Near field earthquake sources scenarios and related tsunamis on the French-Italian Riviera (Western Mediterranean)

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The northern Ligurian margin is one of the active seismic areas in the western Mediterranean. The 1887 earthquake-induced tsunami is quite significant for this area considering the relatively low extent of the rupture plane. The potential local tsunami genesis is therefore a legitimate question because no tsunami warning system can resolve tsunami arrival times of a few minutes along the Ligurian Riviera.

SEISMOTECTONIC SETTING

Despite the moderate present-day seismicity (Figure 1) the area suffered historical earthquakes with magnitude greater than 6. On the 23 February 1887, the Ligurian earthquake was followed by a noticeble tsunami observed along the coast and measured by the Nice and Genoa tide gauges (Figure 2).

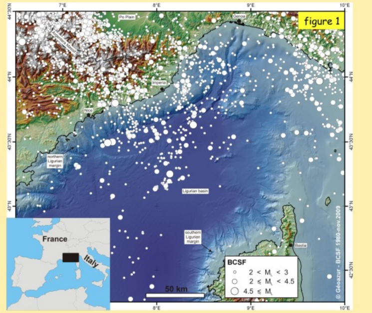


Figure 1 : Seismicity map of the Alps – Ligurian basin junction recorded from January 1980 to November 2011 (catalog from BCSF). The magnitude range is from 2 to 4.7.

FAULT PLANE						
STRIKE	DIP	LENGTH	WIDTH	FOCAL DEPTH	CO-SEISMIC SLIP	MAGNITUDE
N 55°E	16°N	35 km	17 km	15 km	1.5 m	6.9
N 55°E	16°N	26 km	16 km	15 km	1.1 m	6.7

Table 1 : Source characteristics of the 1887 Ligurian earthquake determined from macroseismic intensity data, active tectonics and tsunami modelling (Larroque et al., 2012 and Ioualalen et al., 2013). The two solutions depend on the uncertainties of the maximum wave height recorded at the Genoa tide gauge and used for the tsunami modelling.

From the reappraisal of the 1887 Ligurian earthquake, we propose that this event reaches Mw 6.7-6.9 and could result from the activation of part of the Ligurian thrust (Table 1).

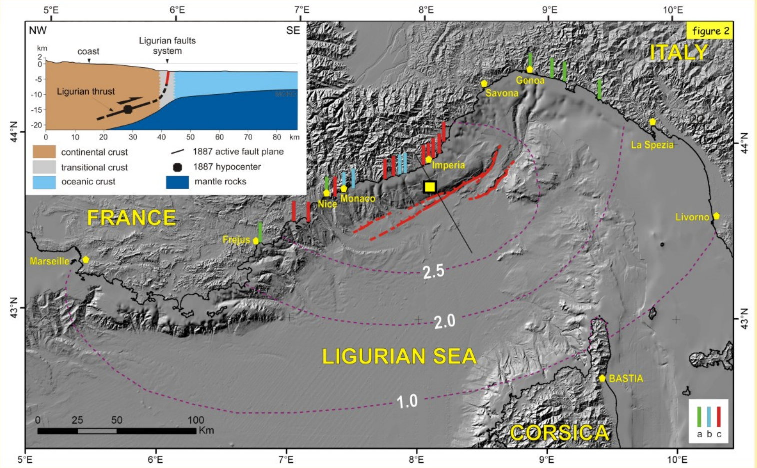


Figure 2 : Southern Alps - Ligurian basin junction. Red lines : 80-km-long Ligurian active faults system characterized by surface deformations; yellow square : 1887 earthquake epicenter; pink dotted lines : distribution of the intensity of the 1887 tsunami [compilation fron A. Laurenti, based on the Sieberg scale (1923)]; a, b, c : local runup observations (0 < a < 0.5 m, 0.5 < b < 1 m, 1 < c < 2 m).
Inset : Cross-section (black line on the map) showing the focal depth of the Ligurian earthquake and the proposed fault plane geometry activated by the 1887 earthquake.

The Ligurian thrust drives the uplift of the northern Ligurian margin since, at least, the Messinian times (~5 Myr) as attested by numerous geological data (Larroque et al., 2011).

TSUNAMI MODELING and COSEISMIC SLIP

In order to evaluate the tsunamigenic potential of the Ligurian thrust we derive relevant rupture scenarios obtained in accordance with the regional geology and with the knowledge of the 1887 Ligurian earthquake and tsunami. As our objective is to allow a foresight discussion, we scan a range of partial (S7, S9) and total (S10, S12) ruptures of the Ligurian thrust to compute the tsunami waves.

Simulating a paleotsunami requires many simplifying assumptions. We underline here the question of the amount of slip the Ligurian thrust may undergo during an earthquake. Following the different scaling laws, the coseismic slip depends upon rupture dimension, geodynamic context (low or high stress drop), kinematics of the fault... Nevertheless, once these parameters are fixed, large uncertainties remain (Table 2).

