Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et 10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Vancouver, Canada ♦ Paper No. 1836

MONITORING, DETECTING AND WARNING OF TSUNAMIS IN NORTH EAST ATLANTIC AREA

Baptista M A[1,2], Matias L[1,3]., Carrilho F.[3] , Annunziato A.[4] , J.M.Miranda[1,] Omira, R[1].

ABSTRACT

The vulnerability of North East Atlantic coastal areas to tsunamis is well known and the need for an early warning system is recognized by national authorities of the member states in the area. After the Sumatra tsunami of December 2004 the IOC-UNESCO decided to implement a global tsunami warning system in 4 broad areas: the Indian Ocean, the Pacific Ocean, the Caribbean and the North East Atlantic, Mediterranean and connected seas (NEAM.

The implementation of the Portuguese Tsunami warning system (PtTWS) monitoring the covering the North East Atlantic area tsunamigenic sources constitutes the natural response to the perception of tsunami hazard in the area. Tsunami occurrences are reported since the year 60 BC and the oldest paleo-tsunami identified until now dates from 5300 BP. At least two tele-tsunamis are known to have crossed the Atlantic Ocean in the 18th century and five tsunamis were recorded since the installation of the first tide gauge stations in Portugal.

The implementation of the PtTWS comprises three major components: the sea level detection network, the seismic detection network and the data collection and analysis from the origin of the tsunamigenic earthquake to the issue of messages to the Civil Defense.

In this paper we present: the design o the offshore tsunami detection network, the status of implementation of the PtTWS and the feasibility of this national center to become a regional warning center for the NEAM region.

This work is a joint effort between the Instituto de Meteorologia the University of Lisbon, the JRC –ISPRA, the Instituto Hidrografico and Instituto Geografico Português in collaboration with PMEL-NOAA.This work was funded by NEAREST and TRANSFER 6FP EU projects and by ERSTA (funded by the Portuguese Civil Defense).

Introduction

After the Sumatra event in December 2004 the Intergovernmental Oceanographic Commission of UNESCO alerted for the need of a global tsunami warning system and divided the three oceans in four regions, each one corresponding to the “jurisdiction” of one regional tsunami warning system: the Pacific, the Indian, the Caribbean and the North East Atlantic, Mediterranean and connected seas.

Tsunami events that affect Portugal mainland Azores and Madeira islands are originated along the Eurasia-Nubia plate boundary, between the Azores and the Strait of Gibraltar.

1 Instituto Dom Luiz
2 Instituto Superior de Engenharia de Lisboa
3 Instituto de Meteorologia
4 Joint Research Centre, European Union

This region can be divided in three main areas : the Azores area, the Gloria Fault, and the south west Iberia domain

The responsibility of Portuguese national Tsunami Warning System (PtTWS) is to monitor this tsunamigenic area and give alert messages to the coastal areas of Portugal mainland and the archipelagos of Madeira and Azores.

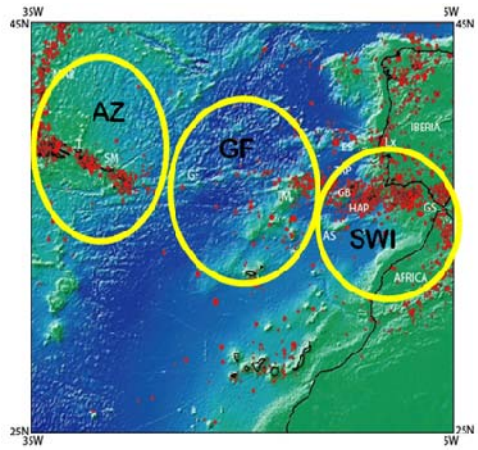
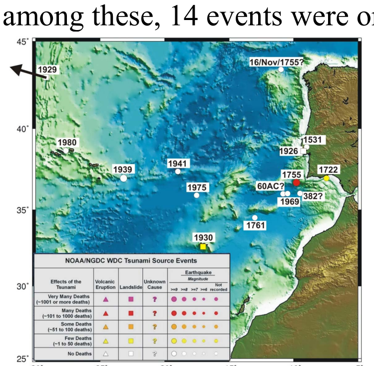


Figure 1 - Three main tsunamigenic areas AZ: Azores, GF: Gloria Fault; SWIT: South West Iberia domain(yellow circles); The Red circles represent earthquake epicenters. MAR – Mid Atlantic Ridge; T – Terceira island; SM – São Miguel island; GF – Gloria Fault; TM – Tore-Madeira ridge; AS – Ampere Seamount HAP – Horseshoe Abyssal Plain; GS – Gibraltar Strait; GB – Goringe Bank; TAP – Tagus Abyssal Plain; ES – Estremadura Spur; Lx – Lisbon.

