



Method for Evaluating Vulnerability to Tsunamis of low-to-medium intensity: Application to the French Côte d'Azur

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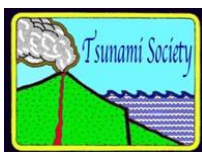
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Method for Evaluating Vulnerability to Tsunamis of low-to-medium intensity: Application to the French Côte d'Azur

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ABSTRACT:

Today, the study of tsunami risk has become a recurrent concern for crowded coastal areas, and this is true even for those that normally seem to be the least prone to the phenomenon. In this framework, the BRGM has for the past five years been compiling and managing an historical database devoted to tsunamis that may have affected the shores of France. Concurrently, simulations of tsunamis for plausible major seismic or gravity-driven events have been conducted. These have indicated that the south of France is indeed subject to the risk of a tsunami of low to medium intensity. Between 2009 and 2010, the research project RATCOM has made it possible to establish the principles for assessing vulnerability and calculating damage and human losses for moderate tsunamis. The method thus developed is complementary to those already proposed for tsunamis of larger intensity. Applications of this method using the BRICE (©brgm) simulation tool for risk scenarios reveal that the level of risk has increased quite substantially over just a few decades, even for tsunamis of low to medium intensity (water height less than 1 m). This is essentially due to the exponential growth of urban development along the coastline and to tourist pressure. Although such events will not cause destructions to buildings comparable to those in Indonesia (2004) and Japan (2011), still weak phenomena can be responsible for serious human losses. On the Côte d'Azur, the potential number of victims is large enough to warrant immediately instating preparatory measures designed to cope with the possibility of such a scenario.

Keywords: tsunami, databases, simulation, damage, France

1. INTRODUCTION

Understanding the risk presupposes assessing the tsunami hazard (endangered zone, intensity of the phenomenon/probability of occurrence). It also presupposes an assessing the vulnerability of stakes with respect to tsunamis. Assessing the tsunami hazard for a region relies on two main components: a solid knowledge of past events and the simulation of tsunamigenic events. An interpretation of these data should make it possible to identify the zones most liable to risk as well as the corresponding level of intensity. Knowledge of past events involves studies of paleo-tsunamis (geological and/or archeological observations, over time intervals that may span several thousand years) and mining archives (intervals generally covering a few centuries, or more rarely Antiquity). The simulation of tsunamigenic events concerns not only plausible fictitious events, but also modeling actual ones in the past. In this latter case, it will be necessary to confront the output of models with information on the most reliable historical tsunamis. A synthesis of all this information (archives, simulations) then allows a hazard assessment to be performed.

In the wake of the catastrophic December 2004 tsunami in the Indian Ocean, a considerable amount of work was accomplished with the purpose of improving our understanding of structural and human vulnerability to tsunamis. On the basis of damage curves in structures versus the tsunami's intensity,

the methods developed follow an approach that is comparable to the ones called on in seismic vulnerability and risk assessments, such as those implemented under HAZUS (FEMA, 2004) or Risk-UE (Lagomarsino *et al.*, 2006; Giovinazzi, 2005). These methods, being intended for strong-intensity tsunamis, do not allow risk to be calculated for low or medium intensity ones, that is, those characterized by energies too low to inflict major structural damage, but high enough to result in human losses. Between 2009 and 2010, the research project RATCOM has made it possible to define, for moderate tsunamis, the principles for assessing vulnerability and calculating damage and human losses. Concurrently, with support from UNESCO, a CENTre d'Alerte aux Tsunamis, CENALT, has been set up. Its role is to monitor strong earthquakes that occur in the western Mediterranean and in the northeastern Atlantic. As to France, the Direction générale de la sécurité civile (DGSC, the directorate-general for civil security) depending on the Ministry of the Interior was assigned the coordination of the ALDES project concerning the descending part of the tsunami alert system. In this framework, several tsunami scenarios with implementation of the assessment method developed in the RATCOM project were carried out along segments of France's southern coast.

Work conducted by the BRGM over recent years, particularly for France's Mediterranean shore, is integrated in the overall chain of assessment and management of tsunami risk, including: the establishment of a database containing historical events, the regional identification of tsunamigenic sources and simulation of plausible major tsunamis, the proposal of a method for assessing damage and losses for low to medium intensity tsunamis and its application for the purposes of local management of the risk.

2. RESEARCH ON TSUNAMIS THAT MAY HAVE REACHED THE SHORES OF FRANCE

2.1. Working method

Research on historical tsunamis that may have affected French coasts (continental France, Réunion Island, the Antilles, New Caledonia), undertaken since 2005, consists in:

- seeking out and acquiring original documentary sources, in manuscript or printed form, that are the most contemporary with the event: these are the so-called “primary sources”;
- covering a very wide scope of investigations, documents sourced in France and elsewhere, and of different sorts: books, scientific and historical articles, manuscripts, newspapers, travel journals, chronicles, earthquake catalogues, etc.;
- simultaneously, looking for weather data: strong storms affecting the coasts of metropolitan France or offshore, hurricanes and cyclones in the French islands of the Indian Ocean, the Pacific Ocean and the Caribbean Sea;
- if feasible (i.e., subject to the quality of data), analyzing and interpreting the physical characteristics and calibrating these phenomena according to the Ambraseys-Sieberg scale (six degrees of increasing intensity);
- seeking to determine the cause of the event: earthquake, ground movement, underwater explosion, volcanic eruption, meteorite, seiche, meteorological depression, or still unknown.

Concerning events for which the documentary description leaves no doubt as to the tsunamigenic nature of the phenomenon (movements of ebb and flow of the water, retreat of the sea followed by inundation in a specific space-time frame, etc.), each event is described by a series of parameters characterizing the tsunamigenic wave at the location where the tsunami was observed. As of today, the catalogue references 80 events (Lambert and Terrier, 2011) structured in a database accessible on the web at www.tsunamis.fr.

