ASTARTE

Assessment, STrategy And Risk Reduction for Tsunamis in Europe

Grant Agreement no: 603839

Organisation name of lead contractor: IPMA

Coordinator: Maria Ana Baptista

Deliverable 10.48[1]

Lessons learned from the ASTARTE test sites[2]

Due date of deliverable:	M42[3]
Actual submission date to PC:	M42[4]
Start date of the project:	01/11/2013
Duration:	36 months

Work Package:	10 “Dissemination and Exploitation of Results”[5]
Lead beneficiary of this deliverable:	METU

[1] Deliverable number, e.g., 4.3.

[2] Deliverable name

[3] M1 – November 2013; M36 – October 2016 (please check DoW for the expected delivery date)

[4] M1 – November 2013; M36 – October 2016

[5] Please indicate the number and the name of the work package, e.g. - 1 “Coordination Management and Procedures”

Author(s):	Leading Authors: Maria Ana Baptista; Martin Wronna Contributors: CEA: Audrey Gailler, Angélique Monnier, Agathe Fontaine, Anne Loevenbruck CNRST: Benchekroun Sabah, Rachid Omira, El Mouraouah Azelarab, Ibn brahim Aomar CNRS: Franck Lavigne UB: Miquel Canales, Galderic Lastras METU: Sena Acar, Betul Aytore, Ahmet Cevdet Yalciner, Nilay Dogulu, Hasan Gokhan Guler, Gizem Ezgi Cinar, Ozge Cabuk, Ceren Cankaya, Utku Kanoglu NGI: Carl B. Harbitz, Finn Løvholt, Sylfest Glimsdal UNIBO: Fillippo Zaniboni, Stefano Tinti, Alberto Armigliato, Gianluca Pagnoni[6]
Version:	1.01

Project co-funded by the European Commission within the Seventh Framework Programme (2007-2013)	
Dissemination Level[7]	
PU Public	X
PP Restricted to other programme participants (including the Commission Services)	
RE Restricted to a group specified by the consortium (including the Commission Services)	
CO Confidential, only for members of the consortium (including the Commission Services)	

[6] Indicate the authors of the report

[7] Please mark with X the dissemination level of the deliverable (check DoW if any questions arise)

TABLE OF CONTENTS

EXECUTIVE SUMMARY

The ASTARTE project (Assessment STrategy And Risk Reduction for Tsunamis in Europe) aimed to develop a holistic strategy for mitigation of tsunami impact in the NEAM region (North East Atlantic, Mediterranean and Adjacent Seas). ASTARTE selected nine sites distributed along the coasts of the North East Atlantic and Mediterranean.

ASTARTE test sites are vulnerable to tsunami impact generated by different source mechanisms: earthquakes, landslides and volcanic eruptions. They cover a broad range of values at risk namely: buildings and other infrastructure, industrial facilities, harbors, road network, fisheries, aquaculture and tourist areas. Test sites provide the possibility to test most of the approaches developed during the project, thus providing a “test bench”, where the different methodologies are tested in a diversity of geological and social environments.

One major challenge of ASTARTE is to go from “locally tested methodologies” to “regional and global strategies” applicable in a wide diversity of situations.

This document presents a comprehensive overview of the main results on tsunami hazard, vulnerability, risk and awareness obtained by all ASTARTE participants, extensively tested in the test sites, but with a global meaning and so must be considered when developing a European tsunami resilience program.

At the moment of writing this report, on the 21st of July 2017, an earthquake and tsunami stroke Bodrum - where ASTARTE had its second annual meeting in 2015 - in Turkey and Kos in Greece leading to casualties and noticeable damage.

DOCUMENT INFORMATION

Project Number	FP7 - 603839	**Acronym**	ASTARTE
Full Title	Assessment, STrategy And Risk Reduction forTsunamis in Europe		
Project URL	http://www.astarte-project.eu/		
Document URL			
EU Project Officer	Denis Peter		

Deliverable	**Number**	D10.48	**Title**	Lessons learned from the ASTARTE test sites
Work Package	**Number**	WP10	**Title**	Dissemination and Exploitation of Results

Date of Delivery	**Contractual**	M42	**Actual**	MXX
Status	version 1.01		final □	
Nature	prototype □ report X dissemination □			
Dissemination level	public X consortium □			

Authors (Partner)	Instituto Português do Mar e da Atmosfera			
Responsible Author	**Name**	Maria Ana Baptista	**E-mail**	Astarte@ipma.pt
	Partner	IPMA	**Phone**	

Abstract **(for dissemination)**	This document provides a summary and a critical overview of the lessons learned during the studies conducted at all test sites. ASTARTE considers nine test sites distributed along the Mediterranean and Northeast Atlantic coasts. These sites are the places selected to test ASTARTE methodologies and to implement interconnections between Work Packages. Here, ASTARTE teams interacted with stakeholders and society.
Keywords	Tsunami Hazard, Tsunami Risk.

Version Log			
Issue Date	**Rev. No.**	**Author**	**Change**
21 July 2017	1.01	Baptista et al.	First consolidated version

LIST OF FIGURES AND/OR LIST OF TABLES

ABBREVIATIONS AND ACRONYMS

ASTARTE, Assessment, Strategy and Risk reduction of Tsunamis in Europe

DRR, Disaster Risk Reduction

DTM, Digital Terrain Model

GIS, Geographic Information System

GPS-RTK, Global Position System Real Time Kinetic

IOC, Intergovernmental Oceanographic Commission

MSL, Mean sea level

NEAM, North East Atlantic and the Mediterranean

PTHA, Probabilistic Tsunami Hazard Assessment

SBTHA, Scenario based Tsunami Hazard Assessment

SWIM, South West Iberian Margin

SZ, Source Zone

TEU, Twenty-Foot Equivalent Units

TF, Typical Fault

CHAPTER 1 Introduction

1.1 Scope of the report

This document provides a summary and a critical overview of the lessons learned during the studies conducted at all test sites. ASTARTE considers nine test sites distributed along the Mediterranean and Northeast Atlantic coasts. These sites are the places selected to test ASTARTE methodologies and to implement interconnections between Work Packages. Here, ASTARTE teams interacted with stakeholders and society.

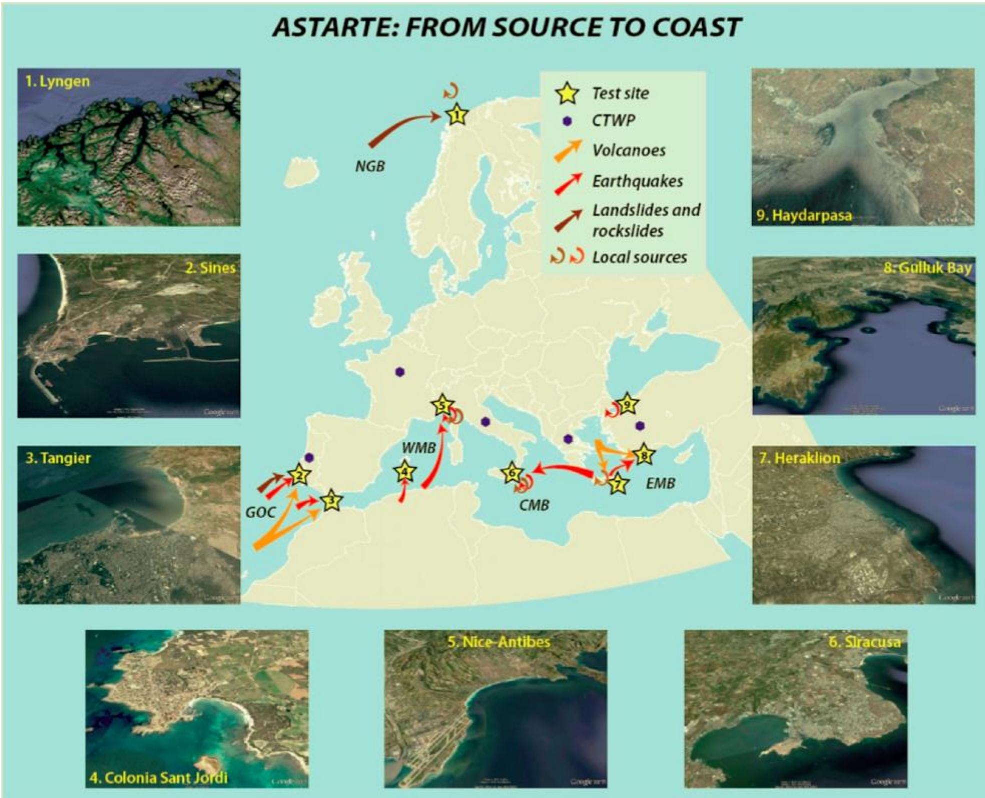


Figure 1: ASTARTE test sites

1.2 Brief overview of ASTARTE test sites

ASTARTE selected nine test sites distributed over the North East Atlantic and Mediterranean (NEAM) basin. The ASTARTE test sites were chosen to be representative regarding the potential tsunami sources, vulnerability and diversity of landscapes and socioeconomic elements at risk. (see figure 1)

The Lyngen fjord test site is located in northern Norway (69°34'38" N 20°20'58" S). The area is remote and sparsely populated compared to the other test sites, but there are several villages close to the fjord (e.g. Lyngseidet, Skibotn, Olderdalen, with less than 900 inhabitants each). The total population is 6000 (2014 census) and growing, owing to positive immigration. Most people live within the tsunami prone area. Beyond farming, activities are fishing, fish processing, tourism and light industry (mainly at Furuflaten). Infrastructure comprises harbors, transport (ferries and roads), industrial buildings, and power lines. The ferries and the boats on the fjord, together with the road running along the shoreline, are the only alternatives for transport and travelling in the region. Also the power lines are considered critical infrastructure of high regional importance. It is the only ASTARTE test site only exposed to non-seismic tsunamis. The study area is about 1200 km^2, with special focus on 3-4 villages.

Nice test site is the largest city of the French Riviera and welcomes a very large number of tourists every year, notably for seaside activities. Moreover, its waterfront hosts the second French airport and many other facilities. The work performed during ASTARTE focused mainly hazard assessment related to seismic sources based on a worst-case scenario approach, and including parameters and sensitivity analysis. Forecast capabilities, the definition of optimum sensor locations and large scale accessibility mapping and evacuation simulations were also tested.

Sines test site is located on the west littoral margin of the Iberian Peninsula, about 150 km south of Lisbon, hosting one of the most important industrial harbors of the Portuguese west coast. In 2015, Sines harbor ranks 17^{th} position in terms of container management (TEU) in Europe. Tourism and fisheries are other major activities in the area.

