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Modelling of Tsunami Propagation in the Vicinity of the French Coast of the Mediterranean

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Abstract. The problem of tsunami-risk for the French coast of the Mediterranean is discussed. Historical data of tsunami manifestation on the French coast are described and analysed. Numerical simulation of potential tsunamis in the Ligurian Sea is done and the tsunami wave height distribution along the French coast is calculated. For the earthquake magnitude 6.8 (typical value for Mediterranean) the tsunami phenomenon has a very local character. It is shown that the tsunami tide-gauge records in the vicinity of Cannes–Imperia present irregular oscillations with characteristic period of 20–30 min and total duration of 10–20 h. Tsunami propagating from the Ligurian sea to the west coast of France have significantly lesser amplitudes and they are more low-frequency (period of 40–50 min). The effect of far tsunamis generated in the southern Italy and Algerian coast is studied also, the distribution of the amplitudes along the French coast for far tsunamis is more uniform.

1. Introduction

Earthquakes in France are moderate, and the probability of strong destructive earthquakes is weak. Data of earthquakes in France are summarised by Levret *et al.* (1994), Lambert and Levret (1995), and Laurenti (1998). Tsunamis are rather rare events. Usually, this problem is studied for overseas French territories in Pacific and in Atlantic, and significantly less – for metropolis. In the last review paper, Heinrich (1999) has mentioned the importance of studies about the tsunami-risk for the French Riviera (Cannes–Nice). Data of historical tsunamis in Mediterranean was recently summarised in the catalogue by Soloviev *et al.* (1997, 2000). Also, the catalogue of tsunamis generated in Italy and in Côte d'Azur (France) was prepared by Tinti and Maramai (1996) as a part of an unified catalogue of tsunamis in Europe. This catalogue was edited in electronic form within the framework of the European project GITEC in 1998. Data of both catalogues are used here to collect and analyse the known data of tsunami manifestation on the French coast of the Mediterranean. Data are rather poor, in particular, tide-gauge records of tsunamis are known only for two events: February 23, 1887 in Genoa and Nice (Eva and Rabinovich, 1997), and October 16, 1979 in Nice and Villefranche (Tinti and Maramai, 1996). Such statistics cannot be used for direct estimates of tsunami-risk. For these cases the numerical simulations of hypothetic tsunamis with sources in the seismic active zone can provide the set of "synthetic" tsunamis and can be used for comparable analysis of tsunami-risk for different points along the coast. The modelling of prognostic tsunami propagation in the vicinity of the French coast of the Mediterranean is a main aim of this study. The paper is organised as follows. The historical data of tsunamis in France are described in Section 2. The total number of events is 24, but the reliability of them is weak. Nonlinear shallow-water equations used to simulate the wave propagation from initial displacements in the tsunami source are given in Section 3. Results of numerical simulations of several prognostic tsunamis whose sources are located in the northern part of the Ligurian sea, southern Italy and Algerian coast are presented in Section 4. Numerical simulations emphasise the local character of the tsunami phenomenon for the specific value of the earthquake magnitude in the Mediterranean (6.8). Calculated tsunami records in the northern part of the Ligurian sea display the irregular oscillations with characteristic period of 20–30 min and total duration up to 24 h. Tsunami records for the western part of the Mediterranean coast of France correspond to lower frequency oscillations (period 40–50 min). For the well-known documented event of 1887 our results are in good agreement with observed data and numerical results by Eva and Rabinovich (1997). The runup of tsunami waves on the beach is calculated for simplified geometry of the plane beach. It is shown that the runup effect can amplify the wave amplitude on average twice or three times. Discussion of the numerical results is given in Section 5.

2. Analysis of Historical Data of Tsunamis

Data of historical tsunamis in the Mediterranean are collected in the catalogue of Soloviev *et al.* (1997, 2000). First of all it is important to note that the average value of the magnitude of the tsunami-genetic earthquakes in a basin of the Mediterranean as a whole is 6.8 and it is less than for Pacific (in particular for Russian Pacific coast the mean magnitude is 7.2). According to this catalogue, the total number of events in the Ligurian sea (part of the Mediterranean including French and north-eastern Italian coasts) is 36, including 17 events of seismic origin, 1 – from underwater slide, and 18 – of unknown origin. The return period for the Ligurian sea is estimated at 17 years, the mean intensity of tsunami – 3.8 and maximum intensity – 4. The probability of occurrence of new tsunamis in the Ligurian sea is considered to be high.

Usually the Ligurian sea is considered in the literature as uniform sub-region of the Mediterranean taking into account the seismic zoning of Europe. But historically, many tsunamis generated in the Ligurian sea were not recorded in France.

Our aim is to investigate tsunami manifestations on the French coast only. Below, data of tsunamis provided in the catalogues by Tinti and Maramai (1996), Soloviev *et al.* (1997, 2000), and in the papers (Eva and Rabinovich, 1997; Rzadkiewicz *et al.*, 2001) are used to collect and to analyse tsunamis climbing on the French coast of the Mediterranean. It is necessary to emphasize that some information included in one catalogue is not presented in another one. Also, estimates of reliability of the historical events are different. Owing to the poor quality of historical information and impossibility to check the primary sources, all described events are summarised here very briefly in Table I to describe main features of tsunamis in France.

So, according to the Table I there were 24 events of tsunamis on the French coast of the Mediterranean for large historical period 2000 BC–2000 AD, and most of them (20) occurred in the 19th century. Most of tsunamis were observed in Nice-Cannes (13 events), in Marseilles – 5 events, in Sete – 3 events, and in Island of Corsica – 2 events. Taking into account that the first event was mentioned in 1564, the return period of tsunami for the French coast of the Mediterranean can be estimated at 18 years, as for the Ligurian sea in a whole. In the 20th century there were two events only (in 1924 and 1979), and they both were not related with seismic activity in the Mediterranean.

It is interesting to analyse the origin of historical tsunamis on the French coast of the Mediterranean. Earthquakes are responsible for 11 tsunamis, the submarine landslide – for one tsunami, and unknown sources – for 12 tsunamis (probably, most of them have meteorological origin – so-called “meteo” tsunami, or local landslide phenomena). The reliability of last 12 tsunamis is a very questionable, and some of them are connected with floods in the coastal zone due mainly to heavy rain in “land”, but not with water coming from the sea. As a result, some such descriptions in the catalogue by Soloviev *et al.* (1997) were deleted in the English version of the book by Soloviev *et al.* (2000). Last well-known example is the flooding in Marseilles on 20 September 2000, where the water level raised on up to 3 m, including the historical old harbour “Vieux-Port” (as in many coastal cities of France and Italy). Having no data of meteorological conditions during these tsunamis, we will not investigate such cases.

The submarine slope failure in 1979 occurred during Nice new harbour extension (close to the Nice international airport), and this event (as, possible, some events of unknown origin) underlines the necessity to investigate the geo-technical characteristics of submarine slope sediments along the French coast of the Mediterranean and to estimate the tsunami damage due to instability of sediments in the coastal zone. The numerical simulation of the tsunami generation by the submarine landslide in Nice during the 1979 event was performed by Rzadkiewicz *et al.* (2001). They are in good agreement with observed data. This approach can be used for prognostic estimates of characteristics of the “landslide” tsunamis.

