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THE PROPOSED DESIGN OF A SMART PARKING AREA AS A MULTIPLE USE BUILDING FOR THE EVENTUAL VERTICAL EVACUATION IN CASE OF TSUNAMI IMPACTS IN SALINAS, ECUADOR

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ABSTRACT

Ecuador is a country with high seismic risk, due to its proximity to the Pacific Ring of Fire. Hereby, strong seismic events are able to occur generating tsunamis, of which an impact may be imminent and whose response time will be short for the evacuation of the population to a safe place. Additionally, there are cities along the Ecuadorian coast that lack safe areas, understood as elevated areas and outside the flood or impact area. Therefore, within the current study in the city of Salinas, we contemplate an architectural and structural multi-hazard proposal, which includes tsunamis and earthquakes, as a multi-use type building that allows the vertical evacuation of the population, as well as the considerations of location, space and height of the building.

Keywords: *Smart parking area, multi-purpose building, vertical evacuation, tsunami, Ecuador*

1. INTRODUCTION

Tsunamis occur with great frequency in the Pacific Ocean due to the geodynamic constellation and the interaction of several tectonic plates (Iwasaki et al., 1992; Sladen et al., 2010; Hagen & Azevedo, 2018; Parwanto & Oyama, 2014). Earthquakes such as tsunamis on the seashore are a severe hazard to human life, socio-economic activities and as well as strategic infrastructure (Athukorala & Resosudarmo, 2005; Martinez & Toulkeridis, 2020; Plümper et al., 2017; Wong & Said, 2020; Cochard et al., 2008; Navas et al., 2018; Rodriguez et al., 2017; Pararas-Crayannis, 1980; 1983; 1988; 2002; 2013; 2010; 2012; 2014; 2018; Pararas-Crayannis & Zoll, 2017). Therefore, countries such as the United States, implemented a guide for the design of structures capable of resisting seismic events and later the tsunamis caused by the seismic event in order for these structures to be used as safe zones or vertical evacuation shelters (Park et al., 2012; Mostafizi et al., 2019; Wood et al., 2014; Heintz & Mahoney, 2008).

Ecuador has a high seismic risk, as it is situated along the subduction area of the Nazca oceanic plate with the South American and Caribbean continental plates (Massonne and Toulkeridis, 2012; Acosta, 1983; Gutscher et al., 2000; Padrón et al., 2012; Suhr et al., 2019; Chunga et al., 2019).

Based on the historic record, since the year 1586, some 58 tsunamis were registered in the Ecuadorian coastal profile, of which ten were generated with a nearby source, causing damage and short evacuation times (Chunga & Toulkeridis, 2014, Contreras López, 2013; Rodriguez et al., 2016; Matheus Medina et al., 2016; Toulkeridis et al., 2017; Rodriguez et al., 2017; Chunga et al., 2017). The tsunami hazard is relatively high in Ecuador, since a seismic event is able to cause tsunamis with very short response times for evacuation (Toulkeridis et al., 2017; Edler et al., 2020). Additionally, the small number of natural elevated areas combined with the short evacuation times results for horizontal evacuation to be ineffective (Toulkeridis, 2016; Aviles-Campoverde et al., 2021; Suárez-Acosta et al., 2021).

In Ecuador, several studies have been conducted on tsunamis and their effects, relocations of highly vulnerable areas, vertical evacuations, among other studies of the nature of prevention and mitigation such as resilience to seismic threats and tsunamis on the coast (Toulkeridis et al., 2018; Mato & Toulkeridis, 2018; Celorio-Saltos et al., 2018; Matheus-Medina et al., 2018; Toulkeridis et al., 2019; Toulkeridis et al., 2019; Rentería, 2013).

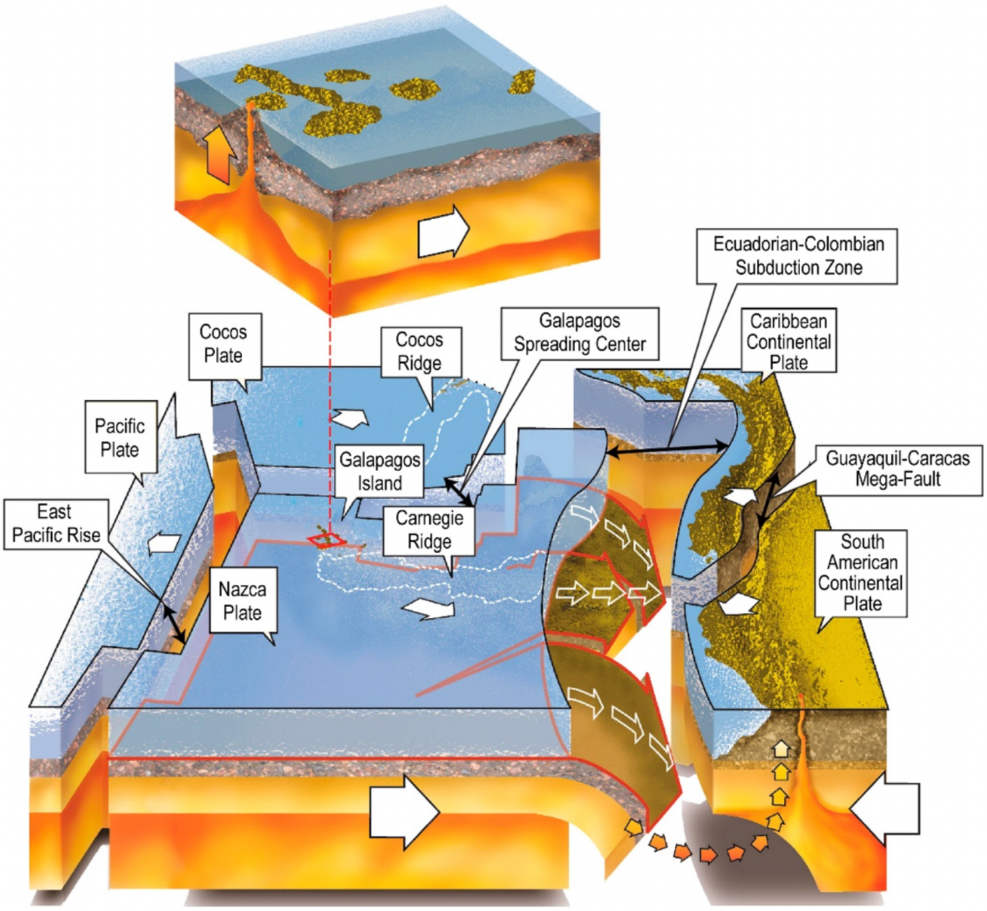

Fig. 1: Geodynamic setting of Ecuador with associated oceanic and continental plates and a variety of plate boundaries, such as the divergent plate boundaries named East Pacific Rise and Galapagos Spreading Center, the convergent plate boundary represented by the Ecuadorian-Colombian Subduction zone, as well as the transcurrent plate boundary represented by the Guayaquil-Caracas Maga-Fault. Also shown the Galapagos Islands and the Carnegie Ridge. Adapted from Toulkeridis, 2013, modified by Toulkeridis et al., 2017.