Tangier test site is the unique representative of IOC – NEAM region outside Europe. Tangier is a port city located in the northern Moroccan coast at the western entrance to the Strait of Gibraltar. It covers an area of about 1685 km^2 with a total population of 948000 inhabitants (Haut Commissariat au Plan, Population Census 2014). This test site undergoes considerable seasonal variability in population especially during summer season due to the tourist flow (circa 30000 people along the beaches).

Colònia Sant Jordi test site covers an area of about 266 km^2 located some 55 km southeast of Palma de Mallorca (Balearic Islands, Spain), between 39º14’N and 39º21’N, and between 2º59’E and 3º11’E. Morphologically, this region includes 30 km of coastline with two main domains east and west of Cape Ses Salines, which represents the southernmost tip of Mallorca island. To the west, the site is occupied with lowlands (<10 m), with a coastal strip made of relatively long sandy beaches or low rocky cliffs less than 1-3 m high. The area has a strong seasonal variability in population, with a considerable increase during summer months.

Güllük bay test site is in southeast of Aegean Sea of Turkey. Güllük bay is formed basically by four large natural coves and many small bays and inlets. Local industries are mainly based on fish farming for sea bass and bream, and the export of bauxite from the recently relocated harbor on the outskirts of Güllük. Furthermore, Güllük bay is one of the seven largest gulfs and bays on the west coast of Turkey and contributes about 80% of countries’ aquaculture production. Public port and nearby private piers in Güllük bay has a capacity of handling over 5 million tons of cargo per year. Milas Bodrum Airport is located at the end of Güllük bay on a low elevation area.

The **Siracusa-Augusta** test site includes the city of Augusta: the historical city centre and the military harbour, the large Bay of Augusta; the northern sector of the bay is closed by a 17 km long three-segment breakwater, built to protect the biggest petrochemical hub of Mediterranean Sea (visible in both panels), the Magnisi peninsula (archaeological and natural site, the town of Siracusa, with two harbours and the historical center located in the Ortigia Island. It was declared a UNESCO cultural heritage site in 2005, in virtue of its archaeological and historical relevance; and the Siracusa Bay, important from the touristic and economic point of view.

The **Haydarpasa Port** test site, is the largest container port in the Marmara Region and third largest in the nation. The port and its environs are placed in between two districts (Kadikoy and Uskudar in Anatolian side of Istanbul). The two breakwaters of the port are about 1,700 and 600 m long and, the port is operated by General Directorate of Turkish State Railways (TCDD). The handling and storing general cargo and container, ro-ro handlings (built-in or shore-based ramps that allow the cargo to be efficiently rolled on and off the vessel when in port), and short/long distance passenger transfers are the main components of the port.

The **Heraklion** test site is the largest city in Crete, and the administrative capital of Crete. It is an important shipping port and ferry dock. It has a population of 170,000 but, during the summer, this number nearly doubles. The international airport is the second in Greece in terms of daily movements. Many hotel complexes are located on the coastline and most of the beaches are very crowded during the summer. Moreover, 4 km SE from the city centre there is the industrial zone of Heraklion and 4 km E from the city there is the international airport of Heraklion. Many of the administrative buildings such as Civil Protection, Police and Fire Brigade are also situated very close to the coast.

CHAPTER 2 Lessons learnt on Tsunami Hazard Assessment

2.1 Seismic and non-seismic sources

While seismic sources are the most important tsunamigenic structures for all southern sites (Sines, Tangier, Nice, Gullen, Siracusa and Haydarpasa), because of the **complex Eurasia-Africa plate boundary**, non-seismic sources, particularly landslides and rockslides, are relevant in specific environments and have a critical role in the northern European coasts. In the eastern Mediterranean volcanic tsunami sources must also be considered.

2.1.1 Cadiz Gulf and the Mediterranean

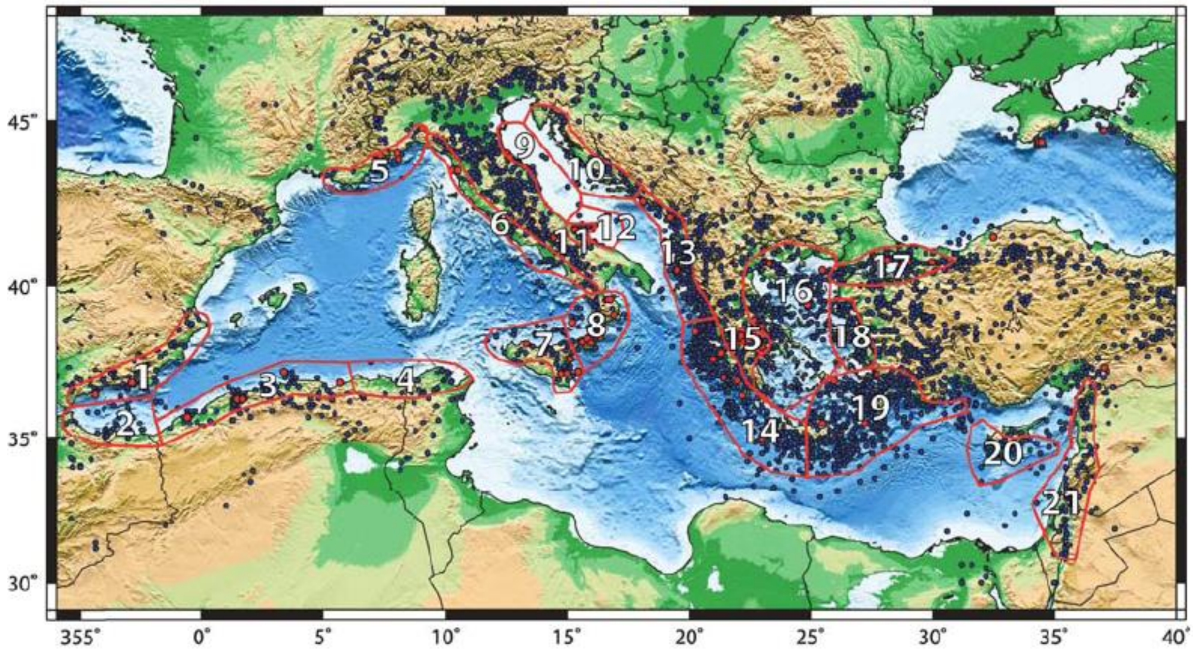


Figure 2: Tsunamigenic source zones considered (from Sørensen et al. (2012)).

Sines is located on the west littoral margin of the Iberian Peninsula, about 150 km south of Lisbon. Historical records report that earthquake induced tsunamis impacted Sines in the past. The site is exposed to local, regional and distant sources. Regional sources include tsunamigenic earthquakes in the South West Iberian Margin (Johnston, 1996; Zitellini et al. 2009; Omira et al, 2009; Gutscher et al. 2002; Barkan et al., 2009, Baptista and Miranda 2009). The November 1st, 1755 tsunami was the most devastating event in the history of the NE Atlantic, in terms of loss of live and destruction. However, it was not the unique great tsunami in this region. Distant sources include tsunamigenic earthquakes on the Gloria Fault (Baptista et al., 2016) and in the Caribbean subduction arc (Omira et al., 2015).

The Balearic Islands, including the test site **Colònia San Jordi**, were affected by the tsunami triggered by the Zemmouri-Boumerdes earthquake on May 21st 2003, which produced considerable economic damage along the Balearic coastlines. More than 200 boats sank or grounded, and the tsunami damaged coastal and harbour infrastructures. Some seaside shops and restaurants were flooded, as well as local roads. Luckily no human lives were lost, probably due to low exposure caused by time and date of the event. In historical times, three other tsunamis originating from the North African margin have impacted the Balearic Islands (1756, 1856, 1980), with inundations reported in Cala Santanyí in 1756, when sea water entered ~5 km inland according to historic reports. Along the coastline from Colònia Sant Jordi to Cape Ses Salines, imbricated boulder fields (~20 t per single boulder) lay on the lower slopes as well as in the supratidal zone, on top of 1-3 m high cliffs. These have been identified as possible tsunami deposits, which have been radiocarbon dated at 500 BP and 1400 BP (Scheffers and Kelletat, 2004).

Submarine landslides have been identified in most of the continental margins surrounding the Balearic Islands and, generally, in the Western Mediterranean. Many landslides occupy the slopes of the Balearic Promontory, especially around Ibiza Island and in the Mallorca Channel. Landslides are also abundant in the Ebro continental margin and the Gulf of Lion. Many landslides occupy the upper most layers of the sedimentary sequence, indicating that they occurred in relatively recent times. Five of these landslides, for which a larger variety of geophysical and sedimentological data are available at present, have been modelled, namely BIG'95 debris flow in the Ebro continental margin, and Jersi, Nuna, Joan and Ana slides in the Ibiza Channel, between Ibiza Island and mainland Spain.

Heraklion test site is characteristic of the Eastern Mediterranean environment. In the historical past, very large earthquakes produced large tsunamis that inundated the **entire eastern Mediterranean basin** (e.g. Papadopoulos et al., 2014). For example, the earthquake and tsunami destructive events of AD 21 July 365 and 8 August 1303 were among the largest ever reported in the Mediterranean region (Guidoboni et al., 1994, Ambraseys, 2009, Papadopoulos, 2011). The sources of these events were situated off the western and eastern Crete, respectively. There is no historical or other evidence on how Heraklion was likely affected by the 365 tsunami, since it was a little developed area, but as regards the 1303 tsunami it is documented that it caused heavy damage and human deaths in Heraklion. In the instrumental period, the 9 July 1956 tsunami, produced by a M7.5 tectonic earthquake in the South Aegean Sea, inundated the north coast of Crete and caused damage in Heraklion. Maximum observed wave heights up to ~15 m were reported in the near-field of the 1956 tsunami. In the north coast of Crete, including the Heraklion test-site, observed wave heights of 2-3 m were reported (Galanopoulos, 1957).

Nevertheless, i*n* pre-historical times, the largest tsunami in the E Mediterranean was produced by the giant Late Bronge Age (late 17th century BC) eruption of the **Santorini** (Thera) volcano situated about 120 km to the north of Heraklion. Numerical simulations of the Minoan tsunami indicated wave heights up to ~25 m in north Crete (Minoura et al., 2000; Bruins et al., 2008). On 29th September 1650 (Old Style), after the paroxysmal phase of a strong eruption taking place in Kolumbo submarine volcanic edifice, lying outside of the Santorini caldera, a large tsunami was generated which inundated violently Heraklion and caused damage to vessels (Dominey-Howes et al., 2000).

Concerning the Siracusa test site it was concluded that the **far-field tsunami sources located in the Western Hellenic Arc are the dominant contribution for the estimated wave heights of dangerous tsunamis**. Nevertheless, landslides had probably a role in the historical tsunamis of 1693 and 1908.