Taking into account :

(1) the scaling relation of Wells and Coppersmith (1994) (WC94) and Leonard (2010) (L10),

(2) the two indicators available (the Fault Length and the Fault Area),

(3) that each segment of the Ligurian thrust may break separetly as 30-40-km-long rupture or simultaneously as a roughly 80-km-long rupture, we obtained the range of values in Table 3.

Our preferences (pink and red in Table 2) are in the higher range of estimated values, close to Leonard (2010) SCR estimates.

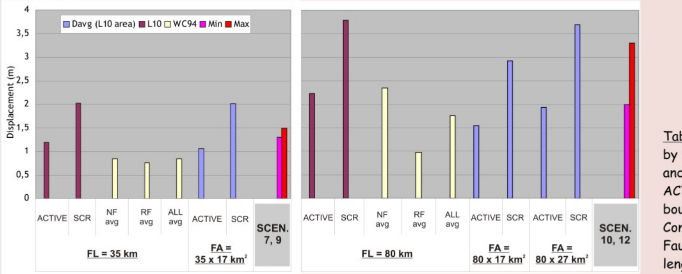


Table 2 : Mean displacement predicted by the scaling relations of Leonard (2010) and Wells and Coppersmith (1994). ACTIVE: faults located in active regions (plate boundaries), SCR: faults located in Stable Continental Regions. NF : Normal Faults, RF: Reverse Faults, ALL: all faults averaged together. FL: fault length, FA : fault area.

CONCLUSION

We explored the tsunami coastal impacts of earthquake scenarios involving the Ligurian thrust :

-> We show a relationship between the faulting characteristics (coseismic slip, centroid location...) and the MWH coastal distribution.

-> The tsunami impacts are generally quite local related to the limited spatial extension of the ruptured area (from 35 km to 80 km fault length).

-> Depending of the earthquake scenarios, runup from 2-3 m up to 5-10 m are evidenced with amplitude as high as more than 25 m for the specific case of the Nice harbour and for a very extreme scenario.

-> The MWH distribution map helped to display high hazard areas and we confirmed that focusing process related to the local bathymetry and to the wave directivity is crucial.

TSUNAMI COASTAL IMPACT

We propose that each segment of the Ligurian thrust may break separetly as 30-40-km-long rupture (S7, S9; Table 3) or simultaneously as a roughly 80-km-long rupture (S10, S12). Simulations are performed with a 100 m grid spacing and the use of the Funwave Boussinesq fully nonlinear model. In these tests, several parameters (kinematics, strike...) are kept constant [see Ioualalen et al. (2013) for a complete range of tests].

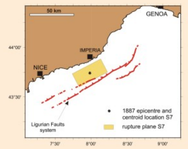
scenario	centroid			kinematics	Φ (strike)	δ (dip)	L (length)	W (width)	Δ (m)	M_o (N m)	M_w
	E	N	d								
S 7	8.08°	43.70°	15 km	reverse	N55° E	16° N	35 km	17 km	1.5	2.95 10^{19}	6.9
S 9	7.55°	43.58°	15 km	reverse	N55° E	16° N	35 km	17 km	1.5	2.95 10^{19}	6.9
S 10	7.815°	43.640°	15 km	reverse	N55° E	16° N	80 km	17 km	2.0	7.94 10^{19}	7.2
S 12	7.815°	43.640°	9 km	reverse	N55° E	16° N	80 km	27 km	3.3	2.24 10^{20}	7.5

Table 3 : Fault rupture scenarios implemented in the Okada dislocation model used in the Funwave code.

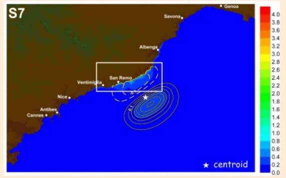
d is the depth of the centroid (the centroid is the geometrical center of the rupture plane). For the kinematics, the rake angle is kept constant 90°. Φ, δ, L and W characterize the rupture plane. Δ is the co-seismic slip. M_o the seismic moment and M_w the corresponding magnitude computed following Hanks and Kanamori (1979).

S 7

S7 is the "historical scenario" reconstructed for the 1887 Ligurian event (Larroque et al., 2012).



The Maximum Wave Height (MWH) produced by the simulation S7 is in the range of 1.60-3.20 m in the area of Imperia-San Remo. These values are consistent with the runup observed near Imperia after the earthquake (Figure 2).



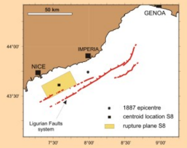
Runup distribution for the computational domain along the coast and the associated intial tsunami produced by the sea floor vertical deformation (in meters): dashed lines are for subsidence and continuous lines are for uplift with 5 cm isocontours.

