Earthquake Engineering, Tenth World Conference © 1992 Balkema, Rotterdam. ISBN 90 5410 060 5

Tsunami risk in the city of Arica, Chile

Joaquín Monge
Universidad de Chile, Chile

ABSTRACT : Arica, the northernmost city of Chile, has experienced in the last four centuries three strong earthquakes of magnitude 8 to 8.5, accompanied by tsunami that destroyed part of the old city. Nowadays, these areas have been rebuilt and the city has extended, occupying to the north the lowlands that were inundated during the tsunami of 1868 and 1877. A long seismic silence of 114 years as well as a recent seismic activity that started with a Ms = 6.9 earthquake in Aug. 8, 1987 with epicenter located 80 km south of Arica suggests that a severe earthquake and tsunami can occur in the next future. An estimation of the areas that can be flooded by this tsunami is done and the danger to lives and the loss of property are evaluated in a preliminary way. Recommendations on measures for the protection of Arica against tsunami are presented.

1 THE TWO SEISMIC SOURCES THAT AFFECT ARICA

Two families of earthquakes are defined in the region (Comte et al, 1989). One of them has their rupture area between latitudes 15º-18º S, in the south of Perú; the second one, between latitudes 18º-24º S, in the north of Chile. The return period for earthquakes of M = 7.5 to 8.5 is approximately 120 years for the first family and 112 years for the second.

Using a biparametric Weibull distribution, the probability that one earthquake of either family occurs right now is 60%. However, the magnitude will not be necessarily equivalent to the events of 1868 and 1877.

Fig. 1 shows the isoseismals of the 1868 earthquake and Fig. 2 those of the 1877 earthquake (Kausel, 1986). He estimates that the area of intensity VIII or larger corresponds to the area of rupture.

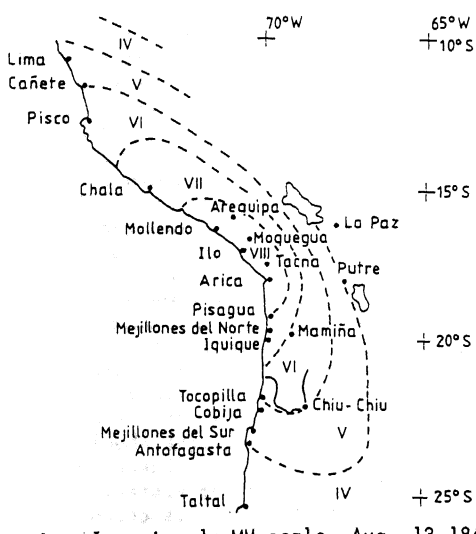

Fig. 1 Isoseismals MM scale, Aug. 13,1868 south of Perú earthquake (Kausel, 1986)

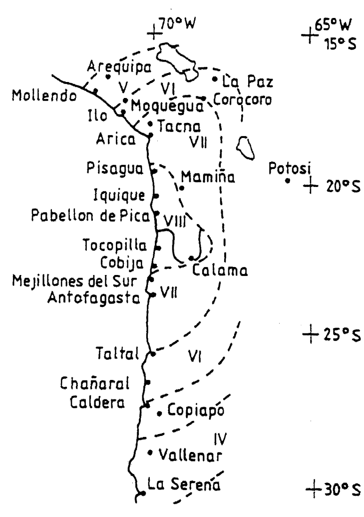

Fig. 2 Isoseismals MM scale, May 9, 1877 north of Chile earthquake (Kausel, 1986)

2 HISTORICAL TSUNAMI IN ARICA

The city of Arica is located in the north of Chile, close to the boundary of Perú. It has a population of about 180 000 inhabitants. It was founded in the sixteen century and has experienced since 1513 several earthquakes of magnitude 7.5 to 8.5, some of them accompanied by severe tsunami. These correspond to the earthquakes of :

Nov. 21, 1604 Ms=8 1/4-8 1/2, m = 3
Aug. 13, 1868 Ms= 8.5, m = 4
May. 9, 1877 Ms= 8.3, m = 4

Three other tsunami m=1 have also occurred.