2.1.2 North-Eastern Atlantic

The potential tsunamigenic sources in the NE Atlantic, where **Lyngen** test site is located, were preliminary assessed within the framework of the EU project TRANSFER (Tsunami Risk And Strategies for the European Region, www.transferproject.eu), Based on modelling and evaluation of the corresponding tsunami scenarios, potential rockslides located in the fjords of Western Norway were considered the only high risk tsunamigenic sources in the NE Atlantic (the fjords in Greenland were not investigated). Submarine landslides off the Norwegian continental margin, rockslides in Northern Norway, as well as earthquakes off the Portuguese coastline were identified as sources constituting moderate tsunami hazard (Harbitz et al., 2009). Tsunamigenic earthquakes in the North Sea, the Norwegian Continental Margin, and the Norwegian–Greenland Sea were considered non-critical (Bungum and Lindholm, 2007). The Jan Mayen and Iceland volcanic sources, the landslide sources north of Svalbard (Vanneste et al., 2010) as well as the Grand Banks, Canary Islands (Løvholt et al., 2008), Cape Verde, and Caribbean far-field (Harbitz et al., 2012) sources were considered non-critical with regard to tsunami hazard in the NE Atlantic. It should be noted that important segments of the continental margins surrounding the northern North Atlantic and Arctic Ocean are not mapped in sufficient detail.

While rockslides are normally more frequent and can generate locally severely damaging tsunamis, the relatively infrequent landslides on low gradient continental slopes include some of the largest mass wasting events on earth and can generate damaging far field tsunamis.

At least six very large landslides have occurred in the Norwegian and Greenland Basins during the last ~20ka, giving a frequency of 1 per ~3-to-4 ka. The Storegga Slide at 8.2 ka produced a far-field tsunami (Harbitz, 1992; Bondevik et al., 2005; Hill et al., 2014). The Trænadjupet landslide (~4500 BP; Laberg and Vorren, 2000) and the much older Bjørnøyrenna landslide both have volumes up to ~1000 km^3. Deliverable D8.8 describe tsunamis generated at two different locations within the Norwegian Basin, one at Trænadjupet and one at Bjørnøyrenna. through a scenario based tsunami hazard assessment (SBTHA). The various landslide scenarios comprise volumes ranging from ~10 km^3 to ~1100 km^3, and thus demonstrate possible impacts if such events should occur today.

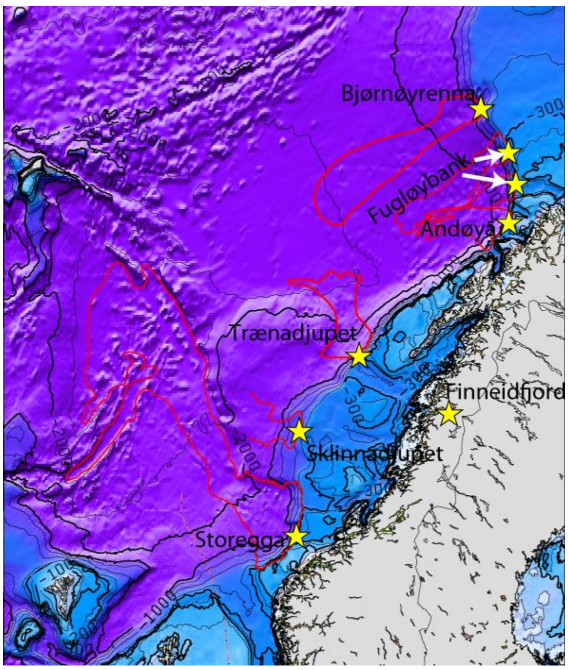


Figure 3: Probably tsunamigenic submarine landslides in the Norwegian Basin

Numerical modeling of tsunami generation by landslides represents huge challenges in terms of landslide disintegration and flow mechanisms, water/landslide interaction, huge dimensions and long run-out distances, as well as propagation and inundation in complex geometries. The Lyngen fjord test site may be impacted by tsunamis from both these kinds of sources, and served as an excellent laboratory for testing methodologies to be developed for landslide tsunamis in ASTARTE.

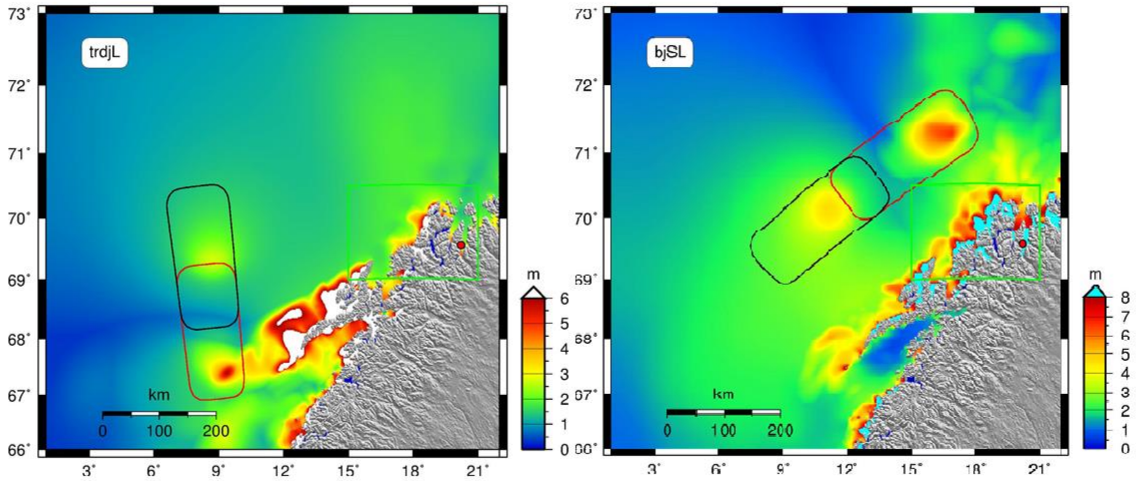


Figure 4: Distribution of maximum surface elevations during the propagation phase for a submarine landslide of 1100 km3 at Trænadjupet (upper panel) and for another submarine landslide of 1100 km3 from Bjørnøyrenna (lower panel). The red and black box is the initial and final position of the slide, respectively. Lyngseidet within the green box is marked with a red dot.

In D3.12, the generation of landslide tsunamis due to both basic block slides and retrogressive landslides are investigated through sensitivity tests. The methodology and choice of parameters for the sensitivity studies are taken directly from Løvholt et al. (2015) and aims to demonstrate how the basic parameters influence on the tsunami generation. The study shows that tsunamis generated by subcritical landslides are sensitive to the initial landslide acceleration. While the acceleration is the most important factor for small Froude numbers, the Froude number itself will determine the maximum surface elevation for large initial accelerations. For retrogressive landslides, the generated tsunami is stretched and reduced in height by increasing the time lag between the subsequent blocks. It is also shown that dispersive models are needed (linear shallow water models not appropriate).

Potential tsunamis from rockslides along the Lyngen fjord

Historical background

On June 30th 1810 a rockslide was released from Pollfjellet mountain into the fjord Lyngen (**Error! Reference source not found.**). The rockslide is among the biggest observed in Norway, the release area indicates a width of almost 2 km. The rockslide induced three giant waves that did severe damage. Several farms were washed away and 14 people were killed (the area was very sparsely populated). The waves were observed more than 20 km to both sides of the rockslide area. In the head of the fjord Storfjorden the waves were 2 m high (it is not clear whether this refers to run-up or wave height). A number of other large rockslides have been mapped in this county, some of them leaving huge rockslide deposits in the fjords. Many of the large rockslides were released about 11 500 – 10 500 years ago, i.e. shortly after the last glacial period.

Figure 5: Pollfjellet Mountain with the release area of the 1810 rock slide (photos: C.B. Harbitz; upper panel 2015, lower panel 2007).

The unstable Nordnes rock slope

Thorough geological investigations of the rock slope at Nordnes, Lyngen, reveal movements up to 4-5 cm per year for a potential 11 Mm^3 rockslide. Introductory studies by NGI show that such a rockslide will cause run-up heights up to 20 m in the nearest village Lyngseidet on the opposite side of the fjord and impact the whole fjord system (Braathen et al., 2004; Lauknes et al., 2010; NGI, 2008, 2010, 2013; NGU, 2009; Nordvik et al., 2010, NVE, 2016; https://www.nve.no/flaum-og-skred/fjellskredovervaking/jettan/). Based on the numerical simulations performed for a series of rockslide/tsunami scenarios, land-use and evacuation planning for rockslide tsunamis in Lyngen is prepared by Troms County, the local municipalities, and the preparedness centre Nordnorsk Fjellovervåking (NNFO, http://www.nnfo.no/beredskapsplan.188322.no.html). Further rockslide tsunami studies for Nordnes and other locations in Lyngen are presently in preparation by NGI.

The rock-slope monitoring involves high-tech instrumentation such as lasers, crackmeters, tiltmeters, rod extensometers, GPS network, and instrumented boreholes. A permanent Early Warning System is based on an operational cell phone warning starting at least 72 hours before the occurrence of a predicted rockslide. In 2013, the Barents Rescue international emergency exercise simulated a destructive rockslide from the Nordnes Mountain. Under the umbrella of the Norwegian Directorate for Civil Protection, the exercise promoted cooperation between various authorities in the Barents Region, in addition to authorities at national and international levels (http://www.dsb.no/).

Figure 6: The unstable rock slopes at Jettan, Midtre Nordnes, and Indre Nordnes (zoom-in in lower panel). (photos: C.B. Harbitz, August 2015).

2.2 SBTHA vs PTHA Approaches

ASTARTE performed Scenario Based Tsunami Hazard Assessment (SBTHA) for Nice and Heraklion test sites, and Probabilistic Tsunami Hazard Assessment (PTHA) for Sines and Tangier. While SBTHA produces mainly inundation maps with flow depths and inundation limits for a specific scenario or a set of scenarios (even with a priori probability of each scenario), the probabilistic approach predicts the probability of flooding for a exposure time. Both approaches considered only earthquakes induced tsunamis. PTHA was based on a logic tree approach including uncertainties. Logic-tree branches included: (i) possible source zone and magnitude recurrence within this zone; (ii) possible fault where the rupture can take place; (iii) earthquake source location within the fault; (iv) earthquake slip distribution; and (v) tidal stage. Scenarios considered magnitudes between 7.5 and 9.0. Omira et al. (2015) and Omira et al. (2016) present a detailed description on the PTHA and the logic tree approach used within ASTARTE for Sines and Tangier: results focus 50% probability of tsunami flooding for 500 and 1000-year return periods in Sines and the surrounding areas.