Tsunami waves impacts are predominantly located in the immediate vicinity of the earthquake location. Site effects are mainly responsible for the coastal wave amplification. The MWH along the coast are located at focusing areas : FC 1 near San Remo, FC 2 near Riva Ligure and Cipressa, FC 3 near Imperia and FC 4 near Diano Marina.

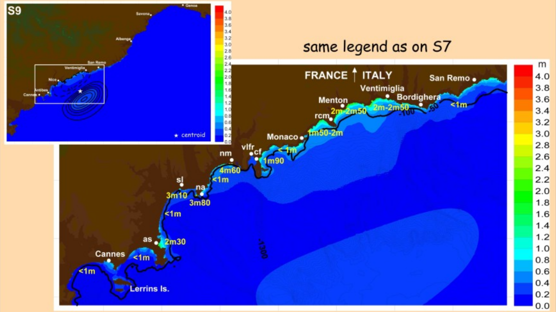
Runup distribution in the Imperia area : in yellow the local values. FC are the focusing areas located above submarine spurs. Black line : -50 m isobath.

S 9

S9 has the same parameters as S7 with a centroid shifted westward to take into account the potential rupture offshore Nice and Monaco.



The interest of this scenario is to predict runup within the French Riviera following a "Ligurian type" earthquake. The main result indicates an overall range of MWH of severeal meters similar to S7.



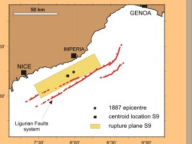
Locally, significant spots appear, mainly due to local bathymetry characteristics :

-> In particular more than 4 m runup is predicted in the center of Nice (nm on the figure) which is due to the pronounced land slope of 4% compared to the neighboring 2%, enhancing the usual slope effect. In the same range, we observe 3.80 m at the Nice international airport (na).

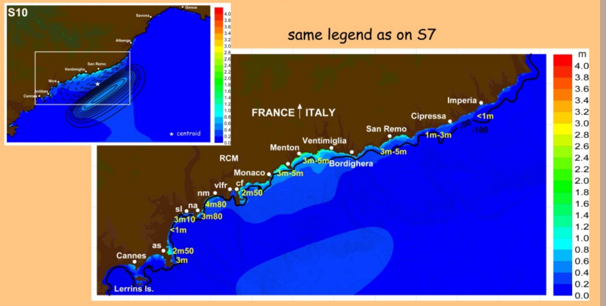
-> The site of La Salis (as, east of Cannes) displays also a significant MWH of 2.60 m. This area was also the spot of the MWH of the 1979 tsunami following the submarine slide of the continental slope offshore the Nice airport.

S 10

S10 corresponds to 80-km-long and 17-km-wide rupture of the Ligurian thrust with a 2 m coseismic slip.



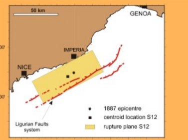
Although there is no record of such strong event during historical times, the S10 and S12 scenarios helped to obtain a full picture of the MWH distribution on the Ligurian coastal area.



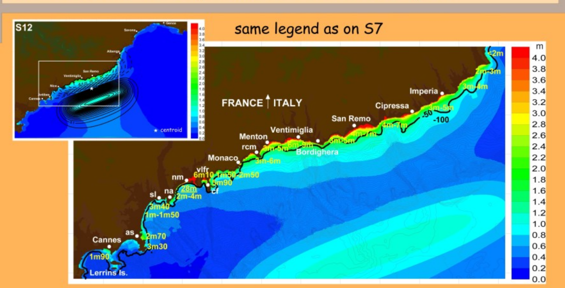
The MWH reaches values of 5 m, i.e. the double of S7 and S9 scenarios, as expected for larger rupture area and coseismic slip. We recover an overal MWH peak distribution similar to S7 and S9 attesting for same processes of focusing point.

S 12

S12 corresponds to 80-km-long and 27-km-wide rupture of the Ligurian thrust with a 3.3 m coseismic slip.

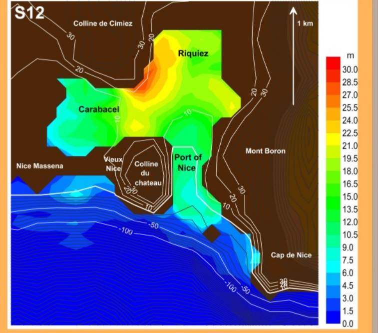


With such characteritics of the rupture plane and coseismic slip, MWH over 5 m occupies an area ranging from Nice to Imperia.



A special issue is the Nice city center with a main feature (28 m MWH) computed at the "colline de Cimiez". The wave first inundates Nice harbor, then propagates northward to Riquiez (inundation of more than 1 km) and takes the pathway westward between the "colline du Chateau" and "colline de Cimiez" inundating downtown Nice (inundation of nearly 2 km).

For this scenario, the incoming wave is sufficently high to overpass the northern part of the harbour dock and pursue its propagation inland. It is suggested that within the harbour, a seiche-like wave is trapped and builds up and inundates the lowest area.



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