The information about “earthquake” tsunamis in France is rather poor: for instance, an earthquake magnitude is known for four events (1564, 1808, 1846 and

Table I. List of tsunamis on the French coast of the Meditearranean

No.	Date	Reason	Points in France	Tsunami intensity	Reliability
1	1564, July 20	Earthquake	Nice, Antibes Villefranche	3–4	Definite
2	1775, October 22	Earthquake	Corsica		
3	1808, April 2	Earthquake	Marseilles (15 cm)	1–2	Questionable
4	1812, June 28		Marseilles	3–4	Probable
5	1818, February 23	Earthquake	Antibes, Var	2–3	Probable/questionable
6	1831, May 26	Earthquake	Nice	3	Questionable
7	1844, July 17	Meteo (?)	Sete		
8	1844, October 22	Meteo (?)	Sete		
9	1845, June 20	Meteo (?)	Sete		Questionable
10	1846, August 14	Earthquake	Marseilles	3	Definite
11	1846, December 3	Earthquake	Marseilles	3	
12	1849, July 20	Meteo (?)	Marseilles	3	Questionable
13	1854, February 29		Ligurian Sea		
14	1854, December 29	Earthquake	Nice		
15	1855, May 18		Nice	3	Questionable
16	1862, March 18	Earthquake	Nice		Improbable/questionable
17	1862, November 24	Earthquake	Nice		Improbable/questionable
18	1876, December 23		Nice	3–4	Probable
19	1885, January 16	Meteo	Nice, Cannes, Villefranche	4	Definite/probably
20	1886, November 11	Rain	Frejus, Nice		Very improbable
21	1886, December 17	Meteo	Nice		Very improbable
22	1887, February 23	Earthquake	Antibes Nice (1–3 m), Corsica	3	Definite
23	1924, January 9		Ligurian Sea		Questionable
24	1979, October 16	Landslide	Antibes–Nice (3 m)	4	Definite

1887) only out of 11 events; in fact, no data of tsunami runup heights for almost all events. Only the earthquake and tsunami of February 23, 1887 was well documented. This catastrophic earthquake caused significant damage and numerous casualties in north-western Italy and south-eastern France (Eva and Rabinovich, 1997). For this tsunami, the unique tide-gauge records in Genoa and Nice harbours are found. The epicentre of the earthquake with magnitude 6.2–6.5 is located on the continental slope 20 km offshore from Imperia (Italy). The seismic characteristics of this event were studied by Ferrari (1991). The earthquake was produced by

Table II. Parameters of tsunami-genetic earthquakes for the French events

Year	Month	Date	Latitude, N	Longitude, E	Magnitude
1564	07	20	44°	7°20′	6.2
1808	04	02	44°51′	7°15′	5.6
1818	02	23	43°45′	8°	–
1831	05	26	43°40′	7°45′	–
1846	08	14	43°31′	10°32′	5.6
1846	12	03	43°20′	10°45′	–
1854	12	29	43°45′	7°50′	–
1887	02	23	43°53′	8°	6.4

release of stress along the offshore normal faults oriented parallel to the coast. Parameters of the earthquake source are: strike 71°, dip 85° (almost vertical), slip 90°, and displacement 35 cm (pure thrust), length 45 km, width 10 km, fault centre depth 10 km. As a result, the calculated initial sea surface displays two ellipses with opposite displacements: negative – in coastal area (less than 2 km of depth) and positive – in deepest area (Eva and Rabinovich, 1997). The numerical simulation confirmed that the first wave in nearest points (Cannes–Genoa) was negative. The second important result of simulations is the demonstration of the resonant character of the tsunami propagation in the Ligurian sea with the characteristic period of about 23–28 min and formation of the edge waves. The amplitude comparison is not given, but it is pointed out that the observed spectrum of tsunami in the Genoa harbour exceeds the computed spectrum approximately by 10 times, having the same peaks corresponding to the resonance frequencies.

Information on the earthquakes induced tsunamis on the French coast is summarised in Table II, their epicentres are given in Figure 1 (descriptions of several earthquakes do not contain exact coordinates, and such events are not considered here). In fact, all tsunami-genetic earthquakes can be divided into three groups. First of all, there are two “land” earthquakes in 1564 and 1808. In the first case, the earthquake occurred relatively close to the seacoast and can induce horizontal and vertical motions of sea bottom (or subsidence of the coast), which led to water oscillations. The mechanism of tsunami generation by the “land” earthquake is not quite developed and this problem needs a more detailed analysis. In the second case of event 1808 the earthquake occurred very far from Marseilles and the relation between the water fluxes in the harbour and the earthquake is not clear.

The second group is the “far” earthquakes with epicentres on the Italian coast (Tuscany earthquakes of 1846). Usually, far earthquakes of large magnitude can effectively generate tsunami waves (many events in Pacific were related with such earthquakes), and waves can propagate over large distances. The magnitude of the

Figure 1. Epicentres of earthquakes induced tsunami on the French coast of the Mediterranean.

1846 earthquake was not sufficient (5.6) to generate significant waves, and the relation between this earthquake and the water motion in Marseilles is not clear (probably such waves should be recorded first in Cannes–San Remo). Taking into account the high seismicity and large intensity of the west coast of Italy, this area should be considered as the possible zone of generation of tsunamis affected in France.

The most important zone of tsunami generation is located in the vicinity of the coast between Nice and Imperia, where four events occurred (1818, 1831, 1854, 1887), including the disastrous tsunami of February 23, 1887 with the runup height of 2 m, described briefly above. Earthquakes in this area are very shallow, with focal depth of about 10–20 km and can induce significant waves in spite of relative small magnitude (6.2–6.5).

We would like to emphasize that catastrophic earthquakes near Genoa can produce also tsunamis on the French coast, but historically, according to the catalogues by Soloviev *et al.* (1997, 2000) two earthquakes (1703 and 1751) in this zone generated local tsunamis at Genoa only.

It is clear from given analysis that the derivation of quantitative estimates of tsunami risk for the French coast of the Mediterranean based on the historical information only is a problematic task. For such situations the synthetic method is developed (for instance, Curtis and Pelinovsky, 1999). It is based on wide application of numerical simulations of real events and possible tsunamis from different hypothetical sources, whose characteristics are chosen from historical data and analysis of seismicity of the given area. This approach allows to compare the characteristics of tsunami in different coastal points and gives preliminary estimates of the tsunami risk. Below, some scenarios of possible tsunami propagation in the Mediterranean affecting the French coast will be developed.

3. Mathematical Model

Usually, tsunami waves are low-frequency long waves, and the appropriated mathematical model is the shallow-water theory, for instance, in the form of Saint-Venant equations

$$\frac{\partial \eta}{\partial t} = \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y}, \tag{1}$$

$$\frac{\partial M}{\partial t} + \frac{\partial}{\partial x}\left(\frac{M^2}{D}\right) + \frac{\partial}{\partial y}\left(\frac{MN}{D}\right) + gD\frac{\partial \eta}{\partial x} + \frac{gm^2}{D^{7/3}}M\sqrt{M^2+N^2} = 0, \tag{2}$$

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial x}\left(\frac{MN}{D}\right) + \frac{\partial}{\partial y}\left(\frac{N^2}{D}\right) + gD\frac{\partial \eta}{\partial y} + \frac{gm^2}{D^{7/3}}N\sqrt{M^2+N^2} = 0, \tag{3}$$

where M and N are the horizontal components of the discharge per unit width, $D = h + \eta$ is the total depth, $h(x, y)$ is the still water depth, $\eta(x, y, t)$ is the surface displacement, g is the acceleration due to gravity, and m is the Manning roughness coefficient. Sometimes, effects of the water wave dispersion can be important, if wave period is too small (a few minutes). We will not consider here dispersion effects due to robust character of performed simulations in the coastal zone (see below), where such effects can play an important role.

