4.1 Final publishable summary report

Contents

Executive summary

Tsunamis are high-impact natural disasters. The 2004 Boxing Day tsunami killed more than 250 000 people in the Indian Ocean. Seven years later the Tohoku-Oki tsunami in 2011 devastated Japan, one of the world best-prepared countries against tsunami hazards. These events showed the limitations of current knowledge on sources, coastal impacts and mitigation measures.

All types of tsunami sources exist along the coasts of Europe: in the North East Atlantic, Mediterranean and Connected Seas (NEAM), such as earthquakes in the Hellenic Arc, the Anatolian Fault, north of Algeria and South-western Iberia; volcanic activity in the Canaries, Santorini and other sites; and mega-landslides in the Norwegian margin. ASTARTE aimed at improving knowledge on the long-term recurrence of tsunamis and generation mechanisms, developing new computation tools for tsunami simulation and strategies for tsunami hazard and risk assessment, better understanding of tsunami interactions with coastal structures, and identifying the key components of tsunami resilience and their implementation in the NEAM region.

ASTARTE completed an assessment of potential tsunami sources in the NEAM region including uncertainty treatment and tsunami sensitivity to source parameter values. ASTARTE addressed the neotectonics of the Africa-Eurasia plate boundary, the role of submarine mass failures in tsunami generation, the turbidite record as a proxy for past seismicity and tsunamis, and submarine landforms and coastal deposits associated to tsunami events.

ASTARTE produced new methods for inverse modelling, analytical benchmarks for model validation based on laboratory experiments on marine structures common in the Mediterranean Sea, physical experiments to address tsunami-structure interactions, and numerical models for simulation of tsunami induced flows and sediment transport. Moreover, ASTARTE presented novel forecasting techniques based on emulation rather than simulation.

ASTARTE hazard assessment studies included scenario-based and seismic probability-based approaches. The results, presented as maps, depict flow depths and inundation limits for a specific scenario or a set of scenarios, also addressing the *a priori* probability of each scenario, with the probabilistic method yielding the probability of flooding for a particular exposure time. ASTARTE probabilistic studies resulted in the design of the pioneer TSUMAPS-NEAM project, a direct application of the Probabilistic Tsunami Hazard Assessment (PTHA) method for earthquake-generated tsunamis. The final TSUMAPS-NEAM map will constitute the first European-wide, PTHA-based effort intended for Civil Protection users. ASTARTE conducted new vulnerability studies at local scales in a number of test sites, applied especially to assets like buildings, industrial plants and coastal infrastructures.

The ASTARTE Pilot Analysis Support Platform represents a prototype tool aiming to visualize and manage results associated to tsunami hazard and risk analyses. Both scientists and risk managers can take advantage of this tool, as it offers an intuitive way to inspect quantitative data.

ASTARTE assessed the operational infrastructures in the NEAM region and the possibility of integrating meteoceanographic data to improve Tsunami Early Warning Systems (TEWS). ASTARTE also reviewed the governance of TEWS coordinated by UNESCO in the region.

ASTARTE goal was the fostering of tsunami resilient societies. ASTARTE involved citizens to assess preparedness skills and attitudes in NEAM communities. The results show a low level of awareness of tsunami hazard in the area. ASTARTE recognized the need for new evacuation plans including safe sites and new educational materials in tsunami-prone coastal sites.

ASTARTE developed a tool for emergency management: FIND – Finding Inaccessible people in Natural Disasters (http://accessible-serv.lasige.di.fc.ul.pt/~find).

On the 20th of July 2017, an earthquake and tsunami stroke Bodrum (10 km at south of ASTARTE test site Gulluk -where ASTARTE had its second annual meeting in October 2015- in Turkey and Kos in Greece leading to casualties and noticeable damage. Lessons should be learned on the preparedness of local populations and tourists face to these events.

