Teachings from the Tōhoku-Oki event: tsunami hazard scenarios along Japanese and Italian coasts

The Tōhoku-Oki earthquake (M=9.0) has provided an unprecedented opportunity to utilize Japan's monitoring networks (e.g., GPS, seismic and DART buoys) to gather data. The implications of the new observations, especially about the dynamical properties of tectonic faults, need to be further explored and integrated in sound physical models of earthquakes to go towards better quantification of the related hazards. The "scenario based" tsunami hazard assessment applications to selected areas of the Japanese and Italian coasts (i.e., Adriatic Sea) will be discussed

Insegnamenti dall'evento di Tōhoku-Oki: scenari di pericolosità di tsunami lungo le coste giapponesi e italiane

Il terremoto di Tōhoku-Oki (M=9.0) ha offerto l'opportunità senza precedenti di utilizzare le moderne reti di monitoraggio (e.g. di GPS, di strumenti sismologici e di boe di tipo DART) giapponesi per la raccolta di dati scientifici. Le implicazioni delle nuove osservazioni, in particolare sulle proprietà dinamiche delle faglie tettoniche, richiedono di essere ulteriormente esplorate e integrate in robusti modelli fisici dei terremoti al fine di andare verso una migliore quantificazione dei rischi connessi. La valutazione della pericolosità di tsunami basata sugli "scenari" e la sua applicazione ad aree selezionate lungo le coste giapponesi ed italiane (i.e. Mare Adriatico) viene qui discussa

■ *Fabio Romanelli*

The Tsunami phenomenon, that has reached a global attention with the 2004 event in Sumatra, has strongly come back on the current scene because of the recent devastating earthquake in Japan (March 11th, M 9.0), causing over 20000 people to die and whose damages at Fukushima nuclear plants are still on the chronicles in these days. These and other catastrophes call for an increased attention in dealing with tsunami disasters, both on alert systems (e.g., DART systems) and hazard maps. In particular the unexpected magnitude of the latest event and the consequent inefficiency, particularly for tsunami barriers, impose us to put new consideration on the concept of "maximum credible earthquake" and on the hazard-scenarios based on it.

Modeling a hazard scenario has the main purpose to assess the maximum threat expected from a studied phenomenon in a certain area and to give specific directives to local authorities in order to prevent and mitigate serious consequences on the population, the infrastructures and the environment. To build scenario-based tsunami hazard maps for a specific

■ **Fabio Romanelli**
University of Trieste, Department of Mathematics and Geosciences

coastal area one has first to characterize the seismic sources (or other tsunamigenic events, not considered in this study) and select the earthquake scenarios that can drive the hazard. By means of the modeling we then calculate the maximum amplitude of the vertical displacement of the water particles on the sea surface and the travel time of the maximum amplitude peak, since they are the most significant aspects of the tsunami wave and also are the only characteristics always recorded in the chronicles and therefore in catalogues. The horizontal displacement field is calculated too, and, on average, it exceeds the vertical one by an order of magnitude approximately (this accounts for the great inundating power of tsunami waves with respect to wind driven ones). It is important to point out that the extremely efficient analytical modeling techniques (computation times are of the order of seconds and are bound to decrease with the natural rate of improvement of computers) for real time simulations can be very useful also for integration in a Tsunami Warning System, since they can be compared with real time incoming open-sea level data, in order to validate, or close, an impending alarm.