Tsunami events in this area are a consequence of the compressive tectonic environment of the Ibero-Maghrebian area (Gracia et al. 2002; Gutscher et al. 2006, Zitellini et al., 2009), the transcurrent motion along the Gloria Fault and surrounding area (Kaabouben et al. 2008) or the effect of far away sources , such as the Grand banks 1929 tsunami (Baptista and Miranda 2009). -The North East Atlantic has been the place of several catastrophic events like the well known 1st November 1755 destructive earthquake and tsunami. The oldest event reported in the written documents dates from 60 BC but the sedimentary record reveals the occurrence of high energy deposit 5300BP (Ruiz et al. 2005). The recent revision of the Portuguese tsunami catalogue (Baptista and Miranda2009) includes a list of 17 events since the year 60BC and, among these, 14 events were originated by earthquakes of magnitude greater than 8.



.
Figure 2 - Summary of the Portuguese catalogue of tsunamis

If we consider the descriptions in Baptista and Miranda (2009) we conclude that in this area, from 60 BC until 1881(installation of the first tide gauge station in Portugal), the historical or pre-instrumental period, and from 1881 until present we can identify:

(i) 2 tele-tsunamis, the 1755.11.01nd the 1761.03.31both crossed the entire basin causing destruction in coastal areas located more than 1000 km from the source ;

(ii) 2regional events in the historical period: 60 BC and 382 DC; according to the descriptions caused the drowning of slands offshore Cape São Vicente (southwest Portugal);

(iii) 3 regional events during the instrumental period, after 1881, generated by 3 submarine earthquakes of magnitudes equal or greater than 8: 1941.11.251969.02.28 and 1975.05.26hese events generated tsunamis recorded at the tide stations located more than 100 km from the earthquake epicenter

(iv) 3 local tsunamis 1531,1722, 1926 (Portugal mainland) and two local tsunamis in the Azores: 1939 and 1980

According to the Decision Matrix for the NEAM region the PtTWS must regional tsunami warnings for cases ii –iv. The situation described in (i) requires the issue of an ocean wide tsunami watch and requires the cooperation between two regions the NEAM and Caribbean regions.

Depth	Location	(Mw)	Tsunami Potential	Bulletin Type
<100 km	Sub-sea or very near the sea (<30 km)	5.5 to 7.0	Small potential for a local tsunami	Information Bulletin
		7.0 to 7.5	Potential for a regional tsunami<1000 km	**Regional Tsunami Advisory**
		7.5 to 7.9	Potential for a destructive regional tsunami<1000 km	**Regional Tsunami Watch** **Ocean-wide Tsunami Advisory**
		≥7.9	Potential for a destructive ocean-wide tsunami>1000 km	**Ocean-wide Tsunami Watch**
	Inland	5.5	No tsunami potential	Information Bulletin
≥ 100 km	All Locations	≥5.5	No tsunami potential	Information Bulletin

Figure 3 - Decision Matrix for the North East Atlantic (IOC_UNESCO 2006)

The PtTWS is hosted by the Instituto de Meteorologia (IM), operating on a 24x7 basis. IM is the Portuguese National Tsunami Focal Point (NTFP) for the NEAMTWS.

Due to its geographical situation Portugal is the natural candidate to act as a Regional Tsunami Watch Center for the North East Atlantic area and the regional actor to assure the operational “link” between the NEAM and Caribbean TWSs.