Based on the aforementioned, the current study analyzed the historical data of earthquakes and tsunamis that occurred in Ecuador, as well as tsunami projections for the city of Salinas. Therefore, the height of potential tsunami waves has been numerically modeled, which served as the basis for the implementation of a smart parking center design, which in turn could serve as a temporary shelter in the event of a necessary vertical evacuation. The same parking center needs to have characteristics of a design that will be able to resist seismic movement and the impact of tsunami waves.

2. STUDY AREA AND NUMERICAL MODELING OF INCOMING WAVE

Salinas is one of the most visited coastal cities by tourists due to its marvelous beaches and modern hotel services. Located in the province of Santa Elena, with a warm climate and low hills, it is a great attraction for domestic as well as international tourists. This last characteristic makes Salinas a highly vulnerable city to the impact of a tsunami because it does not have natural elevated areas. Tsunami risk studies indicate that Salinas is a city with large areas vulnerable to flooding and also with a large influx of people during certain times of the year because it is a highly frequented tourist place (Toulkeridis et al., 2017; Matheus-Medina et al., 2018; Ioualalen et al., 2018). The location of the city of Salinas, and its coastal configuration, expose it to the arrival of tsunamis that could occur throughout the Pacific, so much so that the last two large tsunamis (ie Chile 2010, Japan 2011) arrived at this location, causing strong eddy currents, although they did not cause flooding, these were distant events (Pararas-Carayannis G., 2010; Simons et al., 2011; Norio et al., 2011; Rentería et al., 2012; Lynett et al., 2013).

The only historical record of a local event for the city of Salinas occurred on October 2, 1933 when a strong earthquake off the coast of Santa Elena, caused sea level disturbances, but failed to flood the city (Soloviev, 1984). The historical records are consistent with the GPS observations where a coupling between the tectonic plates cannot be evidenced, however, given the tectonic configuration of the entire region, and the records of paleotsunami events very close to Salinas, experts suggest the possibility of a large earthquake of at least 8.2 Mw. (IOC / UNESCO, 2020).

The characterization of tsunami using numerical models is scarce for this locality. (Renteria, 2007) proposed as a scenario the earthquake of December 12, 1953, of 7.3Mw, located in the Gulf of Guayaquil, and although the simulated disturbances were insignificant, it can be seen how the tsunami covers the entire peninsula, allowing inferring the consequences of a major event. (Ioualalen et al., 2014) proposes a hypothetical scenario of 8.0Mw for the same area, again the effects can be seen in the southern part of the peninsula, although the study does not go into detail about the effects in the city of Salinas. In 2019, INOCAR published a tsunami flood map for the city of Salinas based on a scenario of 8.4Mw in front of the peninsula; this map indicates that the wave height could reach up to 7 meters in some points of the city (INOCAR, 2019).

In this study, a flood map is proposed that considers the rupture plane proposed by the experts (IOC / UNESCO, 2020), and the magnitude proposed by (INOCAR, 2019), that is, 8.4 Mw. For tsunami modeling, the MOST model is used in its ComMIT interface (Titov, et al., 2011). The digital model was built from the topography data of the SIGTIERRAS Program of the Ministry of Agriculture and Livestock of Ecuador, and the bathymetry taken from (Ryan, et al., 2009). The model does not assume any tidal state, and is referred to the mean sea level.

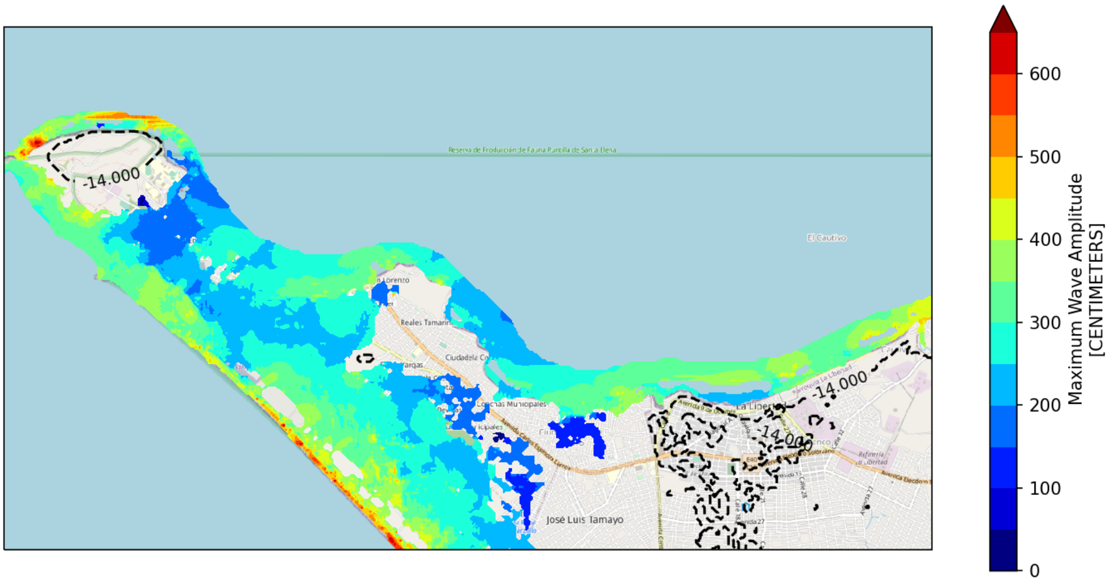

Fig. 2. Tsunami flood map for Salinas, based on an 8.4Mw earthquake off the Santa Elena peninsula.

Figure 2 illustrates the numerical modeling of a tsunami produced by an 8.4Mw earthquake off the Santa Elena peninsula.

The tsunami wave front impacts the peninsula from both the north and south sides, flooding the city of Salinas from both directions. This is an important piece of information for risk management purposes, since under this consideration, the only way out for the population is vertical evacuation and evacuation towards the hill of the Naval Base. It can be seen that some points of the coastline reach heights of up to 6 meters. The depth of flooding within the city, that is, the laminar flow of water, is between 3 and 4 meters, with currents that can fluctuate, within the city between 4 and 6 m / s (Fig. 3).