1. ASTARTE background

Major tsunamis are high impact natural disasters. However, moderate tsunamis happen every year inflicting damage near the source. In 2004, the Boxing Day tsunami killed hundreds of thousands of people from tens of nations along the coastlines of the Indian Ocean. Tsunami run-up exceeded 35 m. The catastrophe shocked the world. Particularly unfortunate were the casualties far away from the source region. In countries like India, Sri Lanka and Somalia many deaths could have been avoidable would population warning systems be in place. The 2004 mega-tsunami demonstrated the need for operational Tsunami Early Warning Systems (TEWS) around the world. However, Tsunami Warning Systems (TWSs) are only one of the various components of tsunami preparedness and resilience**. Resilience must be built through the enhancement of national and local capabilities to manage and reduce risk, in this case, tsunami risk (UNISDR, 2007).**

Seven years after the Boxing Day tsunami, in spite of some of the best warning technologies and the best levels of preparedness in the world, the Tohoku-Oki tsunami in 2011 dramatically showed the limitations of scientific knowledge concerning tsunami sources, coastal impacts and mitigation measures. More than 15,000 people died, and more than 250,000 buildings were damaged or collapsed, altogether with coastal defences and critical infrastructures. In Kessenuma, Japan, despite the emergency manager ordered the residents to evacuate, even while the earthquake was in progress and without waiting for the official warning, over one thousand died. The experience from Japan raised serious questions on how to improve the resilience of the coastal communities, how to upgrade the performance of coastal defences, how to adopt a better risk management, and on the strategies and measures to be prioritized for rebuilding the damaged coastal areas.

The on-going set up of the North East Atlantic, Mediterranean and adjacent seas region (NEAM) TWS needed to consider these lessons when developing societal and structural resilience, also considering that, on average, there is one 10 m in height tsunami per century in the region and many more of smaller size. Most types of potential tsunami sources exist in the NEAM area. Sources of earthquake-triggered tsunamis include geological structures with neotectonic activity such us the Hellenic Arc, the North and East Anatolian Faults, the fracture zones in the Western Mediterranean Sea and Southwest of Iberia. Mega-landslide-induced tsunamis may occur along the Norwegian margin but not only. Volcanic-induced tsunamis may happen, for instance, in areas like Santorini, Stromboli and the Canary Islands.

The ASTARTE consortium comprised twenty-six partners from sixteen countries including a unique group of European institutions deeply involved in tsunami research. Some of these groups are operating or organizing existing TWSs, with links to the UNESCO-IOC community that is endeavouring to build the NEAM TWS. The ASTARTE partnership included in the operational front the five Tsunami Service Providers in the NEAM region, namely CEA (France), NOA (Greece), INGV (Italy), IPMA (Portugal) and KOERI-BOUN (Turkey).

ASTARTE privileged international cooperation linking NEAM scientific and operational institutions to highly ranked institutions in Japan and the USA. Consequently, the consortium integrated four major non-European institutions that are in the forefront of the development of operational TWSs (namely the Pacific Marine Environmental Laboratory, PMEL-NOAA, in the USA; and the Earthquake Research Institute, ERI, in Japan), of research on coastal impacts (namely the Port and Harbour Research Institute, PHRI, in Japan), and of coastal physical modelling (namely the University of Southern California, USC-ISI, in the USA). This cooperation effort covered all topics of tsunami science, including seismology, geology, modelling, engineering, sociology and civil protection professionals.

The ASTARTE partnership aimed at (i) developing improved methodologies for tsunami numerical simulations; (ii) strengthening tsunami hazard and risk scenarios; (iii) addressing end-user needs; (iv) facilitating decision making processes; and (v) creating the ground for fast, effective and shared decisions in future emergencies.

2. ASTARTE objectives

The goal of ASTARTE was to reach a higher level of tsunami resilience in the NEAM region, to improve the preparedness of coastal populations and, ultimately, to save lives and property. To achieve this goal, ASTARTE developed innovative research on scientific problems critical to enhance forecasting skills regarding sources, propagation and impact.

ASTARTE aimed at achieving a better understanding of tsunami interactions with coastal structures, developing new cost-effective computational tools to describe the effects of tsunamis on-shore, developing new methodological approaches to quantify tsunami vulnerability and risk. ASTARTE research aimed at improving tsunami detection and warning. Last but not least, a particular focus was the societal implications of tsunami warning and mitigation, education and training.

To achieve these goals ASTARTE designed ten work packages (WPs): WP 1 devoted to Project coordination and management, WPs 2-5 focused in tsunami recurrence, generation mechanisms, numerical modelling and physical experiments to improve coastal impacts, respectively. Altogether these WPs provided an up-to-date knowledge background to the project. WPs 6-8 focused in tsunami detection, early warning, forecast, and risk assessment. These WPs opened into WP9, which aimed at fostering tsunami resilient societies in Europe. Finally, WP10, focused in the dissemination and exploitation of results.