2.2. Catalogue of tsunamis identified along the French Mediterranean coastline

The origins of a majority of the tsunamis observed along the French Mediterranean coastline are still uncertain. Some submarine landslides, however, have been clearly identified, such as that of Nice in

1979 or the one at Antibes and Villefranche-sur-Mer in 1564, this latter having been triggered by an earthquake, the epicenter of which (Intensity VIII MSK) was situated 40 km inland. Other tsunamis on the Mediterranean coast are indisputably of seismic origin, like that of 1887, widely felt across the Côte d'Azur, or those in 1819 and 1831 that seem to have been limited to the immediate vicinity of French shores (San Remo).

3. SIMULATION OF TSUNAMI SCENARIOS CONCERNING THE FRENCH MEDITERRANEAN COAST

Together with the catalogue of historical tsunamis, the simulation of historical or fictitious tsunamigenic events is an essential prerequisite to assessing the hazard. Indeed, applying scenarios selected for their enhanced impact with respect to the coasts considered, the simulations allow general elements to be obtained as to the potential level of exposure of the coasts and to estimate the incidence and form that the tsunamis might take on reaching the shore. This is the framework in which several scenarios have been proposed. This portion of the work consisted in: 1) the characterization of tsunamigenic sources for the French Mediterranean coast; 2) the preparation of several bathymetric grids at various scales, adapted to near-and far-field tsunamis; 3) the choice and simulation of reference events; 4) the preparation of maps indicating the highest water levels and arrival times on the shore for each scenario.

3.1. Tsunamigenic sources of seismic origin

Because mapping and characterizing active faults of all the western Mediterranean Sea are not possible with the current level of knowledge, the identification phase for tsunamigenic sources of seismic origin necessarily had to be based on seismic zonation. For this purpose, different sources of geological (geological maps of Europe and seismotectonic ones of the Mediterranean Basin, as well as other publications), bathymetric and seismological data were collected and interpreted. These gave rise to a deterministic seismic zonation for the Western Mediterranean (Fig. 1). The zonation obtained (Terrier, 2007) describes for each seismic zone: 1) the main tectonic and seismic characteristics with, as appropriate, the return period for very strong earthquakes; 2) the largest earthquake, either recorded or mentioned in the archives; 3) the parameters of the maximum earthquake selected (magnitude, fault plane rupture dimensions, fault slip...).

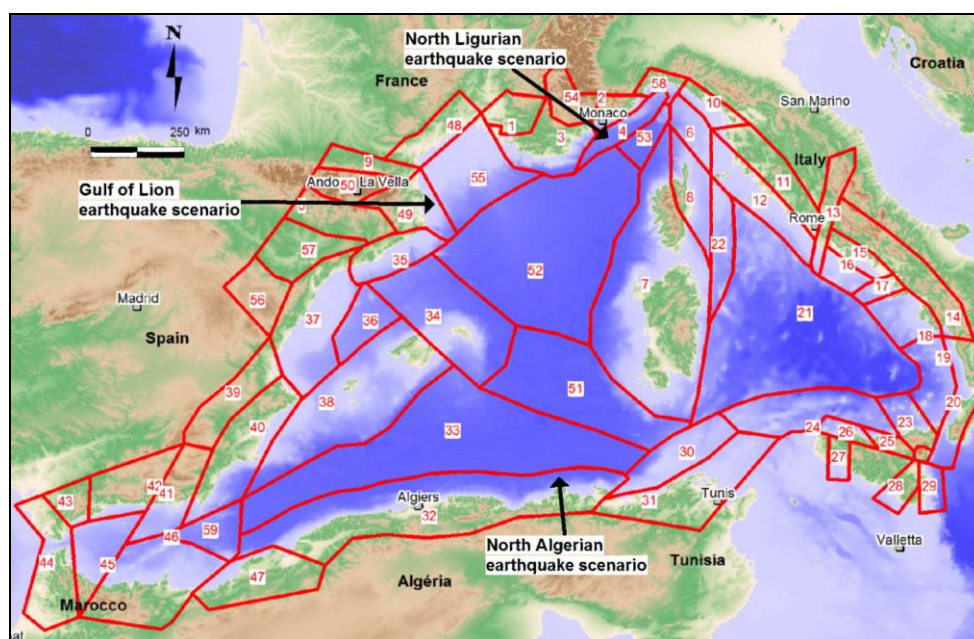


Figure 1 - Seismic zonation and choice of scenarios for seismic sources used in the study of tsunami risk along the French Mediterranean coastline (Terrier, 2007).

3.2. Tsunamigenic sources of submarine landslide origin

Offshore of the French Mediterranean coast, the morphology of the maritime zone is highly irregular morphology, locally featuring steep slopes. It furthermore may be overlain by formations that are relatively thick and poorly consolidated. Thus these zones are conducive to submarine landslides. Based on bathymetric data, as well as knowledge of submarine sedimentary bodies, and supported by known gravity-driven events, fossil or modern-day, a zoning of submarine gravity-driven movements on the continental shelf and foot-slope off the French Mediterranean shores was assigned to IFREMER (Cattaneo, 2007), Fig. 2. Each of these zones is characterized by a typical slide of maximum volume for a return period ranging between several centuries and several millennia. Each typical slide is described by the following parameters: length, width, maximum thickness, mean slope, mean depth, the nature of the destabilized sediments, “SLUMP” or “SLIDE”, “RUNOUT” and direction of propagation. Details about the zoning and how it was achieved are given in Cattaneo (2007).

