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ESTIMATES OF WAVE HEIGHTS ON THE COAST OF CHILE FROM A TSUNAMI GENERATED BY AN EARTHQUAKE July 8, 1730

R.Kh. Mazova[1], A.A Kurkin[1]., N.A Baranova[2], I.A. Smirnov[1]

[1] Nizhny Novgorod State Technical University n.a. R.E. Alekseev, 24, Minin str., 603095 Nizhny Novgorod, Russia. e-mail address: raissamazova@yandex.ru
[2]Auriga, 6/6 Nartova st., office 829, 603104 Nizhny Novgorod, Russia.
e-mail address: Natalia.baranova@inbox.ru

ABSTRACT

The historical earthquake and tsunami occurred almost 300 years ago on July 8, 1730 in the region of Valparaiso, Chile is studied. The earthquake and tsunami of 1730 were considered to be the largest occurred in Chile since the beginning of recorded history. The earthquake destroyed buildings along more than 1000 km coastline and generated a large tsunami. Estimates of the magnitude of the earthquake lie in the range of $M \sim 9–9.3$. The data given in historical documents on the tsunami, caused by this catastrophic earthquake, supports and documents the strong destruction on the Chilean coast, especially in the coastal cities of Concepcion and Valparaiso, where waves, according to historical records on the coasts, reached 9m and 11m, respectively. The parameters of the earthquake source are poorly understood, but, according to estimates from various sources, the earthquake source was about 600-1000 km long along the Chilean coast. In the work, more than 15 scenarios for numerical simulation of the generation and propagation of tsunami waves up to a 5-meter isobath is carried out, depending on the magnitude of the earthquake and, accordingly, on the size of the earthquake source. The numerical simulation was performed within the keyboard model of the earthquake source; the number of blocks in the computations corresponds to the number of faults in the earthquake source and varied from 2 to 12.

Keywords: *tsunamigenic catastrophic earthquakes, tsunami waves, numerical simulation, Chilean coast.*

1. INTRODUCTION

The earthquake of July 8, 1730 with a magnitude close to $M \sim 9$ has an ambiguous treatment, because in various documents describing the event almost 300 years ago, the earthquake and the tsunami that followed it are described in different ways. In this paper, the authors tried to bring a lot of disparate facts to a logical uniformity and propose a model of a possible seismic source that generates tsunami waves corresponding to the few data recorded in historical documents.

In works [1-10] it is shown that the most affected area is located between the cities of La Serena and Santo Domingo. An earthquake in 1730 with a magnitude close to $M = 9$ (some estimates 9.1–9.3) affected a large region stretching over 900 km from Copiapo in the north to Concepción in the south, causing strong destructions in the capital Santiago. It was followed by a strong tsunami that particularly affected the two coastal towns of Valparaiso and Concepción.

However, historical analysis (see, e.g., [1,2]) has suggested the extraordinary idea of two main seismic events and, as a consequence, three separately generated tsunamis of significantly different intensity. Historical records demonstrate three strong earthquake shocks with an interval of approximately 4 and 7 hours. The first shock occurred at 1.30 am, the second main shock between 3 and 5 am, and the third event between 12 and 1 pm. According to the descriptions, the center of Ilhapel at about 1.30 AM the city was attacked by four or five large tsunami waves, of which the third was the largest. The city of Concepción was also hit by 4 or 5 large tsunami waves, of which the second was the largest. The tsunami took about an hour to fill the city with water before it finally receded. Apparently, the tsunami began with the rundown of water from the coast, because on the night of the earthquake, the fishermen noticed that the water was receding from the bay [1-5]. In the city of Valparaiso, a wall of water has formed 3.5 meters above the usual high tide level.

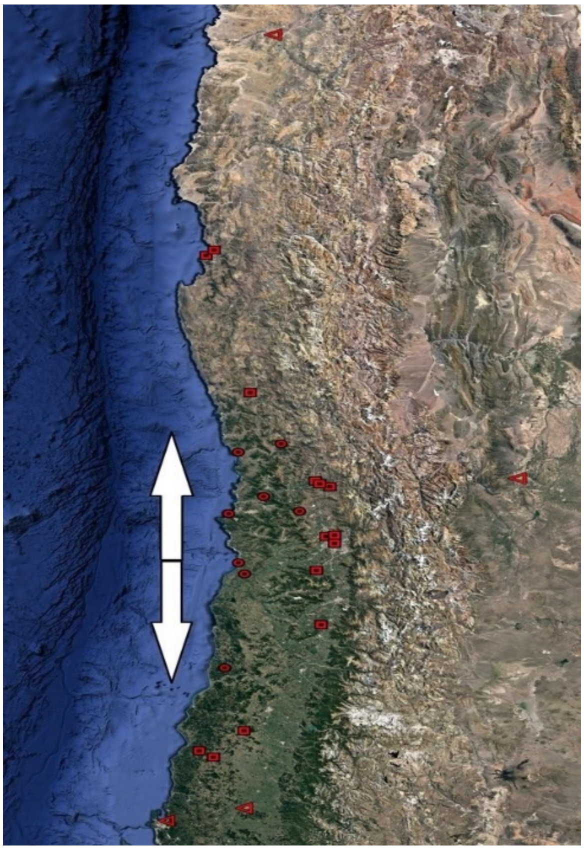


Figure 1. Damage zones of the 1730 earthquake [2].

