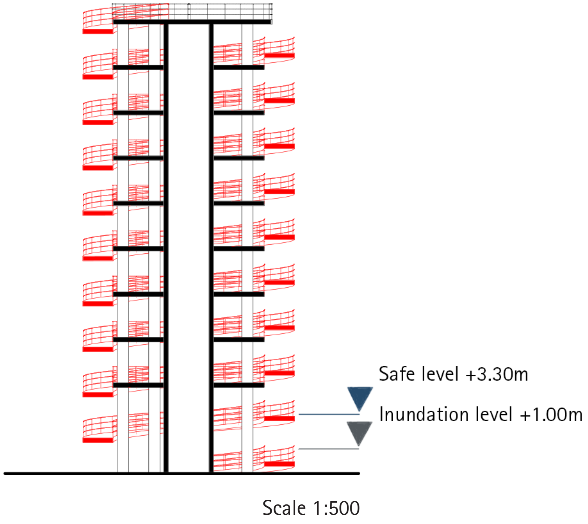
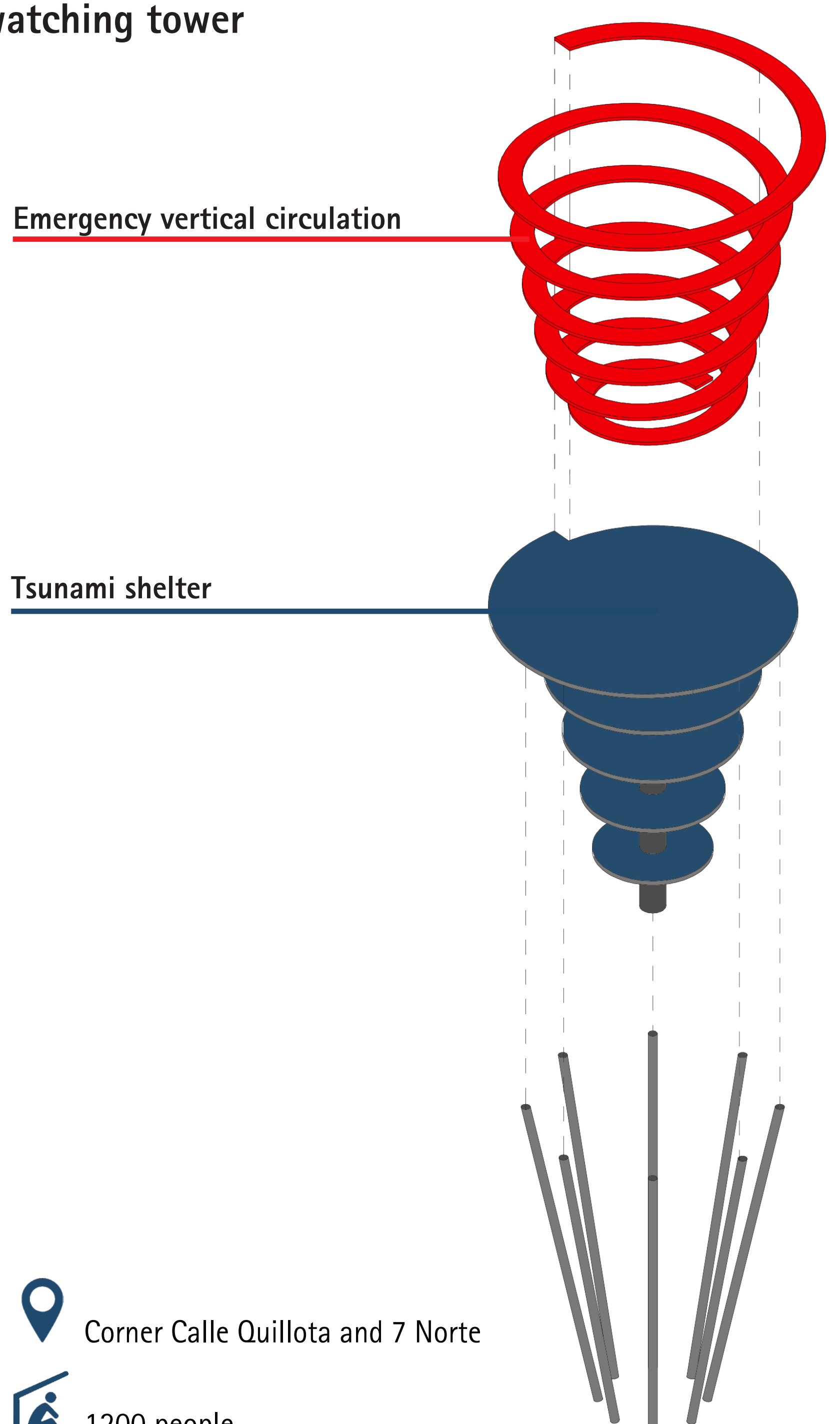
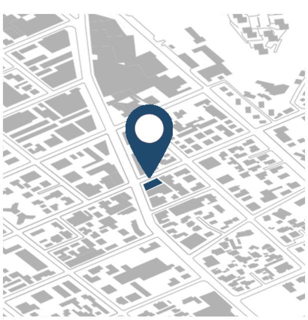


Figure 194:
Cut BB
Source:
Eleonora F. Serpi.

SHELTER 6: The watching tower





Corner Calle Quillota and 7 Norte

1200 people

Figure 195:
Exploded axonometry
Source:
Eleonora F. Serpi.

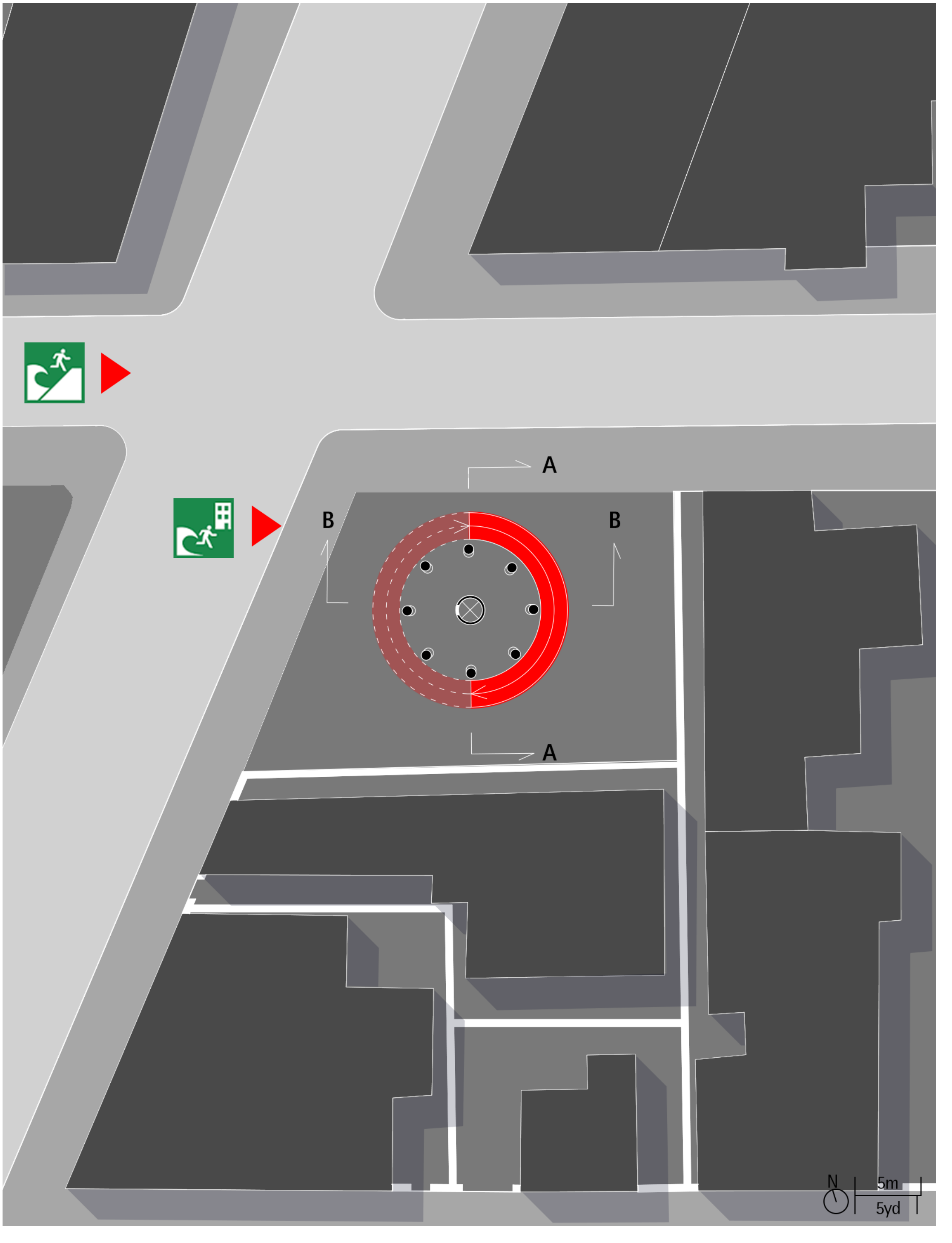
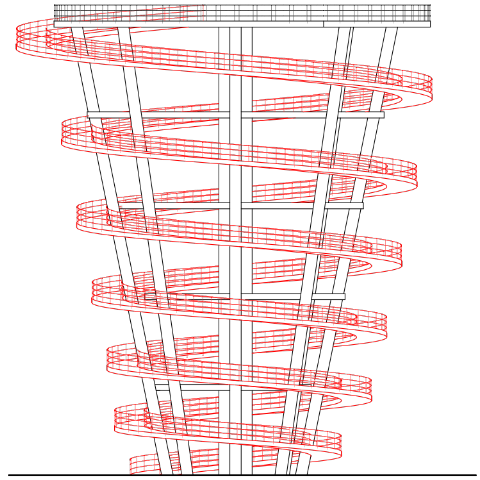
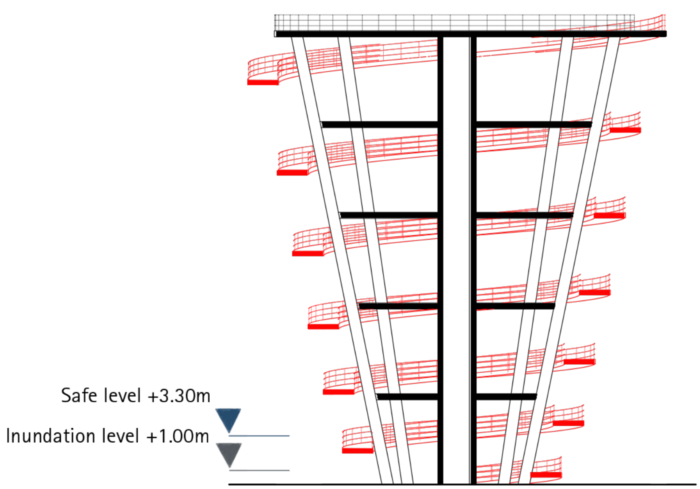


Figure 196:
Groundfloor plan
Source:
Eleonora F. Serpi.



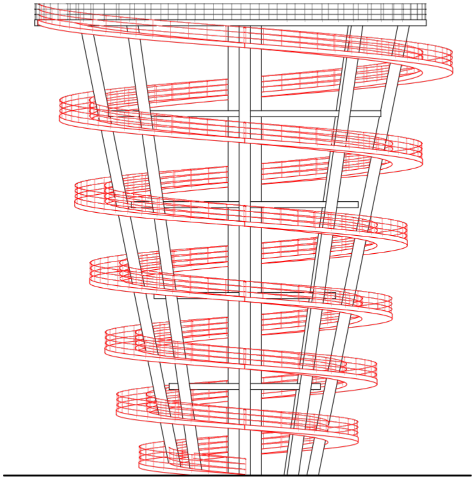
Scale 1:500

Figure 197:
West elevation
Source:
Eleonora F. Serpi.



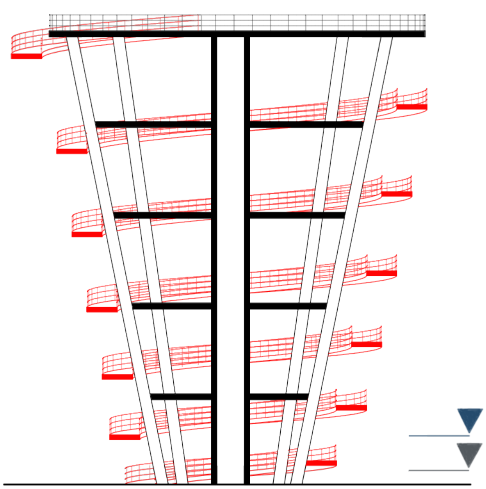
Scale 1:500

Figure 198:
Cut AA
Source:
Eleonora F. Serpi.



Scale 1:500

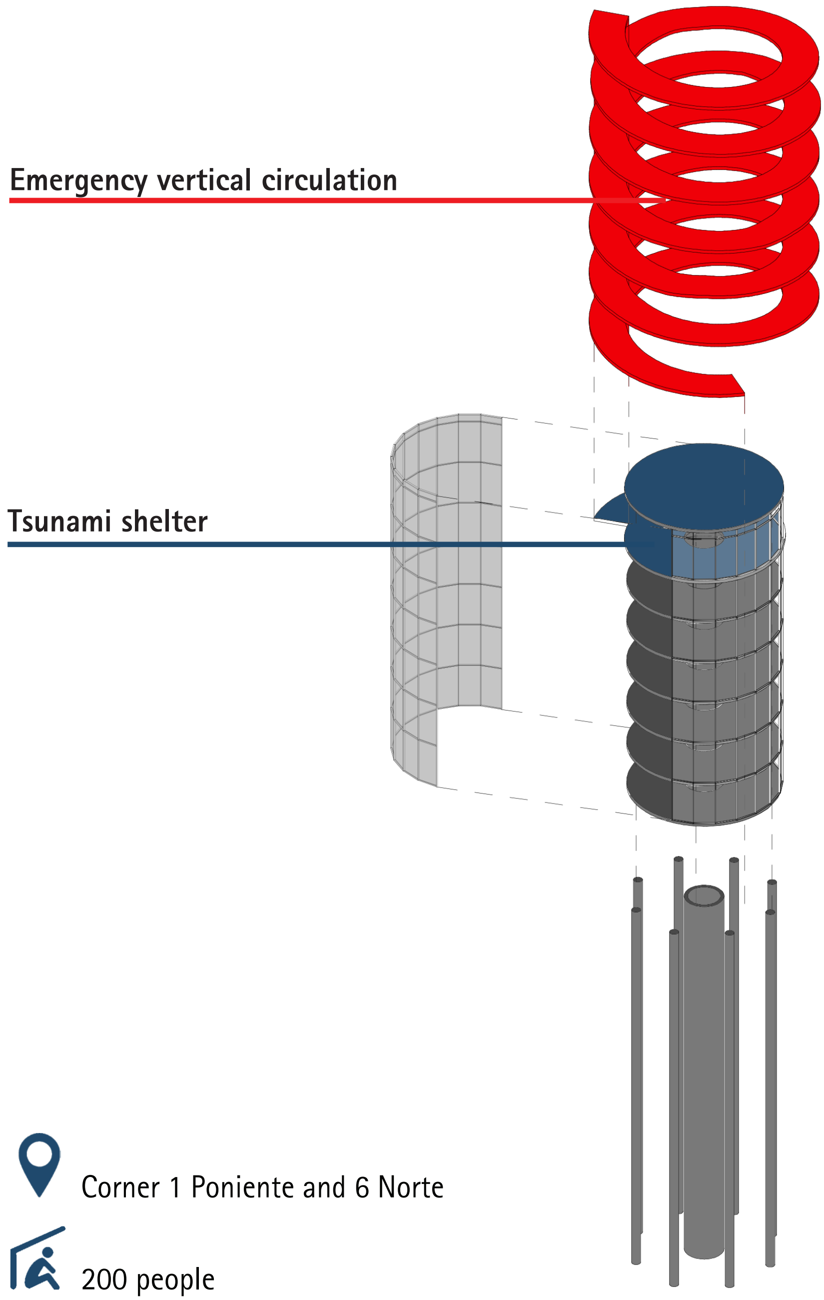
Figure 199:
North elevation
Source:
Eleonora F. Serpi.