The magnitude or degree m of the tsunami is defined by Imamura in table 1. The height is the double amplitude of the wave when it reaches the coast. The maximum run-up elevation is given by Iida (Wiegel, 1970).

Table 1. Degrees of tsunami (Imamura-Iida)

Degree	Height (meter)	Run-up (meter)	Description of damage
0	1 - 2	1 - 1.5	No damage
1	2 - 5	2 - 3	Flooded houses, destroyed boats are driven
2	5 -10	4 - 6	Men, ships and houses are swept
3	10 -20	8 -12	Damage extended along 400 km of coast
4	> 30	16 -24	Damage extended along more than 500 km of coast

2.1 The tsunami of Aug. 13, 1868

It occurred at 5 15 PM local time. 5 ships were at the harbour and from them, boats were sent to the pier in order to bring 50 or 60 people that waited for help. 22 minutes after the earthquake, the sea retired from the shore leaving these boats on land and almost inmediatly advanced, collapsing the pier, sweeping the people and destroying all what was left by the earthquake below the elevation of the San Marcos church.

The loss of lifes was estimated in 300 to 350 people. All the ships were lost and 2 of them, the peruvian battleship America and the US Wateree were left on land by the third wave, that was the highest one and came at 7 05 or 7 10 PM.

The reports give different estimations of the run-up elevations, but from the photos of that time (Alvarez L. et al, 1980) it is possible to estimate these as not more than 12 m. in the old part of the city.

2.2 The tsunami of May 9, 1877

This time the tsunami arrived 45 minutes after the earthquake. The flooded area was similar to that of 1868. The number of deaths was 5, much less than in the former one, which was attributed to the experience of the people after the first tsunami. Other possible explanation may be the larger travel time of the tsunami (45 minutes against 22 minutes). The ship Wateree was carried 2 miles to the north and was left in the position where its boilers still remain.

3 ESTIMATION OF THE FLOODED AREAS

For the estimation of the flooded areas and of the travel time to different points of the coast of the city, a refraction diagram was drawn by the author starting from a wave front located at the isobath - 100 m. The final part of this diagram is shown in the Figure 3.The bathimetry of the sea bottom produces a concentration of flow lines in front of the old part of Arica and also in a sector of the northern part of the city. The refraction coefficients are shown in the figure and represent relative heights of the wave when it reaches the beach.

The topography of the city was found by the author in 1990 in the maps of sewer and water facilities with level lines every 1 m. For those parts of Arica that are not yet built, the available information is that of level lines every 25 m.

Assuming that the maximum run-up elevation in the old part of the city was 12 m in 1868, 1877 and a slope of 1/100 (Cox, 1961), Ro at the depth 3 m was found to be 17.5 m. The values of Ro for other channels of flow were computed by means of the refraction coefficients. The inundated areas were determined assuming a slope of 1/200 in the non-built areas and 1/100 otherwise, taking into consideration the different rugosity. The depth 3 m. was supposed to be at 50 m. from the axis of the street Máximo Lira, that was close to the sea in 1868 and 1877.

From the historical reports (Montessus de Ballore, 1912), run-up elevations of up to 25 m are quoted: there are differences between different reports. One must keep in mind that at the Morro, where channels 1 and 2 arrive, higher run-up elevation that in downtown are found, so it is possible that the higher elevations reported correspond to the Morro. From the old photos (Alvarez et al, 1980) a maximum elevation of 9 m seems reasonable. However, for the sake of safety, an elevation of 12 m has been considered.

Table 1 gives a maximum elevation of the run-up of 16 to 24 m. Considering that Arica is located at the south limit of the rupture areas of earthquakes of the first family and at the north limit of those of the second family, the height of the wave should be less than in points of the coast closer to the epicenter. So, based on the historical evidence the elevation of 12 m is accepted, though the degre of the tsunami is m = 4.