Seismic Detection Network

When an earthquake occurs the seismic data is analyzed in order to evaluate the possibility of tsunami generation. The present seismic detection network installed at IM includes 35 broad band stations, transmitting in real time with a latency less than 10 seconds, and 22 enhanced short period stations, transmitting in near real time (latency of approximately 2 minutes) using VSAT and internet. Data collected at IM includes also real-time data provided by other institutions (IGN, Spain, CNRST, Morocco)

The seismic information collected is processed in near real time using a technical solution mixing SEISCOMP (Hanka et al. 2000) and SEISAN (Havskov and Ottemoler 2005) platforms, enabling the first computation of epicenter and magnitude in approximately 5 minutes after the event onset.

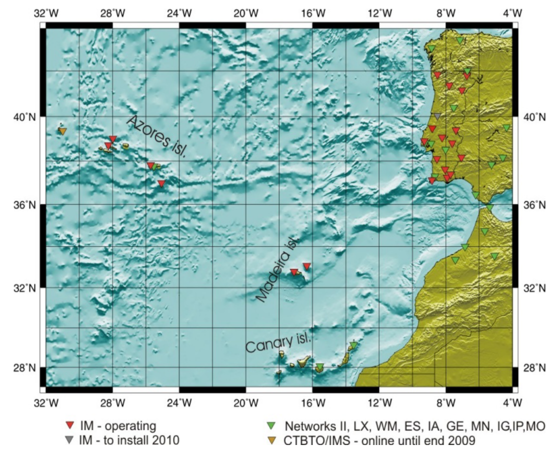


Figure 4- Seismic stations connected to IM, Portugal, in December 2009.

Tsunami Monitoring

The present sea-level detection network includes solely coastal tide stations from Portugal mainland, Azores and Madeira
Currently IM is collecting data in real-time (low latency) from 4 tide gauge stations in Portugal Mainland (Figure 5): Cascais and Lagos operated by the Instituto Geografico Português; Sesimbra and Sines operated by the Instituto Hidrográfico (IH). In addition, the Ponta Delgada station (a GLOSS station operated also by IH) is received at IM trough the GTS communication system with an average latency of 2.5 minutes. In the area, other operators of sea-level tide gauges provide their data trough Internet web pages, making also this data available to the PtTWS but with a considerable larger delay or not with an appropriate sample rate (Figure 5). Among these we would like to mention the Azores University (UA) and the Puertos del Estado (Spain). In the near future this network will be improved by two additional tide gauges in Portugal Mainland to be provided by Instituto Hidrográfico and a new dedicated real-time connection to the Faial tide gauge, under an agreement with the University of Azores.

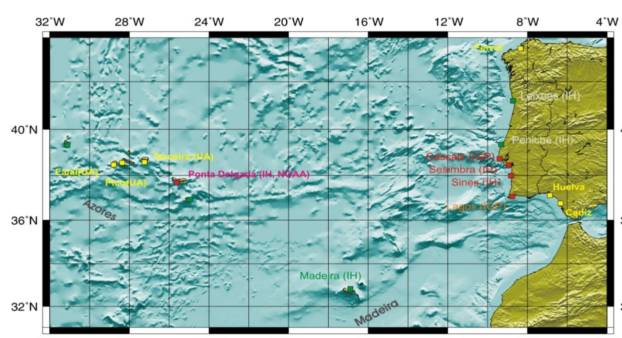


Figure 5- Coastal tide stations connected to IM (December, 2009). Real time stations with a dedicated link in red. Stations accessed on the Internet in yellow.

New stations planned for 2010 in green.

We come to the conclusion that the sea-level offshore detection network is the Achilles' heel of the system in its current state of development. No offshore station is in place and these are essential for tsunami detection before it hits the coast. The shortest tsunami travel times to coastal points in the Gulf of Cadiz are rather short, 20-30 minutes, and this shows the utmost importance of deploying tsunami sea bottom stations.

Recently Omira et al. (2009a) published a study on the design of the "minimum/optimum" offshore sea-level network for the area. This study takes into account the tsunami radiation pattern and the tsunami travel times to the coast, based upon worst credible earthquake scenario in the area, and focus on maximizing warning times and minimizing the number of tsunameters to be deployed.