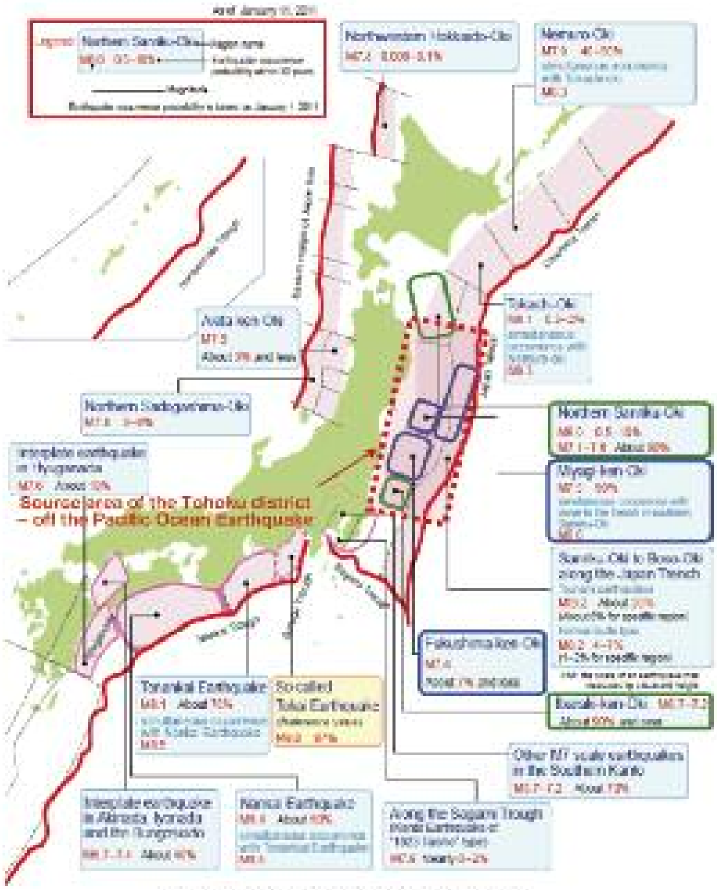
Scheme of the scenario-based Tsunami Hazard Assessment (THA)

Following the guidance provided by the Intergovernmental Coordination Group for the Indian Ocean Tsunami Warning and Mitigation System [1], a tsunami hazard earthquake scenario is built up by specifying the various characteristics of a potentially tsunamigenic seismic source. Schematically, for a scenario based THA the necessary steps are: a) building a database of potentially tsunamigenic earthquake Source Zones, b) each Source Zone includes an active tectonic structure with a Maximum Credible Earthquake and a typical fault, c) provide information on the expected tsunami impact (e.g., height and arrival times) onto the target coastline. The procedure can include additional stages: building a unique aggregated scenario by combining together all of the computed ones (selection of the maximum value of a given physical variable such as e.g., height); subjectivity, and the related uncertainties, can be treated by performing a sensitivity analysis.

One of the critical aspects is in step b) and it is related to the fact that the uncertainties when recurrence interval is *long* and the historical record is *short cannot be overcome,* since Magnitude and location from historical intensity data can be inaccurate and the compilation of existing data is unacceptable or misleading (e.g., [2]). Thus, one of the key points is that the procedure should be progressively updated as knowledge (theoretical and experimental) of earthquake source advances.

THA and the 2011 (M=9.0) earthquake of the Pacific coast of Tōhoku

The Headquarters for Earthquake Research Promotion (HERP) has released evaluation results of earthquake occurrence probability within the next 10, 30 and 50 years, respectively, as shown in Figure 1 for those trench-type earthquakes with a certain magnitude (earthquake occurrence probability within 30 years, based on January 1, 2011). A similar set of faults, but including more earthquake scenarios, was used by Yanagisawa et al. [3] for a deterministic (thus, without any information about the recurrence time) THA: their study focuses on the evaluation of the maximum and minimum water levels caused by tsunamis as risk factors for operation and management at nuclear power facilities along the coastal area of Japan. The design tsunami was verified by comparison with the run-up heights of historical tsunamis, ensuring that the design tsunami is selected as the highest of all historical and possible future tsunamis at the site. The deterministic approach was followed by a probabilistic study (PTHA) by Annaka et al. [4], who proposed a logic-tree approach to construct tsunami hazard curves (relationship between tsunami height and probability of exceedance) and presented some examples for Japan for the purpose of quantitative assessments of tsunami risk for important coastal facilities. This represented Step 2 in the scheme adopted by Tsunami Evaluation Subcommittee (TES) for the Tsunami assessment method for NPP in Japan Society of Civil Engineers (JSCE) (e.g., [5]).



Reference: Earthquake Research Comm., HERP Release [Online]. http://www.jishin.go.jp/main/index-e.html
Partially modified by JNES.