4 EVALUATION OF THE LOSS OF PROPERTY IN CASE OF A TSUNAMI

4.1 Loss of houses

Figures 4 and 5 have level lines that indicate the water pressure, that is the difference between the run-up elevation computed by the method by Cox and the actual elevation of the site. The one story houses can stand pressures up to 1 m, but would be probably destroyed with larger pressures. The apartment buildings are of 4 stories with reinforced concrete walls and slabs and may resist. The partitions and the content of the flooded houses or lower stories of the apartment buildings would be lost.

The number of families in houses and apartment buildings located in areas of possible inundation are given in table 2. The total number of people living there is about 6 000, but it will amount to 9 000 when the houses under construction be inhabited.

Table 2. Number of families in areas of flood

Sector	Houses	Apartments	Total
1 Downtown	56	90	146
2 Tierras Blancas	431	--	431
3 P. Lagos south	234	160	394
4 P. Lagos center	72	--	72
5 P. Lagos north	233	--	233
6 P. Lagos west	700 *	--	700*
Totals	1726	250	1976

* Houses that are in process of construction

4.2 Loss of public offices

A three story reinforced concrete frame building (indicated by C in Fig.4) where many of the public offices of Arica are placed is located in the area inundated by the tsunami of the last century. In case of a new tsunami, the building may possibly resist but most of its contents of files and documents will be lost.

A six story reinforced concrete building called Edificio Alborada (A) belongs to the military forces and is close to the sea. It will be completely inundated.

The Campus Velásquez (H) of the Universidad de Tarapacá wil be partially inundated, as well as the neighbouring Hotel El Paso (G), the Casino of Arica (F) and the Laboratory (I) of the Institute of Research and Testing of Materials (IDIEM) of the Universidad de Chile.

4.3 Commercial buildings

In the old part of the city, most of the construction are occupied as banks, office or bussiness activities. In general, they are old one or two story houses of adobe, unreinforced masonry or in a minor proportion of quincha (canes with mud). However, some new building up to 6 stories are found in the area that will be flooded: for instance, buildings (D) in Fig. 3, where the offices of LAN Chile, the Direction of Municipal Works and theater are located.

4.4 Recreational facilities

Several beaches will be inundated: Infiernillo, El Laucho, La Lisera and other south of Arica and Chinchorro and Las Machas north of the city. Restaurants located at these beaches wil be flooded or destroyed.

The nautical club and other club located near the mouth of the river San José are also at the side of the sea and will be flooded.

The olympic pool and the beisbol stadium, J,K Fig. 5, will be also inundated.

4.5 Other facilities

The international airport of Chacalluta is located at a safe elevation of 50 m. The panamerican highway would not be inundated by a tsunami like those of the last century.

The station of the Arica-La Paz railroad (E) is located in a dangerous zone and so are the first 1.5 km of the track. However, the main installations are in a rather safe elevation of about 20 m over the mean sea level.

The station of the Arica-Tacna railroad, as well as most of the first 6 km of the track, are in zones to be flooded by tsunami similar to those of 1868 and 1877. In fact, this railroad exists since 1855 and at both tsunami it suffered a large destruction. A suggestion is to relocate the track close to that of the Arica-La Paz railroad between Arica and the river Chacalluta.

The port installations, including the Gobernación Marítima (B), port authority, would be of course inundated.

A pumping station (L), Fig.5, is also in the zone of inundation.

5 ESTIMATION OF THE DANGER TO LIFES

Figures 4 and 5 show the time needed for evacuation from the menaced areas to a safe elevation of about 20 m over the mean sea level.

It is very fortunate that no hospitals or jails are located in the areas of possible inundation. No schools are located in areas that were probably flooded in 1868 or 1877. However, one nursery is located in the sector 2 Tierras Blancas and other nurseries presumibly exist in other sectors menaced by inundation.

The authorities in Arica conduct periodical exercises with the children of the schools evacuating them to the railroad track to La Paz, that runs at an elevation of about 25 m, so they are well trained in case of a tsunmi alarm.