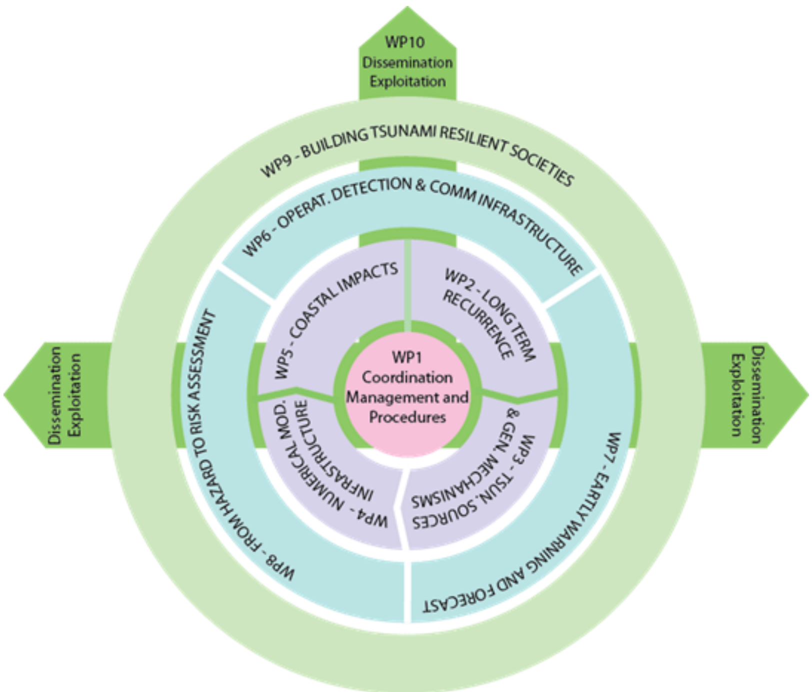

Figure 1. ASTARTE work packages concept

To test methodologies and promote collaboration with stakeholders and populations ASTARTE selected nine test sites in the Mediterranean Sea and Northeast Atlantic Ocean where baseline data was mostly available or could be acquired through marginal efforts (Fig. 2). The test site selection considered the different conditions of the North East Atlantic and Mediterranean basins thought to be representative of the coasts at risks, in particular:

- The possibility of being impacted by regional and local tsunami sources, which put different levels of stress on detection and forecasting.
- The presence of different types of tsunami sources, such as earthquakes, submarine landslides, volcanoes and coastal rock slides. The present configuration of TWSs considers earthquake-induced tsunamis only.
- The presence of different values at risk including industries, harbours and other infrastructures, and ecosystems.
- Different coastal communities such as fishing communities, coastal cities and tourist developments.

This approach was of paramount importance to extract conclusions for the whole the NEAM region. The test site list included three sites in the North East Atlantic Ocean and six in the Mediterranean Sea. The locations in the Atlantic included Lyngen, a fjord-based community in Norway; Sines, an industrial harbor in the Portuguese coast; and Tangier, a tourist area and commercial port in Morocco besides the Strait of Gibraltar. Test sites in the Mediterranean Sea were Colònia Sant Jordi, a tourist spot in the Balearics Islands, Spain; the tourist area and airport of Nice-Antibes in Cote d'Azur, France; the cities of Siracusa and Heraklion in Sicily, Italy, and Crete, Greece; the intensive fish farming Gulluk Bay in southwest Turkey, and Haydarpasa harbour in the Marmara Sea, Turkey.