FIGURE 1 Comparison of the source areas of the main shock and scenario earthquakes evaluated by Long-Term Evaluation Subcommittee, Earthquake Research Committee, Headquarters for Earthquake Research Promotion (HERP)

However, the HERP committee admitted, after the 2011 M9 event, that the size of the source area, which covers the offshore areas of central Sanriku, Miiyagi Prefecture, Fukushima Prefecture, and Ibaraki Prefecture, the consecutive rupturing, and the magnitude 9 were beyond expectation (Earthquake Research Committee, HERP: The evaluation of the Tōhoku District - Off the Pacific Ocean Earthquake released on March 11). Moreover, in contrast to the fact that the rupture spread from the hypocenter to the shallow area of the plate boundary, and slip amount was above 20m, it was assumed that the shallow plate boundary along the Japan trench in the offshore area of Miyagi Prefecture was not able to store a large amount of strain energy, because the area was assumed to be creeping. Some experts, however, commented that the area was strongly coupled, the strain energy has hence been stored for a long time, and the rupturing off the coast of Miyagi Prefecture became the trigger for this earthquake. An interesting insight comes from earthquake dynamics: Ide et al. [6] showed that strong spatial variation of rupture characteristics in the moment magnitude (Mw) 9.0 Tōhoku-Oki megathrust earthquake controlled both the strength of shaking and the size of the tsunami that followed; a combination of a shallow dipping fault and a compliant hanging wall may have enabled large shallow slip near the trench. This results are confirmed by the tsunami waveform inversion performed by Fujii et al. [7]: ocean bottom pressure and GPS wave gauges recorded two-step tsunami waveforms, gradual increase in water level (~2 m) followed by an impulsive tsunami wave (3 to 5 m). The slip distribution estimated from 33 coastal tide gauges, offshore GPS wave gauges and bottom pressure gauges show that the large slip, more than 40 m, was located along the trench axis (Figure 2).

This offshore slip, similar but much larger than the 1896 Sanriku "tsunami earthquake", is responsible to the recorded large impulsive peak. The large slip on the plate interface at southern Sanriku-oki (~30 m) and Miyagi-oki (~17 m) around the epicenter, similar location with larger slip than the previously proposed fault model of the 869 Jogan earthquake, is responsible to the

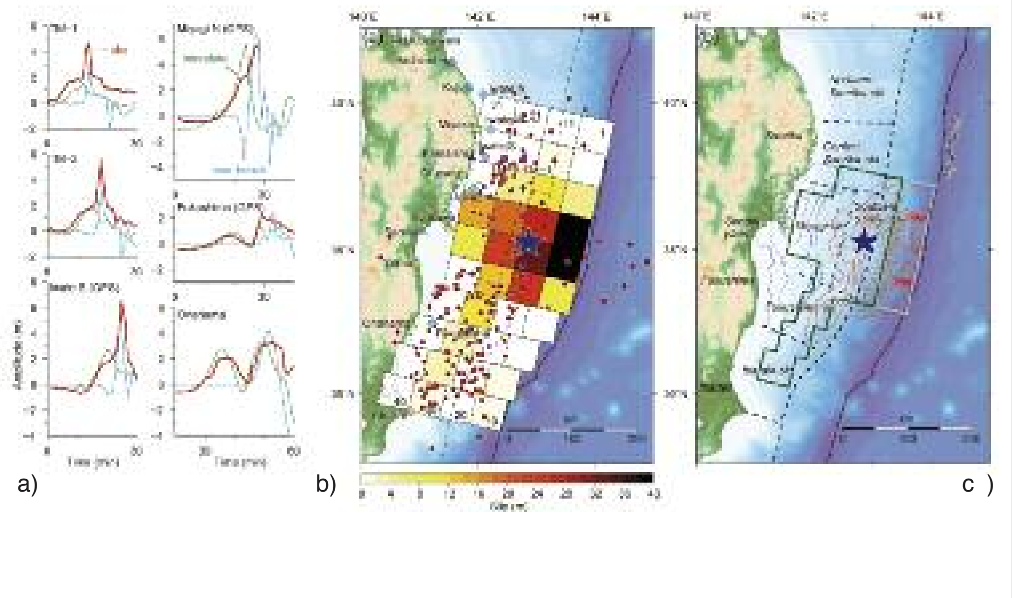


FIGURE 2

a) Observed tsunami waveforms (red curves) at offshore bottom pressure gauges (TM-1, TM-2), GPS wave gauges, and coastal tide gauge. Blue and green curves are computed tsunami waveforms from the large slip near trench (blue) and deeper interplate slip (green) as shown in c).
b) Slip distributions estimated by tsunami waveform inversion.
c) Seafloor deformation computed from the estimated slip distribution. Modified from [7]

initial water rise and presumably large tsunami inundation in Sendai plain.