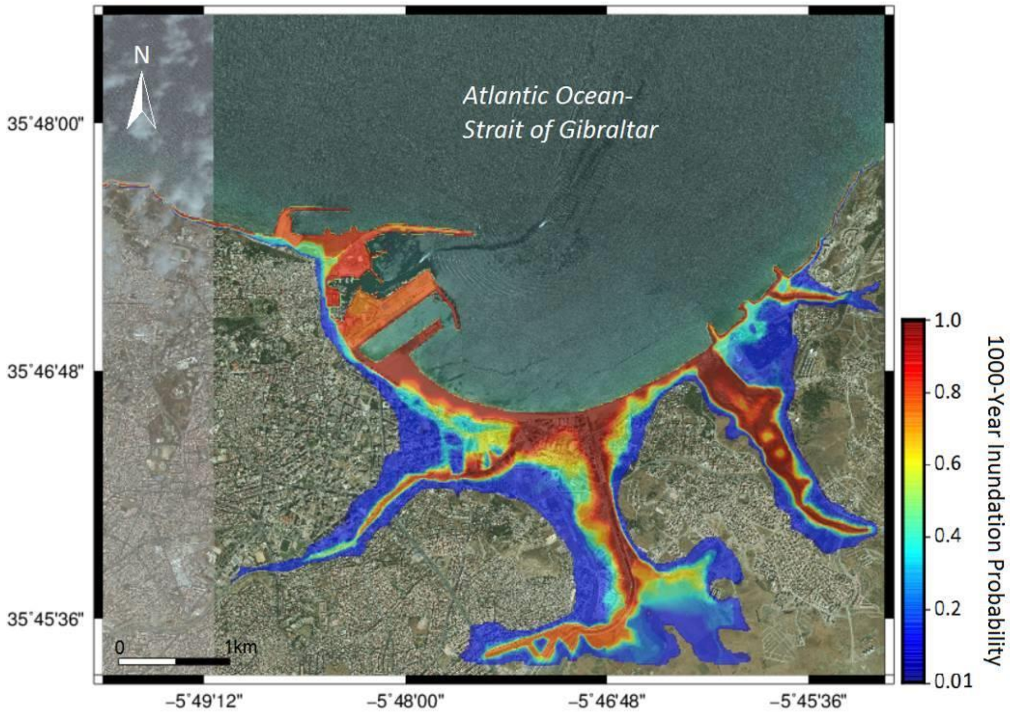


Figure 7: 1000-year probability of tsunami inundation (Tangier site)

In the case of **Nice test site** tsunami impact was estimated through worst-case scenarios based on potential seismic sources. Two principal seismically active areas of the western Mediterranean were considered prone to generate significant tsunamis with impact on the Nice coastline: the north Algerian Margin and the Ligurian Sea. Initial fault parameters (location, strike, dip, fault style) were partly inferred from the CENALT fault database (Gailler et al., 2013; Schindelé et al., 2015). This database results from an extensive compilation of potentially tsunamigenic faults, discretized by 25km-long and 20km-wide rectangular planes. The magnitudes of the ruptures were estimated on the basis of the historical seismicity. The seismic sources are simulated using a set of rectangular fault planes (the number of planes depends on the magnitude). Each plane is described by the longitude, latitude and depth of its centre, its length and width, and the related co-seismic rupture is defined by its slip amount, strike, dip, and rake (see D3.12 for more details). The worst-case scenarios are computed using a Mw=7.5 earthquake offshore Algeria. The simulation leading to the worst tsunami impact in the Nice test site gathers the following parameters: dip = 60°; Slip/length ratio = 2.5m/64km; strike = 96.5°; rake = 90°.

In **Gulluk test site** ASTARTE partners preferred the use of extreme value statistics (EVS) rather than Gaussian distribution (Acar, 2015). The design of harbour protective structures requires the use of extreme wave analysis. The first step of EVS is the determination of **maximum earthquake magnitude** in a period of years for the region. For Gulluk test site, ASTARTE used the seismic data of Kandili Observatory and Earthquake Research Institute for the period 1950-2014 and selected earthquakes of magnitude greater than 4. The representative value of each year in the EVS is the maximum magnitude registered each year.

The results of PTHA show that EVS using Gumbel distribution **gives results compatible with deterministic worst-case approach**.

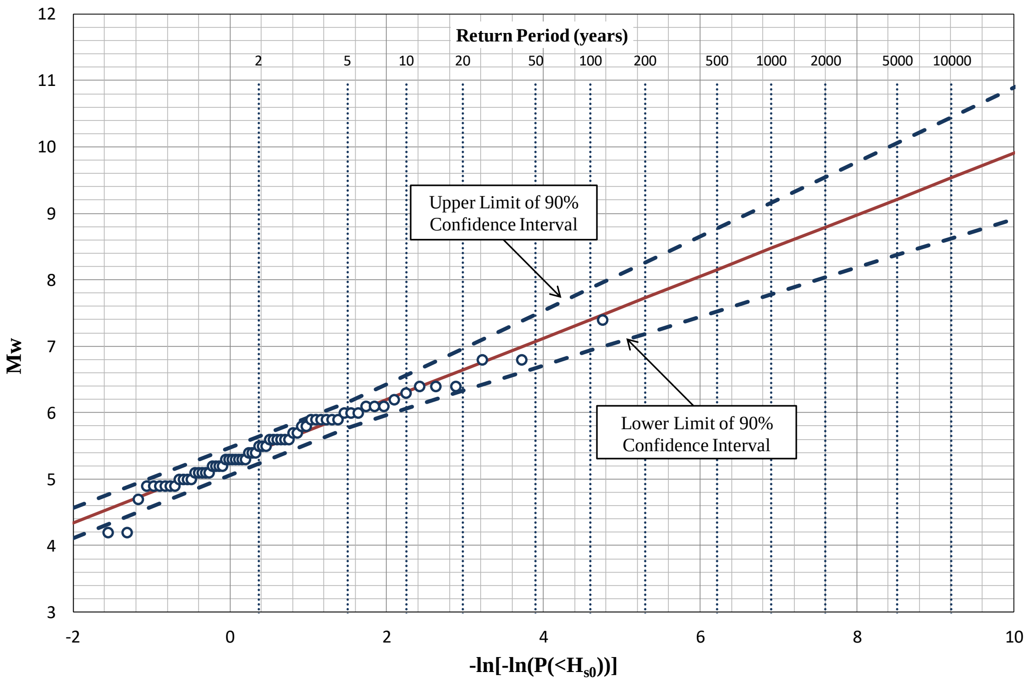


Figure 8.23.

Figure 8: Results of extreme value statistics for probable earthquake magnitudes (Mw) in Gulluk with different return periods

For SBTHA, the choice of the realistic worst-case scenario was mainly based on **maximum historical tsunami events** (Heraklion, Sines, Tangier). In the case of volcanic explosions, expert geological evaluation is the best approach, as was the case of the Minoan eruption tested for Heraklion. **In conclusion, PTHA and SBTHA produce similar inundation zones** for values less than 10% of probability of inundation during 1000-year return period. However, the inundation areas produced by the aggregate scenario - SBTHA - and PTHA methods are different for a return period of 1000-year inundation occurred with a very high probability of inundation occurrence (100%) that is computed using the PTHA. To obtain the same inundation area produced with the aggregate scenario with 100% probability of occurrence we need **to consider much longer return times**. **This result may be explained by the rareness of extreme earthquake events (Mw=9.0) and the use of a Gaussian distribution.**

2.3 Sensitivity on Grid Resolution

The influence of grid resolution on modeling results, in terms of accuracy and computing time, was tested for the Nice test site. The test was performed with the worst-case scenario - an earthquake of magnitude Mw=7.5 off the Algerian margin. The rupture parameters being the most penalizing for a maximal impact along the Côte d'Azur coast (namely dip = 60°; Slip/length = 2.5m/64km; strike = 96.5°; rake = 90°). The grid cell size was reduced from 25 m, to 5 m and 1m. This sensitivity study confirms that there is the best compromise between accuracy in tsunami modeling (e.g., bay amplification, harbour resonance,) involving high-quality datasets of the coastal domain and acceptable computational time costs for our code, can be found. Tests on the grid resolution sensitivity show the need to use smaller cell sizes (5 m) to model local coastal amplifications accurately. **However, the use of 1 m cell size does not provide significantly better results** compared to the huge extra cost in computational time. Figure 3 shows the comparison between 25 and 5 m resolution.

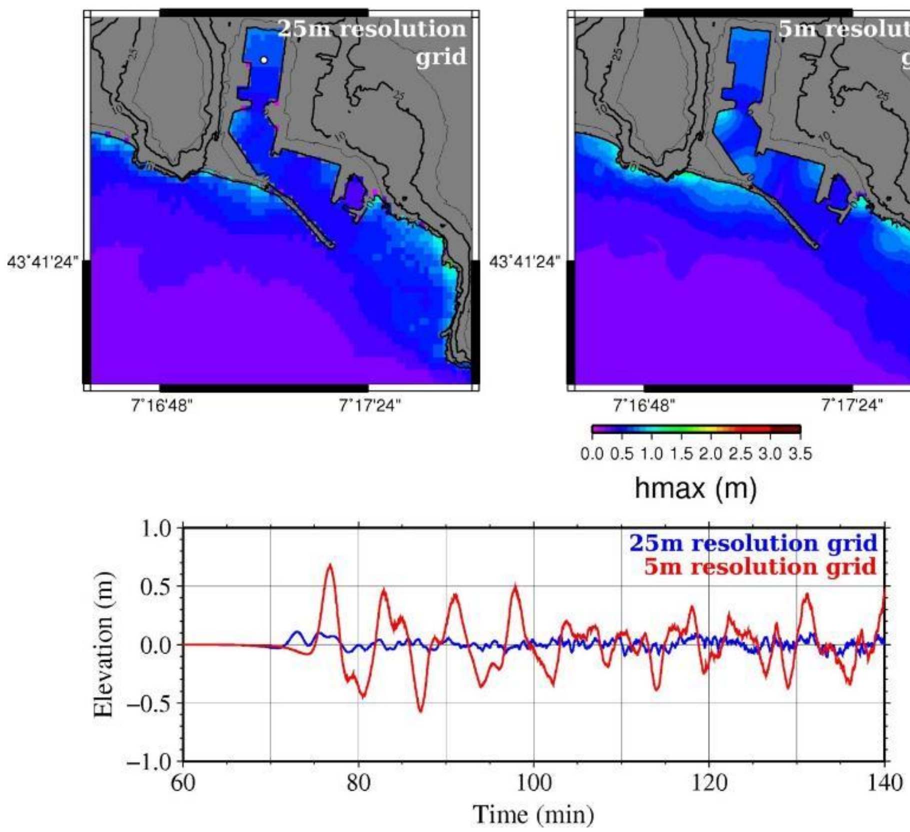


Figure 9: [top] Difference between modeling in the 25m grid and in the 5m grid resolution. [bottom] Comparison at a gage located in the harbour (white dot in the top left figure).