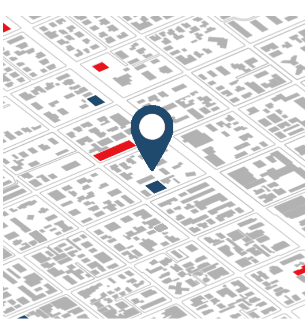


Scale 1:500

Figure 200:
Cut BB
Source:
Eleonora F. Serpi.

SHELTER 7: The turist centre





Corner 1 Poniente and 6 Norte

200 people

Figure 201:
Exploded axonometry
Source:
Eleonora F. Serpi.

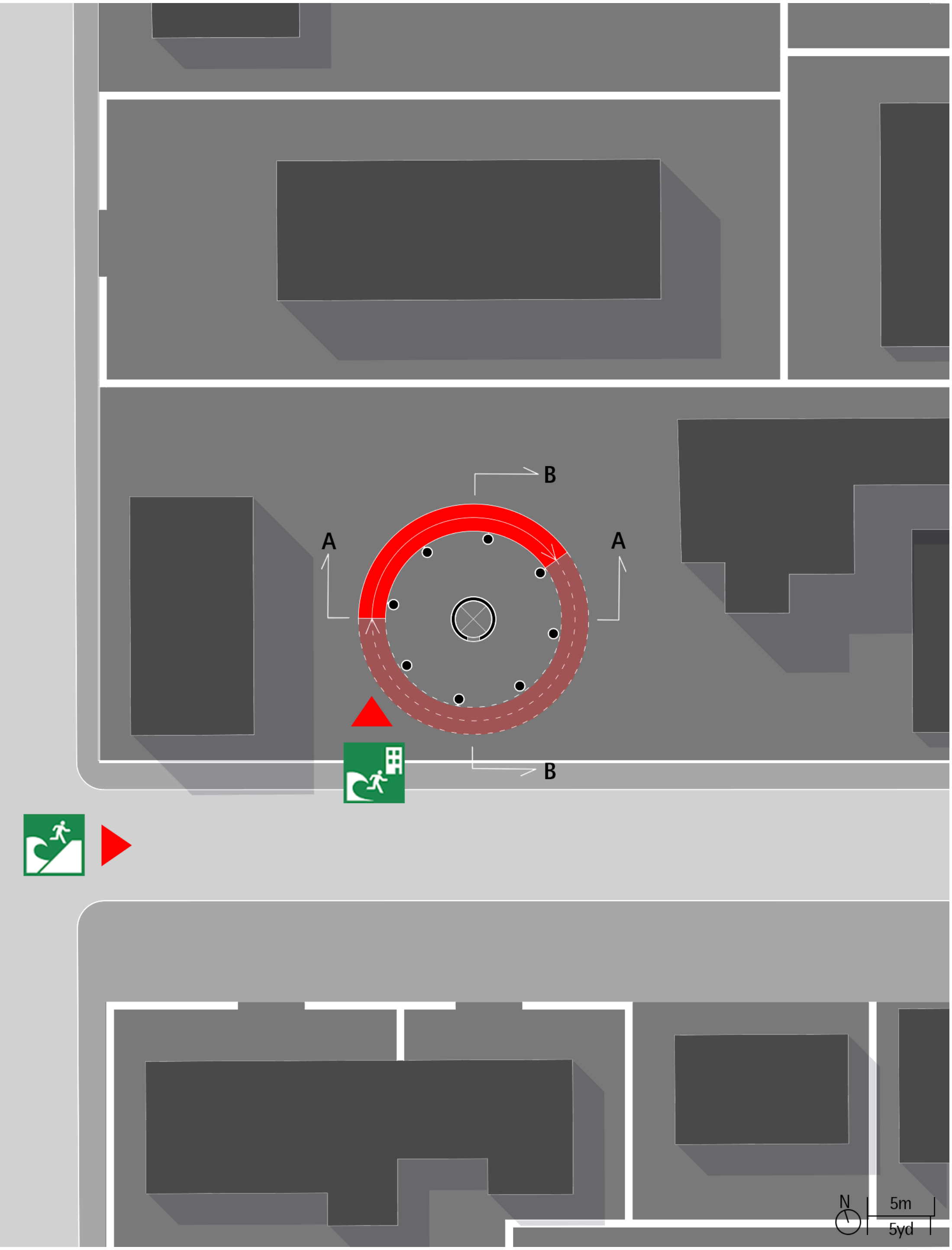
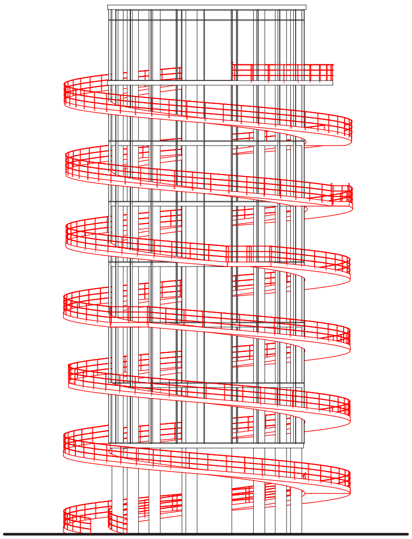
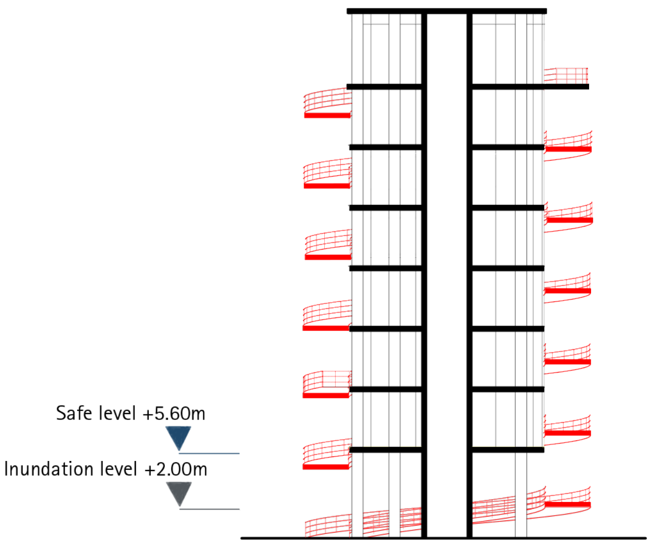


Figure 202:
Groundfloor plan
Source:
Eleonora F. Serpi.



Scale 1:500

Figure 203:
South elevation
Source:
Eleonora F. Serpi.



Scale 1:500

Figure 204:
Cut AA
Source:
Eleonora F. Serpi.

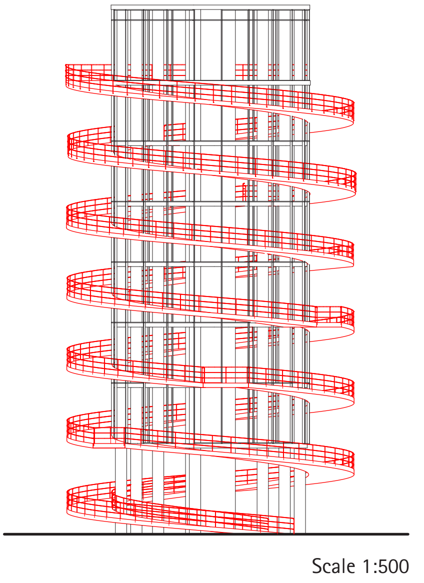


Figure 205:
West elevation
Source:
Eleonora F. Serpi.

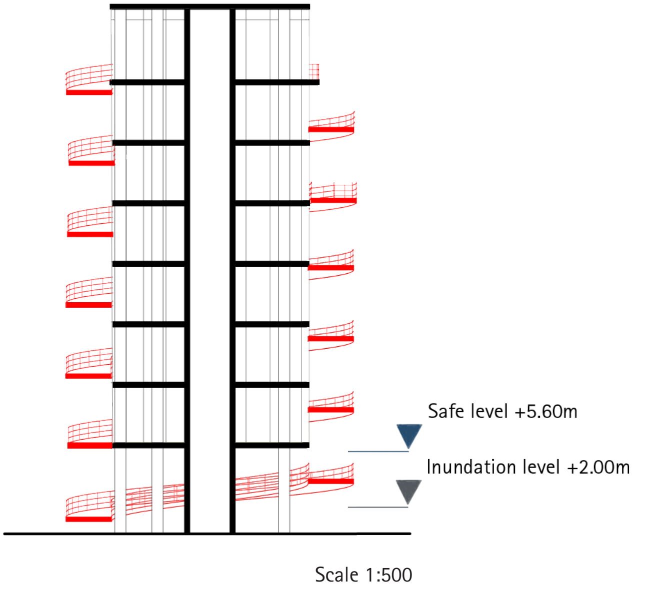
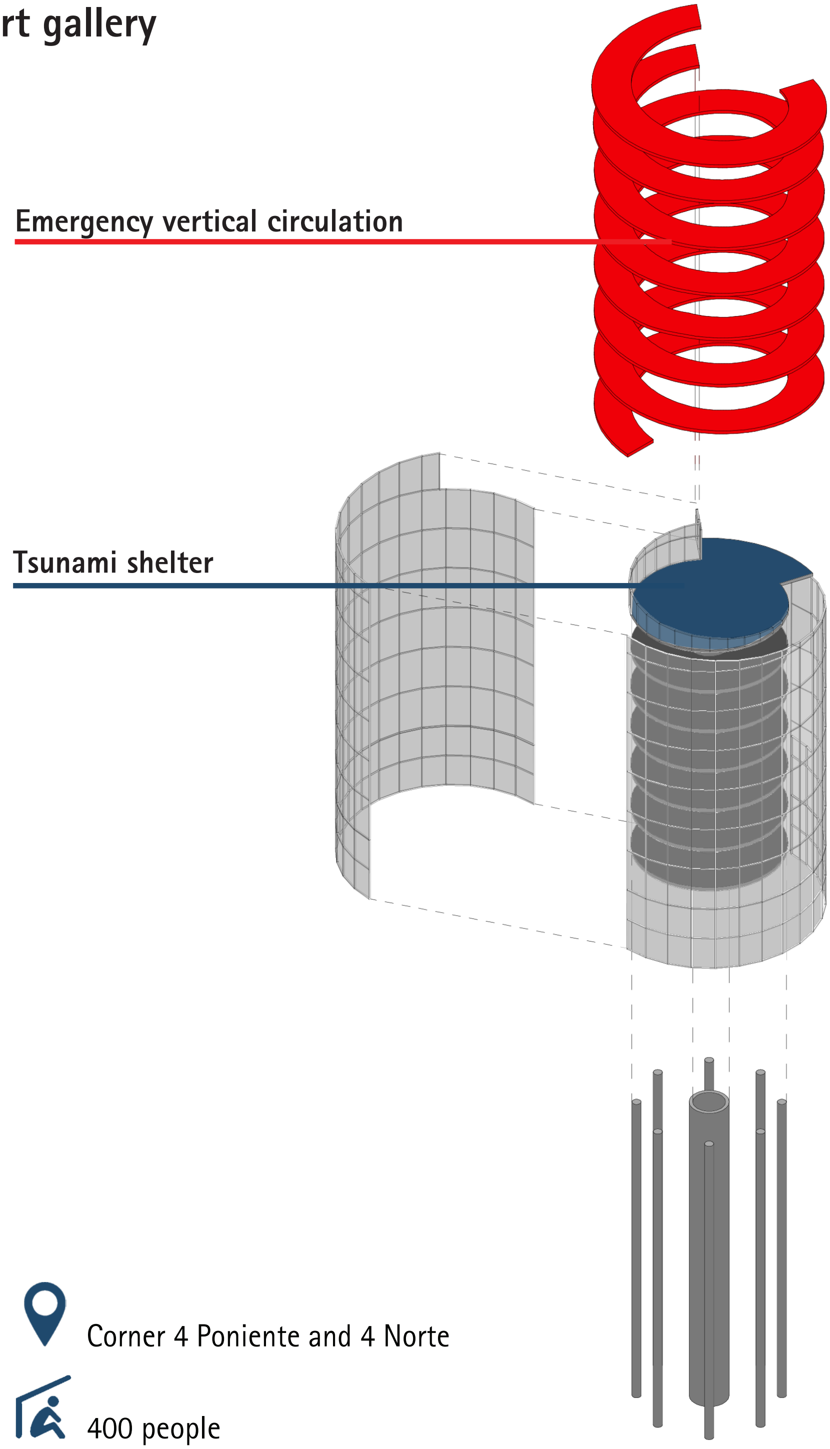
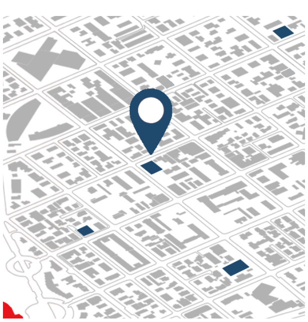


Figure 206:
Cut BB
Source:
Eleonora F. Serpi.

SHELTER 8: The art gallery





Corner 4 Poniente and 4 Norte

400 people

Figure 207:
Exploded axonometry
Source:
Eleonora F. Serpi.

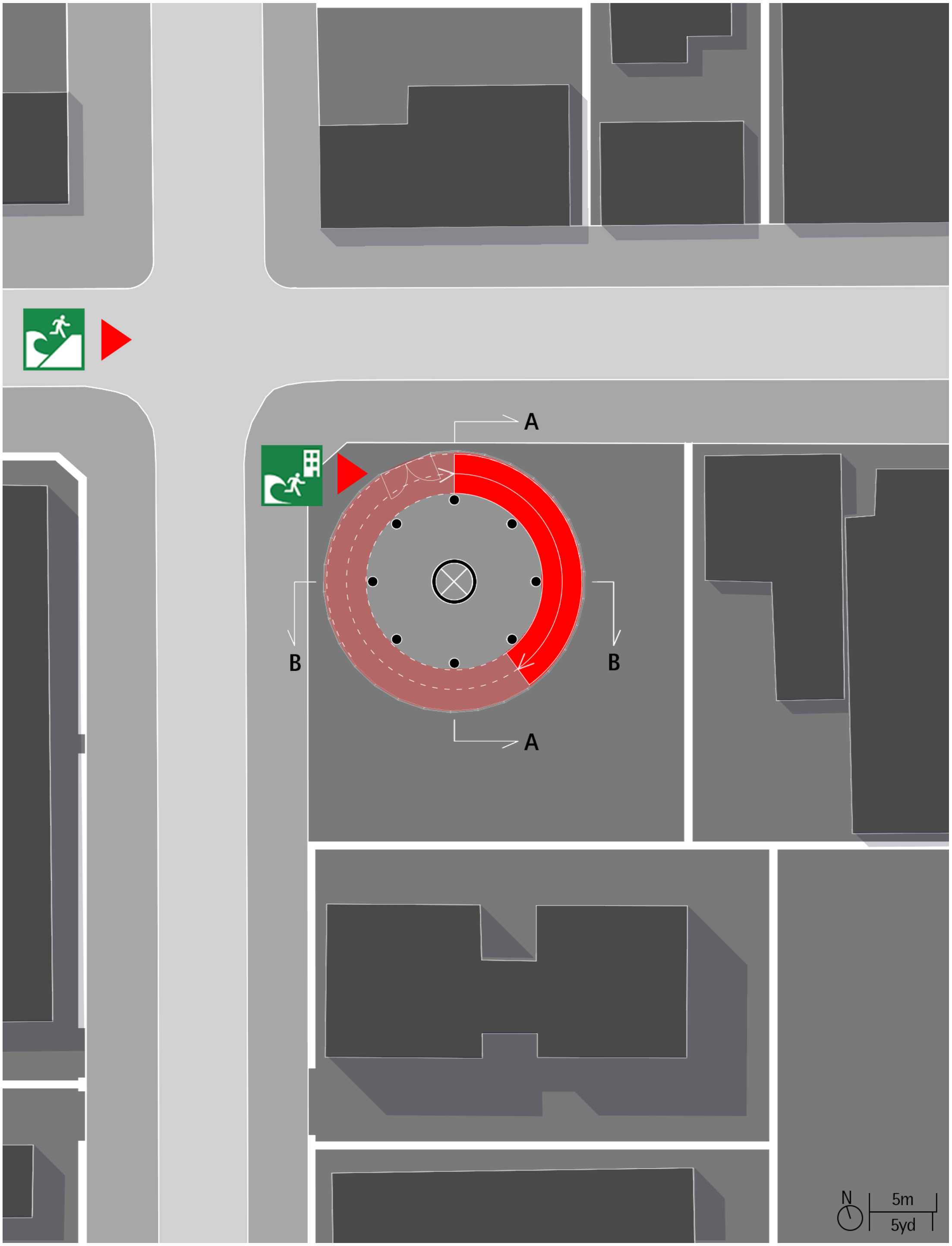


Figure 208:
Groundfloor plan
Source:
Eleonora F. Serpi.