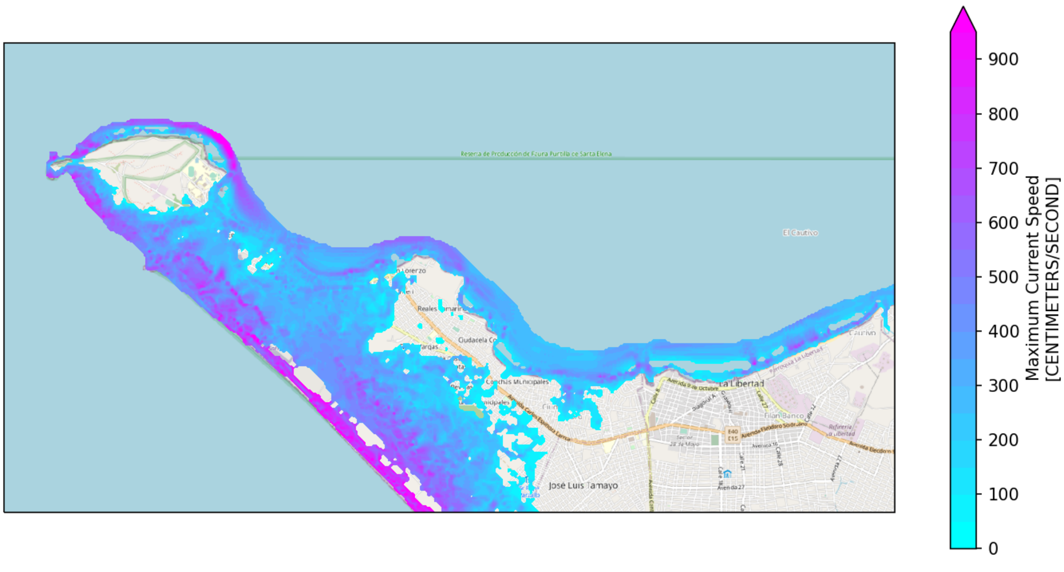

Fig. 3. Tsunami currents map for Salinas, based on an 8.4Mw earthquake off the Santa Elena peninsula.

Previous performed studies appear to project a maximum wave height of up to 6 meters at least for the city of Salinas (Matheus Medina et al., 2016). The results of the current study with modern tools and software, coincides with the height of the tsunami waves of previous studies. Therefore, in the event of a tsunami, the wave would reach the city in an interval of 8 to 12 minutes with an approximate height of 6 meters.

Additionally, like in (Suárez-Acosta et al., 2021), we used the extensively validated tsunami modeling tool, the ComMIT/ MOST model (Community Model Interface for Tsunami), which is an internet-enabled interface to the community tsunami model developed by the NOAA Center for Tsunami Research (NCTR). This interface let one run the MOST model (Method of splitting tsunami), a non-linear shallow water model, which has been extensively, validated from field observations and laboratory experiments (Titov et al., 2011; 2016).

3. METHODOLOGY

A variety of conditions need to be assessed for the design of a structure in the shelter capacity. The distribution of shelters must also be considered, considering evacuation routes and the maximum distance at which the shelters should be located. Therefore, the conditions of the site, space and the elevation of the structure are predominant.

3.1 Site

There are several aspects that must be taken into account, among which the availability of space within the city for the implementation of the project, the speed of movement of people to determine the maximum space between shelters, finally, the existence of structures with a level of adequate performance in the face of multi-threat events and the necessary height to be above the flood level.

In Salinas, the study conducted by Matheus Medina et al. (2016) uses existing structures with sufficient height to define safe zone areas for vertical evacuation. Among which, it stands out that zone 7 covered by the Port Royal Place building does not have the capacity for population density in high seasons, with an approximate deficit of 215 people. Therefore, the proposal must be located in this area. In the figure above, the red dot represents available terrain, approximately 20 meters wide by 45 meters long. In which the development of this proposal is proposed and on which the necessary data for the architectural and structural design will be taken.

3.2. Space

The population density of the area and the number of nearby vertical evacuation structures define the space in the structure. To determine the space, it must be taken into account that the structure is a shelter of short duration, since severe wave cycles do not exceed 24 hours. Another fundamental aspect is that the effective area is considered as a percentage of the total area depending on the concentration of furniture or fixed seats. First, the speed of movement of people in an evacuation event must be estimated, which is approximately 3.2 km / h according to FEMA (FEMA, 2019). And knowing the arrival time of the 11-minute wave previously proposed, it can be concluded that the maximum distance between shelters is 1172 meters or 586 meters from any starting point /Matheus Medina et al., 2016).

On the other hand, the shelter must have a capacity of at least the 215 people mentioned above and once it has been determined that the vertical evacuation shelter is of short duration, a value of 0.93 square meters per person can be used to determine the effective area (F. E. M. A., 2019). Therefore, the minimum effective area of the structure should be 199.95 square meters. Finally, the terrace of the structure will not have fixed seats or furniture, so the effective area is considered 85% of the gross area, thus obtaining that the minimum area of the structure must be 235.26 square meters (FEMA, 2019).

3.3. Elevation

The minimum level that the structure must overcome is the projection of wave height plus percentage of variation of wave height and free edge space as security for the refugees (Fig. 4). The wave height projection for Salinas was estimated at 6 meters high. However, there are several conditions that must be met simultaneously for the wave to reach this maximum height. Among the most important characteristics, it must be fulfilled that the epicenter of the generating earthquake must be close and perpendicular to the coastal profile and the magnitude of the earthquake must be greater than 6.9 Mw. Additionally, as recommended, the design flood level coincides with 30% of the flood level (ASCE SEI., 2016; ASCE SEI., 2000). Thus obtaining 7.8 meters of height of the refuge.

Finally, this value must include a free edge. This value must be the largest of 3 meters or the height of one floor. In this particular case, the free edge is 3.42 meters, resulting in a minimum shelter height of 11.22 meters. In conclusion, the proposal must comply with at least 235 square meters of gross area and 11.22 meters in height.

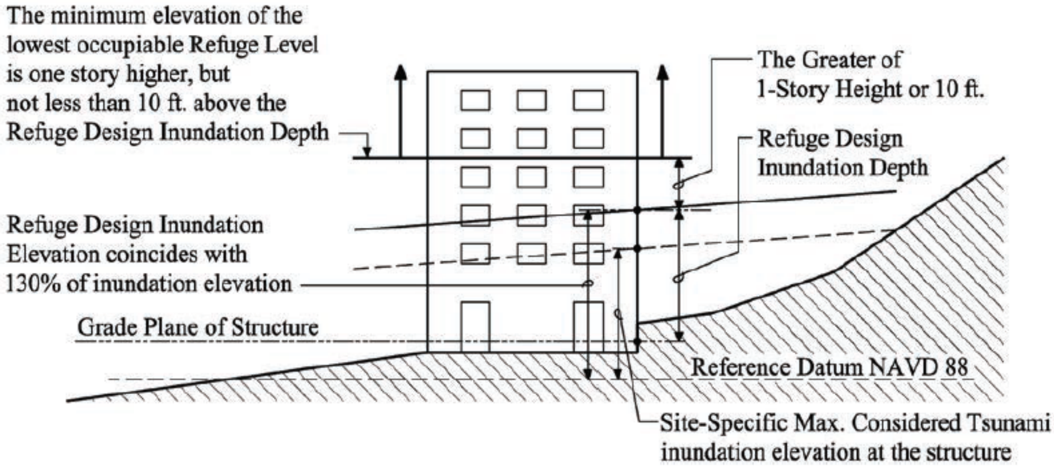

Fig. 4. Elevation consideration (ASCE SEI., 2016).