2.4 Uncertainty on Hazard Assessment

Hazard assessment was the target of a specific deliverable (D8.39) of ASTARTE. The assessment of uncertainty was made for several test sites. In the case of Colònia Sant Jordi (Fisotti, 2016, Lastras et al., 2014) there are several epistemic uncertainties, namely source uncertainties and model uncertainties. Source uncertainty relates to the large uncertainty in the exact specification of the source. Landslide scenarios were computed considering events that have already occurred in the past millennia, and not considering potential future landslides, due to the huge epistemic uncertainty in landslide forecasting. Future landslide sources are unknown in terms of location as well as in terms of dimensions. Modelling past landslide-generated tsunamis yields only a very general idea of a tsunami height range that could reach the test site due to landslides in neighbouring margins. Even through this approach, epistemic uncertainty exists in the exact source description of past landslides, for example in terms of sediment volume, initial velocity, maximum velocity and rheology of the landslide masses. Even if it is impossible to rigorously quantify the exact amount of uncertainty, **an upper bound for wave height can be determined**.

CHAPTER 3 Lessons learnt on the Coastal Impact

3.1 Coastal and Harbor Amplification

For **Nice test site**, the rapid assessment of wave height amplification near the coast was based on the Green's Law. In the deep ocean model the Green law is used: $\eta_2 = \eta_1.(h_1/h_2)^{1/4}$ (with $h_2 < h_1$). In shallower areas, being h_E the depth of a point at the entrance of the bay the wave height is given by equation (1) transfer function inspired from the Green's law is applied on the deep ocean model if $h_0 \leq h_2 < h_E$. This expression provides a linear approximation of the response between the depth h_E at the entrance of a bay or harbor and the target point at minimal depth h_0, where β is the attenuating of amplifying factor as a function of the studied site configuration:

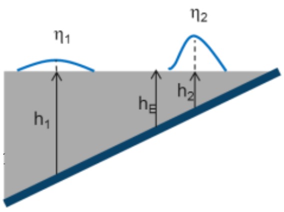
$$\eta_2 = \eta_1.\left[1 + \beta\frac{(h_E - h_2)}{h_E}\right].\left(\frac{h_1}{h_2}\right)^{1/4} \quad (1)$$

Among the combinations of tested parameters, the most relevant for the 3 zones of Nice test site is the following: $\mathbf{h_1 = 500m}$; $\mathbf{h_E = 50m}$; $\mathbf{h_0 = 5m}$. The methodology thus becomes:

(1) if $\mathbf{h_2 \leq 500m}$ ⇨ $\eta_2 = \eta_1$

(2) if $\mathbf{50 \leq h_2 < 500m}$ ⇨ $\eta_2 = \eta_1 . \left(\frac{h1}{h2}\right)^{1/4}$

(3) if $\mathbf{5 \leq h_2 < 50m}$ ⇨ $\eta_2 = \eta_1 . \left[1 + \beta\frac{(hE - h2)}{hE}\right] . \left(\frac{h1}{h2}\right)$



(4) if $\mathbf{0 \leq h_2 < 5m}$ ⇨ $\eta_2 = \eta_2$ at 5m depth

The first encouraging results for the Nice test site show a good agreement with high resolution modelling: the linear approximation provides within 1 minute very few wrong estimates beyond a factor of 2 (Gailler et al., 2017).

3.2 Resonance in harbours

For Siracusa site, the effects of the basic resonance mode on the harbor was studied (the "Helmholtz" mode), showing in this case a period of about 10 minutes and amplification of 7.5, with a second amplification peak around 2 minutes. What is worth to underline is that these frequencies are typical of tsunamis (of tectonic origin or induced by landslides), which poses a problem for the **expected consequences of a tsunami attack for boats and vessels** moored in the harbor and for possible flooding of harbor docks and surrounding. Also in Siracusa the number of movable objects, in particular cars and boats, is considerable, which **can increase the level of damage** and can block or hinder the evacuation routes.

3.3 Assessment of vulnerability

Different methods were used for vulnerability assessment because of the different factors that might affect the vulnerability assessment procedure in the test sites. The two existing main classes of structural vulnerability analysis which are currently in use can be distinguished in qualitative and quantitative approaches. The qualitative methods generally characterize the exposure of structures to a hazard by means of attributes from territorial element inventories. This is done by assigning scores to some subjective criteria which are then combined using weighted averages or sums to determine the vulnerability class of each structure. The quantitative methodologies are based on the use of fragility curves (for buildings/structures) and mortality curves (for individuals), that link damage and losses to values of the tsunami parameters.

One of the very first studies regarding tsunami vulnerability performed in the Euro-Mediterranean area, focused a segment of Heraklion test site. Later, the so-called Papathoma Tsunami Vulnerability Assessment (PTVA) model was developed with testing and validation in Greek coastal zones, including Heraklion (Papathoma et al., 2003). In the framework of the FP6 European Project SCHEMA (Scenarios for tsunami Hazard-induced Emergencies Management, www.schemaproject.org) new tsunami damage functions were developed to be used for quantifying the potential tsunami damage to buildings along the European-Mediterranean (EM) coasts. The method considers the distribution of a hazard parameter (inundation depth) and the building typology depending on the type of construction material. An ArcGIS tool has been developed (DamASCHE tool) in order to assess the level of damage on buildings using a damage matrix. The method has been tested and applied in Banda Ache (Sumatra-Indonesia) (Valencia et al 2011), and in several EM test-sites selected for SCHEMA.

A building vulnerability assessment has been made for Sines and Tangier test sites. Tsunami vulnerability was computed for probabilities of occurrence of 20%, 50%, and 80% respectively. Building fragility curves were derived from the 2011 Japanese post-tsunami survey, adapted to the classified constructions. The tsunami damage has been estimated in six levels of damage (D1-Minor, D2- Moderate, D3-Major, D4-Complete, D5- Collapse, and D6-Washed away) and is depicted in vulnerability maps. As expected structures located close to the shore are highly vulnerable to tsunami impact and vulnerability decreases with the onshore distance from the shoreline where the tsunami flow depth is not significant. We learned that the **construction material and the structure elevation plays an important role in controlling the tsunami vulnerability**.

For Colònia San Jordi site, both SCHEMA and PTHA-3 models were used and compared (Fisotti, 2016). Structures have been classified following an adapted version of the building typology classification proposed by Tinti et al. (2011), based on satellite imagery and building characteristics. Damage scenarios have been calculated for tsunami wave heights of 2 m, 4 m, 8 m and 10 m. **Both models indicate that moderate tsunami heights** (TH>2 m) could produce light to important damage to buildings located in the first and second lines in the port and urban beach front area. The results of the application of PTVA-3 model to Colònia Sant Jordi Test Site indicate that **very few structures are vulnerable** in the area for a tsunami height below 1 m.

Both in Siracusa and Augusta it was concluded that **SCHEMA tends to underestimate the damage level with respect to PTVA-3**.

3.4 Relative Importance of tsunami-Seabed interactions

Tsunami-induced morphological changes also investigated in Tangier test-site. Main findings show that tsunamis generated by earthquakes with magnitudes greater that Mw>8.75 generate large morphological impact. The total volume (off-shore and onshore) of sediments mobilized reaches between 30 000 m^3 (Mw=8.5) and 245 000 m^3 (Mw=8.75).

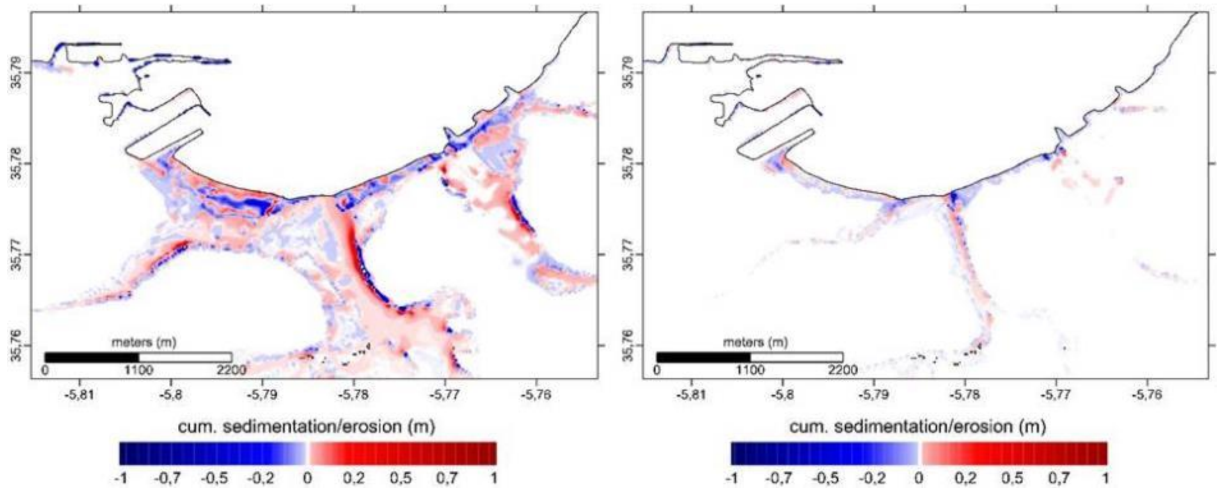


Figure 10: Morphological changes under tsunami impact from: the Mw8.75 CWF scenario [left panel] and the Mw8.5 HSF scenario [right panel].

3.5 Mitigation measures

Haydarpasa test site

In Haydarpasa site, the effect of the existing **breakwaters was shown to reduce effect of tsunami** waves on the coast and harbor. However, wave **overtopping was observed** on breakwaters during tsunamis. It is possible that this overtopping discharge will damage the breakwaters and affect their stability. This may cause a secondary increase in tsunami inundation extent.

Lyngen test site

In D8.8, inundation modelling for the Trænadjupet and Bjørnøyrenna submarine landslide scenarios (above) was performed as part of a scenario-based tsunami hazard assessment (SBTHA) for Lyngseidet. The hazard assessment further includes the 11 Mm3 rockslide tsunami scenario from Nordnes (above). While the landslides located at Trænadjupet and Bjørnøyrenna give run-up heights of 1-10 m at Lyngseidet, the rockslide from Nordnes gives run-up heights of about 20 m.

In D5.3 the effects of possible human-made mitigation structures were investigated. The tsunami source is again the 11 Mm3 rockslide from the unstable rock slope at Nordnes. The run-up heights at Lyngseidet are compared for various "potential" breakwaters introduced on a natural seabed sill outside Lyngseidet. The results show that large structures have only a limited effect on the run-up heights, but some breakwater configurations at least reduce the inundation length with 200-250 m. It should be noted that the tested synthetic structures are large with volumes of more than 1 Mm3.