At nighttime, the evacuation of people that lives in the sectors of Tierras Blancas and General Lagos should take more time that in

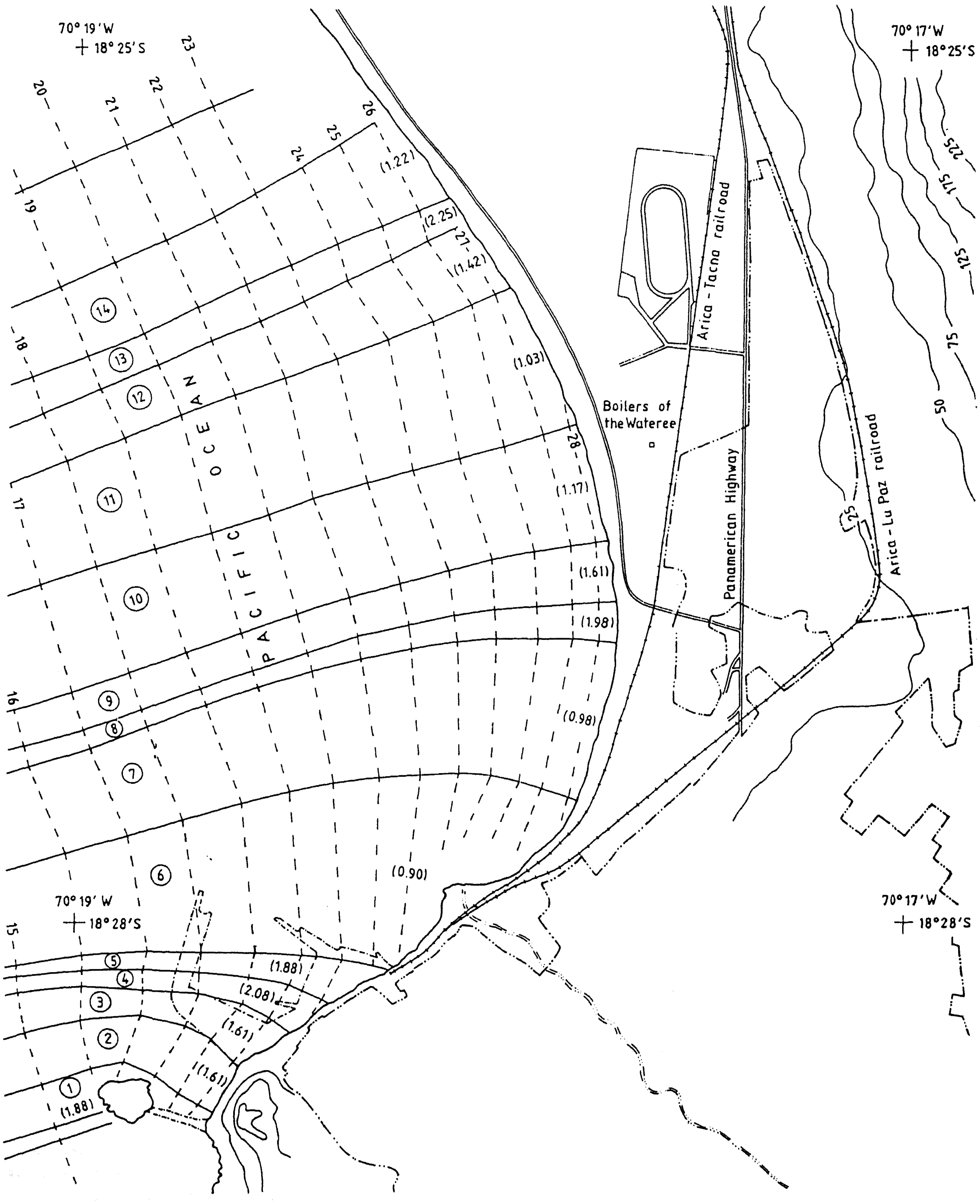

FIG. 3 REFRACTION DIAGRAM FOR A TSUNAMI IN ARICA. SHORE LINE AS IN LAST CENTURY

—— Lines of flow (N) Number of a channel of flow

- - - Positions of wave fronts. Time in minutes

( ) Refraction coefficients

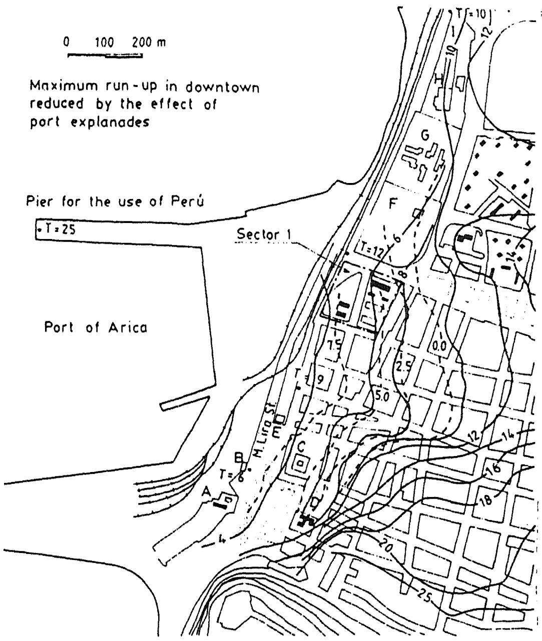

Fig. 4 Downtown Arica
Estimated inundation by a tsunami degree 4
—— Level curves (m) over the mean sea level
----- Water pressure curves (m) for the run-up
T (minutes) walking time to an elevation of 20 m
▪ Apartment buildings (4 stories or more)

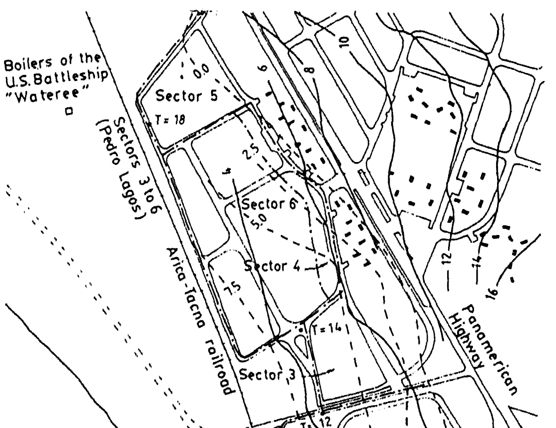

Fig. 5 El Chinchorro Arica
(Same footnotes than in fig. 4)

case of a tsunami that occurs during the day.

The travel time of the tsunami to those sectors is about 6 minutes more than for the old part of Arica, so about 28 minutes are available if the travel time is similar to that of 1868.

The time for reaching an elevation of 20 m starting from the houses that are closest to the ocean was found to be of 18 minutes, walking at 4 km/hour. Other 3 minutes should be added for the duration of the strong motion, since it is impossible to walk during that period, and other 2 minutes for cutting the gas and locking the house. So, the evacuation is possible at daytime for people in good health. At night, an additional time is necessary for dress and 25 minutes should be the minimum time for evacuation. The situation could be dangerous even for people in good physical condition.

As for the old part of the city, it is almost entirely a commercial sector and is practically with no inhabitants during the night, except for a few hotels and houses. The time of evacuation is shorter than that for El Chinchorro. People working at the port is of course more exposed.

For estimating the number of deaths we must consider that about 30% of the families have cars. Most of people living in apartment buildings could find a safe place in the upper stories. That will leave about 6 000 people that will evacuate walking. Small children under 4 years will be probably carried by their parents in arms. The problem will be with very old people or persons that are sick in bed. Assuming that they constitute about 1% and that they will be accompanied by other persons, the number of victims could be of about one hundred.