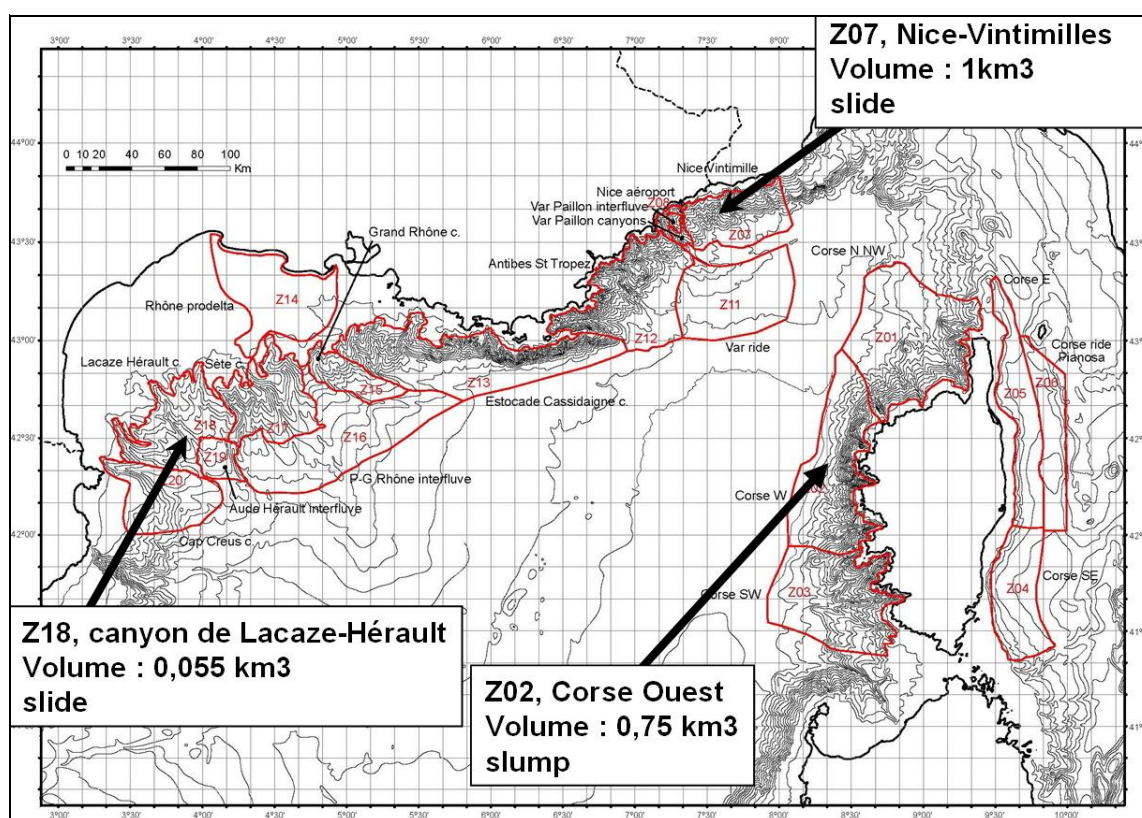


Figure 2 - Zoning of submarine landslides and choice of scenarios for the study of tsunami risk along the French Mediterranean coast (Cattaneo, 2007).

3.3. Simulations of plausible major events

More than twenty simulations performed on low-resolution grids (meshes ranging from 2250 m to 750 m per side) were initially performed. These concern either historical events or fictitious ones. These preliminary calculations allowed the choice of six reference scenarios (Fig. 1 and 2) to be oriented more judiciously, and calculations with a finer mesh were conducted for these. The events involved are maximum plausible ones with return periods ranging from several centuries to a few millennia. The results obtained (Pedreros and Poisson, 2007; Terrier *et al.*, 2007) demonstrate that France's Mediterranean coast is not exempt from tsunamis (Table 1). This said, the expected intensity remains relatively moderate.

Table 1 - A summary of the results of the tsunami scenarios (Terrier *et al.*, 2007).

Scenarios :	Simulation with Magnitude or volume	Maximum amplitude wave calculated near the shore (at 10m depth)	Arrival time calculated	Part of the French coast reached (amplitude > 0.5m)
North Ligurian earthquake	M = 6,8	2m at Antibes	10' to 15'	St Tropez to Nice
North Algerian continental margin earthquake	M = 7,8	4m at St-Tropez, Cannes 3m at La Ciotat, Nice, Villefranche	95' to 100'	Marseille to Menton
Gulf of Lion earthquake	M = 6,7	0.6m at Agde, Port-la-Nouvelle	60' to 80'	Between Perpignan and Béziers
Landslide of the west Corsica continental margin	V = 0,75 km ³	5m to 6 m to the North of Porto	5' to 15'	South-West shore between Porto and Bastia
Landslide of Lacaze-Hérault canyon	V = 0,055 km ³	1.5m at Perpignan 1m at Frontignan and Beauduc	45' to 80'	Perpignan to Beauduc
Landslide of Nice-Vintimille continental margin	V = 1 km ³	4m at Antibes 3m at Nice	10' to 20'	St-Tropez to Menton (until San Remo, Italia)

4. ASSESSING DAMAGE AND LOSSES FOR TSUNAMIS OF WEAK TO INTERMEDIATE INTENSITY

For the French Mediterranean coastline, the analysis of historical tsunamis and simulations of major tsunamigenic events indicate a maximum water-level height of less than 4 m. The tsunamis concerned are accordingly of low to medium intensity, i.e., their degree is less than 4 on the Sieberg scale modified by Ambraseys (1962) or than intensity VI on the Papadopoulos and Fokaefs scale (2005). Between 2009 and 2010, the research project RATCOM has made it possible to define, for moderate tsunamis, the principles for assessing vulnerability and calculating damage and human losses for moderate tsunamis (Monfort *et al.*, 2010). The method developed in this study is complementary to those already proposed for tsunamis of higher intensity. It enables us to obtain a quantitative estimate of damages to individuals and property for different levels of aggression (tsunami scenario), bearing in mind that: 1) The hazard predicted for the French Mediterranean coastline is weak to intermediate, with run-up that does not exceed 3 m; 2) The stakes most exposed there are port areas (the most severely impacted by historical tsunamis) and the population (the recent, postwar tourist phenomenon); 3) In light of the context, and according to the type of structure, this can act as a “shelter.” The following methodological steps are distinguished: choosing and mapping the stakes, assessing their vulnerability, simulating the tsunami and evaluating losses.

4.1. Choosing and mapping the stakes

The choice of stakes takes into account an analysis of feedback from intermediate-intensity tsunamis as well as the socio-economic context (very high population density during tourist seasons). The stakes considered are:

- Population density for each quarter and for different times of year (winter, summer) and of day (night, afternoon), using data on Ponchettes beach in Nice (Robert *et al.*, 2008) as a reference. The breakdown into quarters takes into account the type of building encountered, the nature of land-use (beach, commercial zone, etc.) and topography. Each geographic entity is considered to be uniform with respect to the three aforementioned criteria.
- Camp grounds.
- Underground car parks (number of levels and parking spots).