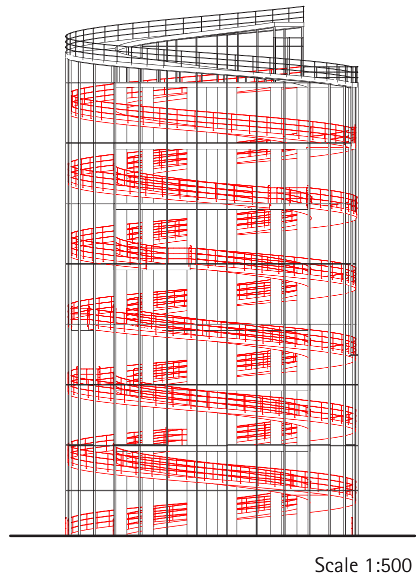


Figure 209:
West elevation
Source:
Eleonora F. Serpi.

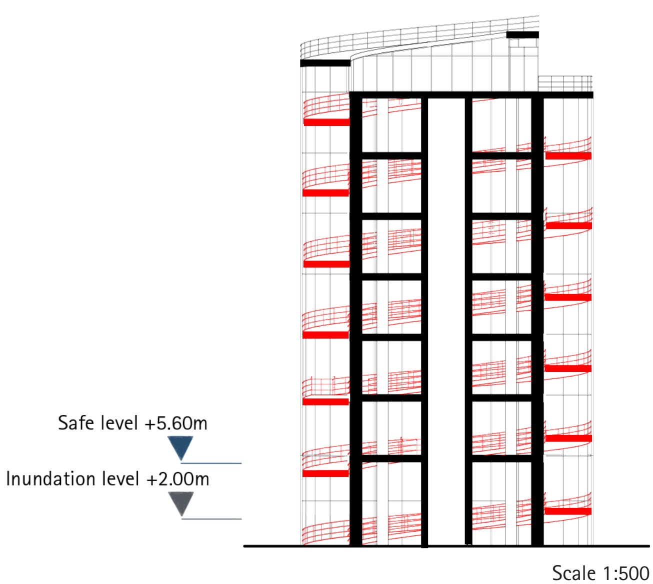


Figure 210:
Cut AA
Source:
Eleonora F. Serpi.

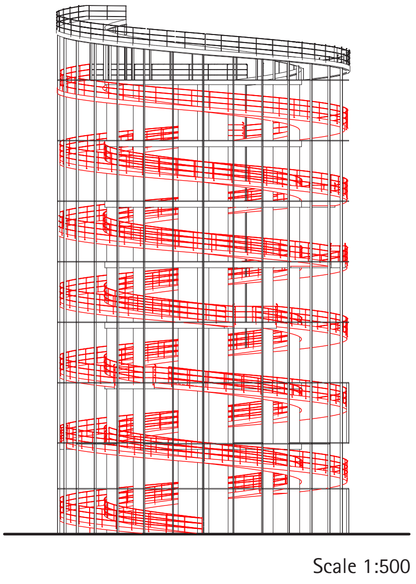


Figure 211:
North elevation
Source:
Eleonora F. Serpi.

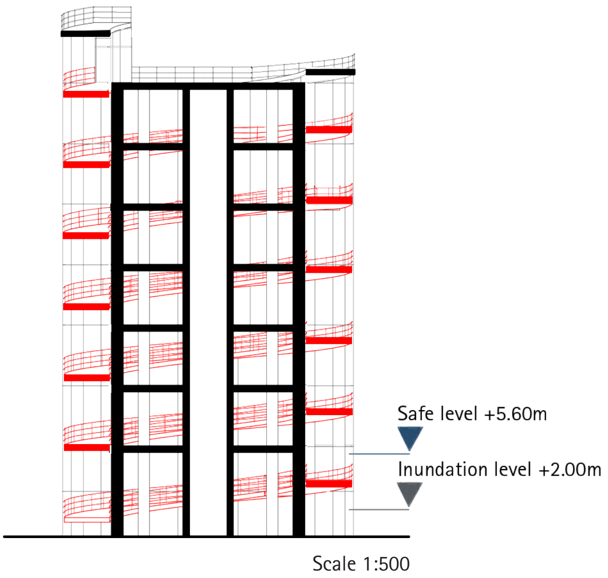
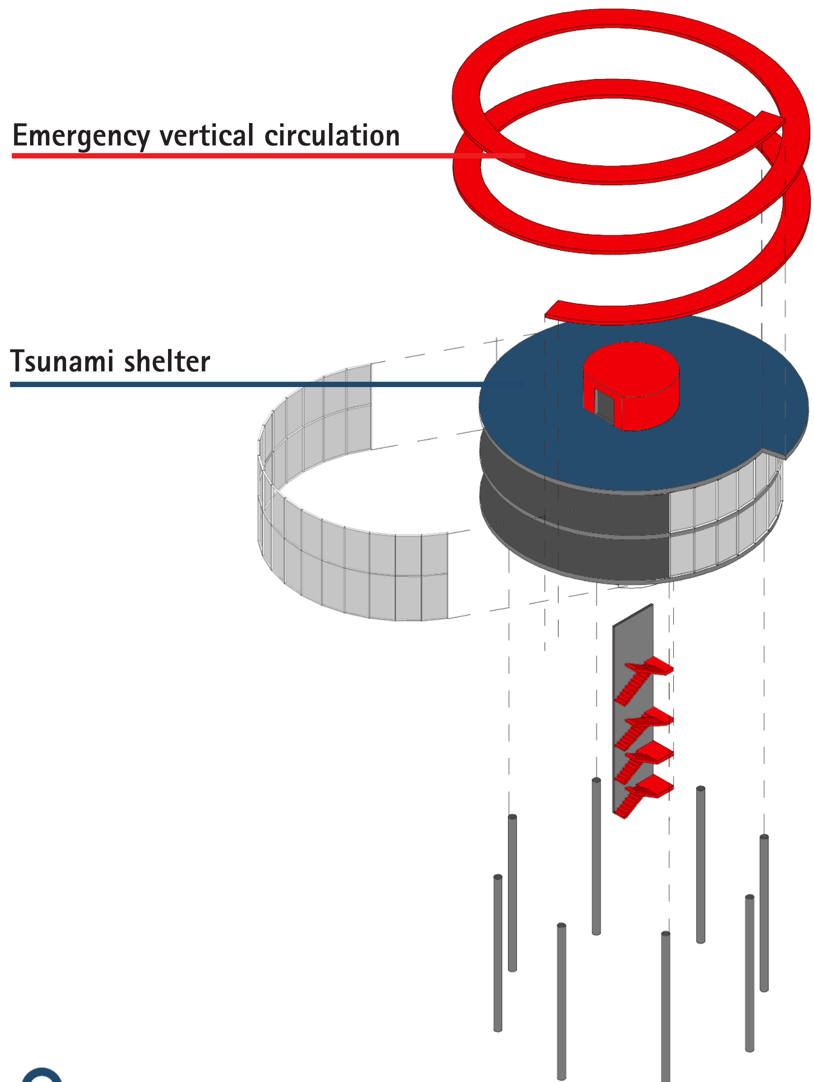


Figure 212:
Cut BB
Source:
Eleonora F. Serpi.

SHELTER 9: The yoga studio



Corner 5 Poniente and 3 Norte

550 people

Figure 213:
Exploded axonometry
Source:
Eleonora F. Serpi.

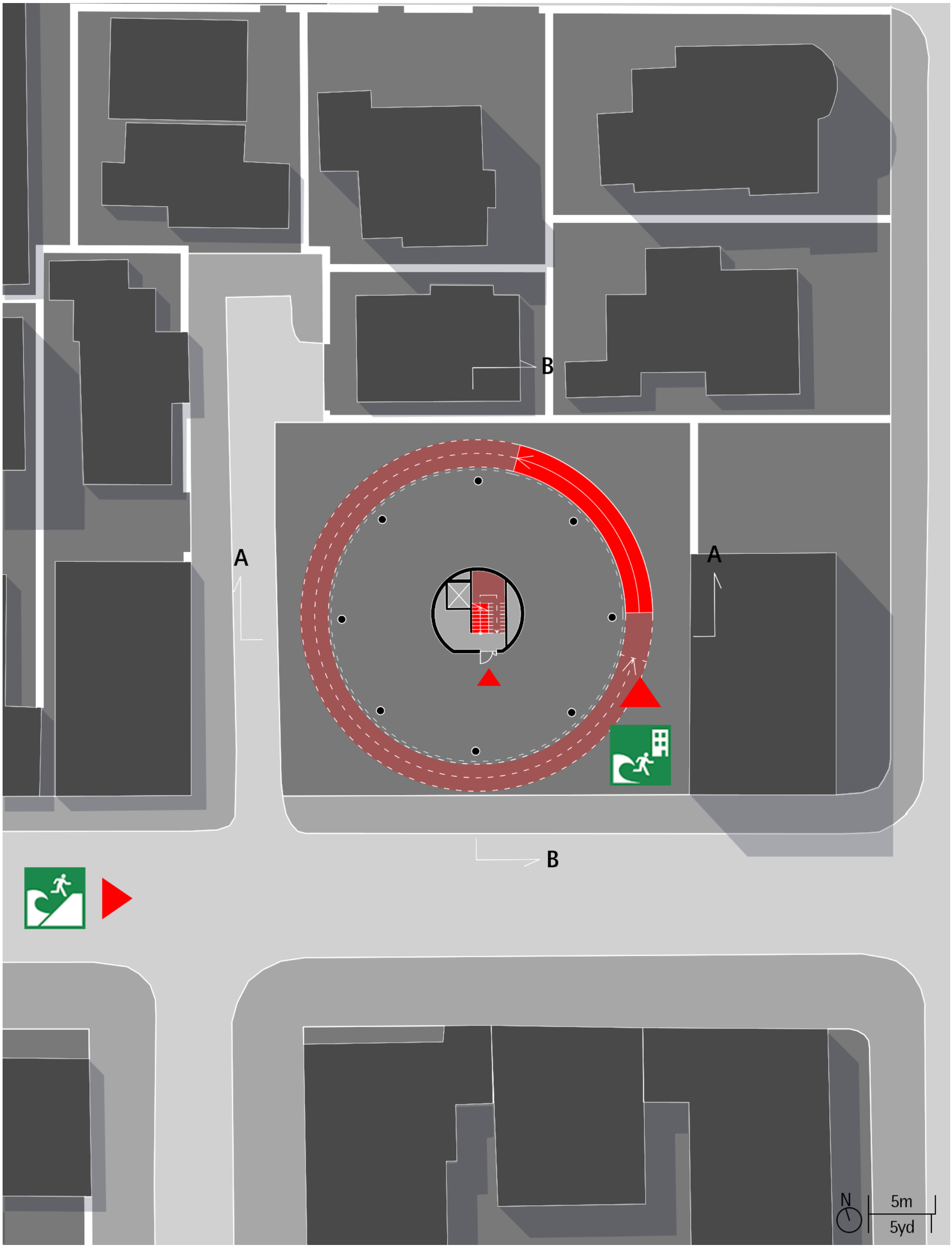


Figure 214:
Groundfloor plan
Source:
Eleonora F. Serpi.

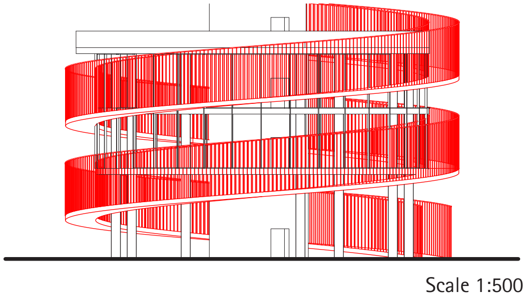


Figure 215:
South elevation
Source:
Eleonora F. Serpi.

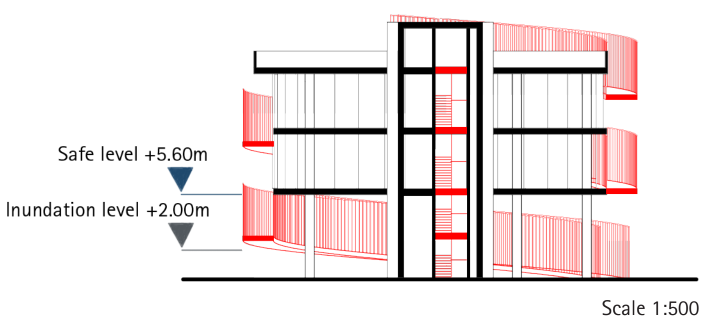


Figure 216:
Cut AA
Source:
Eleonora F. Serpi.

Figure 217:
East elevation
Source:
Eleonora F. Serpi.