4. RESULTS AND DISCUSSION

4.1 Architectural proposal

Salinas is a tourist and hotel city, so a parking building or a hotel are ideal to meet the multipurpose objective of the structure, since, the structures will be in permanent use and would allow economic rewards to the city (Fig. 5). For the proposal, the construction of a garage is proposed, since it offers structural security and great performance in the face of multi-threat events (earthquakes and tsunamis).

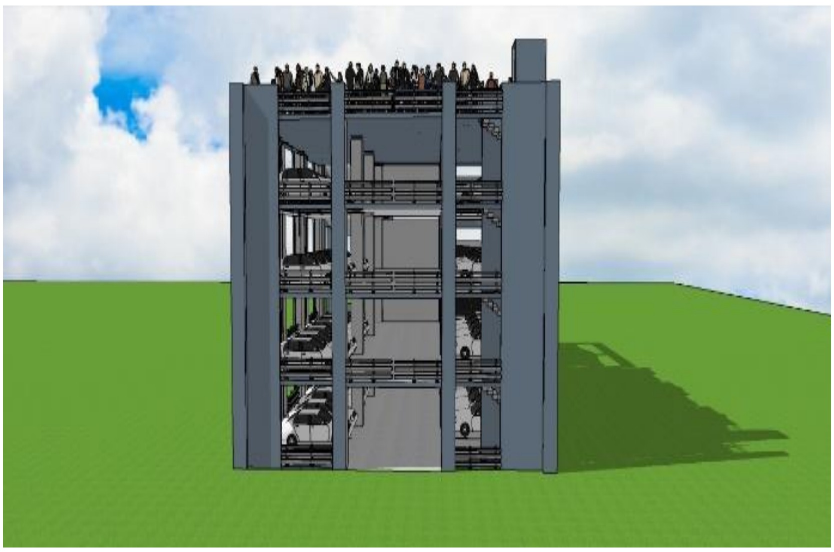

Fig. 5. Architectural proposal, Garage.

As these types of facilities are open structures that allow the free flow of water, making the loads that the building resists due to tsunami actions are significantly lower. Additionally, the vehicle ramps allow an effective vertical evacuation for the large influx of people during the multi-threat event. Once the type of structure to be designed has been defined, it is also necessary to choose the types of vehicles allowed in the parking lot (Fig. 6). The design loads depend on this, and to guarantee a high level of performance, the garage is designed to receive motorcycles and light vehicles, characterized in the following image.

The structure was architecturally designed for the available space presented in section 2.1 with the following layout. The ground floor has space available for 10 light vehicles and 6 motorcycles (Figs. 7, 8).

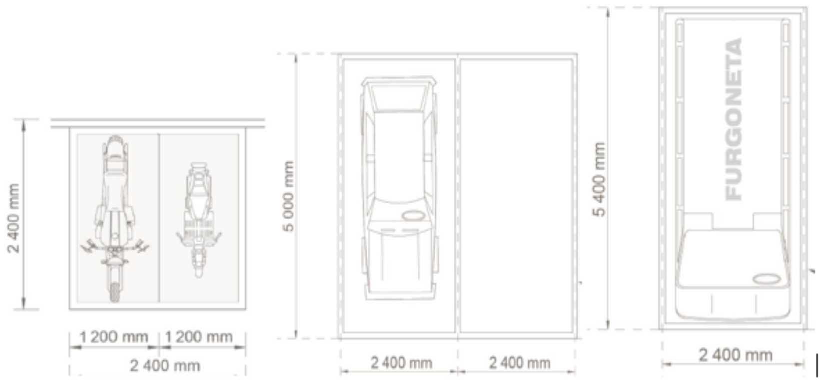

Fig. 6. Types of vehicles (NTE INEN 2248, 2016).