- Marinas and fishing harbors (number of moorage slips).
- Communication lines (highways and railways).
- Seaside buildings (their footprint and structural type). The structure's typology takes into account openings at ground level, the number of stories and the presence of a basement. A distinction is made between light structures (beach huts, for example) and heavy, reinforced constructions.

The characterization of the stakes is defined on the basis of a survey in the field and consultation of regional authorities and tourist bureaus. It is completed by a thorough-going analysis of aerial photos for a range of dates (boundaries of the quarters, distribution of structures and, as appropriate, a mean indication of the level of occupation of the beaches via a head count).

4.2. Assessing the vulnerability of the stakes

4.2.1 Population situated outdoors

Assessing human vulnerability depends schematically on how capable individuals are of protecting themselves (notably through their ability to move around) or withstanding an inundation. Flooding may be characterized according to various physical factors such as duration of submergence, run-up, the current's direction and speed, and the solid load that is transported. Koshimura *et al.* (2006) propose limits beyond which the danger level is significant, with a risk of drowning, that is, a restricted capacity of mobility, calculated in terms of the run-up and current speed. The results in Koshimura *et al.* are globally coherent with those that have been selected by the French authorities in the framework of the elaboration of Plans de Préventions des Risques aux Inondations (flood risk prevention plans). In the context of RATCOM, the aggression component is expressed by the value couple “maximum flood level /maximum speed” at a given moment, Fig. 3. Thanks to this limit, it is possible to identify, over the time the inundation will last, those areas where people will be able or not to withstand the flow on their own. This curve, however, does not factor in the transport of heavy and/or voluminous debris, which are liable to further hinder the mobility of persons.

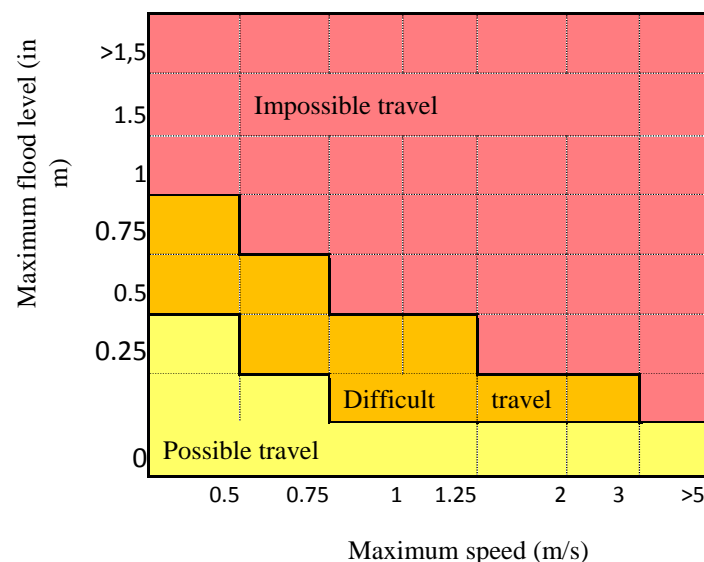


Figure 3 - Limit to the ability to move used in the framework of the RATCOM project.

Based on analyses of feedback from catastrophic tsunamigenic events, Guha-Sapir (2006) and Nishikiori *et al.* (2007) observed mortality rates of between 6% and 10% within a population of individuals swept away by the current. Following the 2011 tsunami in eastern Japan, Mimura *et al.* (2011) calculated a mortality rate ranging between 3.3% and 15% according to location. Based on this work, for an affected population unable to move and situated outdoors, a mortality rate of 10% was determined.

4.2.1 Population situated indoors

The analysis of feedback from historical and modern-day events shows that, except in the case of a tsunami generated by a nearby earthquake (with strongly felt vibrations), in all other instances it is preferable to be inside (excluding basements) than out. The approach for assessing the vulnerability of persons situated inside buildings and subject to the tsunami aggression alone follows the four following steps:

- 1) Typology of the structure with respect to the number of stories and the transparency of the ground floor (Fig.4) :

Type 1. A multi-story building surmounting a transparent ground floor (presence of shops, picture windows...) which allow water to enter the ground floor easily.

Type 2. A multi-story building surmounting a closed ground floor, that is, with walls that protect against the wave impact.

Type 3. A transparent one-story building (ground floor).

Type 4. A one-story building (ground floor) with walls that protect against the wave impact.

Maximum flood level (in m)	H >1,5	2	2	2	2	2	2	2	2
	1 to 1.5	2	2	2	2	2	2	2	2
	0.5 to 1	1	2	2	2	2	2	2	2
	H < 0,5	1	1	1	1	2	2	2	2
Building of type 1 or 3		< 0.5	0.5 to 0.75	0.75 to 1	1 to 1.25	1.25 to 2	2 to 3	3 to 5	> 5
Open ground floor		Maximum speed (m/s)							



Maximum flood level (in m)	H >1,5	2	2	2	2	2	2	2	2
	1 to 1.5	1	1	1	1	1	2	2	2
	0.5 to 1	1	1	1	1	1	2	2	2
	H < 0,5	1	1	1	1	1	1	1	1
Building of type 2		< 0.5	0.5 to 0.75	0.75 to 1	1 to 1.25	1.25 to 2	2 to 3	3 to 5	> 5
Close ground floor, and several storied building		Maximum speed (m/s)							



Maximum flood level (in m)	H >1,5	2	2	2	2	2	2	2	2
	1 to 1.5	1.5	1.5	1.5	1.5	1.5	2	2	2
	0.5 to 1	1	1.5	1.5	1.5	1.5	2	2	2
	H < 0,5	1	1	1.5	1.5	1.5	1.5	1.5	2
Building of type 4		< 0.5	0.5 to 0.75	0.75 to 1	1 to 1.25	1.25 to 2	2 to 3	3 to 5	> 5
Closed ground floor, and single storey building		Maximum speed (m/s)							



Figure 4 - Matrixes for exposure to tsunamis versus structural type.

- 2) Mapping the structure (location, footprint and structural type).