3.6 Tsunami Risk

For tsunami risk assessment, the study made for Heraklion test site shows the need to **compute separately risk to buildings and risk to population.** About risk to buildings it is fairly easy to make an ex-ante calculation of the absolute economic (monetary) losses due to the needs for building replacement, either reparation or reconstruction. This risk for the population is more complex because population is not directly described in terms of geolocation. In the case of Heraklion, it was concluded that the **Census data should be used as a reference**, and to consider the population geographical density as metric of the population exposure, using a **simple mathematical spatial distribution model** for census data. To compute risk we adopted that the average building surface is 100 m2 and 80 m2 for residential and commercial buildings, and adopt cost rates predicted by the State Housing Aid. This assumption is consistent with the field validation survey performed in the area by Papathoma (2003). Since the ELSTAT building data does not include information about the use of each building, from our field survey we estimated that about 80% are residential buildings while the rest 20% are commercial. An additional assumption made for reasons of simplicity is that in each individual building damage **occurred only in the ground floor** without any involvement in the calculations of the rest building floors. This underestimates the calculated cost since in the area of high water depth it is reasonable to assume that upper floors may also suffered some damage. Results are summarized in Tables I and II which shows that the total cost for building replacement, both reparation and reconstruction, is around 250 million Euros for the worst-case scenario. The cost for building reconstruction is nearly 10 times higher than the one for building reparation.

Building type	**Number of buildings**	**Average building surface**	**Cost/m^2 (€)**	**Cumulative cost (€)**
Residential	2048	100	1000	204,800,000
Commercial	512	80	500	20, 480, 000
Total	2560			225,280,000

Table I. Calculated cost for reconstruction of buildings suffering partial or total collapse due to strong tsunami attack in the inundation area of Gazi to the west of Heraklion, Crete Isl.

Damage level	**Number of buildings**	**Average building surface**	**Cost/m2 (€)**	**Cumulative cost (€)**
D2	160	96	250	3,840,000
D3	484	96	450	20,908,800
Σύνολο	644			24,748,800

Table II. Calculated cost for reparation of buildings suffering damage level D2 and D3 due to strong tsunami attack in the inundation area of Gazi to the west of Heraklion, Crete Isl. We adopted that the ratio of residential/commercial buildings is 80/20 and that the average surface of residential and commercial buildings is 100 m2 and 80 m2, respectively. Then, the average building surface is 96 m2.

Uncertainty on vulnerability and risk calculations was studied for Colònia Sant Jordi. It was shown that **epistemic uncertainty rises from the partial lack of input data** to calculate the structural vulnerability and the preservation level of buildings. Results highly rely on the exactitude of the topographic grid used to compute the scenarios, especially for those buildings located in the beach front. In addition, exposure and vulnerability assessments rely on many other factors (country development profiles, temporal patterns, individual and social behaviour, site-specific livelihoods, cultural traditions and gender roles), which are not accounted by any of the models.

CHAPTER 4 Lessons learnt on Tsunami Awareness

4.1 Risk Awareness and preparedness

To assess preparedness skills, resources and attitudes within the communities and among inhabitants of the ASTARTE test sites a single questionnaire (translated in 9 languages) was elaborated. Based on the single questionnaire, this assessment allowed to: (1) evaluate how people consider the tsunami risk (multi-risk approach), how they consider the recurrence and sources (links to WP2 and WP3) and how people would react in future facing a tsunami threat; (2) estimate the needed level of customization and their modalities for awareness and preparedness material in each studied community; (3) to provide data for agent-based evacuation modelling. A total of 1512 interviews were held in the different test sites. The conclusions vary according to the environment, the different coastal communities and the different level of perception on tsunami risk and early warning systems in place.

Figure 11: Social survey carried out in three different cities in the south of France.

A survey was conducted among inhabitants and tourists in the **Lyngen test-site.** However, unlike the objectives of the survey in the other test sites (see deliverable D9.7), our aim was not to measure whether the tsunami risk was a known factor or not, but to start from the hypothesis – based on a discussion with the local authorities – that the population was already well aware of this risk. In fact, the municipal authorities, which are co-responsible for the warning system, consider that the population is ready to evacuate should a warning be issued: in their opinion, the people are well informed about the hazard and evacuation procedures, given the posters on the town hall, reports in the press and the recently conducted evacuation drill (Goeldner-Gianella et al., 2017). The municipal authorities are therefore more concerned about whether the population would be willing to evacuate and whether the feelings that currently prevail are based on trust in the local authorities and their risk management capabilities or, on the contrary, fueled by fear and uncertainty surrounding the risk (personal comments by the local authorities). The social survey we conducted at the Norwegian site was thus a matter of measuring not only knowledge of the potential tsunami risk and the crisis management system, but also confidence in the risk management procedures and risk managers (e.g.

the municipal authorities). The survey was also designed to measure awareness and responsiveness among tourists as in the other ASTARTE sites (Goeldner-Gianella et al., 2017).

A questionnaire was designed to acquire information on the public perception of the potential rockslide tsunami. The number of people surveyed in Norway (99) is relatively low (approximately 3% of the local population), but this is due to the low population density, the fact that only one person per family was questioned, and the low acceptance of participation, in English or even in Norwegian. This low participation may be due to a certain lack of interest in the survey's theme or to the lower level of education in the municipality: 41.7% of the Lyngen population (16 years and over) has a level of education "below upper secondary education" compared with only 27.3% in Norway as a whole (Statistics Norway). The questionnaire took between 15 and 30 minutes in most cases, and comprised around 50 questions, most of which were closed questions although there were a few open questions. They covered the respondents' relationship with the site, their knowledge of the tsunami hazard, their conduct in the event of a tsunami, their awareness and opinion of the alert, and finally, some personal data. Because the questionnaire had not been tested on the Norwegian site, it was revised and completed with subject-specialist Norwegian researchers shortly before its implementation. They added five questions relevant to the site, based on the feeling of threat and the levels of information, surveillance and emergency procedures put in place locally. After the field works, a statistical analysis was carried out for frequency distribution and cross-tabulation, backed up by chi-squared testing.

The survey's results offered to discuss three main questions: is the Lyngen population well-informed about the tsunami risk in general and about the potential evacuation time in particular? Is the local population as confident as the local municipality hope? Is there enough information on the tsunami risk for tourists, given their growing number?

During the survey, the 99 people interviewed face-to-face were approached at random in different places: 62.5% within Lyngseidet, 21% on the ferry crossing the fjord between Lyngseidet and Olderdalen, and around 17% in the neighboring villages. 73% of the people questioned live or work at the site of the survey (39% inhabitants and 33% local workers, respectively) – often having done so for more than ten years (57%) - while the other 27% were tourists. People of Norwegian origin clearly formed the majority of the sample (87%).

With respect to the question of knowing whether "the Lyngen population is well-informed about the tsunami risk in general and about the potential evacuation time in particular", the survey conducted demonstrates that the local population has a fairly clear perception of the tsunami hazard, associated with the potential rockslide from a flank of the mountain into the fjord. However, a number of local inhabitants do not know how much time is available for evacuation, and are unaware that a warning system exists or how they would evacuate. What is more, a very large majority of inhabitants (80%) have not made any particular preparation with regard to the tsunami hazard. The warning and evacuation system introduced over the past few years thus do not appear to be sufficiently well-known and the population is not sufficiently prepared for evacuation, despite the communication work already done by the local and national authorities. Hence, the municipal authorities have still to improve and increase the dissemination of the information, even if it does already exist.

Regarding the question of whether "the Lyngen population is as confident as the local municipality hopes", the survey shows an average degree of trust in local authorities among the people interviewed in Norway. This confidence is higher in respect of hazard surveillance than in the information delivered on risk or its management. However, the population interviewed in Lyngen compared to the population interviewed in other European countries is by far the most satisfied with the measures taken to address the tsunami hazard – especially among inhabitants and local workers – and, alongside Portugal, the most aware of these specific measures. This greater confidence in local authorities, if examined on a European scale, can only motivate the municipal authorities to improve the quality of information delivered locally, which is still inadequate in some regards.

And in respect of whether "there is enough information on the tsunami risk for tourists", the survey shows that **national or international tourists are**, as is the case elsewhere, **less informed about local natural hazards and evacuation conditions**. In fact, the tourists interviewed in Lyngen had a very different awareness and perception of the tsunami risk compared to the people living or working there: tourists are more concerned about the risk of avalanche and are not aware that Lyngen could be affected by a tsunami in the future and are unfamiliar with the tsunami warning system and the time available for evacuation.

In **Sines test site**, the great majority people are aware of the existence of a risk in Sines – 71.4% think that Sines could be affected by a tsunami. **Early warning systems are less well-known and local people are not well prepared for an evacuation**. Indeed, the majority (66.2%) of the interviewees don't know if there is a tsunami warning system. Only a little more than a quarter (26.3%) answers that there is not – which is true because up to now there is no tsunami warning system specifically designated by authorities. Among them, **the majority would prefer that this tsunami warning system uses sirens**.

In the case of **Tangier**, results show that despite a rather bad knowledge of the past events, the great majority of interrogated people (75.3%) **are aware of the existence of a tsunami risk in Tangier**. On the other hand, 81.5 % among the questioned persons declare not having any arrangements or convenient equipment to protect themselves from a tsunami. This shows **a real need to implement educational programs** and awareness campaigns for local communities since this is the only effective way to survive from a tsunami.

In **Colònia Sant Jordi** there is a record of tsunamis impacting the test site in the past: historical sources indicate that tsunamis occurred in 2003, 1980, 1856 and 1756. Onshore tsunami deposits are recorded by imbricated boulder fields, which have been radiocarbon dated at 500 BP and 1400 BP. Nevertheless, **there is no memory of past tsunamis** hitting the study area, although some interviewees referred to the most recent tsunami of May 2003. In contrast, about half of the respondents thought that **Mallorca cannot be impacted by tsunamis**, and neither report precise escape routes. Whereas a proper tsunami warning system does not exist in the study area, **people asked for education and training in order to improve their awareness**. When comparing the answers of local population with tourist during high season, it is underlined how social perception changes depending on the survey period. Despite a rather bad knowledge of the past events – only one of seven respondents think that Colònia Sant Jordi has already been affected by a tsunami - the almost half of interrogated people are aware of the existence of a risk in the zone, and the majority know precursor signs.