THA in the Adriatic basin and conclusions

The tsunami phenomenon is mainly detected in oceanic domains but it can also occur in small basins as the Adriatic Sea. The presence of great waves has been recorded a few times in the past centuries on the Adriatic shorelines, therefore this suggested the idea to evaluate which could be the maximum amplitude reached by a possible future tsunami event. In this framework, Paulatto et al. [8] calculated several synthetic mareograms applying to the shallow water basin case both the theory of modal summation, for offshore seismic sources, and the theory of the Green's function, for inland seismic sources. Both kinds of tsunamigenic events did already occur in the Adriatic domain, as witnessed in many catalogues. They calculated synthetic mareograms varying those parameters most influencing tsunami generation, such as magnitude, focal depth, water layer thickness, etc., in order to estimate the expected values of tsunami maximum amplitude and arrival time, in the whole Adriatic basin, for the selected scenarios. Their results (an example is shown in Figure 3 and 4) suggest that a tsunami with maximum amplitude up to a few meters can be expected also in the Adriatic Sea, in agreement with a number of historical events reported in the catalogues, and as confirmed by a later and updating study performed by Tiberti et al. [9]).

Within the Adriatic Sea, the region most prone to generate tsunamis seems to be the Eastern coast of the basin, where the Adriatic plate presses against the Dinarides and the Albanides. Other regions where this phenomenon can occur are the Gargano Peninsula, the Eastern coasts of Central Italy and the Italian coasts on the Northern part of the basin. Even though the cases of a smaller magnitude and deeper event are more frequent (both in the case of offshore and inland sources), the use of the maximum credible values for calculating the tsunami risk is fundamental in the framework of protecting the Adriatic Sea coasts, especially in such a small and densely urbanized area that does not allow enough time to warn the population after a detection is made.

It has also to be taken into account that even if the seismicity in the Adriatic area is not high, the sea tide is, on average, twice that of the Mediterranean Sea and the coasts are generally quite shallow.

In other words, a modest tsunami wave of a couple of meters may superimpose to a high tide of the order of the meter and thus cause major damages, if not loss of life, in a large number of coastal urban settlements. Particularly in cases like this, the identification of the tsunamigenic sources driving the hazard is of great importance for a proper tsunami risk assessment.

References

[1] ICG/IOTWS, Workshop on tsunami risk assessment for the Indian Ocean, Final Report, Dubai, 4-6 October, 2007.

[2] Bilham, R., The Seismic Future of Cities, Twelth Annual Mallet-Milne Lecture, *Bull. Earthquake Engineering*, 1-49, 2009.

[3] Yanagisawa, K., Imamura, F., Sakakiyama, T., Annaka, T., Takeda, T., and N. Shuto, Tsunami Assessment for Risk Management at Nuclear Power Facilities in Japan, *Pure and Applied Geophysics,* 164, no. 2-3, 565-576, 2007

[4] Annaka, T., Satake, K., Sakakiyama, T., Yanagisawa, K., and N. Shuto, Logic-tree approach for probabilistic tsunami hazard analysis and its applications to the Japanese coasts, *Pure Appl, Geophys,*, 164, 577–592, 2007.

[5] Tsunami Evaluation Subcommittee, Nuclear Civil Engineering Committee, Japan Society of Civil Engineers, Tsunami assessment method for nuclear power plants in Japan, Japan Society of Civil Engineers, 2002 (in Japanese).

[6] Ide, S., A. Baltay, and G. C. Beroza, Shallow Dynamic Overshoot and Energetic Deep Rupture in the 2011 Mw 9.0 Tōhoku-Oki Earthquake, *Science*, 332, (6036), 1426-142, 2011.