- 3) For each type of structure, an exposure matrix is defined (Fig. 4). Based on work by Kelman (2002) and the values considered in the framework of the “Plans de Prévention des Risques” for France, several levels of exposure have been distinguished. These depend on the maximum speed of flow and the maximum run-up:
- Level 0, building not flooded.
 - Level 1, building flooded, people on the ground floor not swept away. Those on the ground floor feel the effects of the wave but can move around. In the case of multi-story building, these individuals can take shelter in the upper levels.
 - Level 1.5, single-level building protected by an outside wall, flooded. People can move around but will have nowhere to take shelter.
 - Level 2, building flooded, people on the ground floor are swept away or trapped. Those on the ground floor are carried off by the waves or drowned. In the case of a multi-story building, people in the higher levels will remain protected. Certain parts of the building may be damaged.

For a population trapped on the ground floor of buildings exposed to level 2 conditions, based on work by Guha-Sapir (2006), a 4% mortality rate is obtained.

Underground levels (cellars and car parks) constitute a specific type. The risk is considered to be level 2 once flooding reaches them.

For aggressions higher than those appertaining to levels 0 to 2, the behavior of the structure can be estimated using vulnerability curves derived from observations of the 2004 Indian Ocean tsunami or those proposed by Guillande *et al.* (2009), Garcin *et al.* (2007), Peiris (2006), and Léone *et al.* (2006).

4.3. The vulnerability of port areas

During a moderate-level tsunami, boats moored in ports number among the property incurring the severest damage. In the Mediterranean, where tides are weak, boats are moored with little slack. In the event of a sudden and strong variation in sea level, docking lines, quickly over-stretched, break, allowing the boats to float free. These will then crash into each other, toss up against port facilities or hit bottom. The variations in level due to the ebb and flow generate strong currents in ports. As to the methodology implemented, the aggression is expressed in terms of a variation in water level (Table 2). The damage estimate is based on analyses of feedback from events occurred in the Mediterranean, like the tsunami owed to the Boumerdès earthquake (2003) or the seiche (‘eigen oscillation’), from 2006 in the Balearic Islands than caused damages in the harbour zones comparable to those of the tsunami. As a rule, damage to small crafts (fishing boats or yachts) is far more extensive than for large ships. For small boats, the risk to those on board will be directly linked to that of the boat itself.

Table 2 - Risk assessment for ports and harbor areas.

Water level variation into the port	Damage level	Damage ratio for ships
< 0.5 m	Acceptable	
0.5 - 2 m	Some ships are damaged. Damages to mobile facilities from the harbor.	Between 10 and 20% (situation of Boumerdès in Menorca or Théoule-sur-Mer, Port Salis in Antibes 1979)
> 2 m, strong currents	High risk to break the moorings. High risk of damages to ships and boats. Damages to some fixed facilities of the harbour.	Situation after seiche event in 2006 in Ciutadella (Menorca)
Harbor dried, big waves above the embankment	Boats and ships hit the bottom. High damage ratio for the ships and facilities.	

5. APPLICATION TO A 1979-TYPE TSUNAMI SCENARIO IN NICE (FRANCE)

The vulnerability assessment method was tested via an application on the Côte d’Azur (southern France), using an event of the Nice 1979 landslide type and four time scenarios: mid-January 2012 at 2 a.m. and 3 p.m. and mid-August 2012 at 2 a.m. and 3 p.m. The landslide parameters chosen for the simulation (Table 3) are drawn from work by Silva Jacinto and Meyniel (2010).

Table 3 - Parameters determined to describe the Nice airport landslide for modelling the tsunamigenic source.

Parameters	Considered values
Coordinates (WGS 84) of the initial gravity center	N 43°38'44.4" E 007°12'55.0"
Coordinates (Lambert 3, m) of the initial gravity center)	X= 993 360 Y= 161 180
Direction of the landslide (referenced to the North)	182.3°
Depth	47 m
Slope from the landslide	1.,2°
Maximal length of the landslide	900 m
Maximal width of the landslide	700 m
Maximal thickness of the landslide	50 m
Density from slipped material	1.4

The numerical simulation of the tsunami’s generation and propagation was performed using the GEOWAVE software (Watts *et al.*, 2003). Subsequently, to model the submergence on land in an urban context (taking into account structures and coastal installations), a coupling was established between the GEOWAVE and SURFWB programs (Marche *et al.*, 2007). As to the bathymetric and topographical data used, these allowed three interconnected calculation grids to be implemented, with a resolution that increased between the foot slope and the shoreline (pixels at 45 m, 15 m and 4 m). The contour and elevation of the built environment and coastal installations drawn from the “building footprint” layer of the BDTopo (topographic database) of the Institut Géographique National (France’s national geographic institute) were superimposed on the digital elevation model. Details about the simulations are given in Le Roy *et al.* (2011).

5.1. Simulation of the tsunami

The maximum heights of the free surface reached during the entire 20-minute interval that was simulated indicate the significant size the tsunami probably attained in Antibes (Fig. 5).

Submergence was computed on a grid with meshes measuring 3.75 by 3.75 m. It indicates that the arrival on the coast of the first wave seems to have caused most of the flooding, with subsequent waves simply reinforcing it, and this with generally lower current speeds. Maximum run-up averages 1 to 2.5 m and, very locally, even 4 to 5 m (Fig. 6). As to the maximum run-up distance (inland from the coastline), the simulation yields 150 to 200 m in the northern portion of the area studied, about 100 m on the wide beach to the north-west (i.e., reaching the buildings), some 60 m at the beach next to the port of La Salis (or slightly more when the water succeeded in spilling over into the streets, and on the order of 110 m in the port of La Salis itself. The outlines of the flooded areas obtained by simulation are fairly compatible with those reported by witnesses (Sahal and Lemahieu, 2010).