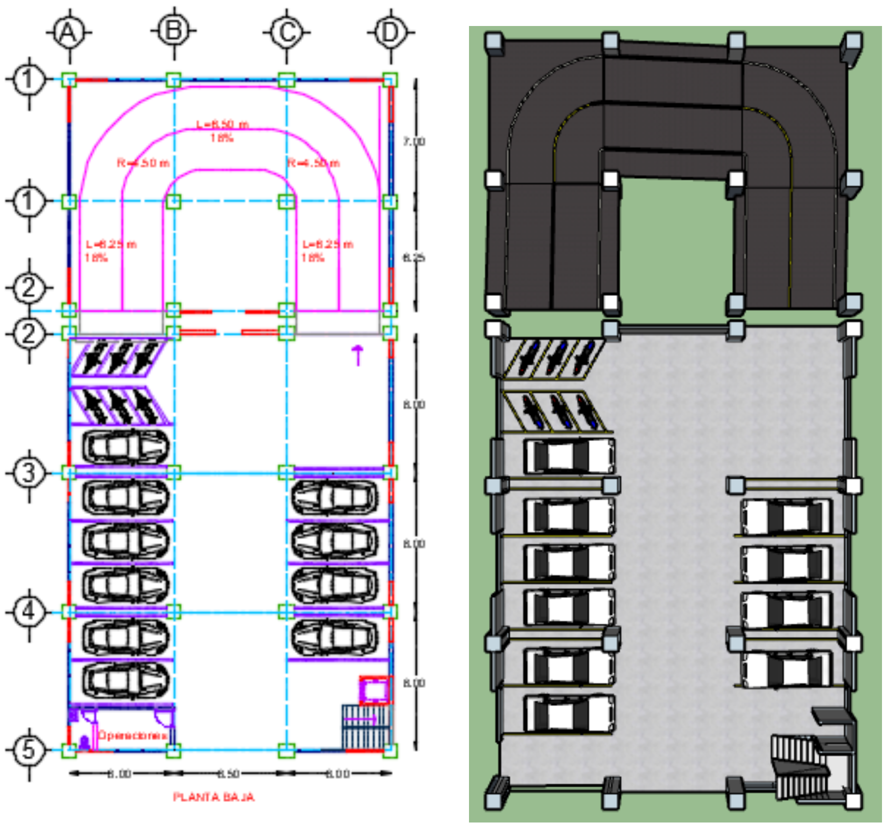

Fig. 7. Layout on the ground floor

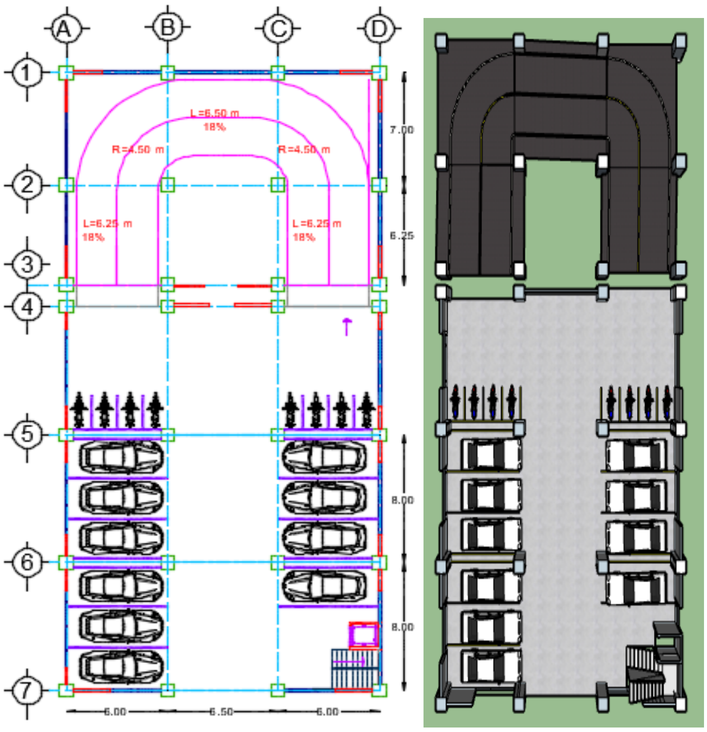

Fig. 8. Distribution in intermediate plants

The intermediate floors have space available for 10 light vehicles and 8 motorcycles. Finally, the upper floor is for the exclusive use as a refuge. And all the space must be free to maximize the number of refugees (Fig. 9).

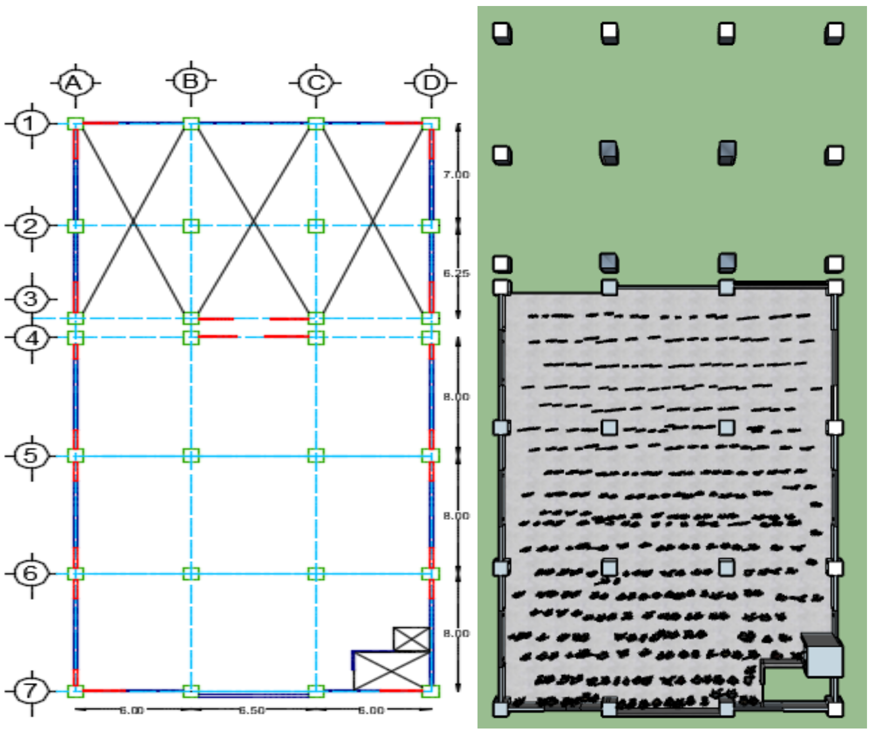

Figure 9. Top floor layout

The architectural proposal is a garage with a dual system of 4 floors and a total height of 13.8 meters; it has a gross area of 424.56 square meters and a capacity for 388 people in the shelter. In addition, it has space for 40 light vehicles, 30 motorcycles (Fig. 10).

Fig. 10. Final architectural proposal

4.2 Structure design

Once the architectural proposal is established, the respective structural design of the building is conducted with the support of specialized software, which is divided into two blocks. The first consists of ramps for vehicle access and the second is designed on its first three floors for parking and on its upper floor for shelter (Table 1; Fig.11, 12)

Table 1. Types of load for structural design

Type of load	Value	Reference
Live load for parking lots	200 kg/m2	(NEC-SE-CG, 2015)
Live cargo for shelter	480 kg/m2	(ASCE SEI, 2000).
Live load for ladder	480 kg/m2	(NEC-SE-CG, 2015)
Dead load of finishes	100 kg/m2	

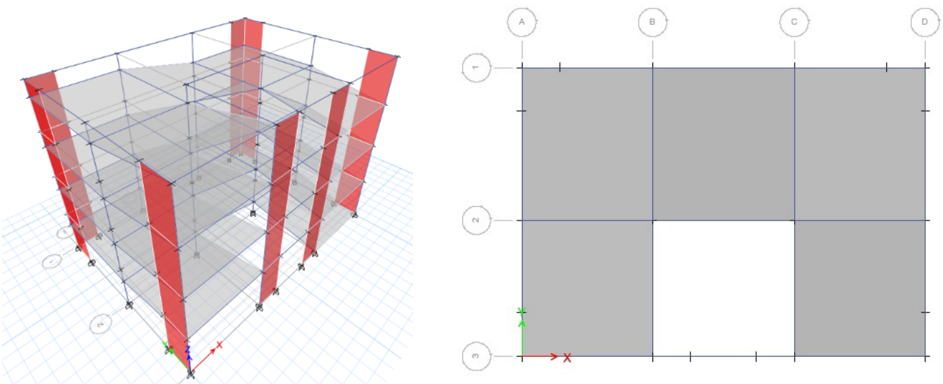

Fig. 11. 3D and plan view of Block 1

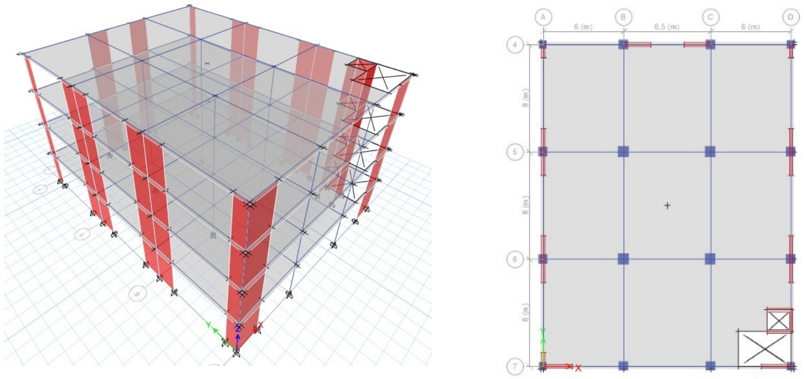

Fig. 12. 3D and plan view of Block 2

Since the structure is multi-purpose, when it is not working as a vertical evacuation shelter, it will be working as a parking lot for vehicles, so different types of cargo are used in its design according to the needs of the structure.