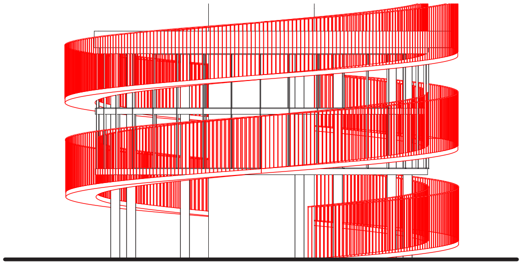
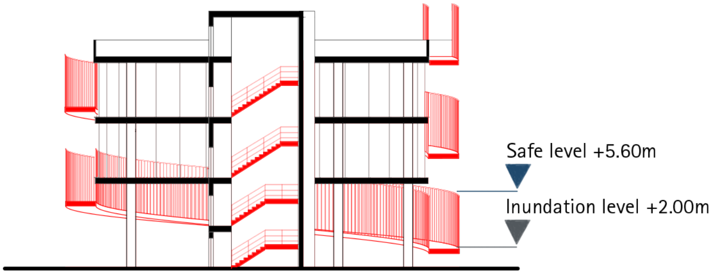
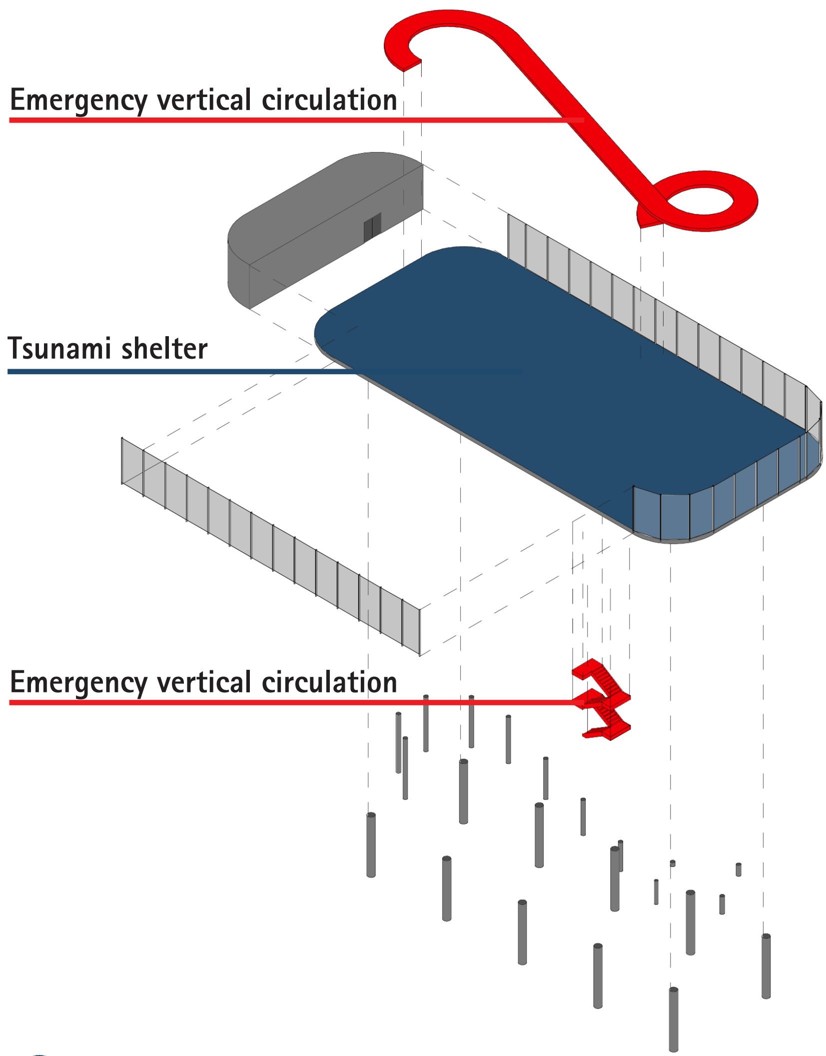
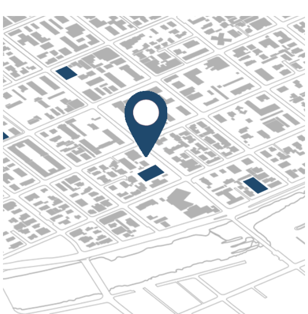


Figure 218:
Cut BB
Source:
Eleonora F. Serpi.



SHELTER 10: The basketball field





Corner 4 Poniente and 2 Norte

1000 people

Figure 219:
Exploded axonometry
Source:
Eleonora F. Serpi.

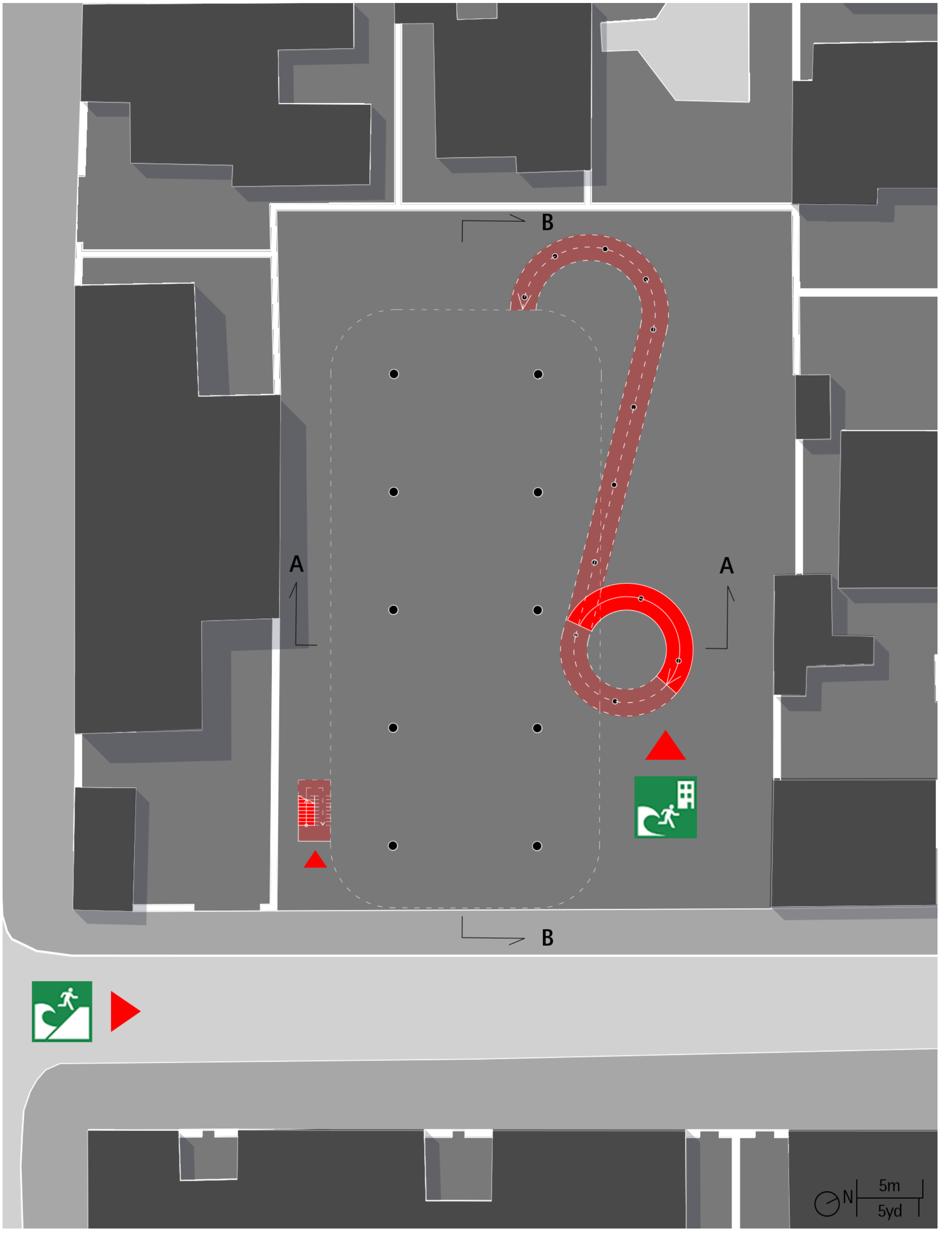


Figure 220:
Groundfloor plan
Source:
Eleonora F. Serpi.

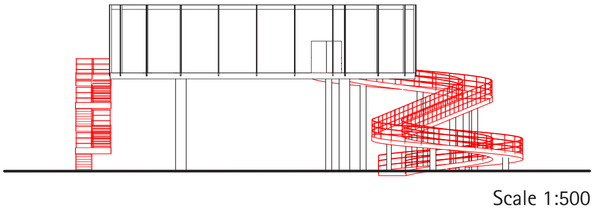


Figure 221:
South elevation
Source:
Eleonora F. Serpi.

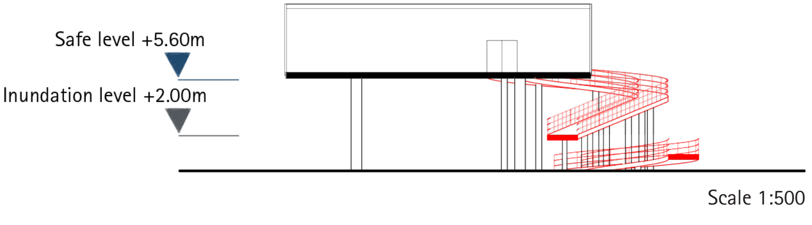


Figure 222:
Cut AA
Source:
Eleonora F. Serpi.

Figure 223:
West elevation
Source:
Eleonora F. Serpi.

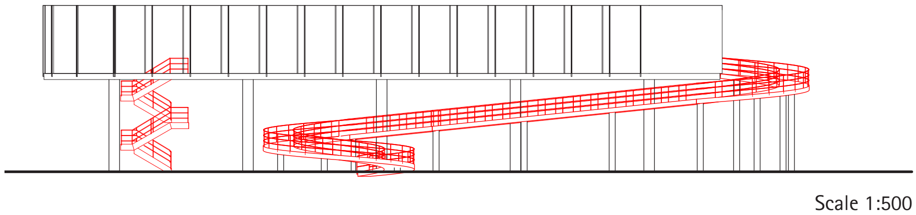
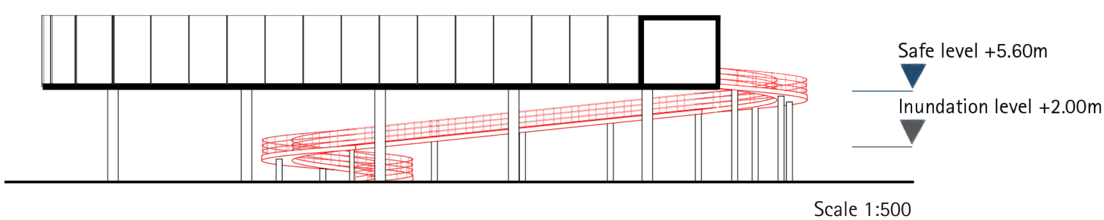
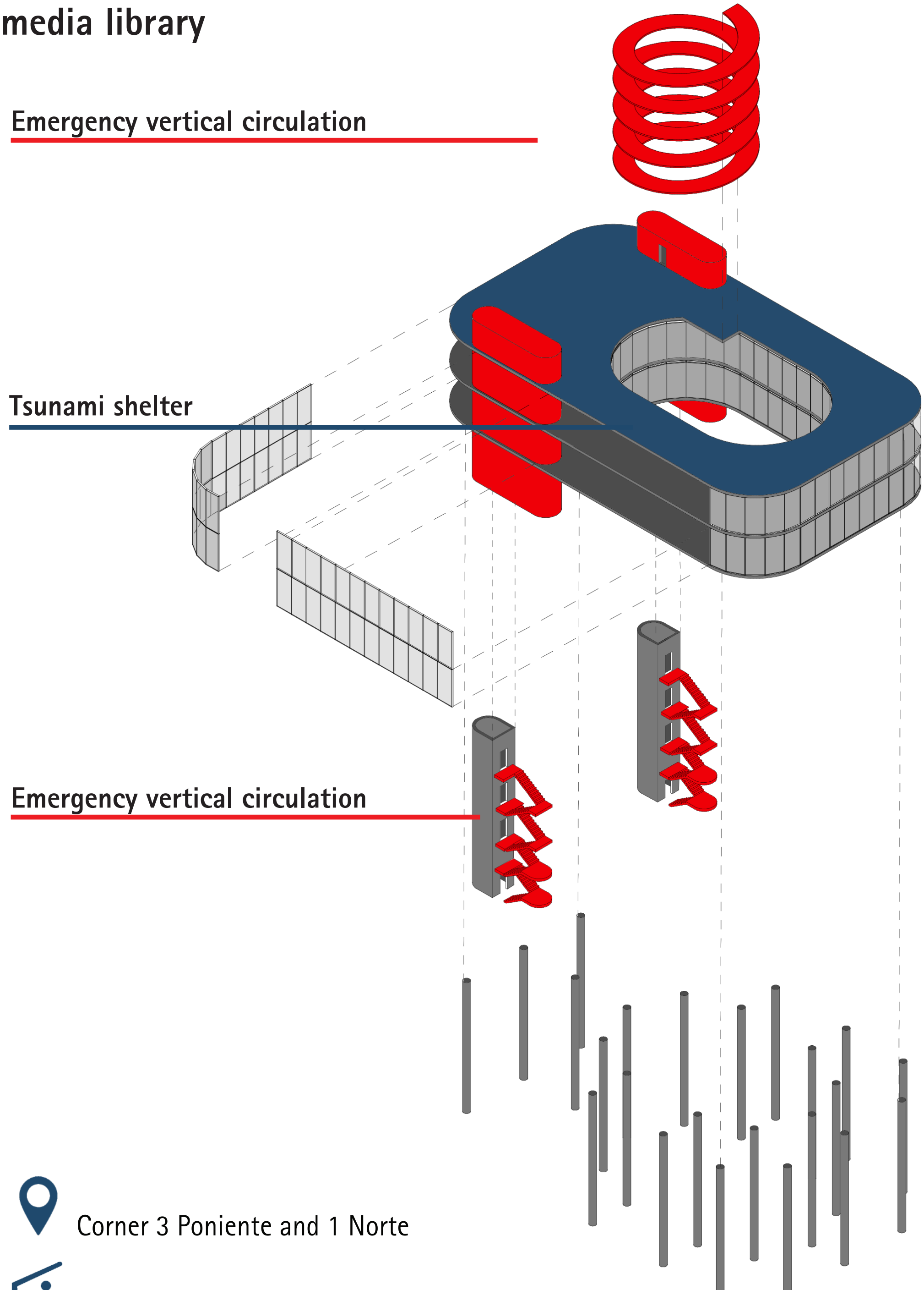


Figure 224:
Cut BB
Source:
Eleonora F. Serpi.



SHELTER 11: The media library



Corner 3 Poniente and 1 Norte

1000 people

Figure 225:
Exploded axonometry
Source:
Eleonora F. Serpi.

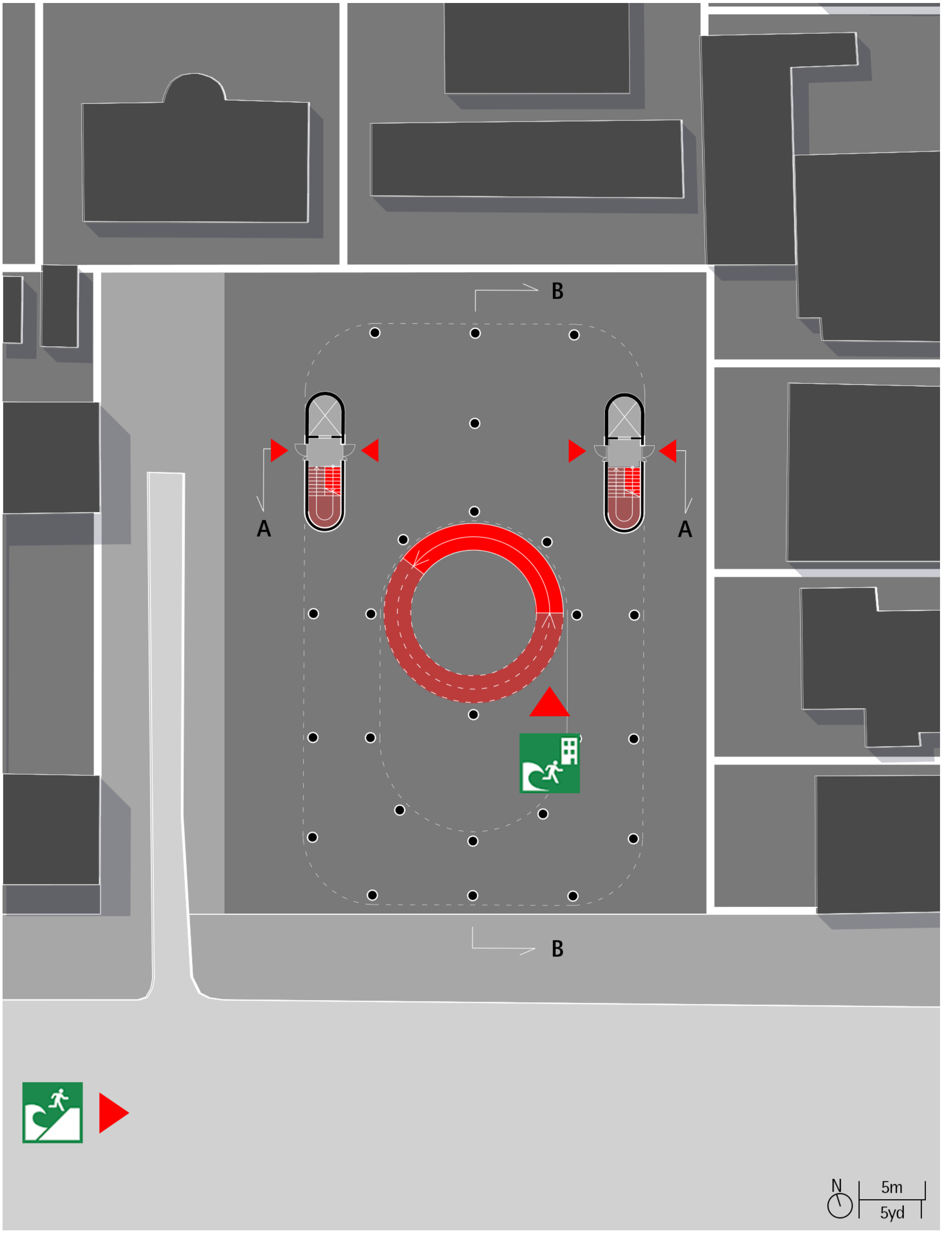


Figure 226:
Groundfloor plan
Source:
Eleonora F. Serpi.