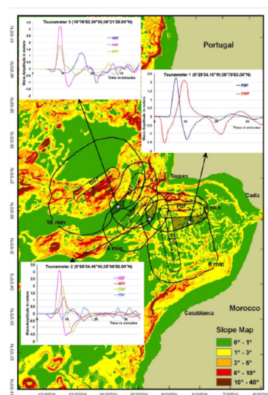


Figure 6 Offshore tsunameter network for the Gulf of Cadiz. White stars are the recommended position of the ocean bottom sensors. Graphs illustrate waveforms recorded by the proposed stations; only waves detected in the time interval (0, 10)minutes are considered for tsunami detection in order to maximize the warning time (from Omira et al. 2009)

The main conclusion of this study points to the installation of three DART-like sensors with a spacing of 110 km are required are required to constitute the deep ocean tsunami monitoring network (Figure 7).

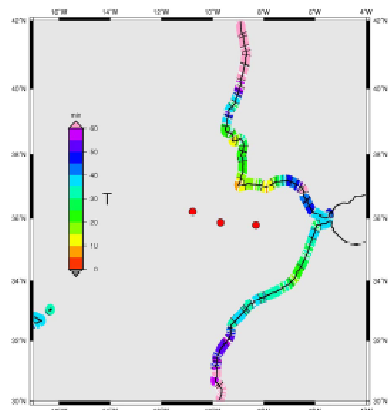


Figure 7- Warning Time along the coasts in Portugal, Spain and Morocco in the Atlantic (Mediterranean areas were blanked), considering that the 3 DART systems proposed in Omira et al. (2009a) paper are available (red dots)

The scenarios database

The state of the art tsunami forecast, in tsunami warning system around the globe, relies on pre-computed tsunami scenarios. A tsunami scenario is a single model run that is calculated ahead of time with the initial conditions carefully selected so that they are likely to represent an actual tsunamigenic earthquake (Greenslade and Titov 2008).

The tsunami scenarios pre-computed database that is used in the PtTWS covers the area along the Azores-Gibraltar plate boundary extending west to the Archipelago of Azores and eastward to the Strait of Gibraltar (Figure 7), using the best knowledge of the structure and the characteristics of the North Atlantic Fault System (Gutscher et al. 2009; Zitellini et al. 2009, Terrinha et al. 2009).

For each earthquake/tsunami scenario the sea-bottom deformation is computed using the Okada's equation (Mansinha and Smiley 1971Okada 1985) using a hypothetical top of the fault depth of 5 km below seafloor (to stay on the conservative side). The initial sea-surface elevation is used as the input to the tsunami propagation model; should the earthquake depth be greater, correction factors are applied to take that into account. The propagation model uses Mader's SWAN non linear shallow water equation model; mass and momentum conservation equations in two dimensions are solved over the calculation space. The initialization of the calculation domain is performed taking into account the size of the initial disturbance (this means that for smaller earthquakes the calculation domain is smaller and the cell size smaller).

The bathymetric grid used in tsunami propagation was generated from a compilation of multisource depth data from multibeam surveys, in the area of interest, digitalized bathymetric charts of different scales. The different data were merged on a unique database and all data transformed to WGS84/UTM coordinates (fuse 29). The final scenario database contains scenarios calculated one point every half a degree, all magnitudes from 6.5 to 8.75 (0.25 interval) in a total of over 6000 scenarios

Operation of the system

Each time an earthquake is detected a pair (Magnitude, epicenter location) is computed. With this information a search in the scenario database is performed in order to choose the appropriate tsunami scenario and the first message is issued including the estimated tsunami arrival time (ETA) and maximum tsunami amplitude on selected sites at the Portuguese coast (the forecast points).

The next level of decision in the PtTWS is taken with the help of the Tsunami Analysis Tool (TAT). TAT is being developed at the Joint Research Centre of the European Commission (JRC) to assist the tsunami warning centre (TWC) operator in deciding if a tsunami has been generated or not, in case of a large enough seismic event.

It is well known that only a few of the large earthquakes do generate tsunamis. It is then essential to confirm the generation of a tsunami using the sea level observations. Through TAT it is possible to compare in real-time the sea level observations and the tsunami waveforms for the selected scenario, allowing for a fast evaluation of the generation of the tsunami (figure 9). This process allows the updating of messages to the Civil Defense and emergency authorities (multiple languages messages may be generated).