Available damage reports and eyewitness accounts support that a tsunami on July 8th 1730 caused extensive destructions in the ports of La Serena, Valparaiso and Concepción. The reports describe that tsunami waves damaged coastal areas of the cities of Concepción and Valparaiso at relatively the same time. Also it was also reported that they caused destructions of agricultural land on the coast of Colchagua. Waves have also been seen in Callao in Peru and along the coast of Japan [2-10]. In works [1,2], some generalization of information from sources [3-10] is given, according to which it can be assumed that the picture of the earthquake and the subsequent tsunami looked as follows [1,2]:

- The first shock: occurred between 1 and 2 o'clock in the morning on July 8, 1730. It was prolonged, but not strong throughout the territory.
- The second shock: occurred between 3 and 5 o'clock in the morning on July 8, 1730. I was the most significant in strength and causing strong destructions of buildings. The main force of the second earthquake fell on the area of modern San Antonio, south of Valparaiso, in Concepción and Santiago, the intensity was much lower, but compared to Concepción, the intensity in Santiago was higher. This shock in Santiago caused a tsunami that propagates from Santiago north towards La Serena and Callao and south to Concepción.
- The third shock: occurred between 12 and 13 o'clock in the afternoon on July 8, 1730. Some sources attribute it to aftershocks that lasted a month after the event, 5 or 6 of which were significant. The third shock likely occurred north of Valparaiso and closer to La Serena, which explains both the damage from the earthquake in the area and the reduced intensity in Concepción. Figure 1 shows a map of the intensity of the earthquake with the zones of the greatest damage to coastal structures from the earthquake.

2. STATEMENT OF THE PROBLEM

The appearance of catastrophic tsunamis can be caused by a complex mechanism of movements in the earthquake source. Usually, for numerical simulation of a tsunami generation, seismic data are used to determine the displacement of the bottom in the earthquake source [11]. The keyboard model of the earthquake source is used in the work, which makes it possible to simulate the complex distribution of wave heights along the coast, obtained during a particular earthquake [12, 13].

Preliminary estimates in this work were made when considering 6 scenarios of the generation of the earthquake source in 1730 by analogy with [2]. The earthquake sources were chosen according to the historical description of the processes in the zones of active faults in the Earth's crust for this earthquake. These scenarios of possible earthquakes were considered, with different kinematics of key blocks into which the seismic source was divided. The magnitudes of the considered earthquakes are: $M = 8.7$ for the first scenario, $M = 8.8$ for the second, $M = 9.0$ for the third, $M = 9.1$ for the fourth, $M = 9.2$ for the fifth, and $M = 9.3$ for the sixth ones. The kinematics of key blocks in the earthquake source was determined by a few data on the manifestations of tsunami waves on the coast during this earthquake, given in [1-10].

To determine the approximate sizes of sources for 6 scenarios, to calculate the length and width of the rupture of the Earth's crust for a given earthquake, Wells formulas were used [14]. The displacement of the wave surface above the seismic source during the formation of the tsunami source was estimated using the Iida formula [15]. Table 1 shows data on the length and width of the rupture of the Earth's crust for the earthquake magnitudes considered in this paper.

Figure 2 shows a map of the computation water area with the points along the coast that were most affected by the tsunami generated by the earthquake considered.

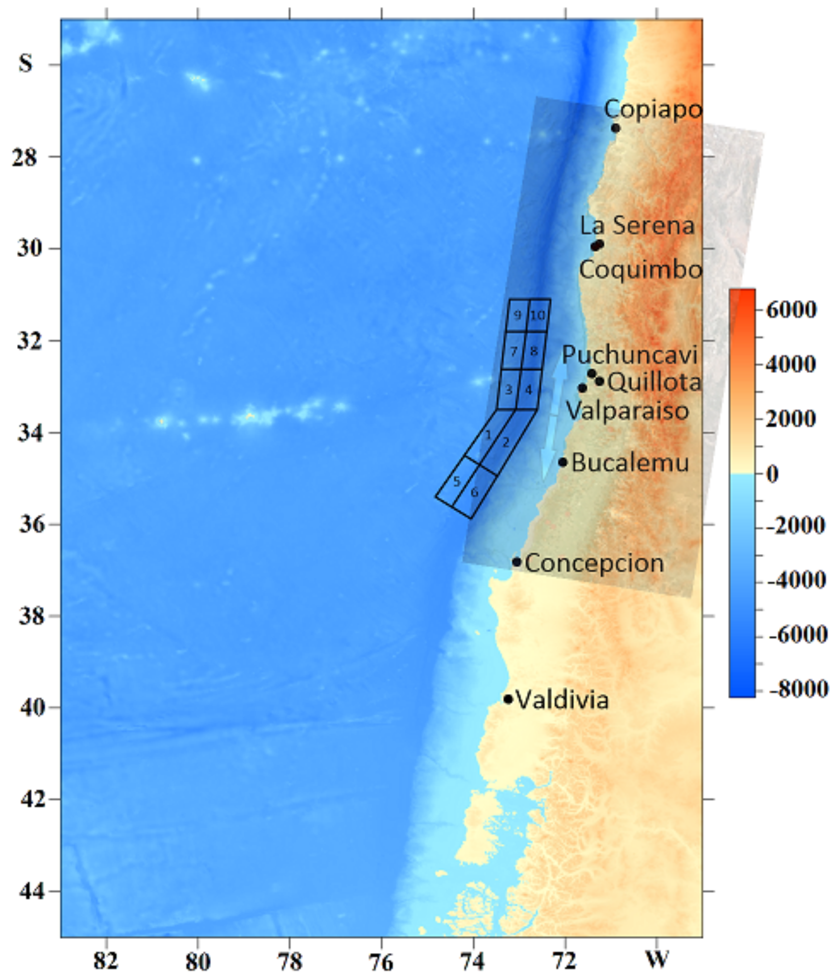


Figure 2. Scheme of the computation water area; blue arrow and dark square indicate zones of the highest intensity of the earthquake and tsunami [1,2]; the dark line marks the contour of the approximate localization of the seismic source taken as the base one in the computations

Table 1. Approximate dimensions of the source and displacement of the wave surface above the source

№ Scenario	Magnitude, M	Rupture length, L, km	Rupture width, W, km	Shift of wave surface, H, m
1	8.7	450	60	10-15
2	8.8	500	65	12-16
3	9.0	650	75	12-20
4	9.1	700	85	15-20
5	9.2	800	90	18-22
6	9.3	850	100	20-25