[7] Fujii,· Y., Satake,· K., Sakai, S., Shinohara, M., and T. Kanazawa, Tsunami source of the 2011 off the Pacific coast of Tōhoku, Japan Earthquake, *Earth Planets Space,* 63, 815-820, 2011.

[8] Paulatto, M., Pinat, T. and F. Romanelli, Tsunami hazard scenarios in the Adriatic Sea domain, *Natural Hazards And Earth System Sciences* (on line), vol. 7, pp. 309-325, 2007.

[9] Tiberti, M.M., Lorito, S., Basili, R., Kastelic, V., Piatanesi, A. and G. Valensise, Scenarios of Earthquake-Generated Tsunamis for the Italian Coast of the Adriatic Sea, *Pageoph*, 165, 2117–2142, 2009.

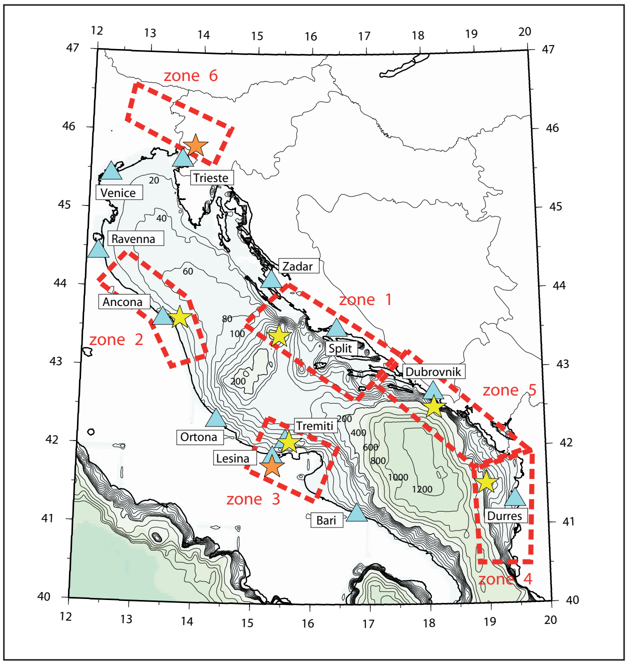
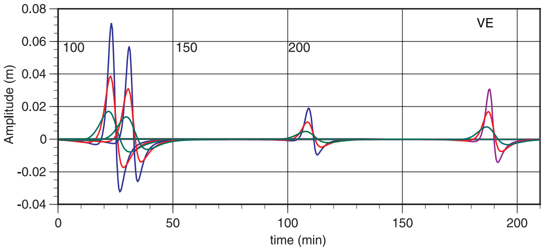


FIGURE 3

Bathymetric map of the Adriatic Sea. The bathymetric contours are drawn with a step of 20 m in the range from 0 to –200 m and with a step of 200 m in the range from –200 m to –1200 m. The contours of the six tsunamigenic zones are shown in red, the blue triangles correspond to the 12 receiver sites, the stars correspond to the epicenters of the considered events (yellow: offshore; orange: inland). Modified from [8]



M		6.5			7.0			7.5		*Travel time (min)*
H (km)	10	15	25	10	15	25	10	15	25	
Durres	0.02	0.01	< 0.01	0.11	0.06	0.03	0.60	0.33	0.15	*109*
Ortona	0.07	0.04	0.02	0.40	0.22	0.10	**2.25**	**1.22**	0.54	*23*
Split	0.06	0.03	0.01	0.32	0.17	0.08	**1.80**	0.98	0.43	*31*
Venice	0.03	0.02	0.01	0.17	0.09	0.04	0.97	0.53	0.24	*188*

FIGURE 4 a) Synthetic mareograms for Zone 1 shown in Figure 3. Focal depth, H =10 km (blue), 15 km (red), 25 km (green). Magnitude: M =6.5.

b) Maximum amplitudes and travel times for the four sites of Zone 1. Scenarios are calculated for three values of magnitude, M=6.5, 7.0, 7.5, and three values of focal depth, H =10, 15, 25 km. Amplitudes are reported in meters and those exceeding 1 m are written in bold style. Modified from [8]