4.3 Performance level

A vertical evacuation structure must meet the levels of operational performance and immediate occupation according to the performance objectives presented by the [45] for both earthquakes and tsunami, this is because the structure must be in good condition. to shelter people seeking to protect themselves from the impact of a tsunami (Fig. 13, 14).

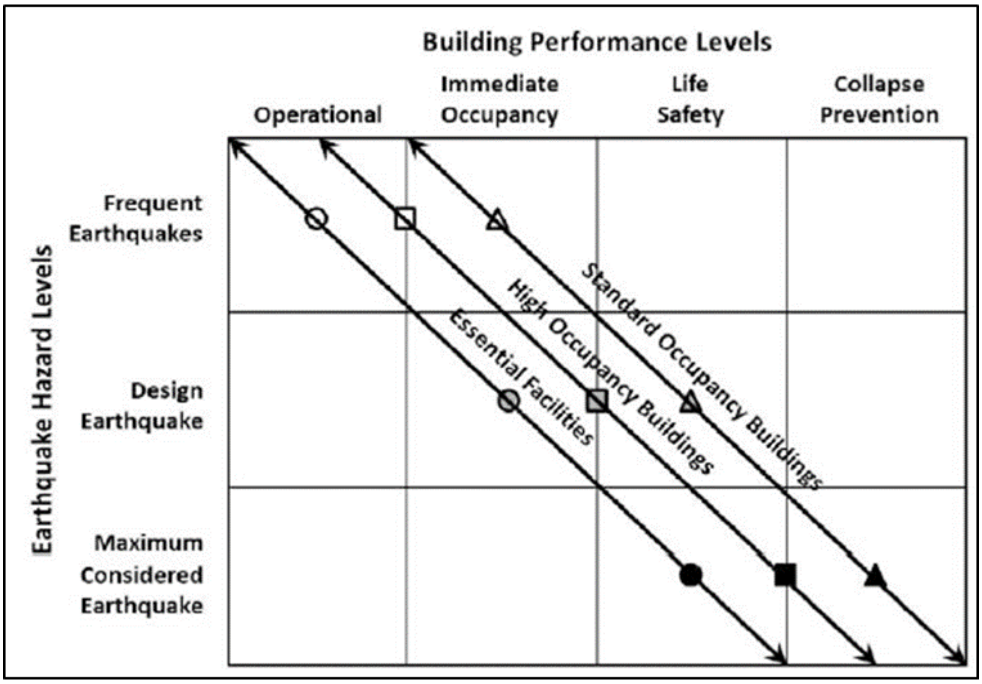

Fig. 13. Performance objectives (FEMA, 2019).

Fig. 14. Tsunami performance targets (FEMA, 2019).

According to the Chilean Association of Seismology and Antiseismic Engineering ACHISINA (2017), it is necessary to have acceptance criteria for essential structures that are at the level of immediate occupation according to the performance objectives. These parameters are classified according to the type of masonry, for the case of ductile masonry the maximum drifts should be 0.7% and for structures with brittle masonry maximum drifts of 0.5% (Fig. 12).

Additionally, certain considerations must be taken for the maximum earthquake considered corresponding to 2500 years, the ASCE SEI. (2000) mentions that the spectrum must be calculated by multiplying the design earthquake corresponding to 475 years by the factor 1.5, and the global acceptance criterion of the structure must be maximum drifts of 1.5% (Fig. 13).

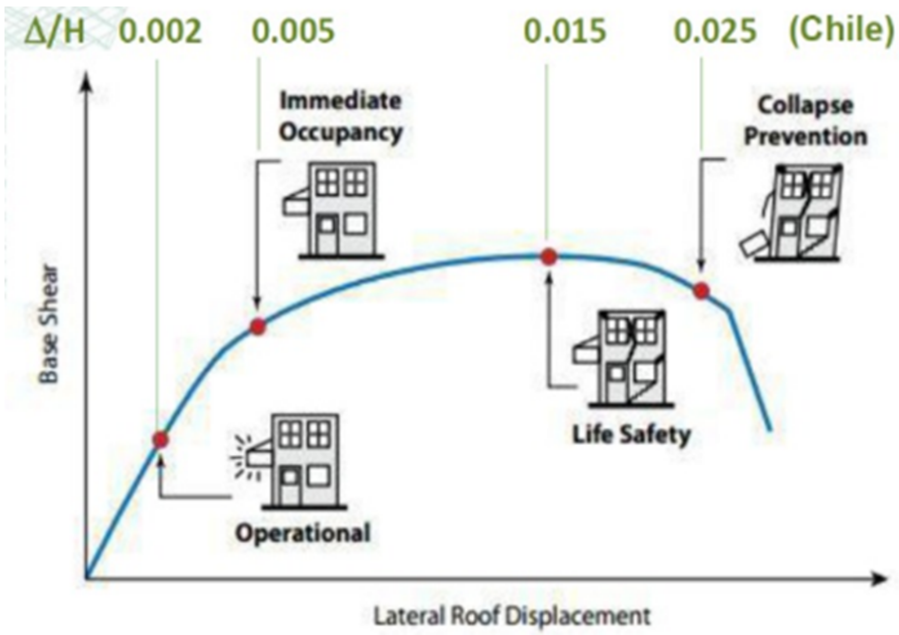

Fig. 15. Drifts for each of the performance levels (ACHISINA, 2017).

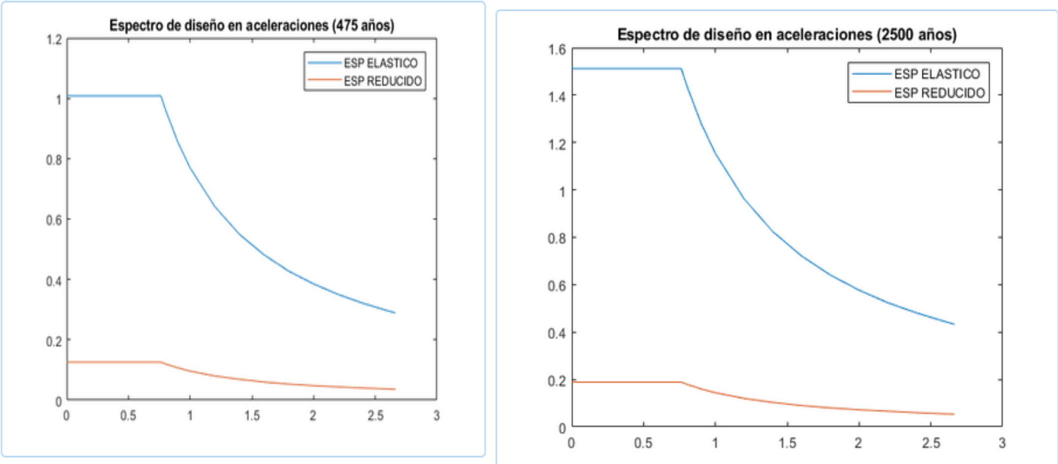

Fig. 16. Design spectra for earthquakes of 475 and 2500 years respectively

4.4 Drift control

The drift control is carried out by applying each of the load combinations with the design spectra for both 475 and 2500, values less than 0.7% and 1.5% respectively must be met in both the X and Y directions of block 1 and 2 (Table 2; Fig. 17).