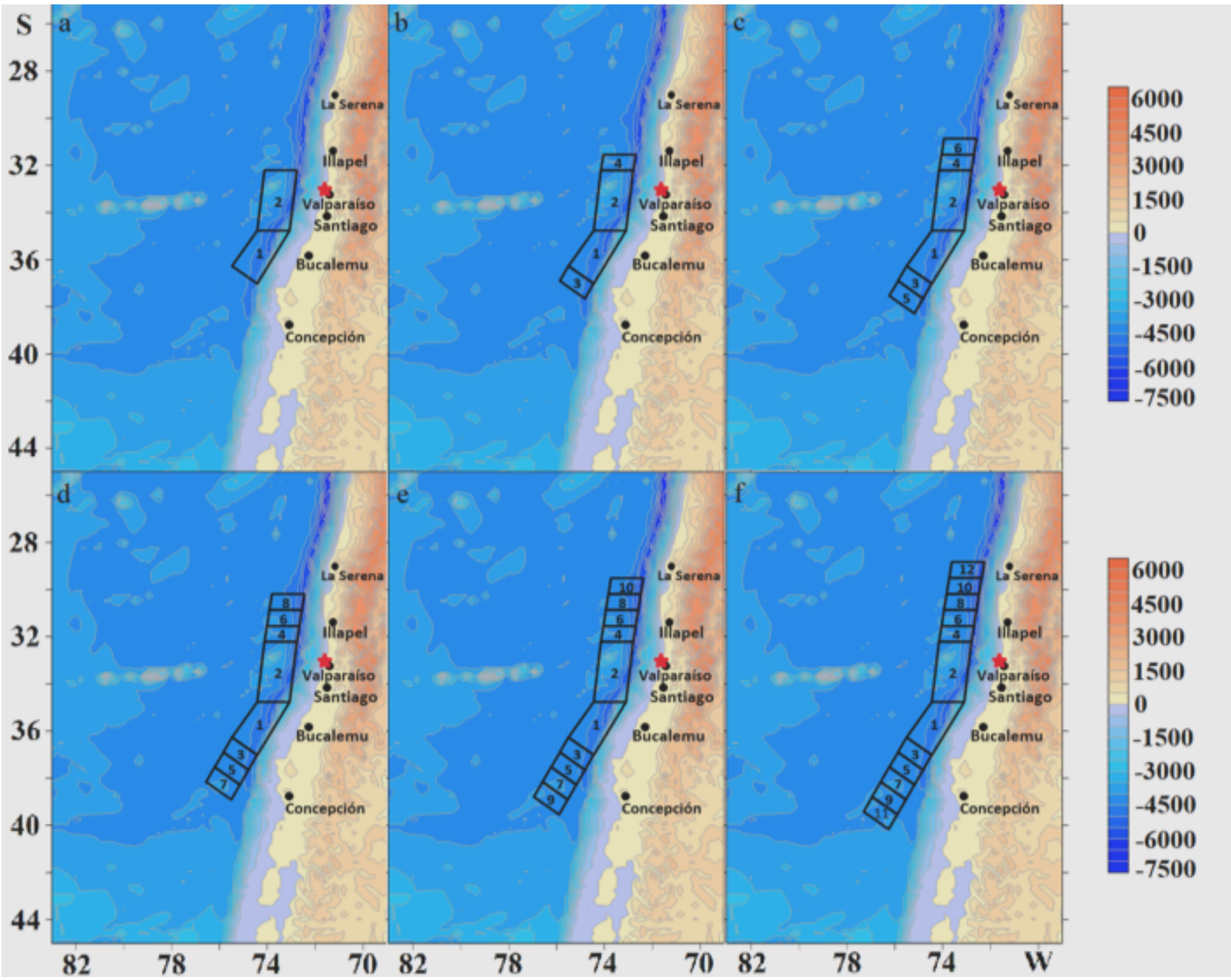


Figure 3. Schematic representation of the source of the earthquake of 1730: a) two-block source; b) four-block source; c) six-block source; d) eight-block source; e) ten-block source; f) twelve-block source

3. NUMERICAL SIMULATION

To describe the modeling of tsunami generation and propagation, a system of nonlinear shallow water equations is used [15,16]. Numerical simulation was carried out using a modified software package built on the basis of a scheme with high algorithmic universality proposed in [12, 13] and built on the basis of the Sielecki-Wurtele scheme [17]. For numerical modeling, the water area of the Pacific Ocean along the coast of Chile from 25° to 45° S and 79°-81° W was considered. For numerical simulations in the Pacific Ocean, a bathymetric map with a half-minute (~ 1.0 km) isobaths section was used.

To simulate the generation of the tsunami source, various displacements of blocks in the earthquake source are considered (see Tables 2-7), which presents the kinematics of the key blocks in the earthquake sources for Scenarios 1-6.

Table 2. The key block kinematics in the earthquake source (Scenario 1)

Block number	**1**		**2**	
Height (m)	-6	9	-5	10
Motion start time (sec)	60	90	0	30
Motion end time (sec)	90	120	30	60

Table 3. The key block kinematics in the earthquake source (Scenario 2)

Block number	**1**		**2**		**3**	**4**
Height (m)	-6	16	-7	15	10	-5
Motion start time (sec)	100	130	40	70	160	0
Motion end time (sec)	130	160	70	100	180	40

Table 4. The key block kinematics in the earthquake source (Scenario 3)

Block number	**1**		**2**		**3**	**4**	**5**	**6**
Height (m)	-6	7	-7	5	5	9	3	5
Motion start time (sec)	100	130	40	70	160	0	180	200
Motion end time (sec)	130	160	70	100	180	40	200	220

Table 5. The key block kinematics in the earthquake source (Scenario 4)

Block number	**1**		**2**		**3**	**4**	**5**	**6**	**7**	**8**
Height (m)	-6	7	-7	5	5	9	3	7	4	5
Motion start time (sec)	100	130	40	70	160	0	180	200	220	240
Motion finish time (sec)	130	160	70	100	180	40	200	220	240	260

Table 6. The key block kinematics in the earthquake source (Scenario 5)

Block number	**1**		**2**		**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Height (m)	-6	7	-7	15	5	9	3	7	4	5	-3	-2
Motion start time (sec)	100	130	40	70	160	0	180	200	220	240	260	280
Motion end time (sec)	130	160	70	100	180	40	200	220	240	260	280	300