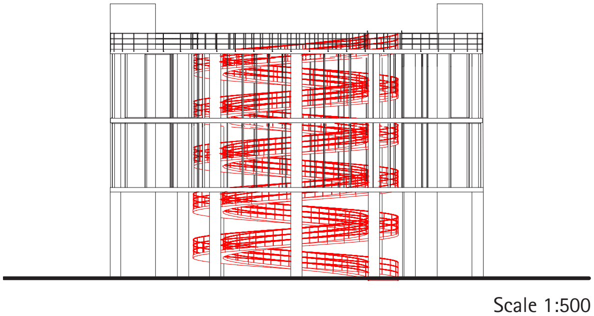


Figure 227:
South elevation
Source:
Eleonora F. Serpi.

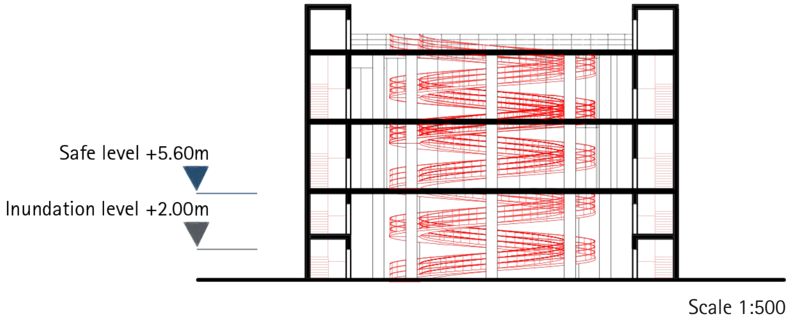


Figure 228:
Cut AA
Source:
Eleonora F. Serpi.

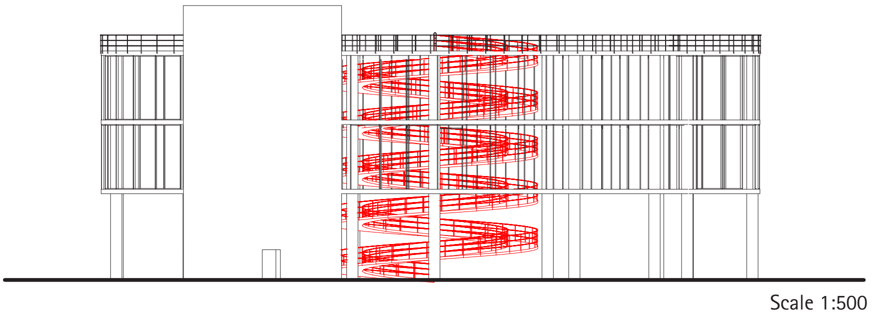


Figure 229:
West elevation
Source:
Eleonora F. Serpi.

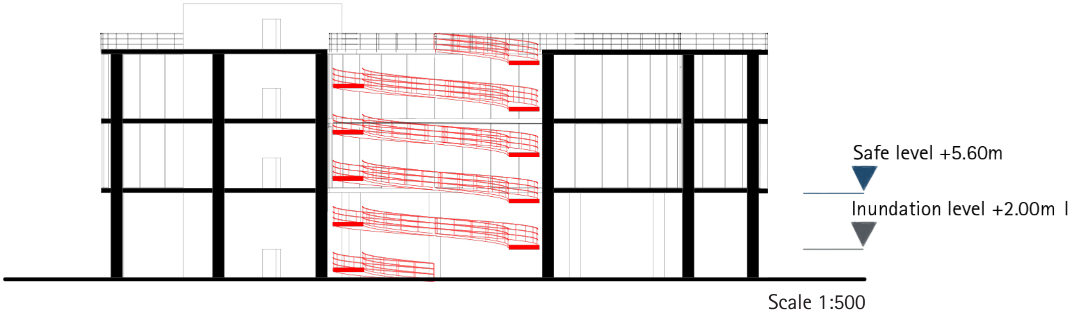
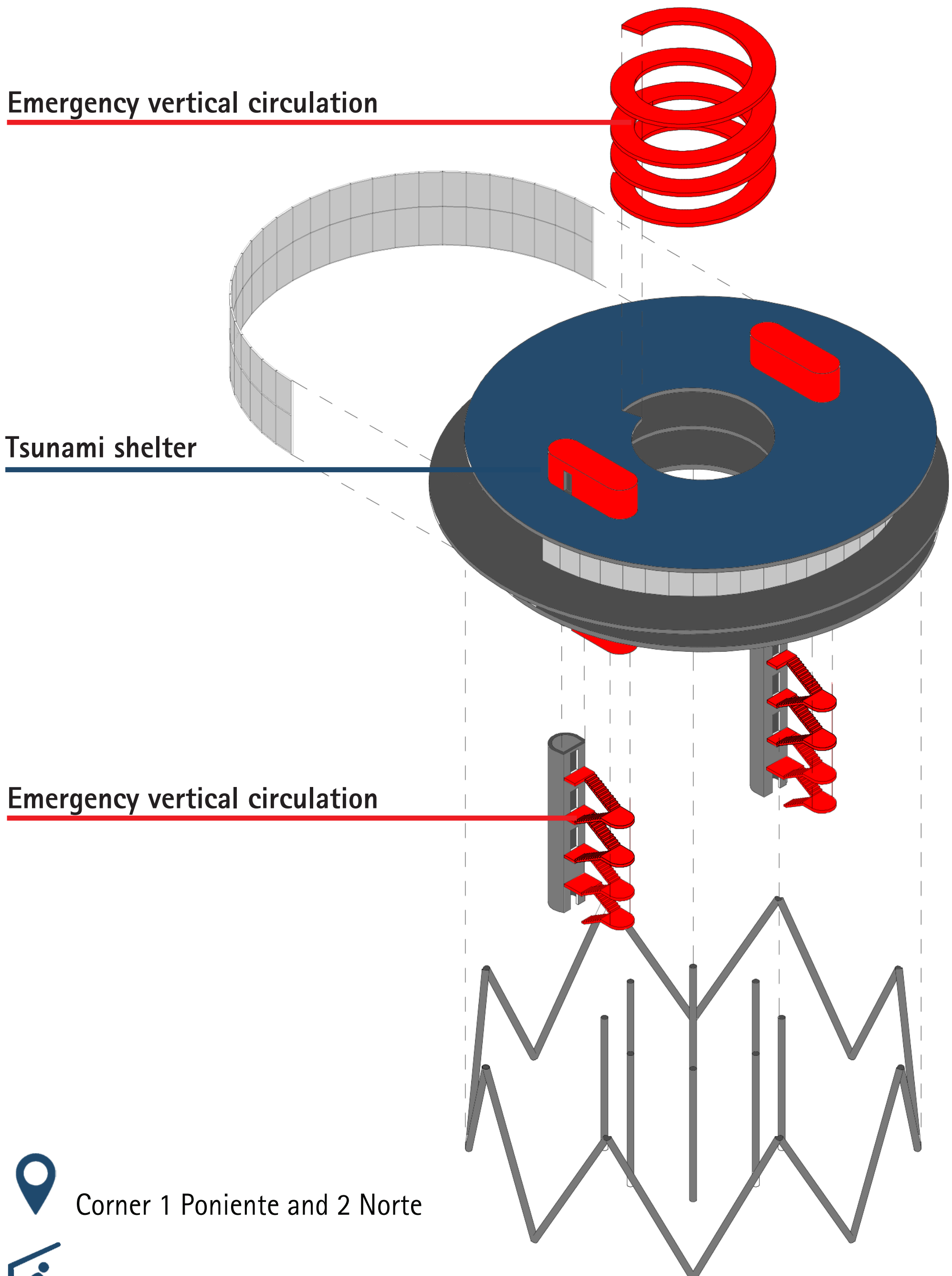


Figure 230:
Cut BB
Source:
Eleonora F. Serpi.

SHELTER 12: The coworking



Corner 1 Poniente and 2 Norte

1000 people

Figure 231:
Exploded axonometry
Source:
Eleonora F. Serpi.

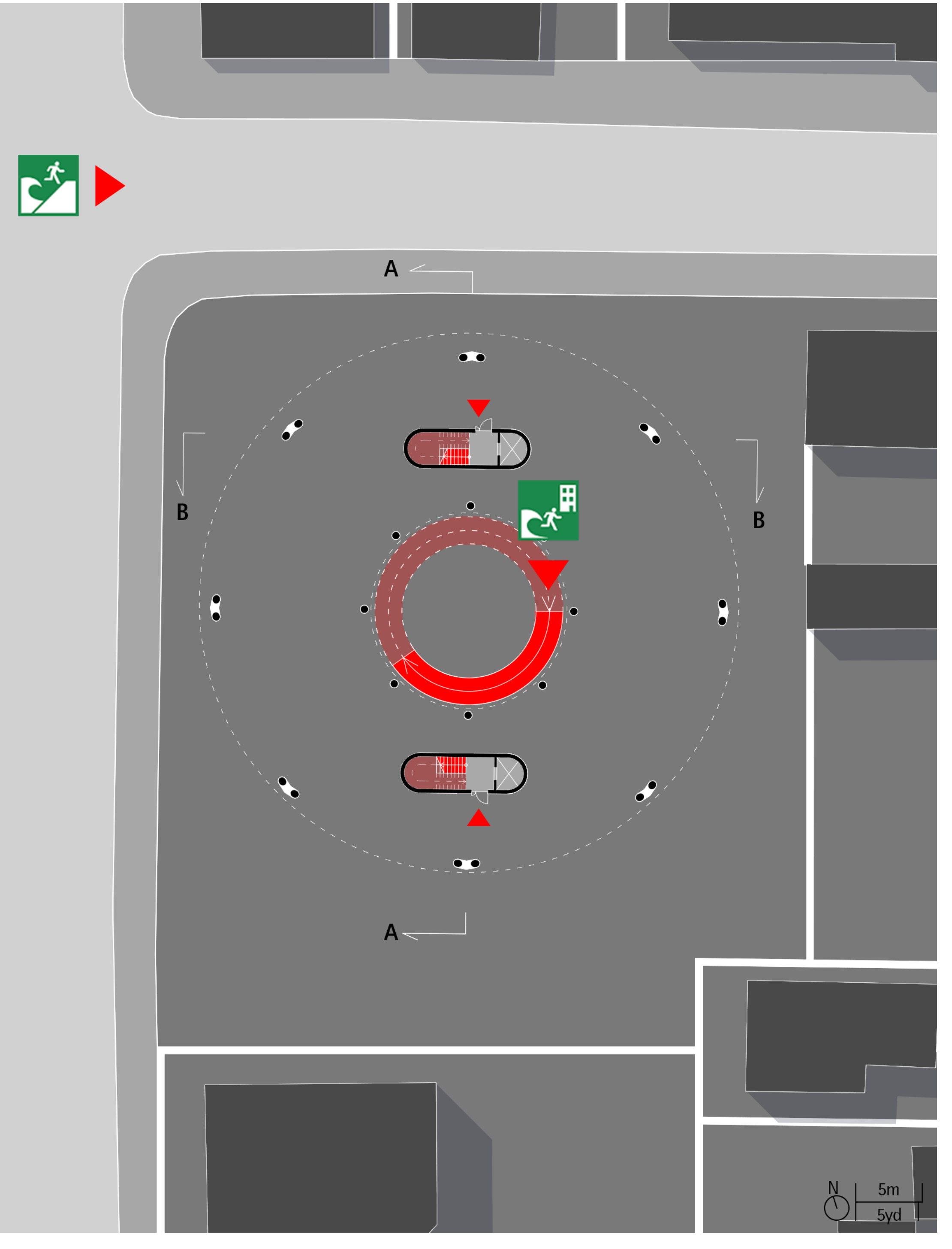


Figure 232:
Groundfloor plan
Source:
Eleonora F. Serpi.

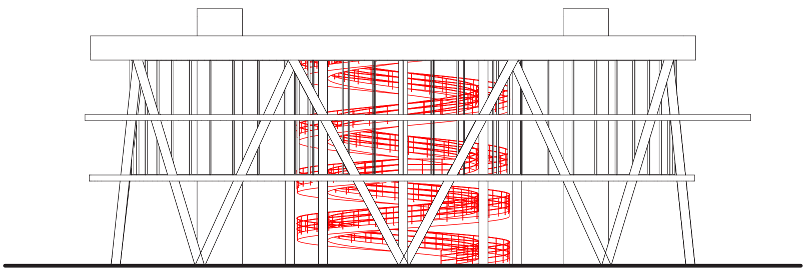


Figure 233:
West elevation
Source:
Eleonora F. Serpi.

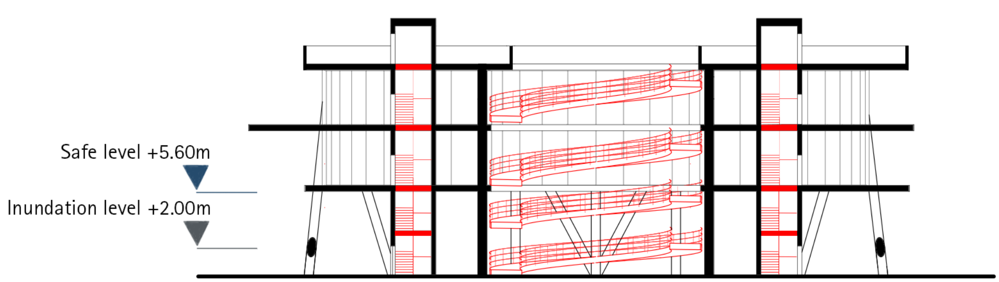


Figure 234:
Cut AA
Source:
Eleonora F. Serpi.

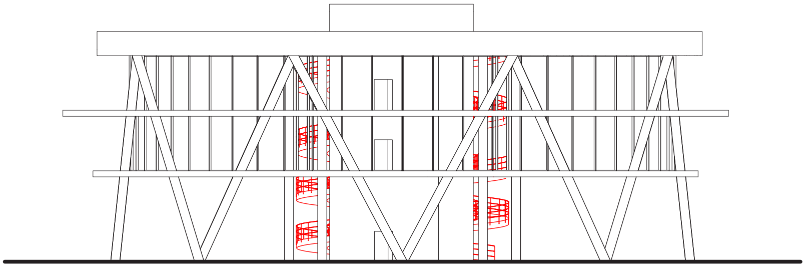


Figure 235:
North elevation
Source:
Eleonora F. Serpi.