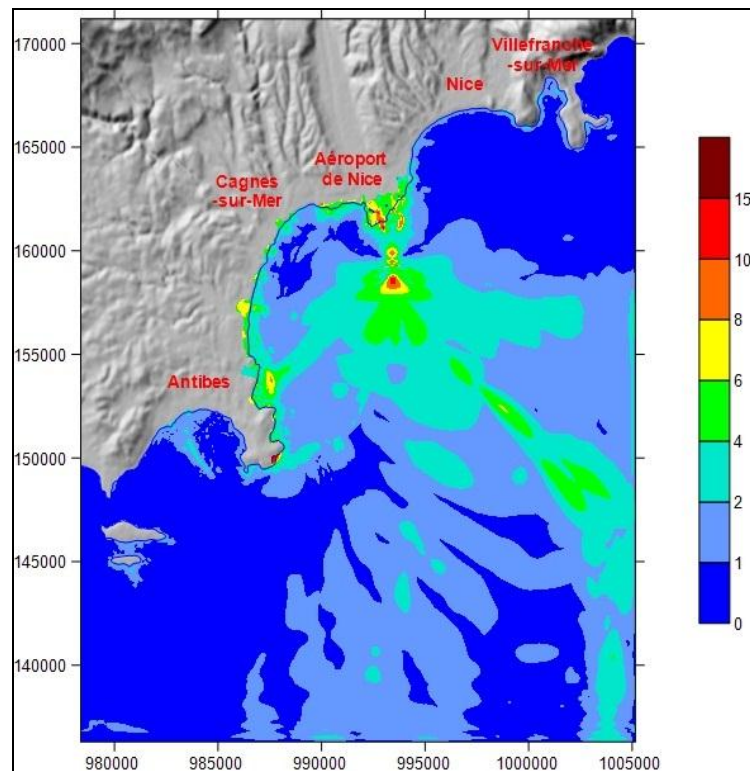


Figure 5 - Simulation of the Nice 1979-type tsunami: maximum elevation (in m) de highest water level.

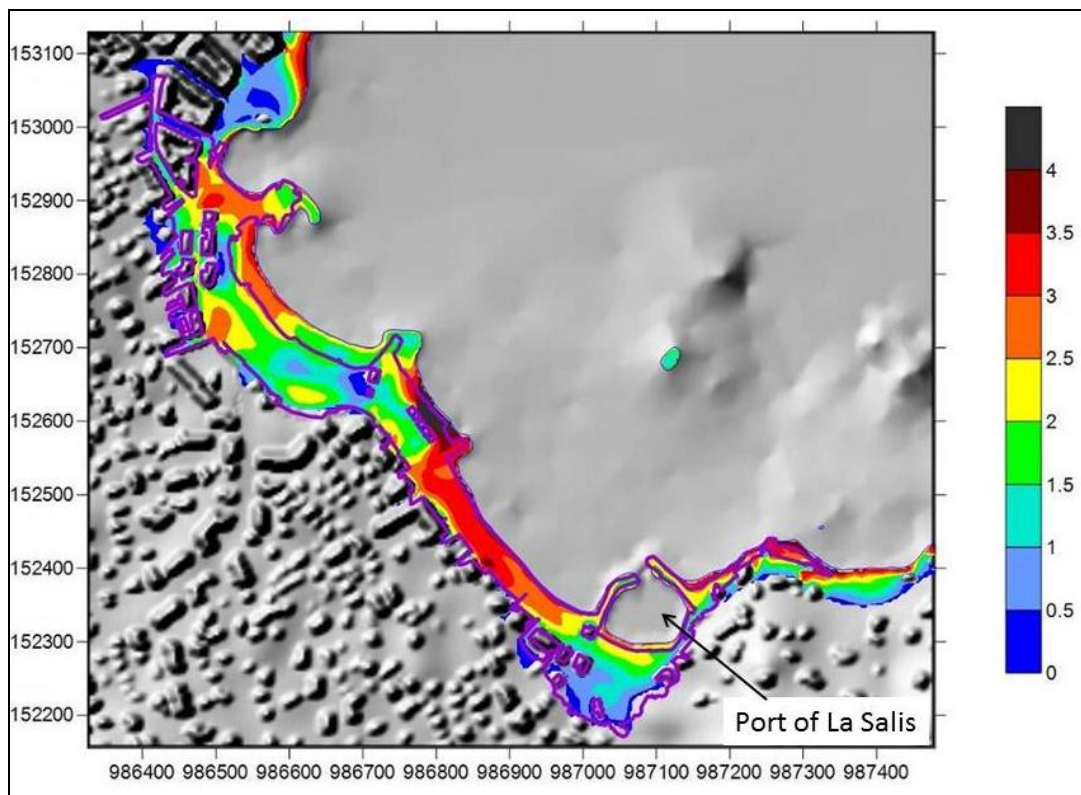


Figure 6 - Simulation of the Nice 1979-type tsunami : maximum run-up heights on land (in meters) and the flooded area identified by Sahal and Lemahieu (2010), in purple.

The simulation indicates furthermore that at the port of La Salis, the arrival of the tsunami results in a slight hollow a little over 5 minutes after the airport landslide (less than 5 cm, undetectable by witnesses), cf. Fig. 7. A wave almost 1.5 m high then penetrated the port some 6 minutes after the slide. The water in the port seems to have had difficulties in flowing out again. This can be explained by the fact that the port's dikes had been largely submerged (the run-up height of the water being on the order of 0.80 m), hence the immediate filling of the basin, whereas once the sea had ebbed, it took much longer for the basin to empty again by overflowing the dikes or via the breach. The maximum level of water in the port was attained after some 11mn40 s., with a water-level increase of 2.5 m.

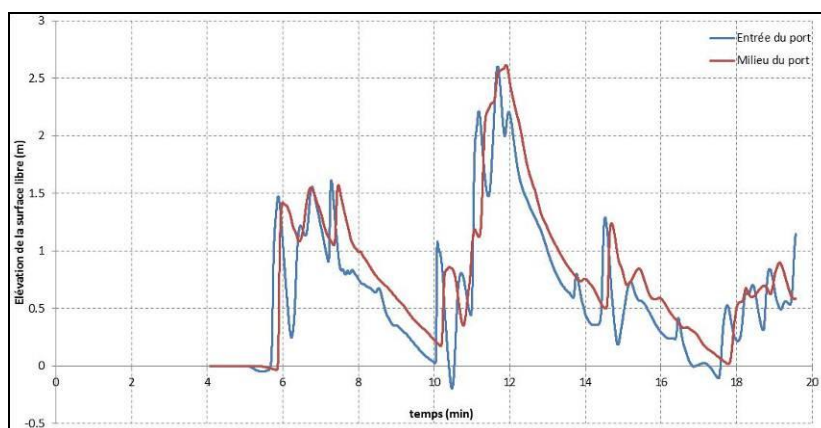


Figure 7 - Simulation of a Nice 1979-type tsunami: elevation of the free surface in the port of La Salis.