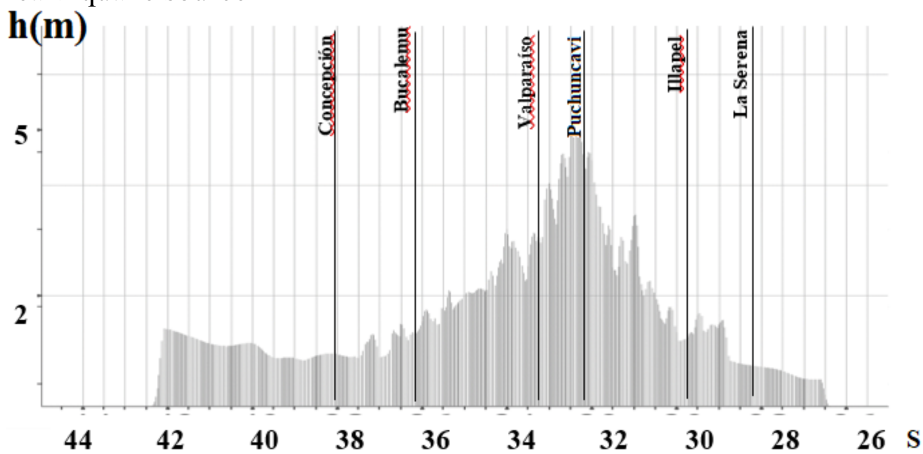
Table 7. The key blocks kinematics in the earthquake source (Scenario 6)

Block number	**1**		**2**		**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Height (m)	-6	5	-7	10	5	10	3	7	4	5	-3	-2	7	3
Motion start time (sec)	100	130	40	70	160	0	180	200	220	240	260	280	300	320
Motion end time (sec)	130	160	70	100	180	40	200	220	240	260	280	300	320	340

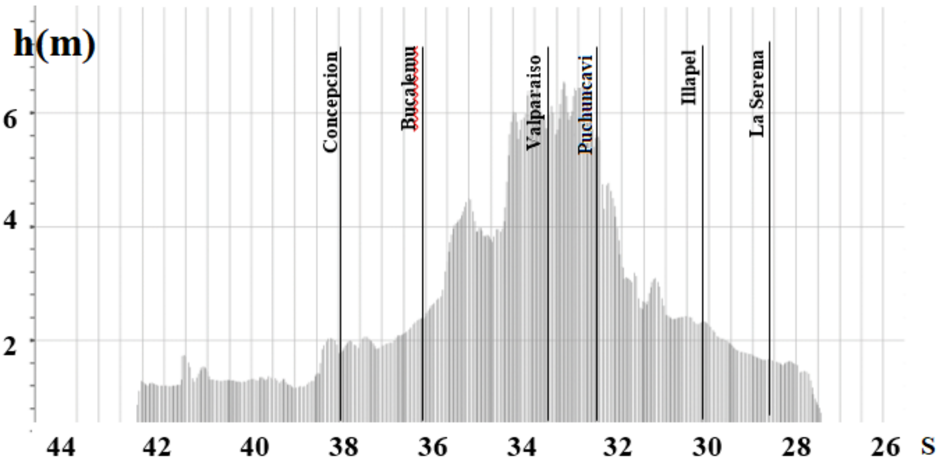
When blocks move in the earthquake source, a tsunami source begins to form on the water surface above the seismic source. There is a displacement of the wave surface and the formation of a wave front, which begins to propagate both to the Chilean coast and to the open water of the Pacific Ocean.

Since the longest block displacement time in the earthquake source, 340 s, falls on the 12-block source (Scenario 6), the formation of the tsunami source takes the same time. The paper considers the propagation of the wave front up to a 5-meter isobath, where the condition of total reflection is set. Figure 4 shows 2D histograms of the distribution of maximum tsunami wave heights on the 5-m isobath along the central part of the Chilean coast.