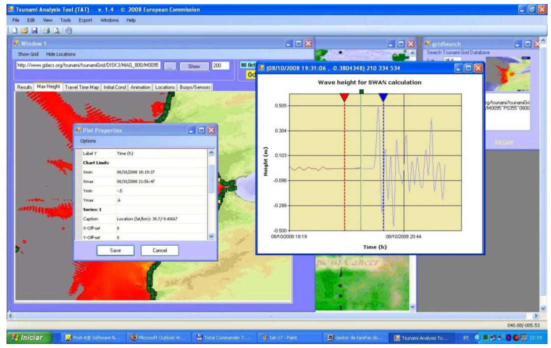


Figure 8- TAT running a synthetic case illustrating the capacity to compare real-time observations with pre-computed tsunami waveforms.

All messages issued by the PtTWS will be structure according to the INEAMTWS operational guide in preparation.

It is important to note that the operational procedures planned for the ptTWS based on tectonically credible scenarios (worst case) extend the basic requirements defined for the NEAM Regional Tsunami Warning Centres (RTWCs) where a simple distance and magnitude criteria is proposed (see the Decision Matrix in Figure 3). However, the recommend message thresholds are to be adopted. The current Alerting procedure defined for NEAMTWS is to send an advisory message if the maximum tsunami amplitude exceeds 0.2 m and to send a watch message if that amplitude is above 0.5 m. Below the 0.2 m threshold Information messages will be delivered to the Portuguese Civil Defense in case of a significant earthquake or in case any size earthquake is felt close to the coast. In addition, dedicated tsunami messages are planned to be broadcast to the responsibles of coastal sensible infrastructures like harbors.

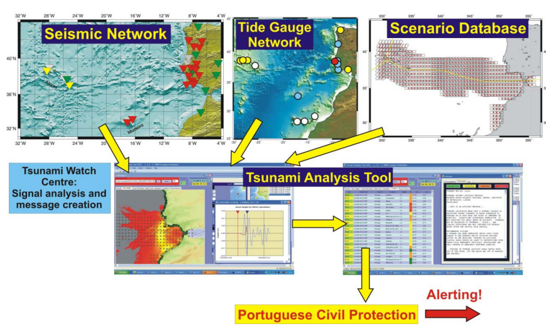


Figure 6 – Main operational components of the PtTWS.

One of the most important activities of the PtTWS operators is the detection of the tsunami event. This is achieved through the analysis of the sea level measurements - bottom pressure sensors, if available and tidal sensors - to check whether they deviate from the usual tidal trend (this tidal filtering is performed automatically by the TAT using a configurable moving average). By comparing the real signal with the expected calculated value for that location it is possible to anticipate the alert level and be able to say what would occur in other locations (tsunami forecast). In case the expected calculated trend does not reflect the real trend, it is possible either to adjust the calculation with a numerical factor or use a different scenario that better represents the current data. This may happen because the initial estimates of the epicenter location, fault depth and rupture mechanism are affected by a large uncertainty and thus the assumed scenario could not reflect the real tsunamigenic source.

TAT contains also dedicated sections for running training simulations which may be very useful for preparing the operators that will be sitting 24/7 at the control panel and need to take appropriate decisions. The simulation mode allows using historical measured events (in Atlantic or other world areas) which are injected at the appropriate time to be compared with simulations from the scenario database.

Final Considerations

The Portuguese Tsunami Warning System under development at IM (figure 10) already comprises all sub-systems required to provide timely tsunami alert messages to the Portuguese Civil Defense authorities, to other National Tsunami Warning Centers in the area and also other Regional TWS (including the Caribbean).

The PtTWS is not yet operational because of lack of support to sustain the additional effort required by a 24x7 service.

The major weakness of the PtTWS in its current configuration is the absence of deep ocean tsunami detection devices and so the tsunami confirmation, or cancellation, messages cannot be issued timely to the most exposed coastal areas South and Southwest of Portugal. However, the coastal tide-gauge already in place can provide accurate information to serve the neighboring countries in the NEAM region that could be affected by a destructive event originated along the Eurasia-Nubia plate boundary.

Due to its geographical situation Portugal is the first country natural candidate to act as RTWC for the North East Atlantic area.