The choice of the tsunami source is usually the most complicated problem in the theory; it needs good knowledge of earthquake mechanism. For rough estimates of tsunami characteristics the simplified piston model is used, it corresponds to the instant lift up of the sea surface due to bottom displacement. The source parameters in the first approximation can be considered as functions of the earthquake magnitude only (see, for instance, Murty, 1977; Pelinovsky, 1996), but it is a very robust approximation. Here we will use the two-parametric (earthquake magnitude and focus depth) model for the tsunami source. Of course, such models should be found from local data, which are absent for the Mediterranean, and we will use the formula obtained for other regions. For instance, for an estimate of the tsunami-risk in the vicinity of the Russian coast of the Pacific it is assumed that the tsunami source dimensions coincide with the dimensions of the macroseismic source (Poplavsky *et al.*, 1997). The initial data here is the fault length in the earthquake source l_0 related with the earthquake magnitude M_0

$$\log l_0 = 0.5M_0 - 1.8, \tag{4}$$

and this formula is valid for the "land" earthquakes too. The dimensions of the tsunami source of ellipsoidal form are

$$a = \frac{l_0 + 2h_f}{2}, \quad b = h_f, \tag{5}$$

where a and b are the large and small semi-axes of the ellipse, and h_f is depth of the earthquake focus. Tsunami waves are usually generated by shallow earthquakes. The height of the sea displacement is found by using the empirical formula

$$\log \eta_0 = -4.31 - 4.36 \log h_f + 1.45 M_0. \tag{6}$$

Again we have to note that these formulas were obtained for conditions in the Pacific, not for the Mediterranean. As a result, the calculation of absolute values of the tsunami heights is not quite correct. But the relation between the tsunami heights in different coastal points should be more realistic, because it depends mainly from the coastal topography and very rough characteristics of the tsunami source (in particular, the source orientation).

Boundary conditions have to be added to Equations (1)–(3). On the open boundaries the well-known condition of the free wave propagation away from domain is used

$$\frac{\partial \eta}{\partial t} + \sqrt{gh}\frac{\partial \eta}{\partial n} = 0, \tag{7}$$

where n is a normal to the open boundary. In the vicinity of the coastline, at the point on the boundary of the discretised domain ("last sea" point) the vertical wall condition is used

$$\frac{\partial \eta}{\partial n} = 0, \tag{8}$$

as a result, the sea level oscillations along this "wall" are calculated. We will assume that the "computed" tide-gauge is located at the last sea point, and its record will be defined as $\eta_w(t)$. The process of the wave runup is not considered herein. But, if we assume, that the beach is plane and the wave comes on almost onshore direction, the runup height, $R(t)$ can be calculated via $\eta_w(t)$; the review of the corresponding formulas can be found in book by Pelinovsky (1996). Here we will use the analytical expression derived recently by Kaistrenko *et al.* (1999)

$$R(t) = \int_0^{t-T} \sqrt{(t-\tau)^2 - T^2}\frac{d^2\eta}{d\tau^2}d\tau, \tag{9}$$

where T is the time of propagation from the last sea point to the shore, and $t > T$. Combination of 2D models for tsunami propagation in the open sea with 1D model of tsunami run-up, was checked on data of tsunami July 12, 1993 in Japan sea recently. This method improves agreement between computed and observed data, significantly (Choi *et al.*, 2001).

The mathematical model described above is solved numerically by using the finite - difference scheme (time step - 9 sec) developed by Vasily Khramushin in the form of special computer package, described in the book by Poplavsky

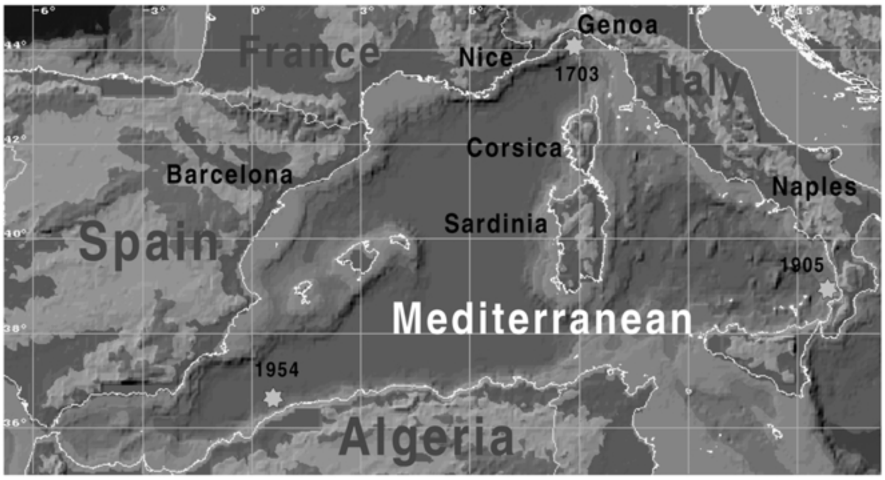

Figure 2. Epicentres of earthquakes used for numerical simulation.

et al. (1997). This package is used below to simulate hypothetic tsunamis in the Mediterranean (bathymetry resolution – 5 min).

4. Synthetic Tsunami Simulation

Taking into account the importance of tsunami generation in the vicinity of Nice–Imperia the four numerical experiments with the wave propagation from the sources located in this area were performed. The location of epicentres of computed tsunamis was the same as for historical tsunamis 1818, 1831, 1854 and 1887; coordinates of these events are given in Table II and Figure 1.

Furthermore, several possible epicentres of tsunamis that can reach the French coast are chosen (Figure 2). The first is the location of the weak earthquake of July 2, 1703 in Genoa (epicentre coordinates: 44°15′N 8°50′E, magnitude 3.2). This earthquake generated a local tsunami, in particular, the sea level in the *Harbour of Genoa* decreased by 1.5–2 m, and the sea was still in this state during a quarter of one hour; a galley ran aground; no information of this event in other points (Soloviev *et al.*, 1997). This example should demonstrate the tsunami propagation from northern Italy to the French coast.

The second is the tsunami propagation from the southern Italy. The earthquake on September 8, 1905 (magnitude 6.9, epicenter coordinates: 38°40′N 16°03′E) was one of the strongest events which occurred in this area. It induced sea level oscillations with period of 7.5 min along the coast of the Tyrrhenian Calabria up to Ishia (maximum runup 6 m at Scalea). This tsunami was not registered in France, but taking into account the large seismicity of southern Italy, this area can be considered as a potential place for generation of strong tsunamis.

And the last one is the tsunami propagation from the North African coast. A strong earthquake occurred on September 9, 1954 on the Algerian coast, near Orléansville (epicenter coordinates: 36.3°N 1.5°E, magnitude 6.7). This earthquake induced tsunami waves, which were instrumentally recorded on the Spanish coast. According to the calculations, the tsunami source was located on the slope of the African continent to north-north-west from the earthquake epicenter (Soloviev *et al.*, 1997).

For prognostic modelling it is assumed that for all events the earthquake magnitude is $M_0 = 6.8$, the focal depth of earthquake is 20 km, the orientation of tsunami source is north-east, and the roughness coefficient is $m = 0.0012$. According to (5)–(6), the displacement of water surface at the tsunami source is 1.5 m, semi-axes of the ellipsoidal source are 40 and 20 km consequently. This value for the earthquake magnitude corresponds to the mean value of tsunami-genetic earthquake in the basin of the Mediterranean as a whole. The chosen source orientation is typical, for instance, for earthquakes in the northern part of the Ligurian sea. Parameters of all events have been chosen identical mainly to demonstrate the geographical features of tsunami propagation and compare the characteristics of tsunami waves for different coastal points.