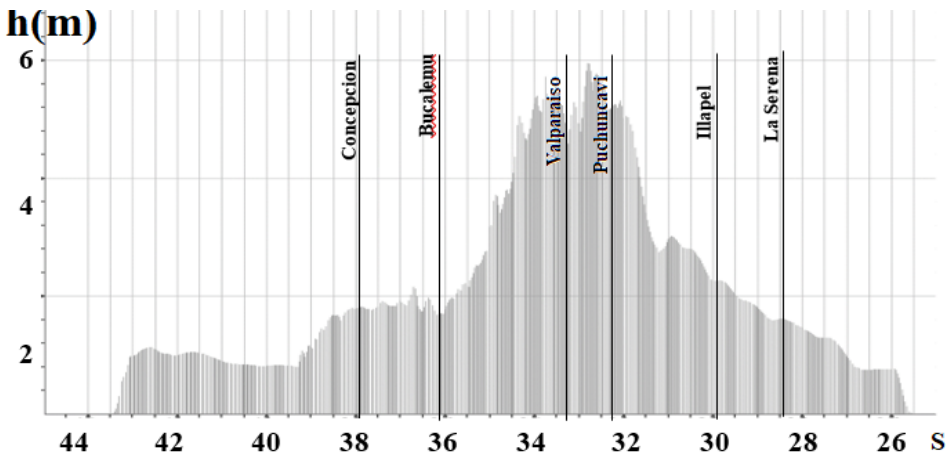
2-block earthquake source



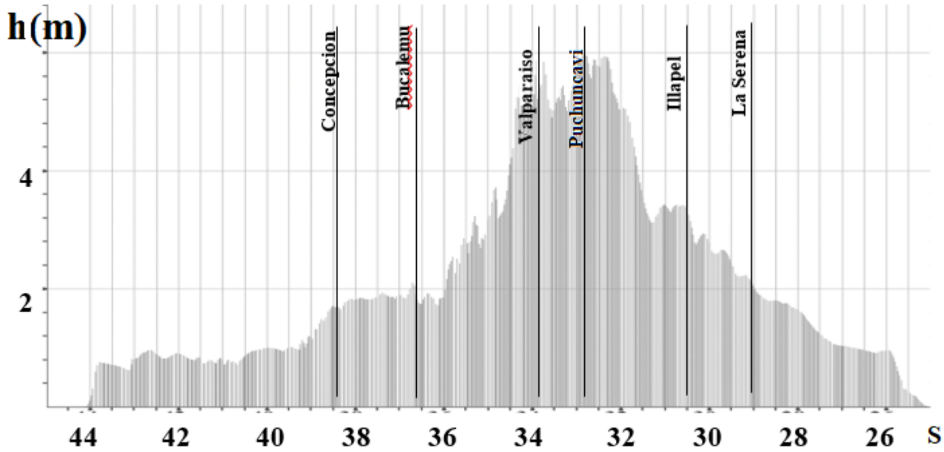
4-block earthquake source



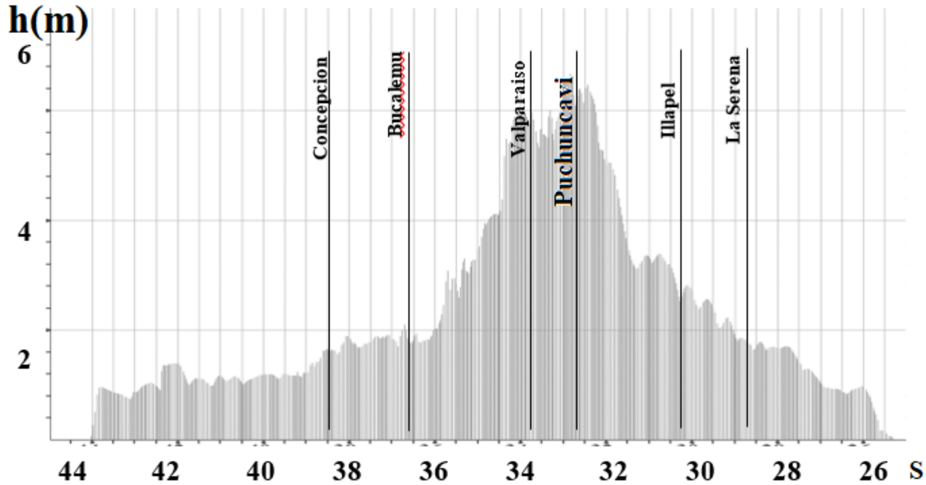
6-block earthquake source



8-block earthquake source



10-block earthquake source



12-block earthquake source

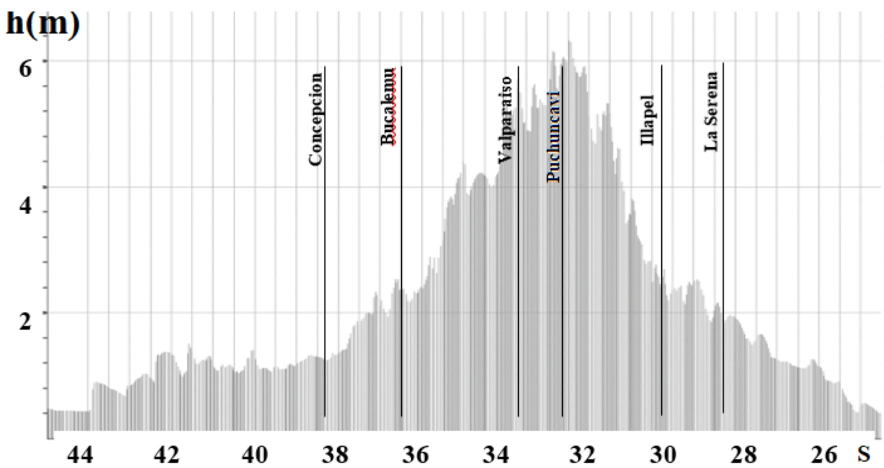


Figure 4. 2D histograms of the maximum wave height distribution along the coast of Chile.

The figures clearly show that the largest wave heights occur in the region of the city of Valparaiso and reach 5 meters. However, according to historical descriptions, there were also large wave heights in the cities of Concepcion and Coquimbo. Based on the estimated results of computations, the following Table of maximum wave heights distribution for a given event can be compile

Table 8. The results of numerical simulation

Wave heights in points on the Chilean coast (m)						
Scenario	**La-Serena**	**Illiapel**	**Valparaiso**	**Puchuncavi**	**Bucalemu**	**Concepcion**
1	1	1,5	5	3	1,7	1,5
2	1,8	2,4	6,2	6	2,2	2
3	1,8	2,4	6	5,8	2	1,8
4	2	3,2	6	6	2	1,8
5	1,8	2,4	6,4	6	2	1,6
6	2	2,4	6,4	5,6	2,4	2

Analyzing the obtained results, it can be noted that the maximum wave height distribution in this setting does not reflect well enough the few historical evidence given in [1-10]. However, the computation details show that the eight-block variant is the most adequate. Based on this scenario, the seismic source was modified by increasing the number of partitions and changing the shape of the source. Figure 5 shows a modified seismic source, for which further studies will be carried out.