In **Siracusa**, despite the historical record, only 25% believes that Siracusa was hit by tsunamis in the past. Nevertheless, almost 80% believe that it will be affected in the future and almost half with waves of more than 10 meters. Further, in case of a felt earthquake most people (95%) would escape from the shore (which is a correct behavior), but a significant percentage would use its own car to escape (which is unwise). One of the most significant results regards the chosen evacuation route: about 80% of the people in Ortigia, that is safe since it is high above the sea level, **would run to the mainland through the bridges connecting the historical center to the residential area**. This would be a very wrong choice since bridges form a bottleneck and, moreover, are in the area most prone to water inundation.

In **Heraklion test site** in the question: "What is a tsunami?", 46.2% gave a general answer and said that a tsunami is a big wave, 24.5% answered that it is a huge wave in the sea caused by an earthquake, 19.8% answered that it is a tidal wave and 8.5% answered that they don't know. The **social knowledge on tsunamis comes in a large part from TV** (32.3%) and media coverage of big events (15%). Also, 12.3% of the respondents learned about tsunamis from school and 11.2% from internet. In the question "In your opinion, how is a tsunami created?" 71.7% answered "from earthquakes" and 12.4% answered "from volcanoes".

Most of the respondents (54%) think that Heraklion has already been affected by a tsunami and 69% of them agree that Heraklion could be affected by a tsunami in the future. Moreover, 27.43% of the interviewed people don't know what the maximum wave height could be in case of a tsunami in Heraklion and 22.12% of them believe that the maximum wave height could be more than 10m. Concerning the local people, 37.78% of them answered that they don't know about the wave's height in case of a tsunami, whereas the majority of foreigners (29.03%) answered that the maximum wave height in the area could be more than 10m. Most Greek tourists (35.71%) believe that the wave's height could be 2-5m. Most of the interviewed people (70.5%) don't know if there is a tsunami warning system in Heraklion and 25% answered "No". In addition, in the question: "How much time is there between a tsunami alert and the first tsunami wave", most foreigners and Greek tourists answered 10 to 30 minutes, while most local people (almost 40%) answered that they don't know.

4.2 Identification of precursor signs

In the case of **Sines**, 77% of the people interviewed know tsunami precursor signs: sea withdrawal, earthquake, big wave and animal behaviour. There are no important contrasts between the responses given by "local", "regional", "national" and "foreign" residents in this respect. Though it is important to mention that **17% of the residents and the foreign people think there are "no precursor signs" of tsunamis**. The great majority of the interviewed people (91%) would go away from the sea front if feeling an earthquake and two thirds (65.4%) if seeing a sea's withdrawal. Only a fifth (20.3%) would look for a higher site. The knowledge of those precursor signs does not necessarily mean that people adopt an adequate evacuation behaviour.

In the case of **Colonia San Jordi** three fourths of interrogated people would go away from the sea front if they felt an earthquake and two thirds if the sea level had suddenly retreat. It is interesting to indicate that almost a quarter would look for a higher site. The majority would evacuate by walking or by running and **more than a third of the respondents envisage an evacuation by car**. Almost all people declare not having planned or prepared equipment to protect themselves from a tsunami.

In the case of **Heraklion**, most of the participants interviewed consider that earthquake and sea withdrawal are precursors of a tsunami.

4.3 Evacuation Procedures

In **Sines test site**, an important part (27.8%) of the people interviewed by ASTARTE, considered that there are less than 10 minutes between a tsunami alert and the first tsunami wave, the majority (32.3%) of the respondents think the first wave could arrive between 10 and 30 minutes. Moreover, a quarter (19.5%) think the first wave could arrive between 30 minutes and 1 hour after the tsunami alert and another quarter (20.3%) estimate there are more than one hour available time. However, if the time of arrival of the first tsunami wave is insufficiently known and often overestimated, the reaction time between the reception of a tsunami warning and the beginning of the evacuation is very short. Indeed, the great majority (82.7%) of the interrogated people declare **they would begin to evacuate "immediately" or in "less than 10 minutes"** if they received a tsunami warning. Nevertheless, it is important to indicate that an important part (53.4%) of the population would "try to find a confirmation from another source" and none of the respondents would follow the given instructions, what could constitute a risky waste of time as well as possible confusion. Mental maps revealed that the great majority would spontaneously evacuate towards considered safe areas. On the other hand, more than **65% would evacuate with their own car** which could have negative effects on evacuation causing traffic jams and/or traffic accidents as well as movements of panic. Another important lesson that we have learned from the social survey in Sines test site is that people (91.7%) **feel insufficiently prepared to protect themselves in case of a tsunami** event. The majority of 58.6% of the interviewed people think that the preparation measures for a tsunami are not satisfactory and 41% that the best way of strengthening this preparation would be more education and training.

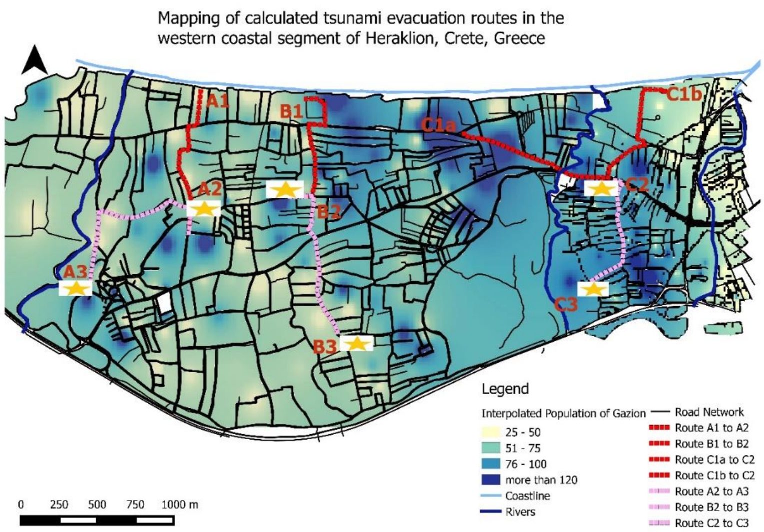


Figure 12: Fastest evacuation routes in the area of Gazi, western segment of Heraklion test-site

In **Nice test site**, an initiative developed in 2014 included questions on the perception of evacuation time and warning system, and how and where would people evacuate. A first model of evacuation strategy of population in case of tsunami has been realized on Saint Laurent du Var (Figure 18). The GIS data is implemented as the environment where the agents are evacuating. It takes care of the ground height (to evacuate on higher place), the streets networks and the buildings (as obstacles and their heights). It is also based on the worst case scenario for a tsunami according to a wave physical model. In this environment, the population is implemented based for its structure from the Astarte field surveys. The model includes agent characteristics like for example, the group effect, age, endurance or rational or irrational behavior during this event. The readability of the urban environment was also taken into account (Plattard, 2016).

In **Heraklion test site** an evacuation exercise was conducted. The exercise was combined with the shooting of a documentary project regarding tsunamis in the Mediterranean by the German TV channel ZDF. It lasted two days from 12 to 13 of April 2016. It should be stressed out that this was the first time a similar experiment was planned and conducted in Greece. For the needs of the exercise 30 volunteers from the local Red Cross organization participated. Their age was ranging from 19 to 41 years old and they were both males and females. Each one of the participants was equipped with a mobile phone, to receive message for the evacuation initiation, and a personal GPS tracker in order to be able to project his/her position in real time. The values were also stored in a database for post event analysis.

Prior to the exercise, three starting points were selected along the coast, close to the shoreline and next to the city center. A safe place (SP) was also selected in advance. A topological analysis revealed that within a short distance from the coast, there is a location (SP) suitable to serve as evacuation area for the population to seek refuge. The area has easy access from the main roads and it is situated on flat and open ground with adequate elevation above sea level. The shortest distance from each starting point up to the safe place was about 800 m. The volunteers were divided into 3 groups (A, B, C), starting from the three respective spots along the coast. An SMS was sent to everybody announcing the initiation of the evacuation procedure, reflecting that a virtual tsunami wave was approaching the coastline. A second SMS was sent only to half of each group members (five members) informing them about the location of the designated Safe Place (SP).

Figure 13: The 30 volunteers from the local Red Cross preparing for evacuation exercise.

The analysis of the results from the GPS trackers showed that **almost half (58%) of those who didn't know the SP in advance, selected the specific safe place and the shortest path to reach it**. The others selected either different routes and/or different safe places. The time needed to reach the SP from A was about 30 min., from B between 15 and 20 min. and from C about 15 min. Similar exercises are planned to be conducted in the future in other coastal cities.

During the interviews conducted in **Lyngen test site**, it was also concluded that in spite of the effort conducted towards the local communities to make them aware of tsunami risk **tourists** (either national or not) are less aware of the risks and also **do not know how to evacuate**. Thus, it would appear necessary to improve the information available to them, without however harming the tourist sector that forms one of the region's few economic activities. The challenge here is not so much to inform them of the necessity to evacuate urgently, as on the Mediterranean beaches, but to inform them of a possible evacuation during their stay. It is especially important to spread the information on tsunamis in Norway because residents or tourists – on land and on cruise boats – are currently increasing in numbers in the fjords.

References

Acar Sena, (2015), "Tsunami Hazard Analysis for Güllük Bay", MSc Thesis, METU, Department of Civil Engineering, Ocean Engineering Research Center, February 2015, (132 pages)

Ambraseys, N. (2009). Earthquakes in the Mediterranean and Middle East: a multidisciplinary study of seismicity up to 1900. Cambridge University Press.

Baptista, M. A., & Miranda, J. M. (2009). Revision of the Portuguese catalog of tsunamis. Natural Hazards and Earth System Sciences, 9(1), 25-42.

Baptista, M. A., Miranda, J. M., Batlló, J., Lisboa, F., Luis, J., & Maciá, R. (2016). New study on the 1941 Gloria Fault earthquake and tsunami. Natural Hazards and Earth System Sciences, 16(8), 1967-1977.

Barkan, R., Uri, S., & Lin, J. (2009). Far field tsunami simulations of the 1755 Lisbon earthquake: Implications for tsunami hazard to the US East Coast and the Caribbean. Marine Geology, 264(1), 109-122.

Bird, D., Dominey-Howes, D., 2008. Testing the use of a "questionnaire survey instrument" to investigate public perceptions of tsunami hazard and risk in Sydney, Australia. Nat. Hazards, 45, 99–122.

Bondevik, S., Løvholt, F., Harbitz, C.B., Mangerud, J., Dawson, A., Svendsen, J.I. 2005. The Storegga Slide tsunami comparing field observations with numerical simulations. Mar. Petroleum Geol. 22, 195–208, doi:10.1016/j.marpetgeo.2004.10.003

Bondevik, S., Løvholt, F., Harbitz, C.B., Mangerud, J., Dawson, A., Svendsen, J.I. 2005. The Storegga Slide tsunami comparing field observations with numerical simulations. Mar. Petroleum Geol. 22, 195–208, doi:10.1016/j.marpetgeo.2004.10.003

Braathen, A., Blikra, L.H., Berg, S.S., Karlsen, F., 2004. Rock-slope failures in Norway; type, geometry, deformation mechanisms and stability. Norw. J. Geol. 84, 67–88.