The computed wave field is recorded in 7 points in the vicinity of the French coast (Perpignan, Sete, Marseilles, Toulon, Cannes, Nice), including the Island of Corsica (Bastia), and in 4 points of Italy (San Remo, Imperia, Savona and Genoa). Each "computed" tide-gauge is located at the "last" sea point in numerical scheme (depth about 20 m) to the nearest coastal point. For this point an assumption of a vertical wall is used. Then tide-gauge data are used to compute the oscillation of water level on the coast, $R(t)$ according to (9).

First of all, let us consider the results of the tsunami simulation from the four hypothetic events, whose epicentres are located at the place of real earthquakes (1818, 1831, 1854 and 1887) and very close to Nice–Imperia. Tsunami records (vertical displacement of the sea surface) for events 1831 and 1887 are shown in Figures 3–4 (only records for northern part of the Ligurian sea are presented here). As expected, maximum amplitude (14–29 cm) is reached in the nearest point to the earthquake epicenter (San-Remo for tsunami 1818, 1831 and 1854; Imperia for tsunami 1887). The 1887 Ligurian tsunami was, in fact, very shallow (see Figure 1), and wave amplitude is maximal for it. The maximal values of the wave amplitudes in different points are summarized in Table III. Tsunami waves in Cannes–Nice have amplitudes (6–14 cm) twice less than in the nearest point (San-Remo or Imperia) for all events. In Genoa wave amplitude is weak (3–4 cm). Because all epicenters are located very close to each other, the variation of wave amplitudes in each points for different events is weak, except for San-Remo and Imperia, for which any shifting of epicenter is comparable with the characteristic dimension of the tsunami source. Of course, absolute values of the wave amplitudes do not matter due to the idealized tsunami source, but the distribution of wave amplitudes along the coast allows to access the damage due to tsunami in different points.

Table III. Maximal values of computed wave amplitudes (meter)

Points/years	1818	1831	1854	1887
Cannes	0.08	0.06	0.08	0.14
Nice	0.07	0.08	0.09	0.14
San-Remo	0.14	0.13	0.2	0.1
Imperia	0.1	0.07	0.09	0.29
Savona	0.03	0.04	0.04	0.07
Genoa	0.04	0.03	0.03	0.04

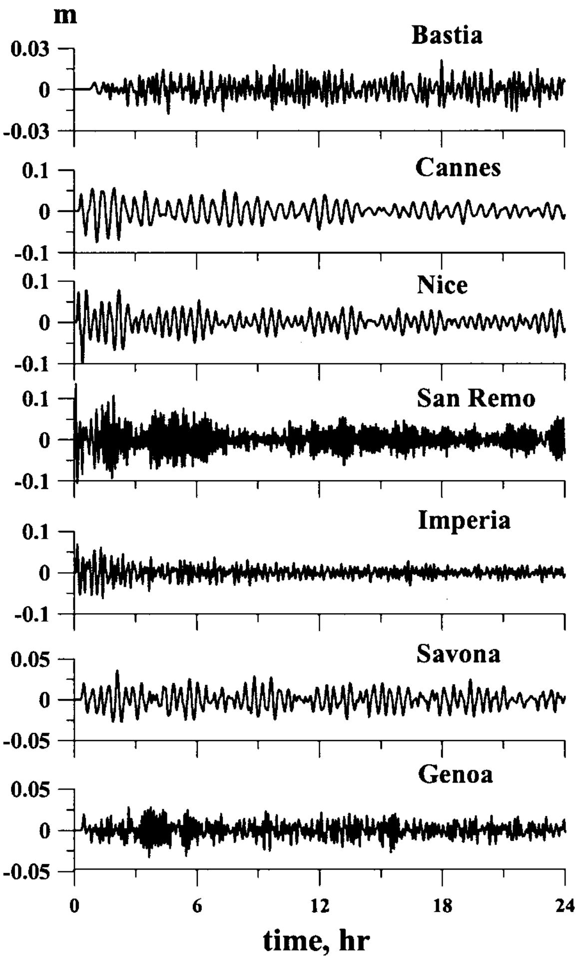

Figure 3. Computed tsunami records for "event" of 1831.

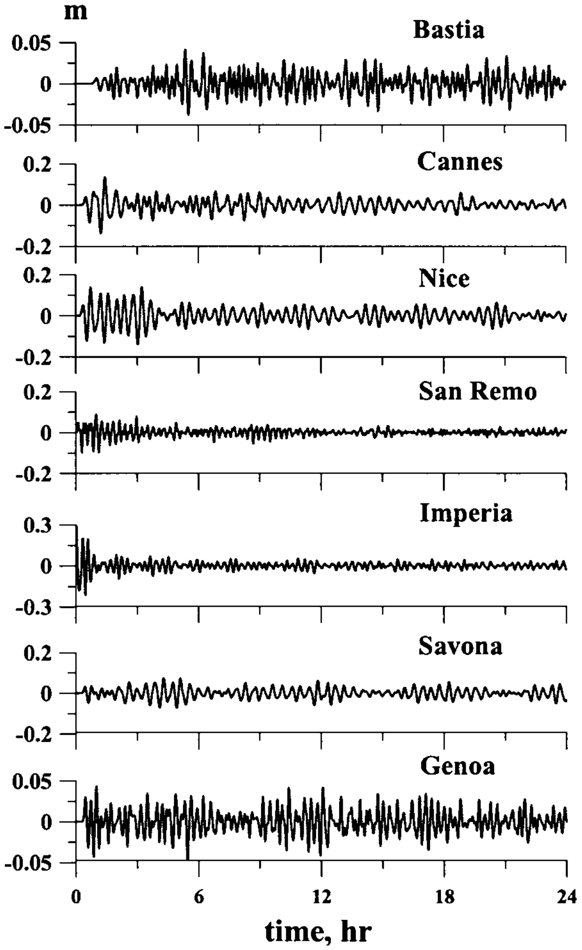

Figure 4. Computed tsunami records for "event" of 1887.

Tsunami record at the nearest point to the earthquake contains, as a rule, the short intense wave train accompanied by long oscillatory tail. In particular, intense wave group in San-Remo (event of 1831) has duration of 3 h, and the second crest is maximal (Figure 3). In Imperia (event of 1887) the maximal one was the first wave, and the first three waves were intense (Figure 4). In all other points (or when the epicenter is not too close to the coast) each tsunami record corresponds to water level oscillations during 10–24 h with the characteristic period of tsunami wave varying in the 20–30 min range at different locations. Such slow level oscillations are specific to the flood (the abnormal tides and ebbs), and this corresponds to the description of the historical events. The origin of these oscillations is related with the resonant oscillations on local bottom irregularities in the coastal zone (as it is known, the periods of the seiche oscillations in the Ligurian Sea as a whole have an order of a few hours, see, Papa, 1984). As a result, the characteristic "visible"