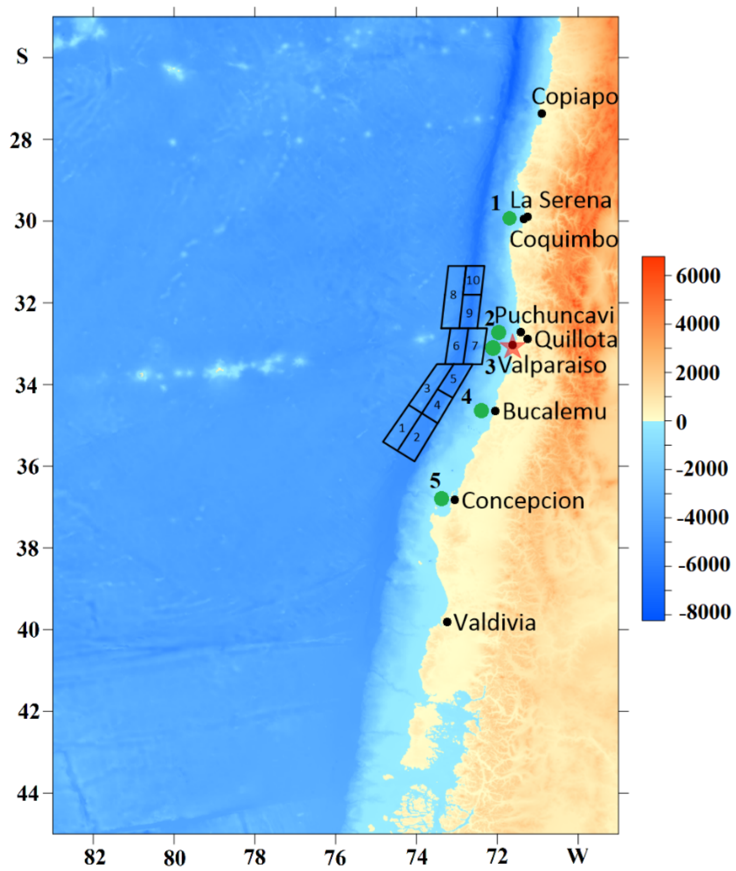


Figure 5. Schematic representation of the seismic source for the 1730 earthquake.

In further scenarios, the kinematics of blocks in the earthquake source is also significantly more complicated. The paper presents a scenario that most closely describes the nature of the manifestation of tsunami waves on the Chilean coast. The Table 9 gives the kinematics of the blocks in the source. The movement starts from block 7 (located close to the earthquake epicenter) for 3 minutes, then, simultaneously with the movements of these blocks, blocks 3-4-5 begin to move south from the epicenter. Blocks 2,5,7,9 and 10 move twice, moving up or down, according to Table 9.

Table 9. Key block kinematics in the earthquake source for Scenario 7

Block number	1	2	3	4	5	6	7	8	9	10
Distance (m)	4	- 4	6	- 5	-6	7	-4	5	-3	5
Start time of first movement (sec)	275	215	155	185	155	60	0	185	90	105
End time of first movement (sec)	305	275	185	215	185	90	60	215	120	155
Distance (m)		6			4		5		-5	4
Start time of second movement (sec)		305			185		305		335	365
End time of second movement (sec)		335			215		335		365	400

Figure 6 shows the generation of the tsunami source when the key blocks move in the earthquake source during the implementation of given scenario (Scenario 7). It is clearly seen that a surface source (tsunami source) is formed in 400 s, and the displacement of the wave surface is clearly visible when moving at the bottom of the corresponding block.

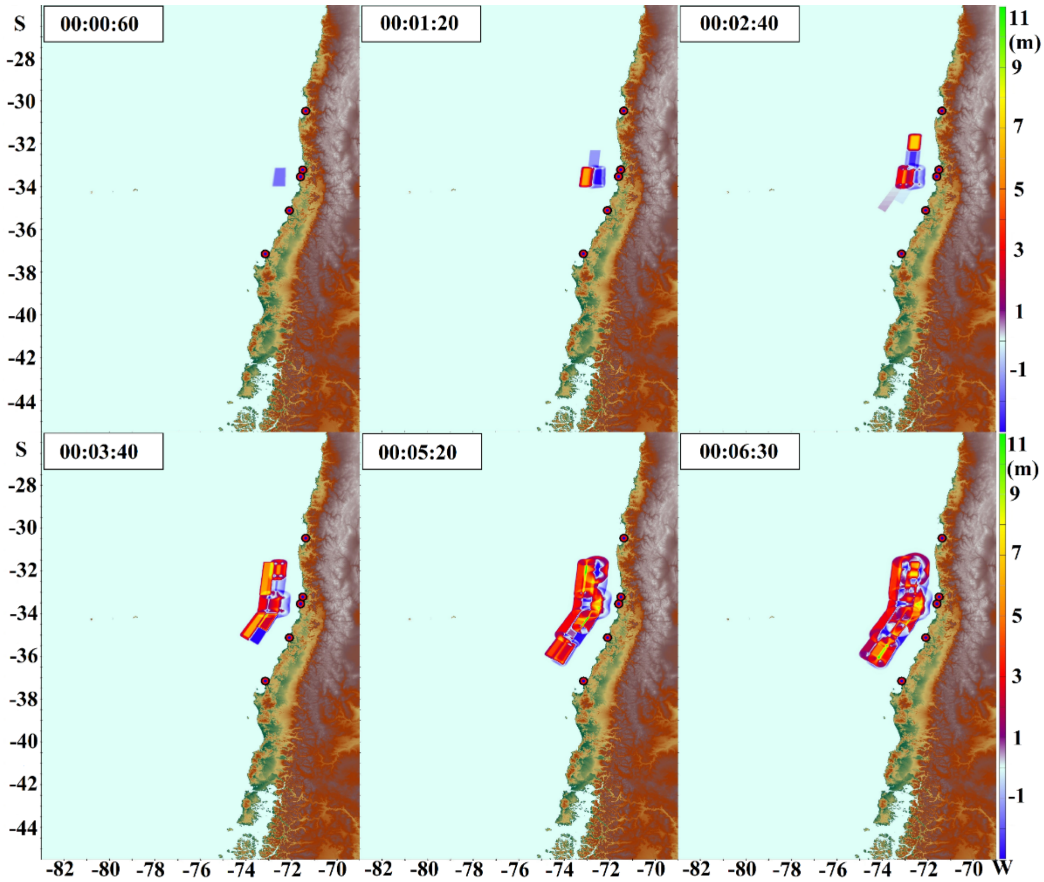


Figure 6. Generation of a tsunami source for 6 time moments during the implementation of a seismic process in an earthquake source (Scenario 7)

Figure 7 shows 6 time moments of the propagation of tsunami waves over the computed water area. It is clearly seen those moments when the wave reaches the corresponding tide gauge. Since the tide gauges are set on a 5-meter isobath, the data shown in Fig. 8 reflect precisely those heights with which the wave approaches a particular point.