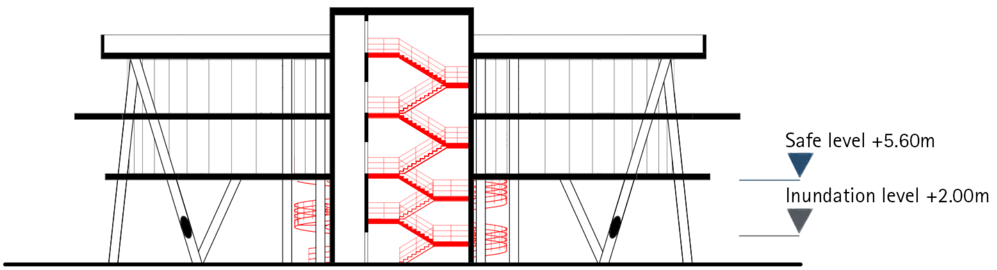
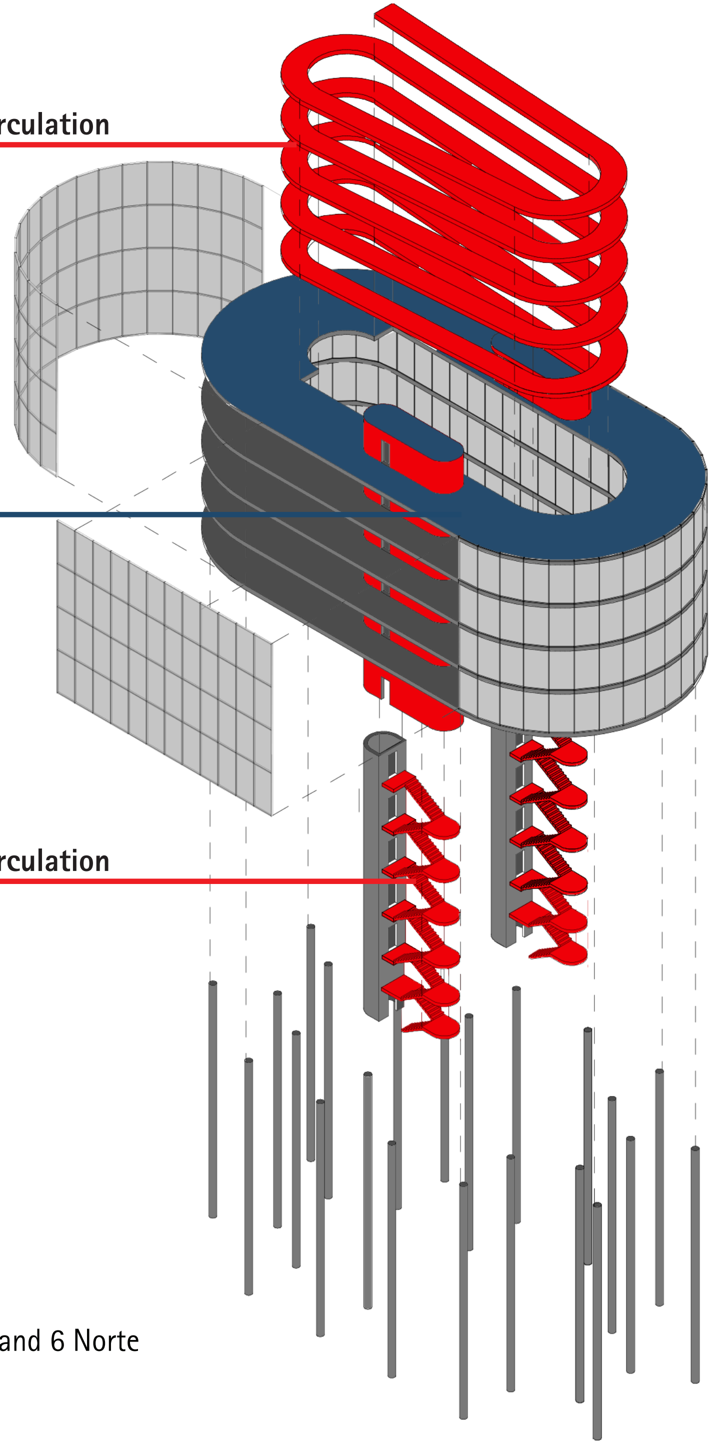


Figure 236:
Cut BB
Source:
Eleonora F. Serpi.

SHELTER 13: The library



Corner 1 Oriente and 6 Norte

850 people

Figure 237:
Exploded axonometry
Source:
Eleonora F. Serpi.

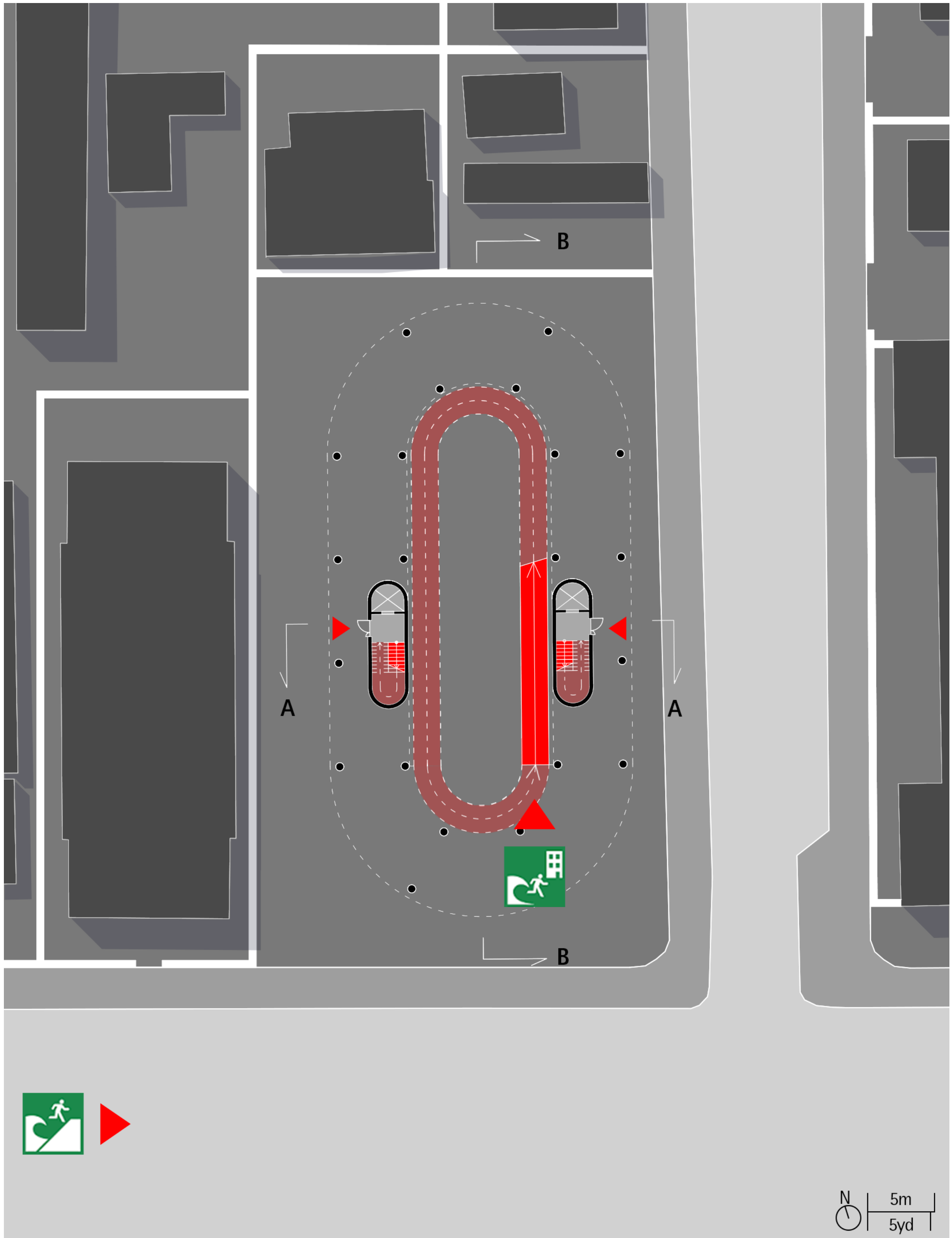


Figure 238:
Groundfloor plan
Source:
Eleonora F. Serpi.

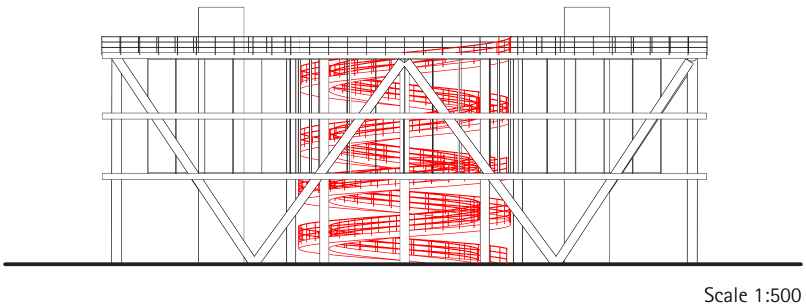


Figure 239:
West elevation
Source:
Eleonora F. Serpi.

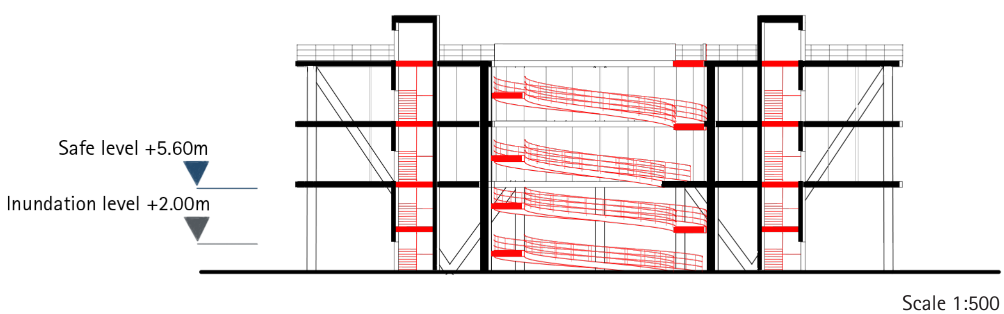


Figure 240:
Cut AA
Source:
Eleonora F. Serpi.

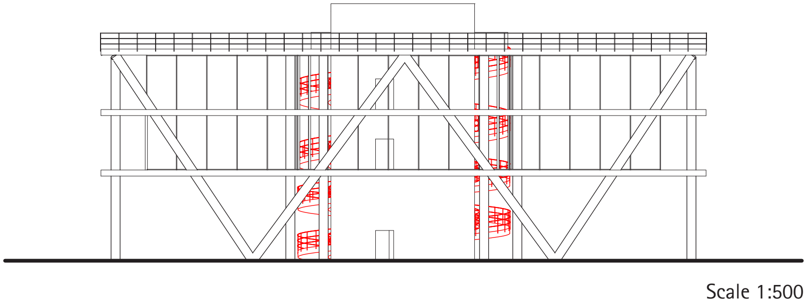


Figure 241:
North elevation
Source:
Eleonora F. Serpi.

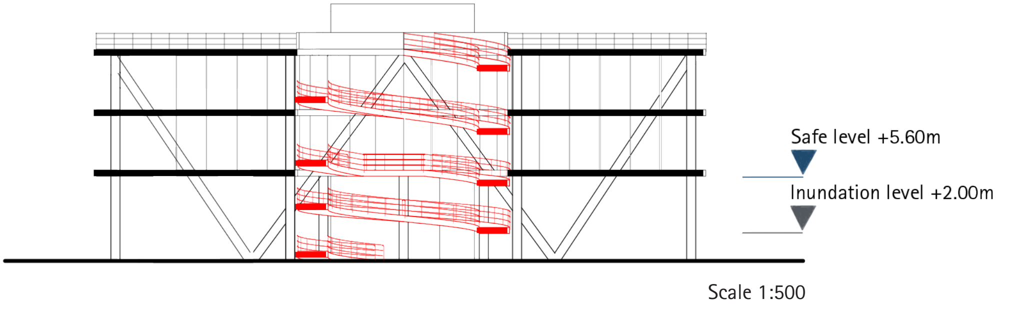
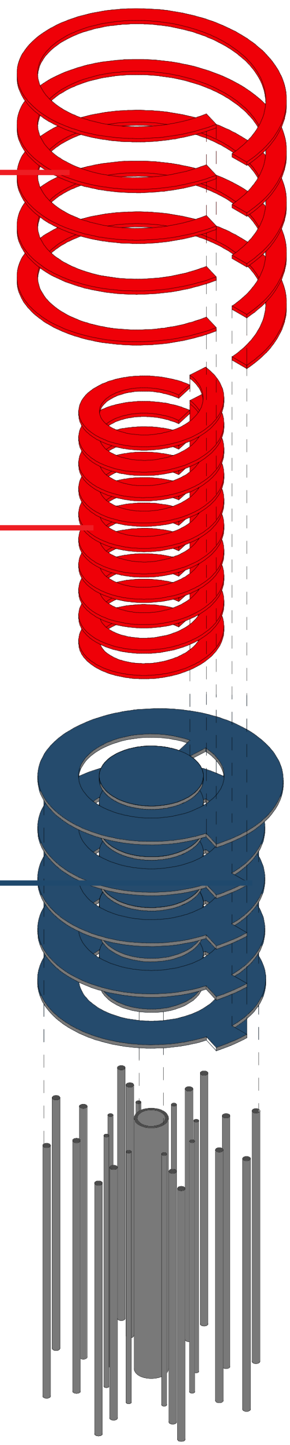
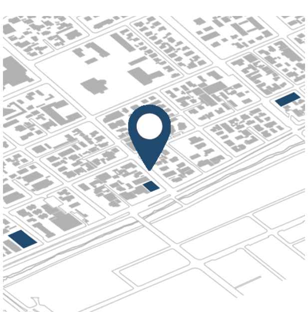


Figure 242:
Cut BB
Source:
Eleonora F. Serpi.

SHELTER 14: The watching tower





Corner 3 Oriente and 1 Norte

1900 people

Figure 243:
Exploded axonometry
Source:
Eleonora F. Serpi.