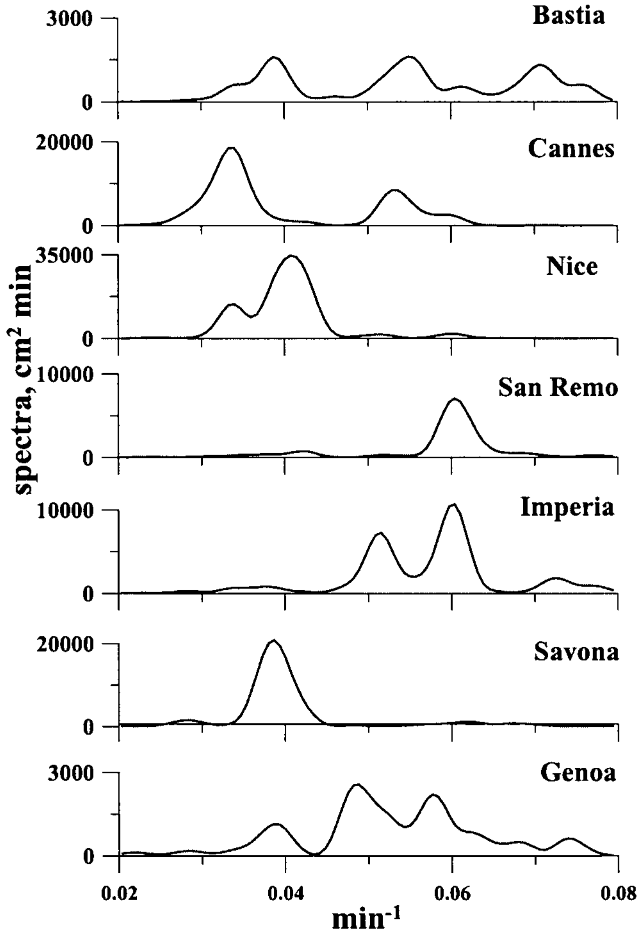

Figure 5. Computed spectra for the 1887 event.

period of waves in Cannes, Nice and Savona is greater than in San-Remo, Imperia, and Genoa for all the four events. Results of calculations of the energetic spectra of the 1887 event are displayed in Figure 5. As it can be seen, the spectral maximum varies from point to point revealing the complex picture of resonances in the basin of the Ligurian sea. The low frequency peak (24–30 min) present in all cities except Imperia and San-Remo, characterises the basin as whole. The high frequency peak (17–20 min) is strong for Genoa, Imperia and San Remo. The resonant periods corresponding to the energetic peak in the spectra are given in Table IV.

Irregularity in the tide-gauge record leads to several groups of tsunami waves approaching the coast, and finally, the sea level oscillations became significant during 10 hours and more after an earthquake. This fact should be taken into account for an evaluation of tsunami characteristics immediately after the tsunami-genetic earthquake.

Table IV. Resonant periods (min) for the 1887 event

Points	Low-frequency	Middle-frequency	High-frequency
Cannes	29.5	18.9	
Nice	24.6		
San-Remo			16.6
Imperia		19.4	16.6
Savona	26.3		
Genoa	26	20.5	17.4

The unique tide-gauge record of the 1887 tsunami at the Genoa harbour is given in the paper by Eva and Rabinovich (1997). This record shows oscillations with height about 10 cm during at least 9 h, characteristic period is 22.5 min. Numerical simulation by Eva and Rabinovich (1997) who used a more realistic model for the tsunami source explains this period as resonance period of the Genoa harbour only. Also, their simulation shown that tsunami began from the negative phase (ebb), but computed spectrum is in 10 times more than observed spectrum. Our simulations have not included the detailed characteristics of the Genoa harbour as well as the non-uniform distribution of water displacement in the tsunami source. Calculated wave height (8 cm) in our model is comparable with the observed height (10 cm). Resonant periods of energetic peak for Genoa according to our calculations is 20.5 min and this value is very close to the observed period (22.5 min) and calculations by Eva and Rabinovich (1997) who obtained 22.3 min. Also the total duration of the tide-gauge record computed for Genoa (Figure 6) is more than 24 h (observed duration is about 10 h), and the waves of maximal height approaching to Genoa several times: 1, 5, 10, 12, 15 and 17 h after the earthquake. The agreement between computations and observations is satisfactory. Large duration of tsunami record is characteristic of all points of French Rivera and this should be taken into account for tsunami warning, and forecasting should be done at least 10 h after earthquake.

It is interesting to compare the characteristics of different tsunamis in one point. Figure 6 shows the computed tide-gauge records of four tsunamis in Nice. Wave records are similar to each other, also the same period of oscillations (about 25 min). As it can be seen, the first group of tsunami waves is more intense for all simulations and its duration is about 2–4 h. Unfortunately, tide-gauge record of tsunami in Nice is known only for “non-seismic” event of 1979. This record contains intense wave train of height about 10 cm during 2 h (characteristic period about 10 min). Duration of this tsunami record corresponds to our calculations, but not the wave period. The same behaviour of the water oscillations is calculated for tsunamis in Cannes.

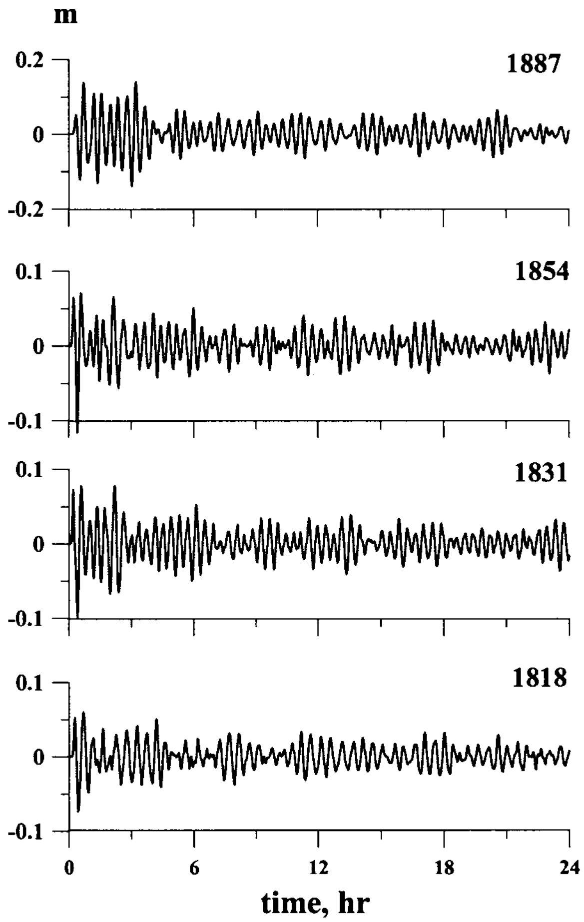

Figure 6. Computed tsunami records for Nice.