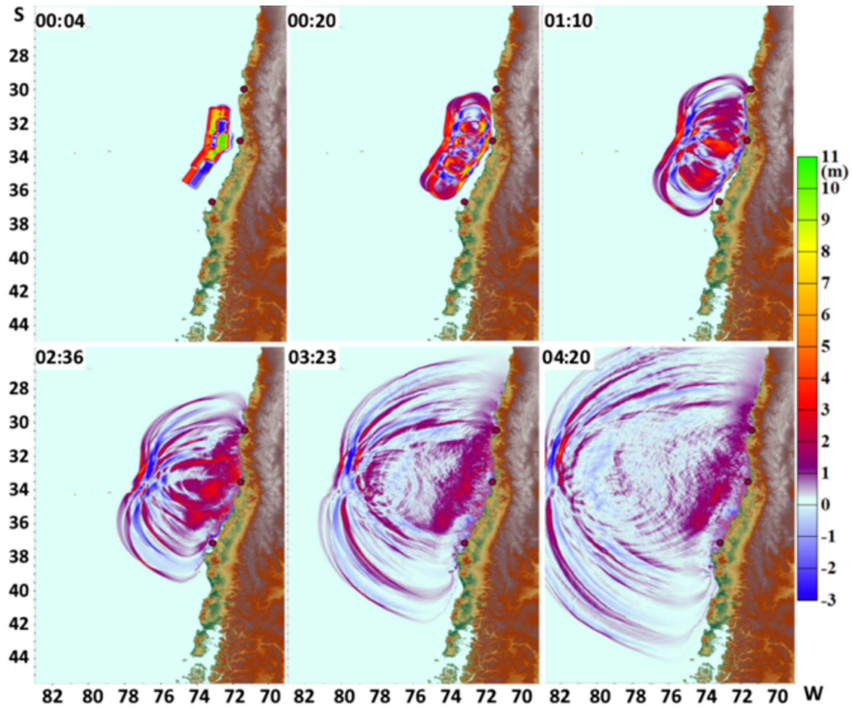


Figure 7. Propagation of tsunami waves over the computation water area (Scenario 7)

A more detailed analysis can be done by analyzing the records from the virtual tide gauge shown in Fig.8.

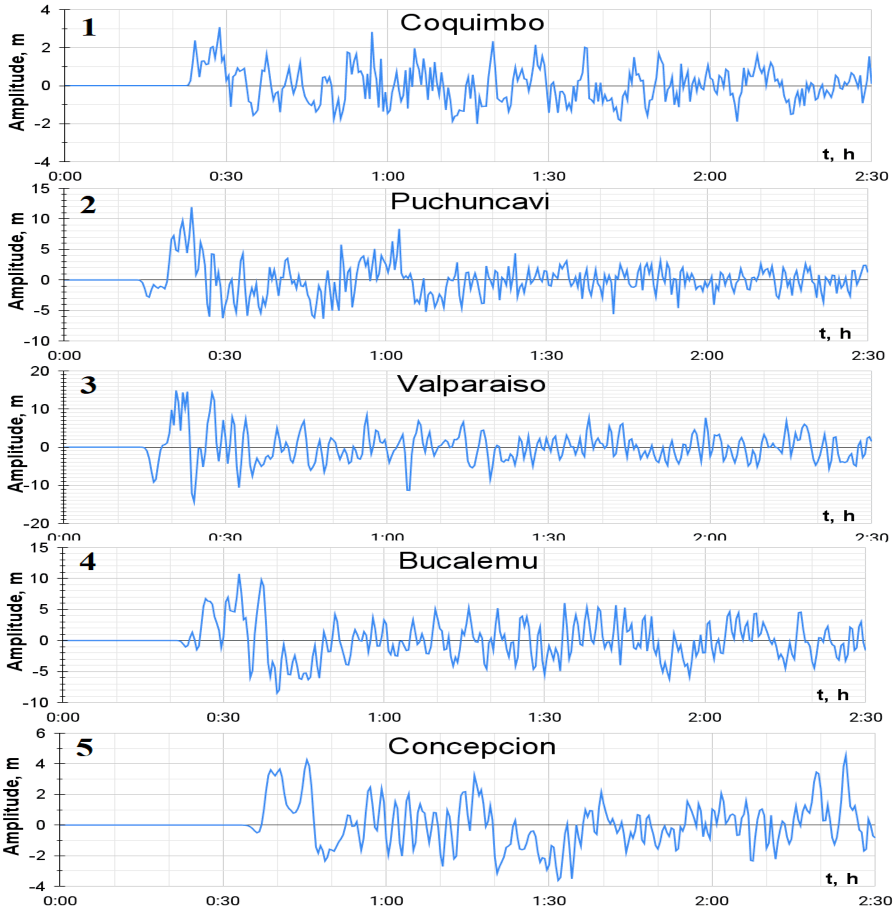


Figure 8. Records from virtual tide gauges for points Coquimbo, Puchuncavi, Valparaiso, Buqcalemu, Concepcion (Scenario 7).

It is clearly seen that in the points located opposite the epicenter of the earthquake, the heights of the waves are quite large: 11-15m. And in the points located to the southwest and northwest of the epicenter, the wave heights are not more than 4m. It should be noted that in almost every point the first wave was not the largest, and the second wave is the largest. The third wave is again smaller in height than the second. Given the description in historical documents, in cities affected by the tsunami, the second wave posed the greatest danger.

According to the 2D histogram of maximum wave heights along the coast in the computation area, shown in Fig. 9, one can see that the largest wave heights are localized opposite the earthquake epicenter, decreasing in height to the northwest and southwest to the cities of Coquimbo and Concepcion.