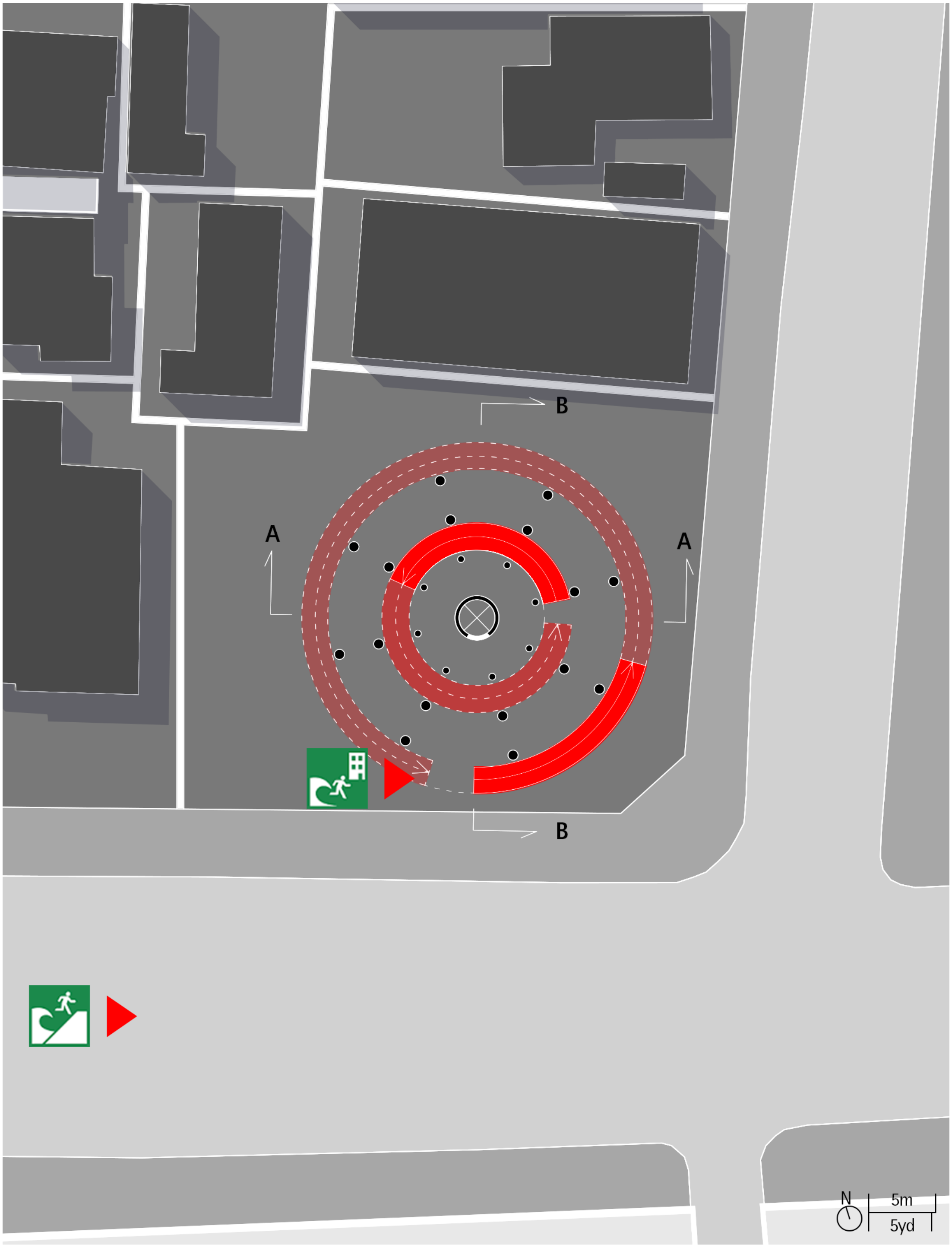
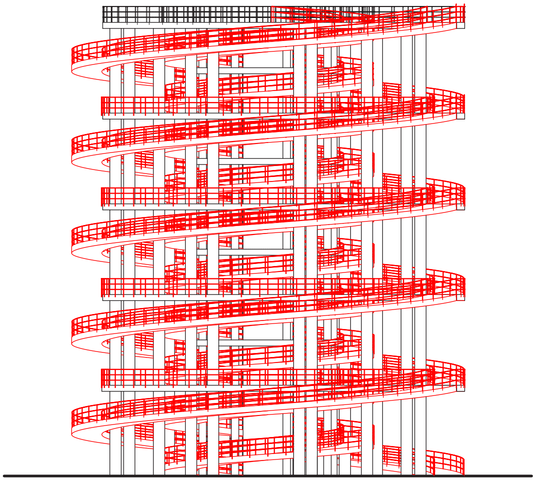
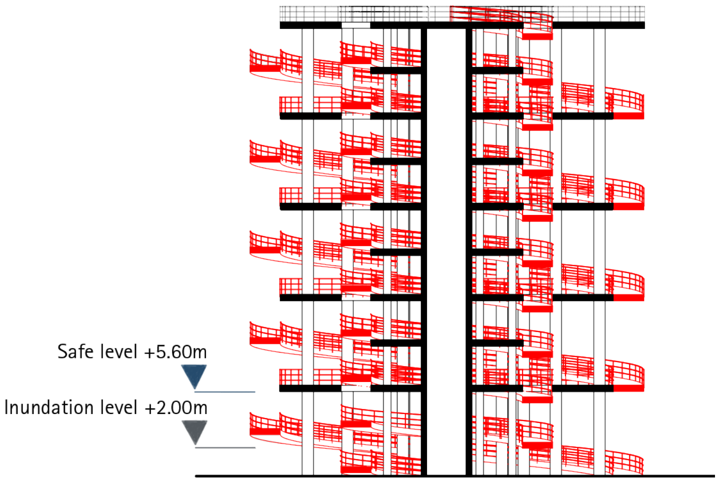


Figure 244:
Groundfloor plan
Source:
Eleonora F. Serpi.



Scale 1:500

Figure 245:
South elevation
Source:
Eleonora F. Serpi.



Scale 1:500

Figure 246:
Cut AA
Source:
Eleonora F. Serpi.

Figure 247:
East elevation
Source:
Eleonora F. Serpi.

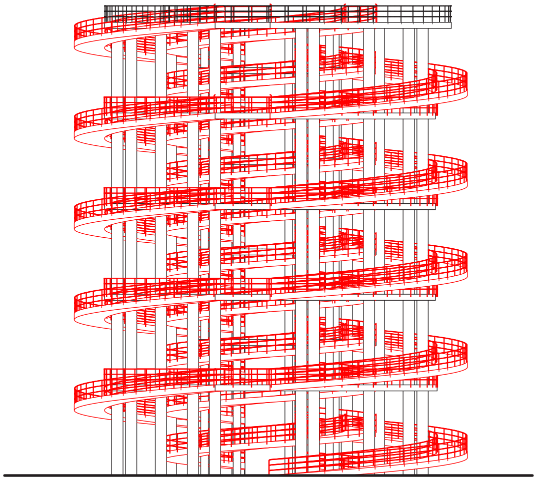
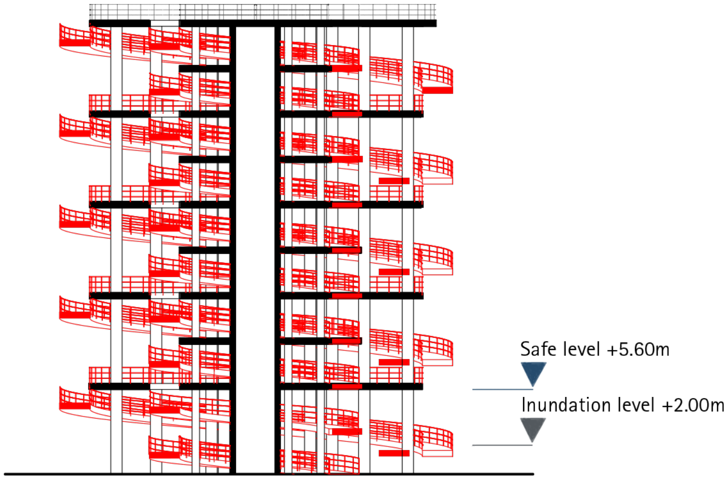
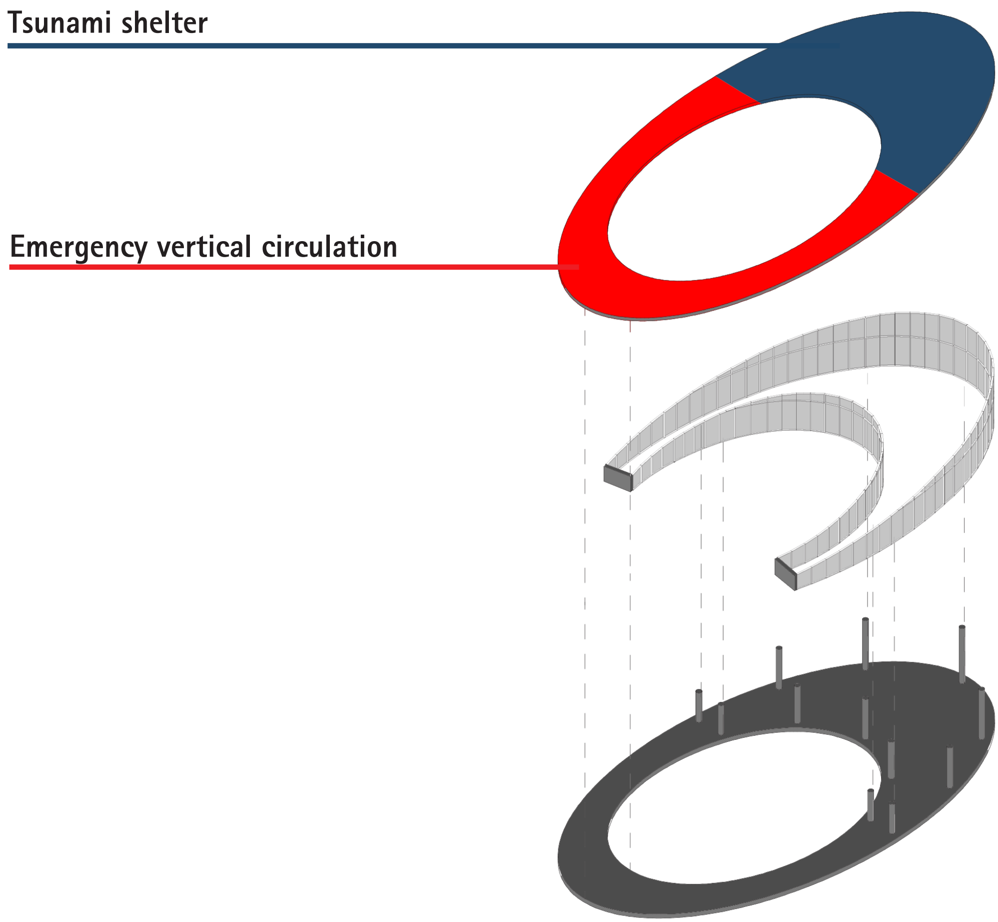
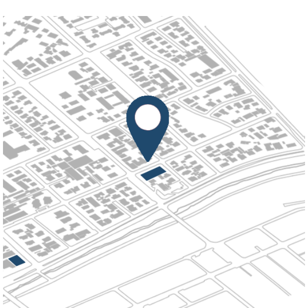


Figure 248:
Cut BB
Source:
Eleonora F. Serpi.



SHELTER 15: The cafe





Corner 5 Oriente and 2 Norte

300 people

Figure 249:
Exploded axonometry
Source:
Eleonora F. Serpi.

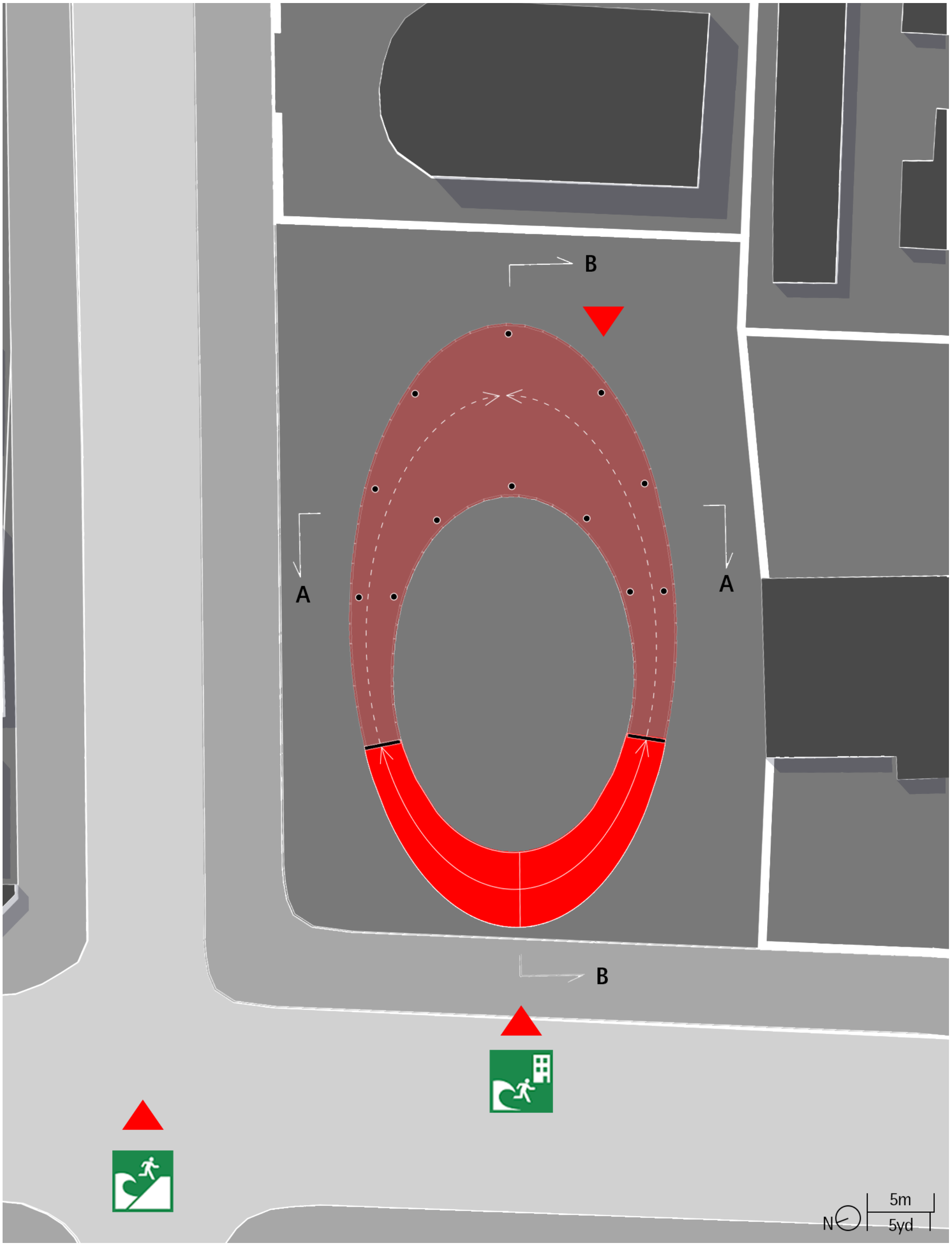
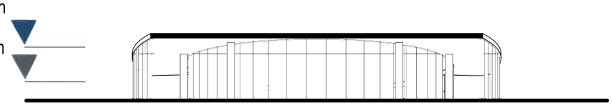


Figure 250:
Groundfloor plan
Source:
Eleonora F. Serpi.

Scale 1:500

Figure 251:
South elevation
Source:
Eleonora F. Serpi.



Scale 1:500

Figure 252:
Cut AA
Source:
Eleonora F. Serpi.

Figure 253:
East elevation
Source:
Eleonora F. Serpi.

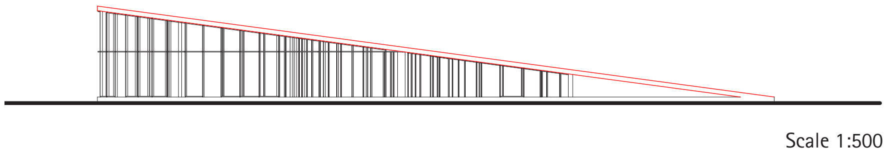
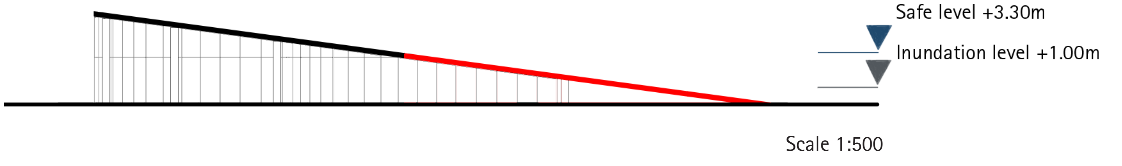


Figure 254:
Cut BB
Source:
Eleonora F. Serpi.