Table V. Maximal values of amplitudes of the run-up/run-off

Points/years	1818	1831	1854	1887
Cannes	0.13/0.12	0.09/0.13	0.12/0.16	0.24/0.22
Nice	0.11/0.15	0.16/0.19	0.16/0.24	0.28/0.26
San-Remo	0.27/0.28	0.25/0.22	0.37/0.33	0.13/0.16
Imperia	0.21/0.17	0.11/0.13	0.16/0.14	0.35/0.38
Savona	0.06/0.07	0.08/0.06	0.08/0.08	0.17/0.16
Genoa	0.08/0.07	0.06/0.07	0.06/0.06	0.07/0.07

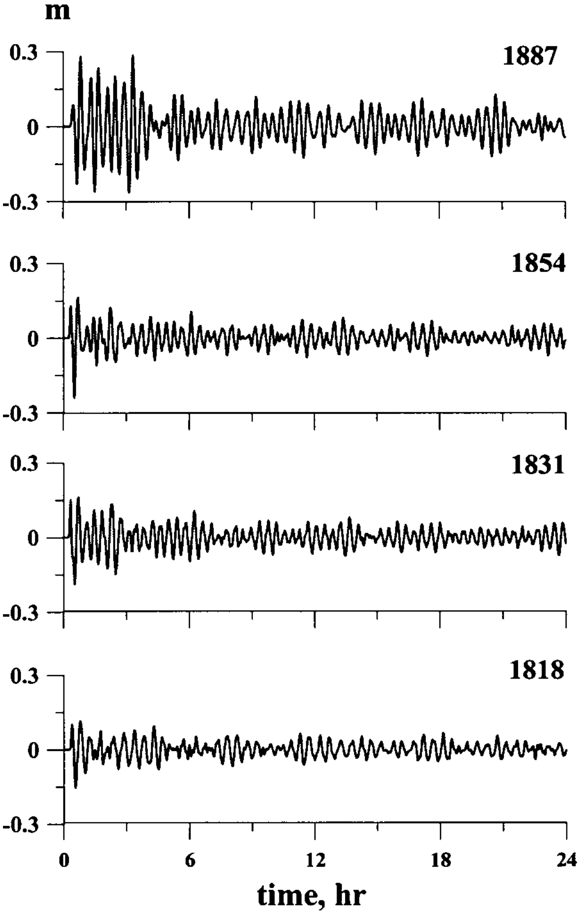

Figure 7. Computed vertical oscillations of the shoreline for Nice.

These tide-gauge records were re-calculated into the vertical oscillations of the sea level on the beach according to (9). Results of the computations are presented in Table V and shown in Figure 7 for Nice. The character of the wave profiles at the tide-gauge point and on the beach is the same. In general, tsunami waves are amplified twice or three times near the shoreline with characteristic periods of 20–30 min. It is important to mention that amplitude of "run-up" approximately is equal to the amplitude of "run-off". Sometimes the run-off is more significant, it occurs after the leading wave, and this fact correlates with many descriptions of tsunamis in the Ligurian Sea.

The western part of the Mediterranean coast of France is protected from tsunamis generated in the northern part of the Ligurian sea by the south part of the French Rivera, see, Figure 1. As a result, the tsunami waves in Marseilles, Toulon, Sete and Perpignan have amplitudes approximately 5 to 10 times less than in Nice and Cannes. In particular, the maximal wave height in the tide-gauge record in

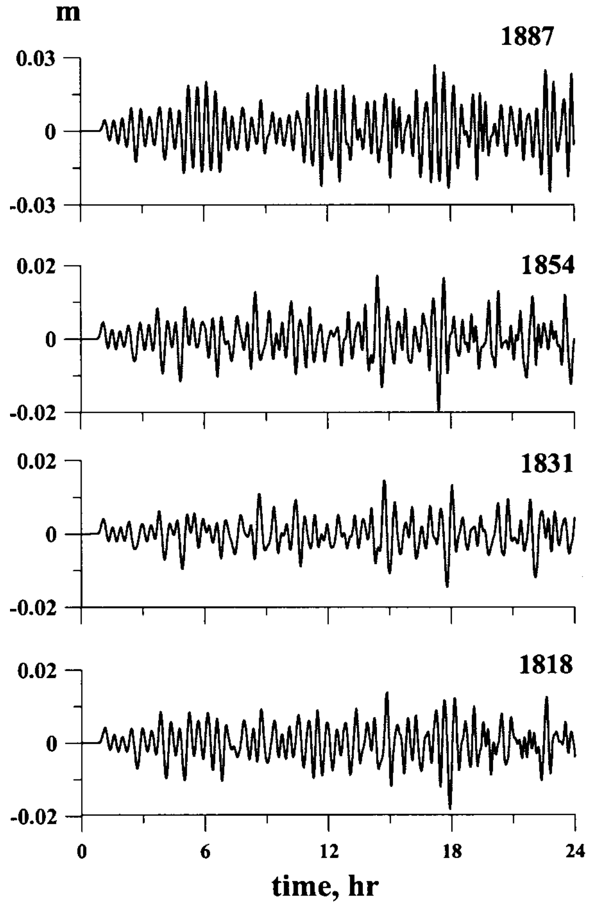

Figure 8. Computed tsunami records in Marseilles.

Marseilles does not exceed 5 cm (Figure 8) and this value is approximately constant for all points between Perpignan and Toulon. More important, since the travel time increases as distance from the earthquake increases, the leading tsunami wave approaches Marseilles approximately 1 h after earthquake, and in Perpignan – 2 h later. Tsunami propagates along the coast as the edge wave mainly, such waves have strong dispersion, and as a result, the most intense group reaches Marseilles 6–18 hours after earthquake. Calculated wave forms in different points of France for the 1887 event are shown in Figure 9, and their spectra – in Figure 10. The characteristic period of oscillation is increased with distance; in Marseilles 26.8 min, Sete – 42.1 min, and in Perpignan - 44.7 min. It is interesting to emphasize that the spectrum of tsunami in Toulon is very wide (resonant period is varied from 26 to 64 min), and this point should be specially investigated.

Tsunami waves in Corsica, according to our calculations, have small height (less than 8 cm) and relative high period (10–15 min). The intense wave group

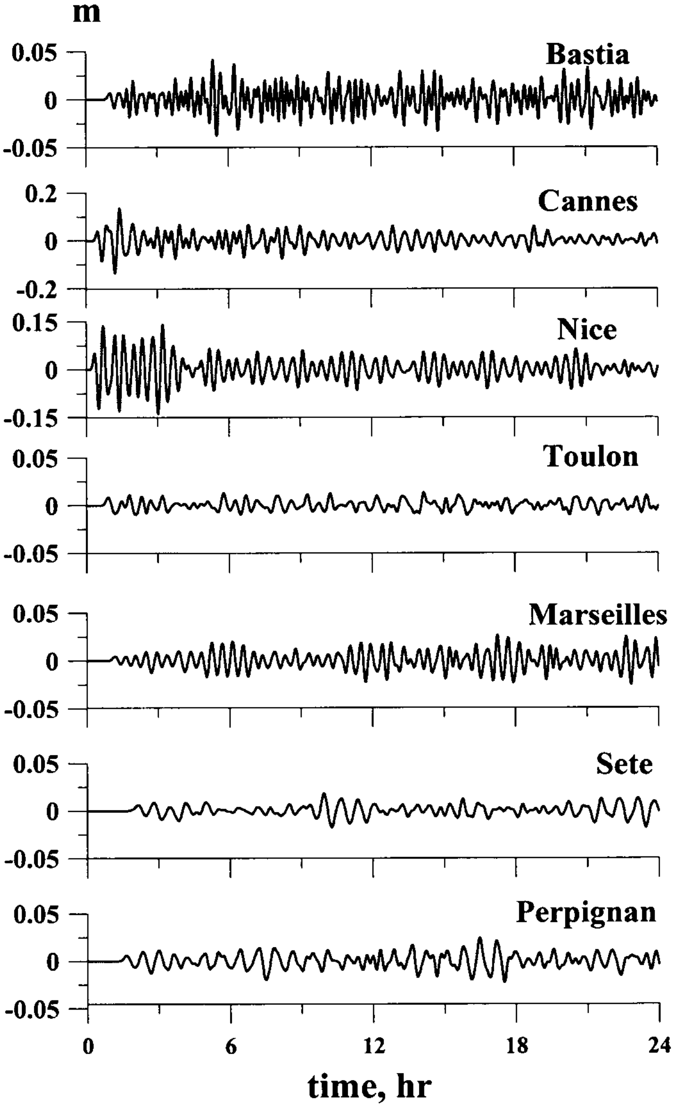

Figure 9. Computed tsunami records for the 1887 event.

approaches Corsica 5 h after an earthquake, meanwhile the leading wave – 1 h only.