The maximum simulated speeds reached by the ebb and flow (norm and direction) very generally indicate values exceeding 3 m/s near the shore (Fig. 8). The analysis of the simulation film shows that the highest speeds were reached during the flow (the wave arrival) phase.

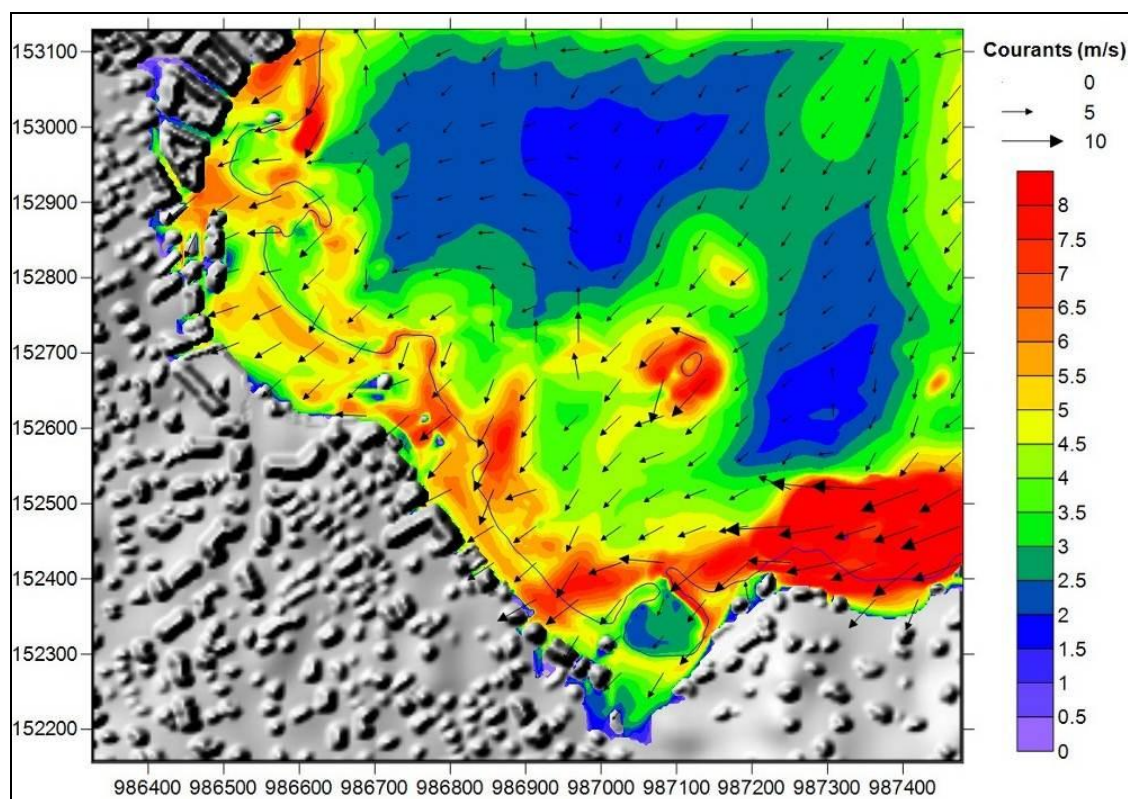


Figure 8 - Simulation of a Nice 1979-type tsunami: Maximum speeds attained by the currents: norms (in m/s) and directions.

5.2. Damage assessment

In 1979, the area most severely impacted by the tsunami was the shore of Antibes, with the death of one individual caught in the basement of his house located near the La Salis beach. In the same part of Antibes, the wave had flooded a street and borne away a dozen cars. The local newspaper reported some one hundred buildings affected by the surge, as well as thirty or so people injured. This event took place on October 16th in the early afternoon..

Using the results of the simulation of the 1979-type tsunami, a damage calculation was performed following vulnerability assessment principles described above and using the BRICE@brgm risk scenario simulation tool (Sedan, 2012). The scenario took into account the current distribution and typology of the built environment, as well as the population density off-season and during tourist season, nowadays situation.

5.2.1. Damage to the built environment

The analysis of the tsunami's impact on buildings does not depend on the season of the year or the time of day when the tsunami arrives. It indicates (Fig. 9), for the 68 buildings affected by the inundation, that 25 would undergo a run-up height exceeding 0.75 m, 34 would be subjected to a current speed of over 1.5 m/s and 42 would present an exposure level of 2 (impossibility for persons inside to escape). This large number of building affected can be explained by the type of buildings with transparent ground floors which are frequently encountered by the shore.