References

Annunziato, A., F. Carrilho, L.M.Matias, M.A. Baptista, R. Omira, 2009):Progress in the establishment of the Portuguese Tsunami Warning System. EMSC (European Mediterranean Seismological Centre) Newsletter, April 2009. ISSN 1607-1980

Baptista, M.A., Miranda J.M., 2009. Revision of the Portuguese Catalog of Tsunamis. Natural Hazards and Earth Systems Sciences, 9, 25-42. Gracia et al., 2002

Gracia, E., Dañobeitia, J., Vergés, J. and PARSIFAL Team: Mapping active faults offshore Portugal (36ºN-38ºN): Implications for seismic hazard assessment along the southwest Iberian margin, Geology, Vol. 31, No. 1, 83-86, 2002.

Greenslade, D.J.M., V.Titov, 2008A Comparison Study of Two Numerical Tsunami Forecasting Systems. Pure appl. geophys. 165 (2008) 1991–2001, DOI 10.1007/s00024-008-0413-x

Gutscher, M.-A., Baptista, M.A., Miranda, J.M.,2006. The Gibraltar Arc seismogenic zone (part 2): constraints on a shallow east dipping fault plane source for the 1755 Lisbon earthquake provided by tsunami modelling and seismic intensity, Tectonophysics doi:10.1016/j.tecto.2006.02.025.

Gutscher M-A., S. Dominguez, G. K., Westbrook, P.Leroy,2009 Deep structure, recent deformation and analog modeling of the Gulf of Cadiz accretionary wedge: Implications for the 1755 Lisbon earthquake, 21 September 2009, Pages 85-97

IOC-UNESCO, 2009a Intergovernmental Coordination Group for the Tsunami Early Warning and Mitigation System in the North Eastern Atlantic, the Mediterranean and Connected Seas (ICG/NEAMTWS), Fifth session, Athens, Greece 3-5 November 2008

Kaabouben, F., Ibn Brahim A., Toto E. A., Baptista, M. A., Miranda J.M., Soares P., Luis, J.F., 2008. On The focal mechanism of the 26.05.1975 North Atlantic Event; Contribution from tsunami modelling. J. Of Seismology. doi 10.1007/s10950-008-9110-6

C. Mader, 2001 “Numerical modeling of water waves” – CRC Press – ISBN 0-8493-2311-8

Mansinha, L. and Smylie, D. E, 1971. : The Displacement Field of Inclined Faults, Bulletin of the Seismological Society of America, 61:1433–1440.

Okada Y, 1985 Surface deformation due to shear and tensile faults in a half-space. Bull Seism Soc Am 75:1135–1154.

Omira R., Baptista, M.A., Matias, L., Miranda, J.M., Catita, C., Toto, E., 2009a. Design of a sea-level tsunami detection network for the Gulf of Cadiz. Natural Hazards and Earth Systems Sciences, 9, 1327-1338.

Omira R., Baptista, M.A., Miranda, J.M., Toto, E., Catita, C., Catalão, J. , 2009b. Tsunami vulnerability assessment of Casablanca – Morocco using numerical modelling and GIS tools., Natural Hazards, DOI 10.1007/s11069-009-9454

Ruiz F., Rodríguez-Ramírez A., Cáceres L. M., Vidal J. R., Carretero M. I., Abad M., Olías M. and Pozo, M., 2005: Evidence of high-energy events in the geological record: Mid-holocene evolution of the southwestern Doñana National Park (SW Spain. Palaeogeography, Palaeoclimatology, Palaeoecology, 229:212–229

Terrinha, P., L. Matias, J. Vicente, J. Duarte, J. Luíse, L. Pinheiro, N. Lourenço , S. Diez, F. Rosas, V. Magalhães, V. Valadares, N. Zitellini, C. Roque, L. Mendes Víctor, and MATESPRO Team (2009. Morphotectonics and strain partitioning at the Iberia–Africa plate boundary from multibeam and seismic reflection data, Marine Geology 267, 156-174.

Zitellini, N., E. Gràcia, L. Matias, P. Terrinha, M.A. Abreu, G. DeAlteriis, J.P. Henriet, J.J. Dañobeitia, D.G. Masson, T. Mulder, R. Ramella, L. Somoza, S. Diez , 2009. The quest for the Africa–Eurasia plate boundary west of the Strait of Gibraltar, Earth and Planetary Science Letters,280,13–50.