Table 2. Floor drifts for the 475-year earthquake in Block 1

Float	Load	Drift	Real drift	<0.70%.
1	earthquake X	0.000637	0.38%	Complies
2		0.001065	0.64%	Complies
3		0.001098	0.66%	Complies
4		0.001085	0.64%	Complies
1	earthquake Y	0.000676	0.41%	Complies
2		0.000954	0.57%	Complies
3		0.000977	0.58%	Complies
4		0.000922	0.55%	Complies

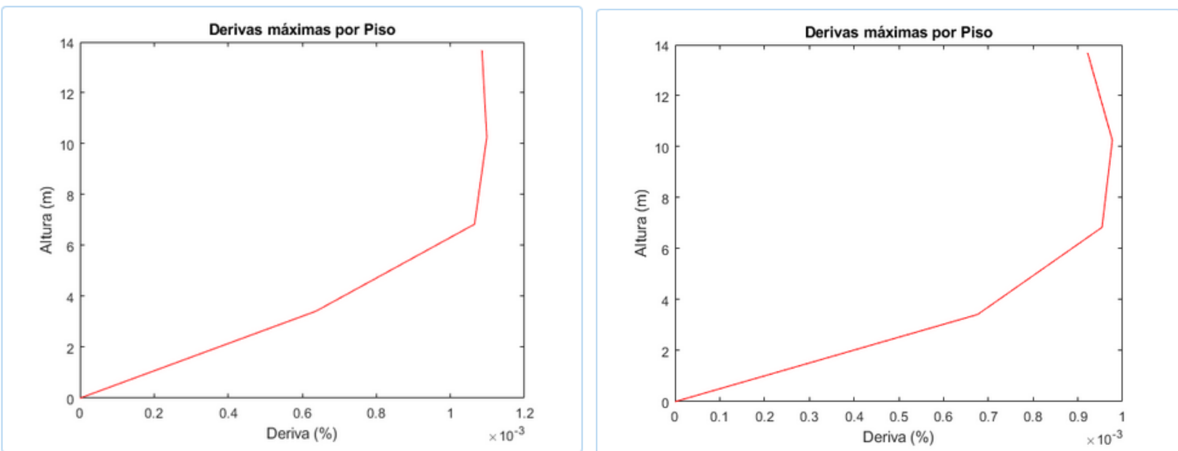

Fig. 17. Drift control in the X and Y direction of Block 1

4.5 Application of tsunami loads

The application of tsunami loads is done according to three cases established by the ASCE (2000), and according to a logical sequence that begins by placing the impact loads and subsequently the sustained loads, both hydrostatic and hydrodynamic, in each one of the porches.

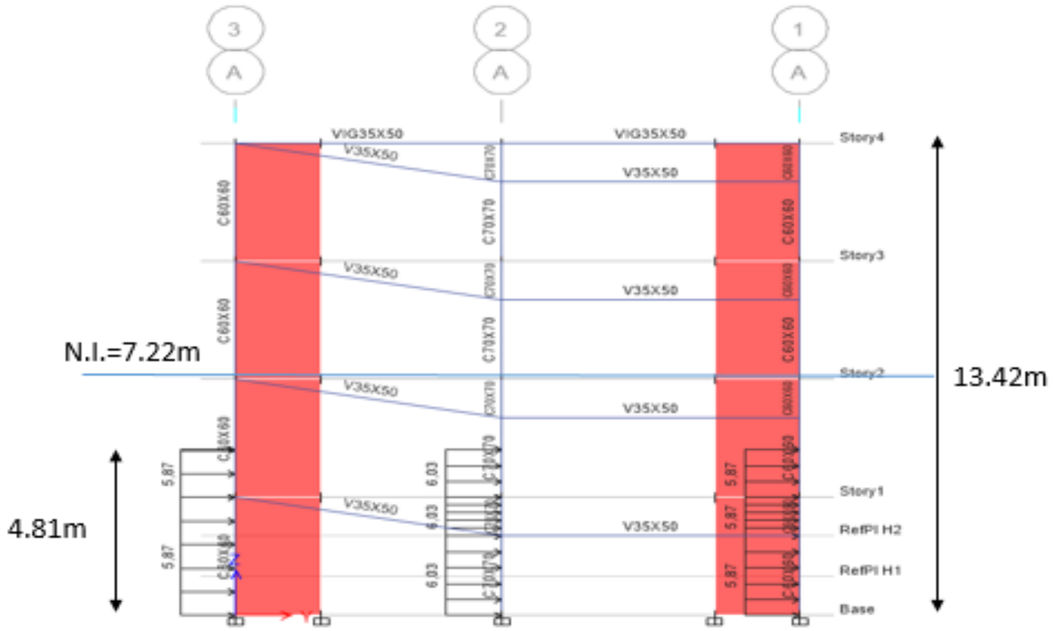

Fig. 18. Application of loads according to case 2

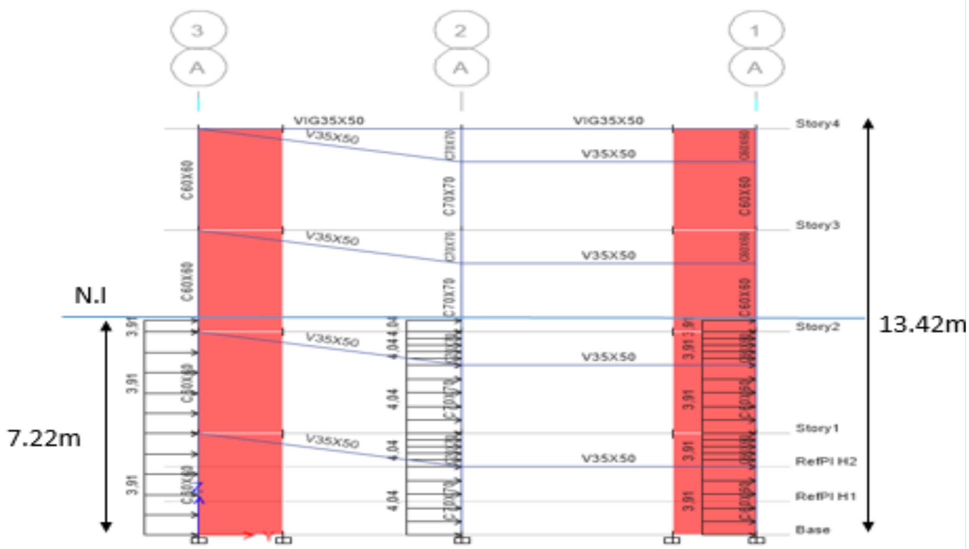

Fig. 19. Application of loads according to case 3

- First case: the exterior flooding is considered without exceeding the maximum height or less than one floor in height, in addition, the hydrodynamic forces combined with buoyancy forces are considered. This case does not apply for open structures.
- Second case: a flood depth equivalent to two thirds of the maximum height is considered in round-trip conditions.
- Third case: the maximum flood height is considered in round-trip conditions.