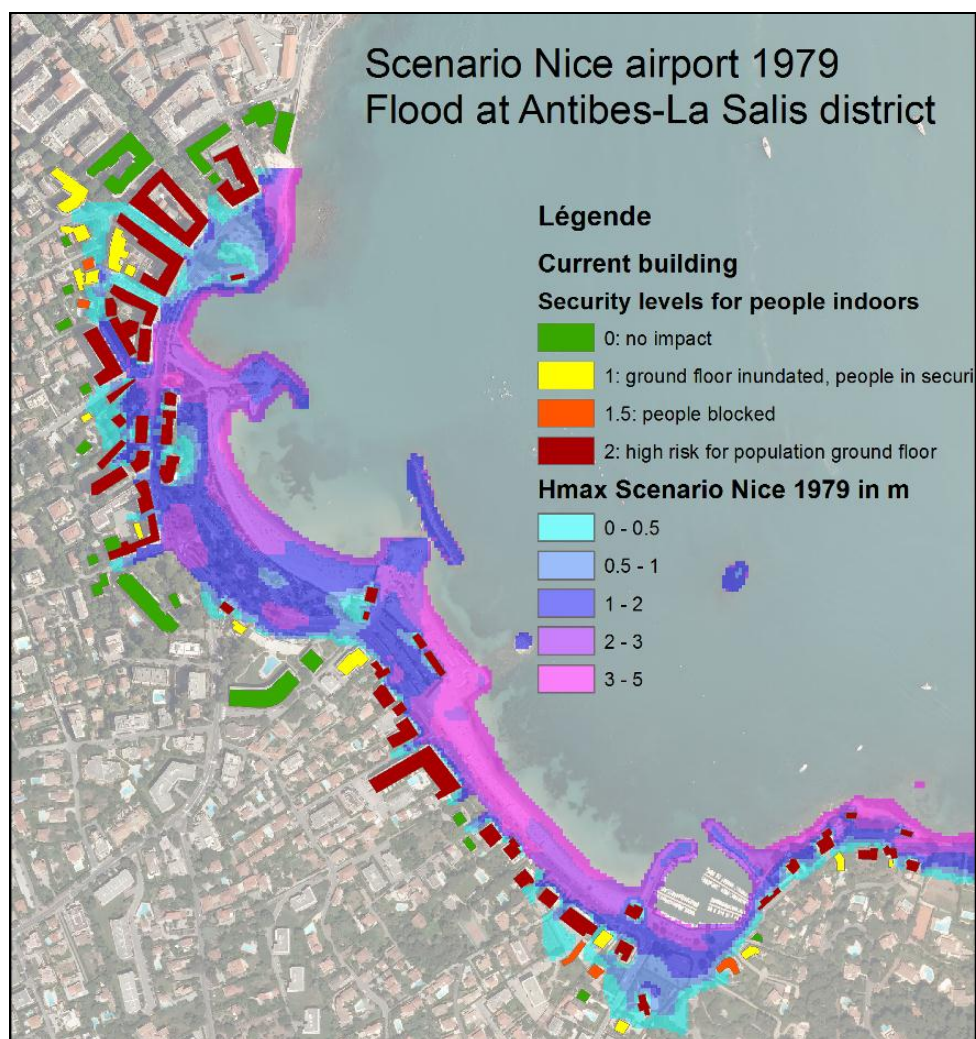


Figure 9 - Exposure levels for buildings in the La Salis quarter (Antibes) obtained with the Nice 1979 scenario.

As to masonry (reinforced concrete) structures impacted, the damage expected would be very minor. Damage would essentially be associated with the impact of the wave and of floating objects against the most fragile portions of the ground floor (windows, doors, picture windows and garden walls). With these water levels, only the lightest-weight structures would incur serious damage, such as the facilities of beach operators.

5.2.2. *Human losses*

An estimation of human losses takes into account the season (summer or winter) and the time of day. The simulation yields run-up heights exceeding 1.5 m and current speeds above 1 m/s for the La Salis quarter. With such a level of aggression, people are unable to withstand the flood. This estimate does not take into account fore-warning or the securing of people on the beach prior to the arrival of the flood. The inundation of the La Salis quarter affects the beaches, walkways, car parks and the busiest adjacent streets.

The number of individuals outside the affected buildings would amount to: 1) 2000 to 4000 people on August 15th in mid-afternoon and 2) 60 to 80 people on January 15th in mid-afternoon.

The mean estimate of the number of persons situated on the ground floor when the event occurs depends on the mean level of occupation of the buildings, according to the season, but also the time of day. Based on the mean occupancy rates proposed for earthquake scenarios (Coburn *et al.*, 2002), mean occupations of 45% in the mid-afternoon and 80% at night have been selected. As to the individuals situated inside the buildings, 42 buildings are considered to present an exposure level of 2. The number of people impacted for a mid-August scenario is at least ten times smaller than that of persons outside: nearly 200 in the middle of the afternoon and 300 at night. However, in winter, the number of persons impacted (between 90 and 150) is higher than that outdoors.

5.2.3. *Damage in ports*

Antibes has several marinas and harbors for fishing boats, totaling about 3000 berths, and an occupation rate in excess of 90%, whatever the season. The assessment for a 1979-type scenario would indicate damage to 8.5% of the boats. The most heavily damaged port would be that of La Salis, with a risk of crafts being stranded (thus with a strong likelihood of damage) in the neighborhood of 50% of the total present.

5.3.4. *Scenario results extended to several municipalities*

The scenario extended to several municipalities in the bay of Nice indicates that if an event similar to that of 1979 were to occur at the height of the tourist season (busiest peak in mid-August, mid-day), the tsunami could impact several thousand people. However, the interval when the beaches are crowded is estimated at 7% of the total time in a year. Generally speaking, the application of this risk-assessment method to an event-based scenario like that of the Nice airport in 1979 allows the following conclusions to be drawn:

- During a summer day, for the bay of Nice, several thousand individuals could be victims of the tsunami (including several dozen fatalities).
- Few urban sectors would be flooded by the event. Only light-weight structures (beach-side straw huts, structures made of wood, sheet metal and with large windows) would be severely damaged. The other buildings (masonry, reinforced concrete), particularly those with one or more stories, represent a risk-reduction factor for the population inside them.
- Ports are the infrastructures most prone to damage by tsunamis. Results indicate that several hundred boats could suffer from this type of event. More precise information concerning the seasonal occupation of each port would enable these estimates to be refined.
- The quality of results on damage assessments depends not only on a knowledge of the stakes and of vulnerability functions, but also on indications concerning flooding (height/speed) caused by the tsunami.

6. CONCLUSION

Historical studies indicate that the French Mediterranean coast has, on several occasions, undergone tsunamis of low to medium intensity. Today, seasonal crowding on the coast results in a level of risk that can be high during certain times of the year. The method currently implemented takes into account the fact that: 1) the built environment can be a risk-reduction factor for people under certain conditions (height and speed of the inundation, building typology, situation of the population when the event occurs) and 2) low to medium intensity tsunamis can cause substantial human losses. Beside exposure of the population, the method also addresses other stakes such as ports, seaside facilities (car parks, camp grounds and highways) and the built environment. In view of the complexity and diversity of the different parameters required to assess damage from tsunamis, it is difficult today to assign an approximate level to the margin of uncertainty inherent to the results obtained. To ensure better credibility to the method that has been developed, and subsequently to the results it produces, the development of the method should be pursued through dedicated research.

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