11.3 The ramps

The ramps, with exception for those of the shelters 3 and 15, 18 which have their autonomous separate structure, have been thought to be design as metallic ramps with 8% steepness, hanged to the building structures through a metallic node. The decision of designing a metallic ramp comes from the desire of thinking the ramp as a repeatable element that can be installed to all the structures, reducing the construction costs. Moreover, a metallic ramp would result lighter than a concrete one, reducing the already high weights that the structure has to withstand in case of emergency and allowing water to flow through, instead of opposing resistance and generating additional loads.

The estimation of travel time within the TVEB may need adjustment for different methods of vertical circulation, in this study, as shown in table 15 (paragraph 12.1.1, page 242), an esteem calculated on the basis of the ambulatory speed through ramps with 2m width and 8% of steepness can guarantee the evacuation of about 2000 people in the 8min frame which is the one supposed at the beginning of the design process for the vertical circulation inside the TVEB to reach the minimum security height.

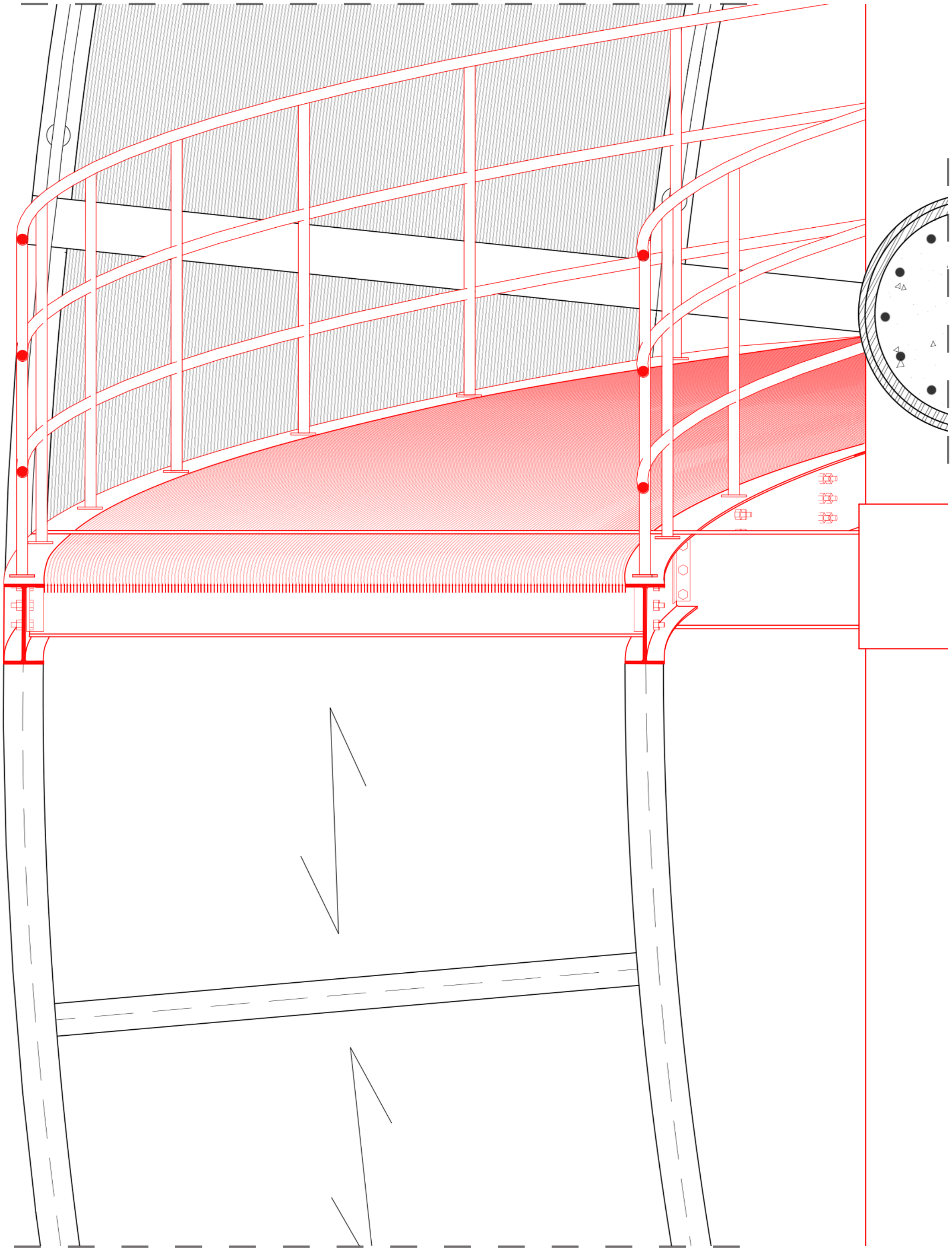


Figure 255:
Ramp plan and cut,
scale 1:20
Source:
Eleonora F. Serpi.

11.3 The new evacuation plan of the Población Vergara

The evacuation plan for the Población Vergara results from the integration of the of the existing horizontal evacuation plan designed by the ONEMI[387] on the basis on the inundation map draft by the SHOA[388] with the new vertical evacuation system composed by 8 existing buildings and the 15 new TVEBs (see figures 256-257). The plan thus composed guarantee the evacuation 33.200 people, corresponding to the 106% of the people who, in case of tsunami alert, wouldn't be be able to evacuate the sector in less than 15min through the existing horizonatl evacuation plan due to the great distance from the tsunami secure zone. The new evacuation plan, to be fully effective, needs to be implemented with new road signs indicating the location and the distance of the shelters. Awareness programs and evacuation simulation will have to be organized to show the population where such shelters are located and how they work.

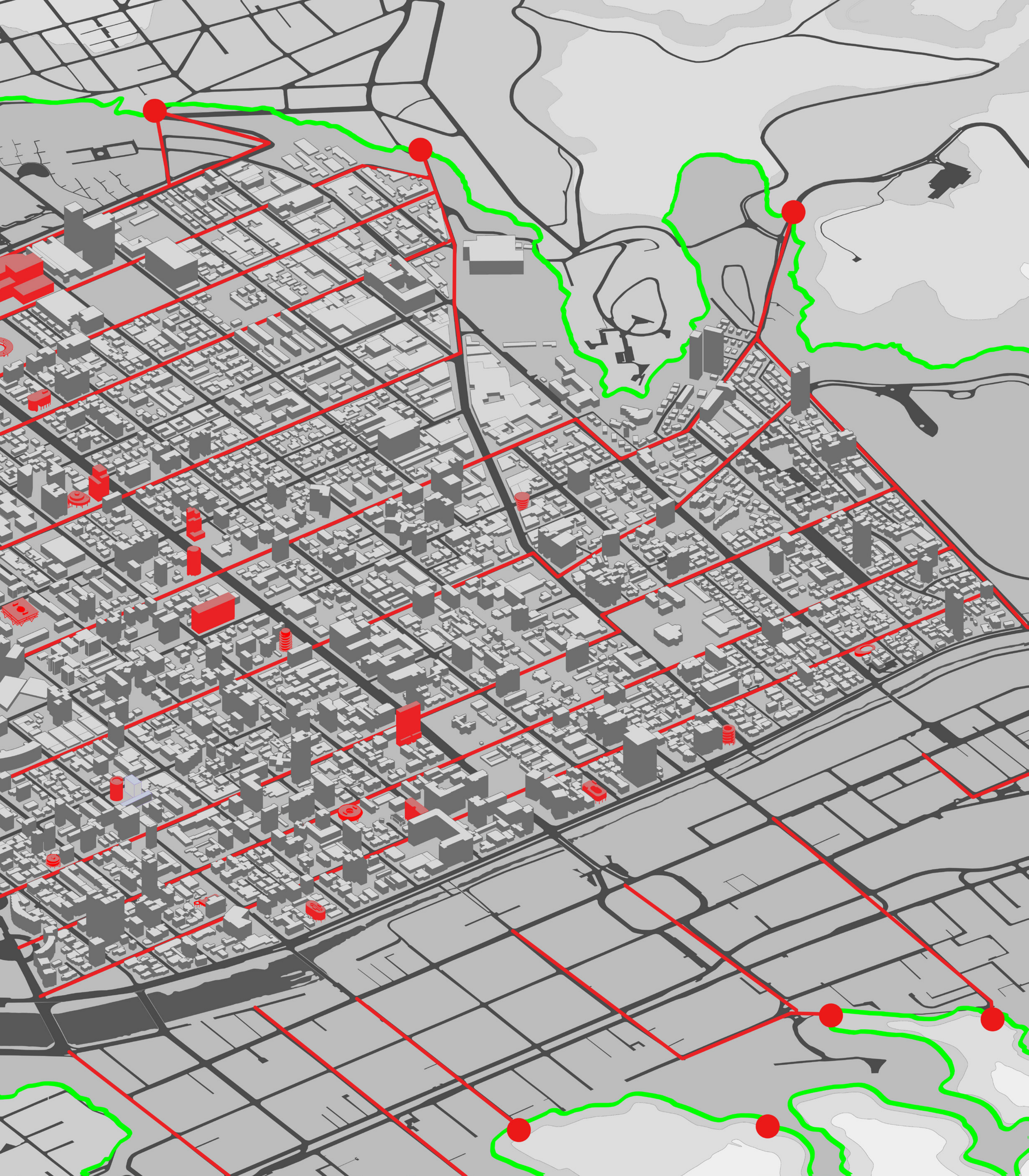
[387]National Emergency Office of the Ministry of the Interior, "Planos de Evacuación. Viña del Mar," accessed May 13, 2018, http://www.onemi.cl/mapas/region/valparaiso/.

[388]Chilean Navy Hydrographic and Oceanographic Center, "Cartas de Inundación por Tsunami (CITSU). Valparaíso - Viña del Mar."

[288]Federal Emergency Management Agency, *FEMA P-646, Guidelines for design of structures for vertical evacuation from tsunamis*, 68.

Figure 256:
Delayering new tsunami
evacuation plan
Source:
Eleonora F. Serpi.

Figure 257:
New tsunami evacuation plan
of the Población Vergara
Source:
Eleonora F. Serpi.



DISCUSSION

Natural disasters, not to be confused with natural hazards, are a consequence of the interaction between man and nature. They originate when natural and physical vulnerabilities coexist in the same time and space, and their intensity increases with the constant population growth and the consequent urban development. Even if they cannot be predicted, neither prevented, their impact can be mitigated, and the vulnerability reduced through an appropriate risk management strategy. A risk management strategy comprehends four stages: preparedness, resistance, recovery and adaptability, each of them fundamental to improve the city and population resilience to natural disasters.

The exposure of an area to the risk depends on its geophysical characteristics and urban development. Chile, due to its proximity to the subduction zone between the Nazca and South American Plate, and its thousands of kilometers of coast is highly exposed to earthquakes and tsunamis. These two phenomena often combine together aggravating their impact on the built environment, causing life losses and damages to structures and infrastructures. Both life losses and structural damages can be limited, even prevented, thanks to a series of preventive measures.

While the Chilean building code regulate the design of seismic structure, it does not include norms regulating coastal structures subjected to tsunami risk. In an ideal scenario, the best solution to prevent tsunami risk would be to move the built environment further from the coast, away from inundation risk areas. Economic reasons and the human tendency to settle near the coast make this option impossible to be undertaken in most cases, especially as a preventive measure. It is then necessary to adapt the built environment to limit the damages and life losses, and protect the coast from inundation with protective structures, like seawalls, or preferably with natural barriers like sand dunes, coastal forests and beach nourishment. Even if none of the above protective measures proved to be able to stop a tsunami inundation, especially in case of major event, they resulted good mitigation systems able to reduce the strength and the run-up of the inundation.

An effective multi-strategic plan is based also on community preparedness, up-to-date hazard mapping, early warning system and evacuation. Combined, these measures can avoid life losses. Chile has a long record of tsunamis destroying the coast, causing economic damages and life losses but the lesson does not seem to be learnt yet. Viña del Mar is a clear example of it. The higher development of the city is in fact along of its waterfront and on a plan area where most of the services, tourist attractions and residential buildings combine.

Even if city and its inhabitants are aware of the risk menacing them, the city has not yet taken adaptation measure to mitigate the impact of a future event. Today the city disposes of an updated evacuation plan and well-developed alert measure, but recent studies proved not to be sufficient to evacuate all the vulnerable population in time in case of a local tsunami[289]. In the scenario of a near-field tsunami, in fact, the vulnerable population has a very short time, about 10/15 minutes, to undertake disaster-response activities like evacuation and sheltering. This last, at the present time, does not allow the entire population to reach a secure zone in an appropriate time. The studies showed that the death toll in the most affected area, the Población Vergara, can exceed the 800 people during day time[290].

This number is influenced not only by the long distance that has to be walked to reach the security zones, but also by the obstacles that cover the pedestrian area along the main evacuation routes[291], which might cause bottlenecks, falls and panic while the roads are likely to be blocked by traffic jams. To aggravate the situation, some of the particularly at-risk routes are the same that allow escaping the Población Vergara's most vulnerable zones due the proximity not on only to coast but also to the estuary on the Marga-Marga River. In the current scenario, the use of existing high-rise buildings as vertical evacuation shelters is not explicitly sanctioned by the Chilean emergency management fra-

[289] Jorge León, Cyril Mokrani, Patricio Catalán, Rodrigo Cienfuegos, and Carolina Femenías, "Examining the role of urban form in supporting rapid and safe tsunami evacuations: a multi-scalar analysis in Viña del Mar, Chile," Procedia engineering 212 (2018): 629-636.

[290] Ibid, 635.

[291] Ibid, 635.

mework, but it is currently suggested by ONEMI as an alternative measure in case of imminent danger. Some potential buildings can be identified but these are not designed or built to allow a safe ingress and sheltering of people. The disciplines that guide and control the urban development can therefore play a decisive role and have great influence on the overall outcome of an emergency evacuation.

Vertical evacuation strategies have already been adopted in countries like Japan, Indonesia and USA, their effectiveness have been proved by post-disaster reports following the 2011 Tohoku tsunami[292]. Vina del Mar is a great candidate how such evacuation can enhance the resilience of the city face a tsunami.

[292] Michael MacRae, 629-636.

CONCLUSIONS

Evacuation plans are part of the preparedness phase of a disaster management cycle, in the same phase architecture proved to be able to interpret the needs dictated by the emergency, translating them into real solutions thus allowing the population at risk to survive during the extreme event of a tsunami. The shelter is archetypal form of architecture, binding architecture and survival, the first action and tool to be put in place to keep alive. Many types of emergency shelter exist around the world, declined according to the characteristics of the natural hazard they are designed to withstand. A Tsunami Vertical Evacuation Building, TVEB, can guarantee the minimum survival conditions during a tsunami emergency increasing the degree of resilience of a community at risk, starting from avoiding life losses.

Vertical evacuation is fundamental in all those communities where horizontal evacuation towards natural high grounds in not possible. The new tsunami evacuation plan for the Población Vergara in Vina del Mar shows that, implementing the existing horizontal evacuation plan with a vertical evacuation system, can guarantee the safe and rapid evacuation of all the sectors which are too far away from the tsunami secure zone. The new evacuation system designed combining the existing evacuation plan with 23 TVEBs will allow, in case of tsunami, to evacuate 33.200 people, equivalent to 106% of the resident and floating population found in such sectors, while for the rest of the time the shelters will serve another function, according to their dual program.

The role of architecture in tsunami risk management does not end with the preparedness phase of the cycle, future investigations should focus on the adaptability of the coastal urban form starting with the necessary modification of the Territorial Planning Instruments, IPT, especially of the Communal Regulatory Plan, PRC. These instruments regulate the occupancy and constructability in flood zones and they can contribute to the construction of new building types adapted to the natural hazards that affect the coast. Today, most of the regulatory plans in coastal communes in central Chile do not incorporate special criteria for flood and tsunami risk, making them very vulnerable to the threat. In order to start the transformation towards an adapted coastal edge, it is necessary to start with the education of the population, the authorities and the professionals on the natural risks that affect the coastal area.

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