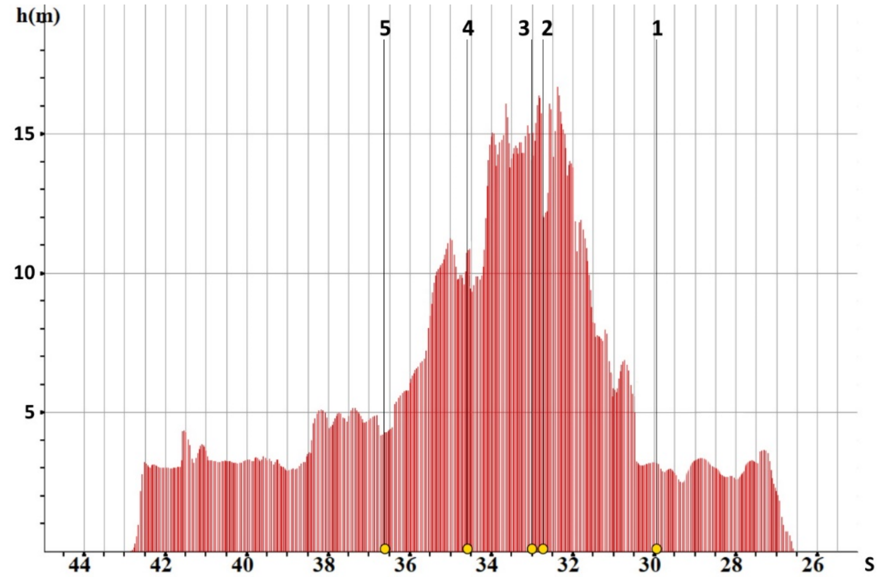


Figure 9. 2D histogram of maximum wave height distribution along the 5 m isobath (Scenario 7). The numbers 1-5 indicate the numbers of virtual tide gauges (Fig. 5).

CONCLUSION

The paper considers a historical event: an earthquake and tsunami on July 08, 1730 with a source located off the western coast of Chile near the city of Valparaiso coast and even, essentially different assumptions about seismic tremors. According to the results of historical data, some authors put forward various hypotheses about the number of earthquakes that occurred in a day from July 8 to July 9, 1730. Also, various works provide contradictory data on the localization of the epicenter of the earthquake. Numerical simulations were carried out for 16 different scenarios with concrete dynamics of the seismic source, within the framework of the keyboard block model of the earthquake source. The mechanism of movement of the keyblocks into which the seismic source was virtually divided is determined by the few data that are given in historical records. The lack of accurate historical data on the heights of tsunami waves on the coast seriously complicated the analysis of the possible implementation of the dynamics in the earthquake source. The results obtained in this work most closely reflect the descriptions of the manifestation of tsunami waves in various parts of the coast. It was found that the average wave height on the selected isobath is about 6m, while the maximum heights in the area of the earthquake epicenter reach 16m. It can be concluded that the smallest-scale division into blocks of a seismic source will allow to specify in more detail the area of wave run-up on the coast in the area of the earthquake epicenter.

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REFERENCES

1. Daniel M. Stewart. Recalibrating the July 8th, 1730 Valparaiso, Chile earthquake: giving historical context to primary sources // URL: https://www.academia.edu/44751468/Recalibrating_the_July_8th_1730_Valparaiso_Chile_earthquake_giving_historical_context_to_primary_sources.
2. Carvajal M., Cisternas M., Catalán P.A., Source of the 1730 Chilean earthquake from historical records: Implications for the future tsunami hazard on the coast of Metropolitan Chile // J. Geophys. Res. Solid Earth/ V. 122. P. 3648–3660. DOI: 10.1002/2017JB014063.
3. Lomnitz C. Major earthquakes and tsunamis in Chile during the period 1535 to 1955 // Geologishe Rundschau International. 1970. V. 59. No. 3. P. 938-960.
4. Berninghausen W.H. Tsunamis reported from the west coast of South America, 1562-1960 // Bulletin of the Seismilogical Society of America. 1962. V. 52. P. 915-921.
5. Cox D.C. Pacific tsunami historic file, U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Boulder, Colorado, unpublished manuscript.
6. Instituto Hidrografico de la Armada. Maramotos en la costa de Chile. Valparaiso, Chile, 1982. 48 p.
7. Cox D.C., Iida K., Pararas-Carayannis G. Preliminary Catalog of tsunamis occurring in the Pacific Ocean. – Honolulu: University of Hawaii, 1967. 274 p.
8. Solov'ev S.L., Go Ch.N. A catalog of tsunamis of the eastern shore of the Pacific Ocean. – M.: Nauka Publishing House, 1975/ 202 p.
9. USGS [Electronic resource]. https://earthquake.usgs.gov/learn/glossary/?termID=150
10. Electronic bathymetry Gebco Digital Atlas [Electronic resource]. – http://www.gebco.net
11. Lobkovsky L.I., Baranov B.V. Keyboard block model of strong earthquakes in island arcs and active continental margins // Doklady AN SSSR. 1984. T. 275. No. 4. P. 843-847.
12. Lobkovsky L.I., Mazova R.Kh., Kataeva L.Yu., Baranov B.V. Generation and propagation of catastrophic tsunamis in the Sea of Okhotsk Basin: Possible scenarios // Doklady Earth Sciences. 2006. V. 410(1). P. 1156–1159. DOI: 10.1134/S1028334X0607035X.
13. Mazova R.Kh., Moiseenko T., Kurkin A.A., Jorge Van Den Bosch F., Gustavo Oses A. Numerical Simulation of a Catastrophic Earthquake and Strong Tsunami of April 1, 2014 near the Northwestern Part of the Chilian Coast // Science of Tsunami Hazards. 2021. V. 40. No. 2. P. 83-100.
14. Wells D.L., Coppersmith K.J. New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement // Bulletin of the Seismological Society of America. 1994. V. 84. P. 974-1002.
15. Pelinovsky E.N. Nonlinear dynamics of tsunami waves. – Gorky: IAP USSR Academy of Sciences, 1982. 226 p
16. Voltsinger N.E., Klevanny K.A., Pelinovsky E.N. Long-wave dynamics of the coastal zone. – Leningrad: Gidrometeoizdat, USSR. 1989. 272 p.
17. Sielecki A., Wurtele M. The numerical integration of the nonlinear shallow water equations with sloping boundaries // J. Comput. Phys. 1970. V. 6. P. 219. DOI:10.1016/0021-9991(70)90022-7.