All the previous hypothetic tsunamis were generated in the vicinity of the area Nice–Imperia. The impact of the far tsunamis is provided by the following numerical simulations, when the tsunami source is located at Genoa (1703), Italy (1905) and Algeria (1954) earthquakes respectively. The results of the simulations are presented in Figures 11–13. In particular, tsunamis, generated near Genoa, propagate toward Nice and Cannes with heights (5–7 cm) 5 times less than in Genoa

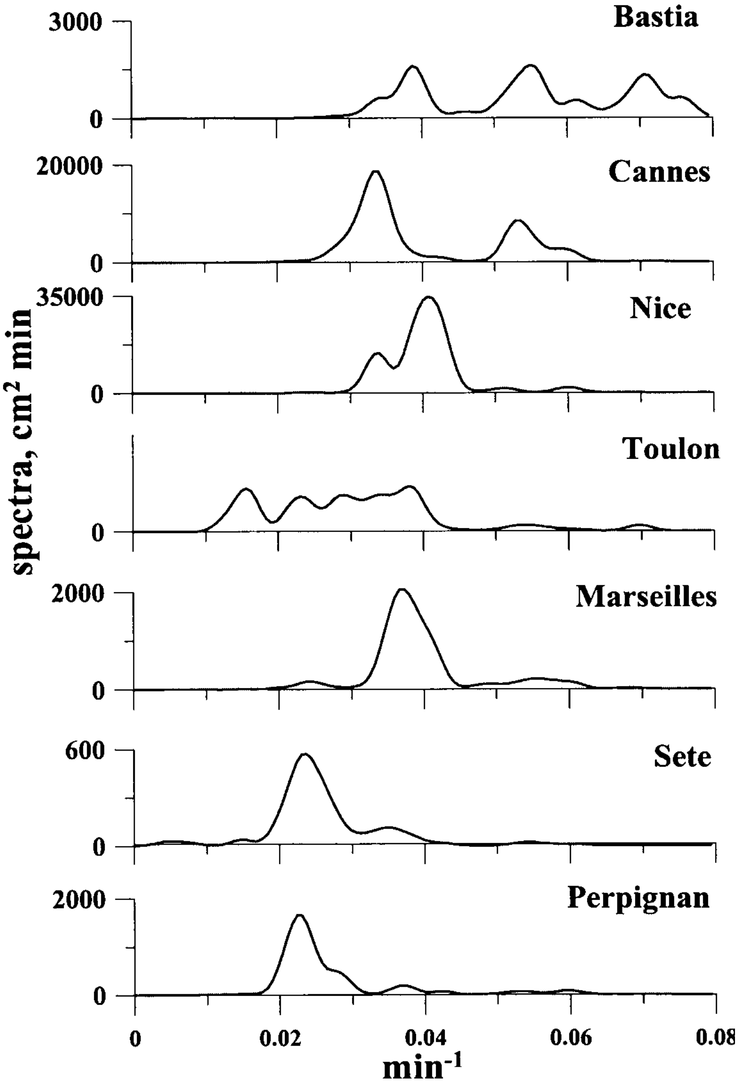

Figure 10. Computed spectra of the 1887 event.

(Figure 11). This simulation, as well as the four previous simulations, emphasises that tsunamis in northern part of the Ligurian sea have a very local character. Tsunamis from southern part of Italy cross the Ligurian sea with large attenuation, because Corsica and Sardinia "screen" France. As a result, the wave heights in different points of France are of the order of 1–2 cm (Figure 12). Characteristic periods of the computed waves in the western part of the Mediterranean are increased and reach 1 h due to scattering of short-length waves. The travel time of tsunami from Italy to the French coast is more than 3 h and this time is enough for warning and mitigation, if extreme strong tsunami will be generated in the southern

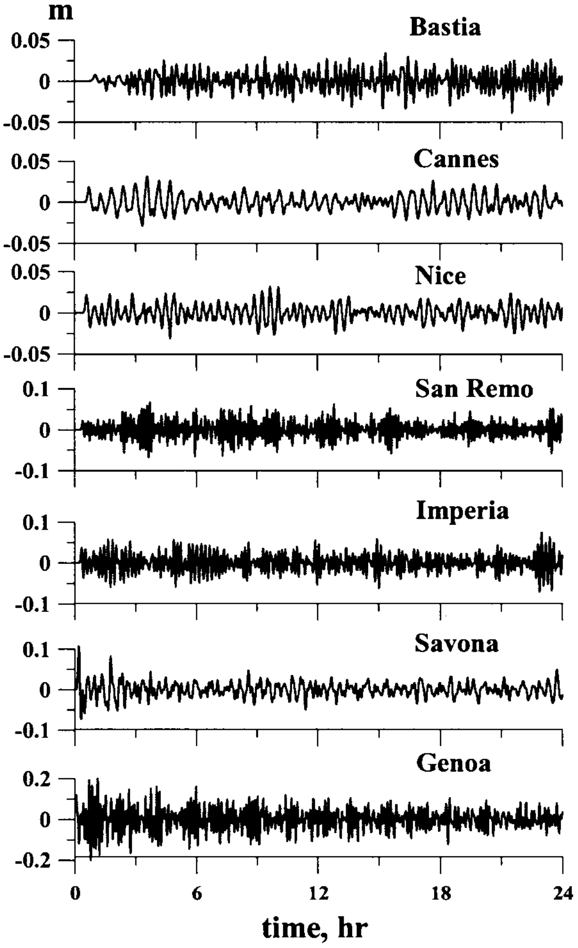

Figure 11. Computed tsunami records for the 1703 Genoa "event".

part of Italy. For earthquakes near the coast of Algeria, all points of France are at the same conditions from point of view of the wave theory, and wave heights are of the same order (1–2 cm) (Figure 13).

Approximately 3–6 h is needed for tsunami to reach the French coast. Calculations of the vertical oscillations of the shoreline for all variants according to (9) were performed. As it is expected, the runup stage increases the tsunami height in 2–3 times and this is a typical value for the mean amplification factor of tsunami in the coastal zone. Of course, the calculations of the wave, climbing on a beach, by using the primitive geometry only have preliminary character. For instance, during the 1979 Nice tsunami induced by the submarine landslide, the witnesses reported wave amplitudes of about 1 m, meanwhile the maximal wave amplitude in tide-gauge record does not exceed 10 cm (Tinti and Maramai, 1996). The same data are known for the 1887 Ligurian tsunami (Eva and Rabinovich, 1997). Such significant