4.6 Cost analysis

The potential impact of tsunamis has potential wave heights over 5 meters. As a result, flooding may cover two or three floors, so the refuge level needs to consider such height: However, it would a wave of that height and its flooding impact will directly impact on property. This is critical in Salinas, as it was stated before, because the city is especially susceptible to tsunamis and flooding.

Although recent architecture design proposals have been made to deal with flooding. In a recent article in Insider, Danish architecture design firm, Tredje Natur, has proposed a new concept in architecture named as Pop-up design. This proposal has been developed in cooperation with the engineering companies COWI and RAMBØLL seems to deal with flooding efficiently. This proposal is based on Archimedes principle and seems to give a solution to flooding problems in urban areas (Leanna Garfield, 2017). However, this proposal has not been executed and it is quite expensive, alternative solutions needs to be proposed to protect human beings and provide alternative shelters regarding natural hazards.

This study proposes a new parking garage building that will function as well as refuge in case of a tsunami and flooding. The calculation of work volumes and cost calculation of the proposal is presented using the unit price analysis system (APU), to determine the direct cost. The indirect cost was assumed as 10% of the direct cost. Hereby, the next three tables, which are presented below, list the summary of items and volumes of work, required for the cost calculation (Table 3), the summary of costs for each item (Table 4), while the final table calculates the total cost of the structure, including direct and indirect costs (Table 5).

Table 3. Work volumes

No.	Heading	Quantity	Unit
1	Provisional Enclosure	153.20	ml
2	Cleaning and clearing	689.13	m^2
3	Setting out and Leveling	689.13	m^2
4	Reinforcing steel	46,659.26	kg
5	Plaster	2,100.94	m^2
6	Simple concrete columns and walls f´c = 240 kg / cm^2	327.08	m^3
7	Underlayment slab	133.20	m^3
8	Slab concrete f´c 240 kg / cm^2	421.98	m^3
9	Slab formwork	740.77	m^2
10	Concrete bleachers	10.16	m^3
11	Lightening (40x40x25)	4,504.00	u
12	Step formwork	69.28	m^2
13	Metal railings Cars	304.35	ml
14	Railing	128.10	ml
15	Beams	284.15	m^3
16	Beam formwork	1,087.84	m^2

Table 4. Summary of unit price analysis

HEADINGS		COSTS
1	Provisional Enclosure	$ 11.55
2	Cleaning and clearing	$ 1.48
3	Setting out and Leveling	$ 1.34
4	Reinforcing steel	$ 2.34
5	Plaster	$ 19.26
6	Simple concrete columns and walls f´c = 240 kg / cm^2	$ 129.99
7	Underlayment slab	$ 233.95
8	Slab concrete f´c 240 kg / cm^2	$ 134.90
9	Slab formwork	$ 12.53
10	Concrete bleachers	$ 124.94
11	Lightening (40x40x25)	$ 3.63
12	Step formwork	$ 12.53
13	Metal railings Cars	$ 190.34
14	Railing	$ 31.71
15	Beams	$ 137.93
16	Beam formwork	$ 19.42

Table 5 Budget price and adjustments (total costs)

No	HEADINGS	AMOUNT	COST	TOTAL
1	Provisional Enclosure	153.20	$ 11.55	$ 1,769.54
2	Cleaning and clearing	689.13	$ 1.48	$ 1,020.50
3	Setting out and Leveling	689.13	$ 1.34	$ 924.03
4	Reinforcing steel	46,659.26	$ 2.34	$ 109,147.94
5	Plaster	2,100.94	$ 19.26	$ 40,453.64
6	Simple concrete columns and walls f´c = 240 kg / cm^2	327.08	$ 129.99	$ 42,515.79
7	Underlayment slab	133.20	$ 233.95	$ 31,161.80
8	Slab concrete f´c 240 kg / cm2	421.98	$ 134.90	$ 56,927.63
9	Slab formwork	740.77	$ 12.53	$ 9,281.68
10	Concrete bleachers	10.16	$ 124.94	$ 1,269.39
11	Lightening (40x40x25)	4,504.00	$ 3.63	$ 16,349.29
12	Step formwork	69.28	$ 12.53	$ 868.06
13	Metal railings Cars	304.35	$ 190.34	$ 57,929.70
14	Railing	128.10	$ 31.71	$ 4,061.80
15	Beams	284.15	$ 137.93	$ 39,192.00
16	Beam formwork	1,087.84	$ 19.42	$ 21,123.56
	TOTAL BUDGETS (USD)			**$433,996.41**

Since the values of the unit price analysis are calculated to 2020, the coefficients of the polynomial formula for the price readjustment are presented.

Table 6. Data for price readjustment applying the polynomial formula

Components			%	**Coefficient**
B	Workforce	$ 93,708.02	23.75%	p1
G	Tools	$ 14,772.67	3.74%	p2
I	Cement	$ 3,813.21	0.97%	p3
J	Stone materials	$ 2,773.24	0.70%	p4
D	Reinforcing steel	$ 79,283.42	20.10%	p5
F	Wood	$ 15,108.41	3.83%	p6
H	Blocks	$ 4,864.32	1.23%	p7
C	Pre-mixed concrete	$ 117,400.14	29.76%	p8
E	Handrail railings for cars	$ 50,403.50	12.78%	p9
X	Others	$ 12,415.27	3.15%	px
	Direct total costs	$ 394,542.19		
	Total budget	$ 433,996.41		

Finally obtaining the following polynomial formula.

$$Pr = \left(0.2375*\frac{B1}{B0}+0.2976*\frac{C1}{C0}+0.2010*\frac{D1}{D0}+0.1278*\frac{E1}{E0}+0.0383*\frac{F1}{F0}+0.0374*\frac{G1}{G0}+0.0123*\frac{H1}{H0}+0.0097*\frac{I1}{I0}+0.0070*\frac{J1}{J0}+0.00315*\frac{X1}{X0}\right)$$

4. CONCLUSIONS

The characteristics of the wave in Salinas were determined as wave height equal to 6 meters and arrival time equal to 8 to 12 minutes.

The multi-use proposal as a refuge area has a capacity for 388 people and as a garage it has a capacity for 40 light vehicles and 30 motorcycles.

Architecturally, the proposal consists of two blocks with a dual system. The first block is the ramps for the vehicles and the second is the parking lot and the refuge area on the terrace.

Structurally, the proposal has drifts of less than 0.7%, which guarantees a performance level of immediate occupancy.

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