Braathen, A., Blikra, L.H., Berg, S.S., Karlsen, F., 2004. Rock-slope failures in Norway; type, geometry, deformation mechanisms and stability. Norw. J. Geol. 84, 67–88.

Bruins, H. J., MacGillivray, J. A., Synolakis, C. E., Benjamini, C., Keller, J., Kisch, H. J., and Klügel, A., 2008. Geoarchaeological tsunami deposits at Palaikastro (Crete) and the Late Minoan IA eruption of Santorini. Journal of Archaeological Science, 35(1): 191-212.

Bungum, H., Lindholm, C., 2007. Tsunamigenic seismic sources in the North Sea, the Norwegian continental margin and the Norwegian–Greenland Sea. NORSAR report October 2007.

Dominey-Howes, D., Cundy, A., & Croudace, I. (2000). High energy marine flood deposits on Astypalaea Island, Greece: possible evidence for the AD 1956 southern Aegean tsunami. Marine Geology, 163(1), 303-315.

Fisotti, S., 2016. Awareness of tsunami risk in the Balearic Islands: Results from a field survey in Colònia de Sant Jordi. Master Thesis, University of Barcelona, 31 p. + ann.

Fontaine, A., Loevenbruck, A., Heinrich, P., Gailler, A., & Hébert, H. (2015, April). Tsunami hazard assessment in Nice, France, and influence of uncertainties in source parameters. In EGU General Assembly Conference Abstracts (Vol. 17, p. 8870).

Gailler, A., Hébert, H., Schindelé, F. & Reymond, D. (2017, accepted with minor revision). Coastal amplification laws for the French tsunami Warning Center: numerical modeling and fast estimate of tsunami wave heights along the French Riviera. Pure and Applied Geophysics

Galanopoulos, A. G. (1957). The seismic sea wave of July 9, 1956. Prakt. Acad. Athens, 32, 90-101.

Guidoboni, E., Comastri, A., & Traina, G. (1994). Catalogue of Ancient Earthquakes in the Mediterranean Area up to the 10th Century. Istituto nazionale di geofisica.

Gutscher, M. A., Malod, J., Rehault, J. P., Contrucci, I., Klingelhoefer, F., Mendes-Victor, L., & Spakman, W. (2002). Evidence for active subduction beneath Gibraltar. Geology, 30(12), 1071-1074.

Harbitz, C.B. 1992. Model simulations of tsunamis generated by the Storegga Slides. Mar. Geol. 105, 1–21, doi:10.1016/0025-3227(92)90178-K

Harbitz, C.B., Glimsdal, S., Bazin, S., Zamora, N., Smebye, H.C., Løvholt, F., Bungum, H., Gauer, P., Kjekstad, O., 2012. Tsunami hazard in the Caribbean: regional exposure derived from credible worst case scenarios. Cont. Shelf Res. 38, 1–23.

Harbitz, C.B., Glimsdal, S., Løvholt, F., Pedersen, G.K., Vanneste, M., Eidsvig, U.M.K., Bungum, H., 2009. Tsunami hazard assessment and early warning systems for the North East Atlantic. Proceedings of the DEWS Midterm Conference 2009, Potsdam, Germany, 7–8 July 2009.

Hill, J., Collins, G.S., Avdis, A., Cramer, S.C., Piggot, M. 2014. How does multiscale modelling and inclusion of realistic palaeobathymetry affect numerical simulation of the Storegga Slide tsunami? Ocean Model. 83, 11–25, doi:10.1016/j.ocemod.2014.08.007

Ioualalen, M., Larroque, C., Scotti, O., & Daubord, C. (2014). Tsunami Mapping Related to Local Earthquakes on the French–Italian Riviera (Western Mediterranean). Pure and Applied Geophysics, 171(7), 1423-1443.

Johnston, A. C. (1996). Seismic moment assessment of earthquakes in stable continental regions—III. New Madrid 1811–1812, Charleston 1886 and Lisbon 1755. Geophysical Journal International, 126(2), 314-344.

Laberg, J.S., Vorren, T.O. 2000. The Trænadjupet Slide, offshore Norway — morphology, evacuation and triggering mechanisms. Marine Geology, 171 (1–4), 95-114, http://dx.doi.org/10.1016/S0025-3227(00)00112-2

Lastras, G., Iglesias, O., Canals, M., 2014. Maremotos generados por grandes deslizamientos en el Mediterráneo. Jornada Técnica "El Riesgo de Maremotos en España. Proyecto de la Directriz Básica de Protección Civil ante el Riesgo de Maremotos. Escuela Nacional de Protección Civil, 29-30 September, Madrid, Spain.

Lauknes, T.R., Piyush Shanker, A., Dehls, J.F., Zebker, H.A., Henderson, I.H.C., Larsen, Y., 2010. Detailed rockslide mapping in northern Norway with small baseline and persistent scatterer interferometric SAR time series methods. Remote Sens. Environ. 114, 2097–2109.

Løvholt F, Pedersen G, Harbitz CB, Glimsdal S, Kim J. 2015 On the characteristics of landslide tsunamis. Phil. Trans. R. Soc. A 373: 20140376. http://dx.doi.org/10.1098/rsta.2014.0376

Løvholt, F., Pedersen, G., Gisler, G., 2008. Oceanic propagation of a potential tsunami from the La Palma Island. J. Geophys. Res. 113, C09026.

Løvholt, F., Vanneste, M., Harbitz, C.B., De Blasio, F., Urgeles, R., Iglesias, O., Canals, M., Lastras, G., Pedersen, G. Glimsdal, S., 2014. Modeling potential tsunami generation by the BIG'95 landslide; In S. Krastel et al. (Eds.): Submarine Mass Movements and Their Consequences, Springer, Series "Advances in Natural and Technological Hazards Research, 37: 597-515.

NGI, 2008. Flodbølger etter mulig fjellskred Nordnes, Lyngen kommune — Beregning av mulige fjellskred og flodbølger. Norwegian Geotechnical Institute Report 20071677-1 (in Norwegian).

NGI, 2010. Flodbølger etter mulig fjellskred Nordnes, Lyngen kommune II — Grovanalyse for et skredvolum på 22 millioner m3. Norwegian Geotechnical Institute Report 20100617-00-1-R (in Norwegian).

NGI, 2013. Flodbølger i Lyngen etter mulig skred, Nordnes, Lyngen kommune III — Detaljberegning av oppskylling for skred på 11 millioner kubikkmeter. Norwegian Geotechnical Institute Report 20130206-01-R (in Norwegian).

NGU, 2009. Faren for fjellskred fra Nordnesfjellet i Lyngenfjorden, Troms. Geological Survey of Norway Report 2009.026 (in Norwegian).

Nordvik, T., Blikra, L.H., Nyrnes, E., Derron, M.-H., 2010. Statistical analysis of seasonal displacements at the Nordnes rockslide, northern Norway. Eng. Geol. 114, 228–237.

NVE, 2016. Fare- og risikoklassifisering av ustabile fjellparti. Faresoner, arealhåndtering og tiltak. NVE-rapport 77/2016.

Omira R., Baptista M. A., Matias L. 2015. Probabilistic Tsunami Hazard in the North East Atlantic from Near- and Far-field Tectonic Source. Pure App. Geophys. 172(3-4), 901-920. Doi:10.1007/s00024-014-0949-x.

Omira R., Matias L., and Baptista M. A. 2016. Developing an event-tree probabilistic tsunami inundation model for NE Atlantic coasts: Application to a case study. Pure and Applied Geophysics, 173(12), 3775-3794. Doi:10.1007/s00024-016-1367-z.

Omira, R., Baptista, M. A., Matias, L., Miranda, J. M., Catita, C., Carrilho, F., & Toto, E. (2009). Design of a sea-level tsunami detection network for the Gulf of Cadiz. Natural Hazards and Earth System Sciences, 9(4), 1327-1338.

Papadopoulos GA and Papageorgiou A, 2014. Large earthquakes and tsunamis in the Mediterranean region and its connected seas. In: Extreme Natural Hazards, Disaster Risks and Societal Implications, Cambridge University Press.

Papadopoulos, GA, 2011. A seismic history of Crete, Earthquakes and Tsunamis: 2000BC-2011 AD. National Observatory of Athens, Ocelotos Publications.

Papathoma, M., Dominey-Howes, D., Zong, Y., & Smith, D. (2003). Assessing tsunami vulnerability, an example from Herakleio, Crete. Natural Hazards and Earth System Science, 3(5), 377-389.

Scheffers A., Kelletat D., 2004. Bimodal tsunami deposits – a neglected feature in paleo-tsunami research. In: Schernewski G., Dolch T. (Eds.) Geographie der Meere und Küsten. Coastline Reports 1: 67–75.

Schindelé, F., Gailler, A., Hébert, H., Loevenbruck, A., Gutierrez, E., Monnier, A., ... & Rivera, L. (2015). Implementation and challenges of the Tsunami Warning System in the Western Mediterranean. Pure and Applied Geophysics, 172(3-4), 821-833.

Sørensen, M. B., Spada, M., Babeyko, A., Wiemer, S., & Grünthal, G. (2012). Probabilistic tsunami hazard in the Mediterranean Sea. Journal of Geophysical Research: Solid Earth, 117(B1).

Tinti, S., Tonini, R., Bressan, L., Armigliato, A., Gardi, A., Guillande, R., ... & Scheer, S. (2011). Manuale per Scenari di Pericolosità e di Danno in Caso di Tsunami.

Valencia, N., Gardi, A., Gauraz, A., Leone, F., & Guillande, R. (2011). New tsunami damage functions developed in the framework of SCHEMA project: application to European-Mediterranean coasts. Natural Hazards and Earth System Sciences, 11(10), 2835-2846.

Vanneste, M., Harbitz, C.B., De Blasio, F.V., Glimsdal, S., Mienert, J., Elverhøi, A., 2010. The Hinlopen–Yermak Landslide Arctic Ocean — geomorphology slide dynamics and tsunami simulations. In: Shipp, R.C., Weimer, P., Posamentier, H.W. (Eds.), The importance of mass-transport deposits in deepwater settings. SEPM Special Publication 95.

Zitellini N., Gràcia E., Matias L., Terrinha P., Abreu M. A., De Alteriis G., Henriet J. P., Dañobeitia J. J., MAsson D. G., Mulder T., Ramella R., Somoza L., Diez S., 2009. The quest for the Africa–Eurasia plate boundary west of the Strait of Gibraltar. Earth and Planetary Science Letters, doi:10.1016/j.epsl.2008.12.005.