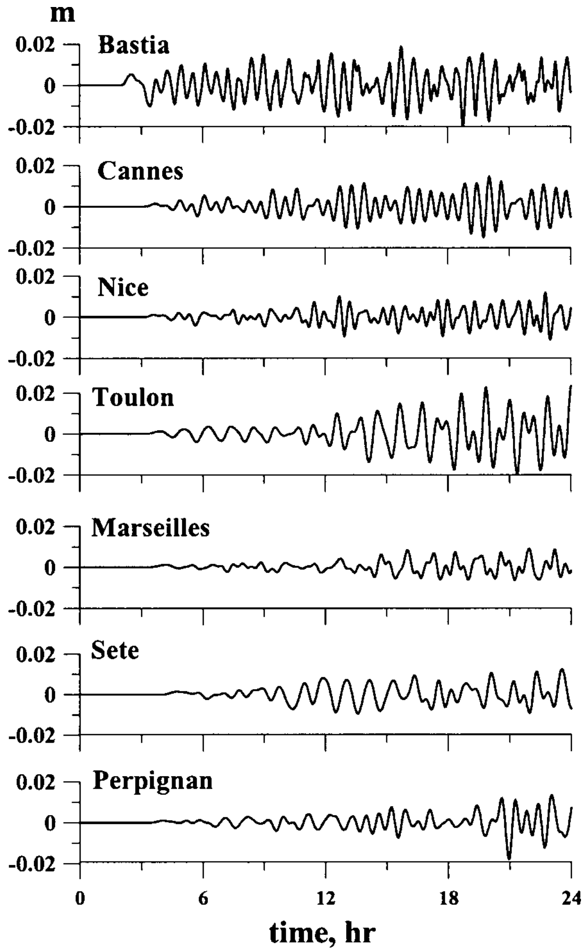

Figure 12. Computed tsunami records for the 1905 Italy "event".

amplification (10 times) can be related with specific topographical features of the coastal zone (bays, harbours, etc) and corresponding analysis should be done for each city on the Mediterranean coast.

5. Discussion

Analysis of historical information has shown that there were 24 events of tsunamis on the French coast of the Mediterranean for a large historical period 2000 BC–2000, and most of them (20) occurred in 19th century. The return period of tsunami for the French coast of the Mediterranean can be estimated at 18 years. 13 events were observed in Nice–Cannes, 5 events – in Marseilles, 3 events – in Séte, and 2 events – in Corsica. The earthquakes are responsible for 11 tsunamis, the submarine landslide - for one tsunami, and unknown sources – for 12 tsunamis

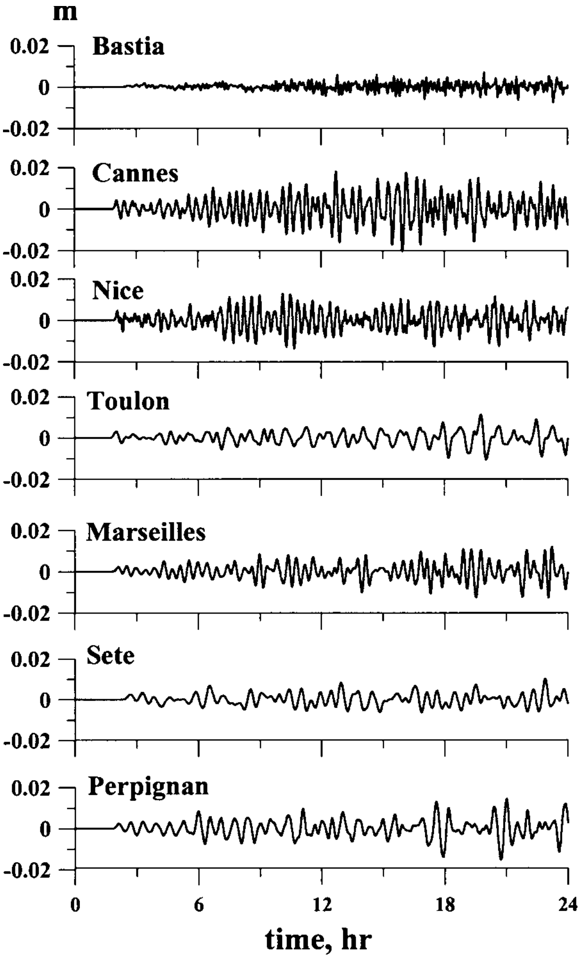

Figure 13. Computed tsunami records for the 1954 Algerian “event”.

(probably, they have meteorological origin, or local landslide phenomena). The information of “earthquake” tsunamis in France is rather poor. For instance, the earthquake magnitude is known for four events (1564, 1808, 1846 and 1887) only from a total of 10 events. In fact, all tsunami-genetic earthquakes can be divided into three groups presented in Figure 1. The first group (four tsunamis) is located in the vicinity of the coast (Nice–Imperia), the second group is defined by two “land” earthquakes (to north from Nice), and the third – earthquakes in Italy.

The aim of our research was to study the characteristics of possible “seismic” tsunamis on the French coast of the Mediterranean. Numerical simulation of tsunami propagation was done within the framework of the nonlinear shallow-water theory. The tsunami sources were located at the places of historical tsunamis (in the vicinity of Nice–Imperia, Genoa, southern Italy, Algeria). Parameters of the tsunami source were the same for all cases, it corresponds to the ellipse with semi-axis, 40 and 20 km, the maximal water displacement is 1.5 m. Formally such parameters are characteristic of an earthquake with magnitude 6.8, this value is an average one for all tsunami-genetic earthquakes in the Mediterranean. The ellipse is oriented in direction north-east as for earthquakes in the vicinity Nice–Imperia. The same source for all cases allows to analyse main geographical features of tsunami propagation and to compare different coastal zones with possible tsunami damage. The results of simulation confirm the observed fact that tsunamis in France have a very local character and this is related with the relative weak magnitudes of possible earthquakes in the vicinity of France. With the same conditions, the earthquakes in the northern part of the Ligurian sea affect the strongest tsunami in the nearest coast point. Our model is tested with data of the 1887 tsunami. Characteristic amplitude and period of the spectral maximum are in good agreement with observed tide-gauge record and calculations of Eva and Rabinovich (1997). The western part of the Mediterranean coast is protected from these tsunamis by the southern part of the French Rivera. Tsunamis generated in southern Italy are more affected by Corsica that "screens" part of France. Tsunamis generated in the vicinity of the African continent are weak on French coast and their amplitudes are of the same order. Tsunami record is represented as a long-periodic wave group everywhere with crest and trough amplitudes of the same order. Total duration of the tsunami record is about 10–20 h and this should be taken into account for tsunami warning. Characteristic period of oscillations varies from one point to another point (20–30 min), but it is less for the northern part of Ligurian sea than for the western part of the Mediterranean (30–45 min). The travel time of tsunamis depends on the location of the earthquake and it is several hours for Italian and African earthquakes. If the tsunami is generated in the vicinity of Nice–Imperia, the travel time to Nice is a few minutes for Nice and Cannes, and 1–2 h – for the western part of the Mediterranean. Wave heights on the tsunami records have an order of magnitude of a few cm for the points far from earthquakes, and a few ten cm for the nearest points. Climbing of the tsunami waves on a beach for simplest geometry increases these numbers in average by a factor 2–3. Based on real information of the tsunami tide-gauge records and observed wave heights on the beach during the 1887 Ligurian and 1979 Nice tsunamis, the amplification factor can reach 10 at selected points. It means that the nearest earthquakes in the vicinity of Cannes–Imperia can generate tsunami waves with maximum runup of a few meters and induce significant damage on the coast. For the next step, resonance properties and wave climbing on a beach should be studied in details for French coast of the Mediterranean.

It is important to mention that we considered here only "seismic" tsunamis with the same source, this is very convenient to clarify the main geographic conditions of wave propagation from various areas in the Mediterranean. Of course, this analysis should be extended by taking into account more detailed information of possible local tsunami mechanisms in different tectonic regions. For prognostic aims possible landslide and meteo tsunamis should be also considered. Then the evaluation of tsunami risk for the French coast of the Mediterranean can be done using all possible mechanisms of the tsunami wave generation.

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