6 COST OF RELOCATION OF HOUSES

The apartments built by the government have an area of about 60 square meter per family, in average. The cost in Santiago, including urbanization, is of about US $ 12 000. In Arica it becomes more expensive, since the steel, wood and other materials are produced in the south of Chile. So, the cost in Arica can be estimated in US $ 16 000 per unit.

The cost of houses is lower and can be estimated in US $ 12 000 per unit.

The total cost will be about :

1726 houses at $12 000	= $ 20 712 000
250 apt. units at $ 16 000	= $ 4 000 000

The total cost is about 25 million US $.

The density is of 3 000 families (or about 15 000 inhabitants) per square km.

In the old part of Arica, the exposed area excluding parks and squares is of 28 Ha (1 Ha = 10 000 square meter). By comparing with the area occupied by houses and apartment buildings and assuming a similar cost for unit area, the cost of relocation would amount to 11 millions US $.

No estimation has been done on the possible damage to properties indicated by A, B, F, G, H, I, L, nor to the recreational facilities or railroads.

7 FINAL COMMENTS

This study has a preliminary character. It can be improved in several ways :

By means of inverse refraction diagrams, the rupture areas of the 1868 and 1877 earthquakes and the initial wave fronts can be determined (Diaz et al, 1991). From these, new refraction diagrams can be drawn and a better estimation of the flooded areas obtained.

A topographical survey of the non-built lowlands at the north of Arica and in some sectors of the city seems necessary.

The effect of the explanades of the port in reducing the height of the run-ups should be taken into account.

However, some conclusions can be obtained and some recommendations given :

New urban developments in areas that may be flooded have been recently stopped, but there are houses in a construction stage where the contractors obtained permit before that prohibition was inforced.

The local authorities considerer that 25 m over the mean sea level is a safe elevation. This seems somewhat conservative: probably 20 m should be also conservative.

Nurseries should be moved from the areas of probable inundation.

The files and documents of publics buildings in areas of flooding should be moved to other buildings in safe areas.

Protection works against tsunami must be considered. A wall following the track of the Arica-La Paz railroad in downtown Arica is a possible partial solution for that sector.

A wall following the Arica-Tacna railroad is much more expensive, but would give a better protection to both the downtown and the northern areas. A breakwater is an altenative solution. A study of coasts of these solutions may indicate if the relocation of houses in areas affected by a tsunami should be preferable.

AKNOWLEDGEMENTS

The National Fund for the scientific and technological development (FONDECYT) and the Department of Civil Engineering of the Faculty of Physical Sciences and Mathematics of my university have financed this work.

Rodolfo Saragoni and Bernardo Aguilera gave a most valuable collaboration.

REFERENCES

Alvarez, L., Chacón, S., Dauelsberg, P. and Franulic, D. 1980. Arica en el tiempo, Universidad de Chile, Sede Arica.

Comte, D., Pardo, M., Eisenberg, A. 1989. Análisis cuantitativo de los grandes terremotos del norte de Chile y sur del Perú. Estimación del peligro sísmico. 5as. Jornadas Chilenas de Sismología e Ingeniería Antisísmica, Viña del Mar, Chile, Vol. 1, pp 279-289.

Cox, D.C. 1961. Potential tsunami inundation areas in Hawaii. Tsunami research programe, Hawaii Institute of Geophysics, University of Hawaii, report Nº14.

Díaz, J., Lorca, E., Barrientos, S. 1991. Tsunamis en el estudio de fuentes sísmicas en el sur de Perú y norte de Chile. Sexto Congreso Geológico Chileno, Viña del Mar, Chile, pp 709-713.

Kausel, E. 1986. Los terremotos de agosto 1868 y mayo 1877 que afectaron el sur del Perú y el norte de Chile. Bol. de la Academia de Ciencias Nº 1, Vol. 3.

Montesus de Ballore, F. 1912. Historia sísmica de Los Andes meridionales. Segunda parte. Santiago : Cervantes.

Wiegel, R.L. 1970. Earthquake Engineering, Prentice Hall.