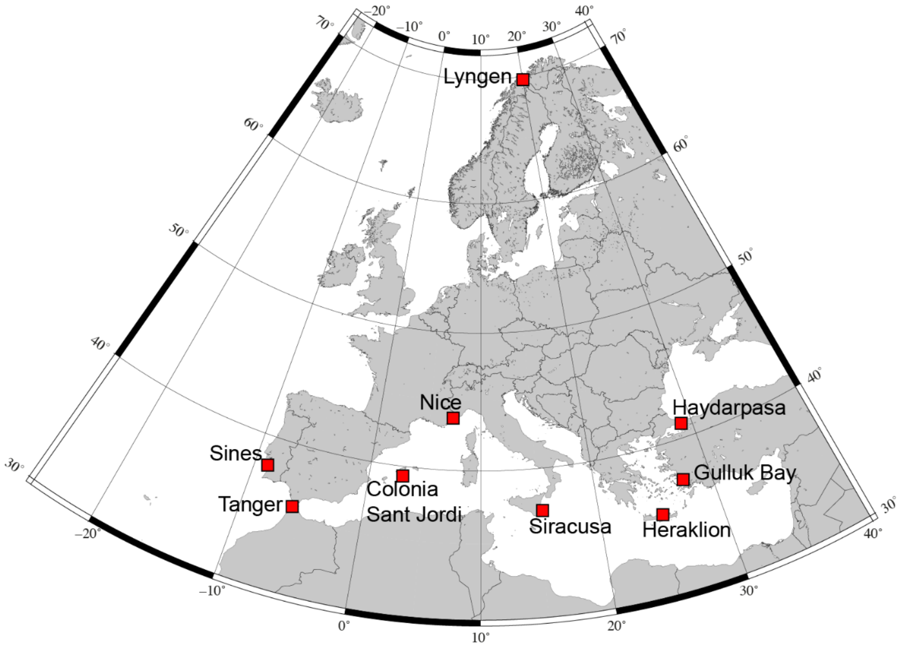

Figure 2. ASTARTE test sites.

3. ASTARTE results

3.1 Progress on long-term recurrence of tsunamis and generation mechanisms

Long-term recurrence of tsunamis in the NEAM region is a key topic in tsunami science. Understanding the neotectonics of the Africa-Eurasia plate boundary, the role of submarine mass failures (SMF) for tsunami generation and the resulting record of mass transfer deposits (MTDs) as a proxy for past seismicity, seafloor landforms associated with tsunami events and the coastal record of tsunamis were, among others, some of the addressed key issues. MTDs mostly include turbidites, homogenites and debrites of various types. ASTARTE intended to go beyond the improvement of tsunami catalogues by incorporating new geological and geophysical contributions for the assessment of the long-term recurrence rates of significant events in sensitive areas of the NEAM region. Research on long-term recurrence rates of tsunamis in critical NEAM areas included tectonic sources, landslides and volcanic sources. ASTARTE researchers performed marine surveys for the acquisition of geophysical data and long cores to fulfil the objective of achieving a better knowledge of tsunami recurrence. Also, onshore surveys targeted paleotsunami deposits in selected areas.

As a result of this research, the main question that remains regarding the impact of tsunamis on the coasts of Europe is not "if" but "when" will they occur again. A better understanding of recurrence must objectively rely on knowledge of past occurrences and processes as critical information to detect future occurrences. **ASTARTE completed the assessment of the potential tsunami sources in the NEAM basin**. This evaluation included the treatment of **uncertainty** and **sensitivity** to source parameters.

Specific achievements are listed below:

- The comparison of the earthquake records and tsunami catalogues, recently revised, showed that, in the NEAM region, 70% of submarine earthquakes of magnitude greater than 8 are tsunamigenic. This percentage reduces to 25% for earthquake magnitudes between seven and eight reducing again to 7% for magnitudes greater than six.
- The **recurrence intervals of tsunamis vary significantly from place to place** as a function of geodynamic setting, rate of active deformation and triggering mechanisms and their calculation is also influenced the type of geological records and methods of study. Recurrence intervals of earthquake-generated tsunamis from 100 years to 250 years were found in the Ligurian and Algerian margins, whilst intervals for volcanic collapses of 150 ky were found in the Canary Islands.
- **Offshore Norway**, in the Vesteralen Islands, a low shear stress horizon occurs 10 m below the sea floor that is stable in static conditions but can be re-activated as a low shear surface during M>4.5 earthquakes. Although historical earthquake data show that isostatic rebound-related seismicity of up to Mw=5 has occurred it **is not probable that a large magnitude event will occur**.
- T**he west coast of Ireland and Southwest Iberia is susceptible to landslide-generated tsunamis**. Following this finding, Ireland added tsunamis in their official list of risks. A **new statistical emulator**, developed in the framework of ASTARTE, was used to simulate submarine sliding, tsunami generation and propagation with an application to the Rockall Bank, in the North East Atlantic Ocean. Recurrence rates of tsunamigenic landslides in the SW Iberian margin (SWIM) and adjacent basins remained to be ascertained as only one tsunamigenic landslide had been reported previous to ASTARTE (i.e. the North Gorringe landslide). Within **ASTARTE two new potentially tsunamigenic landslides were reported**, which are the (South Hirondelle landslide and the Tagus delta landslide. Consequently, further work seems necessary to inspect for other outcropping or buried large-scale landslides, eventually with tsunamigenic potential.
- **In South Portugal tsunami recurrence remain to be ascertained**. The anomalous sedimentary levels and large scale chaotic sediment bodies (>30 km long at ~50 m below contemporary sea level) that indicate MTD deposition remain to be further understood. However, it is a fact that these high energy events occurred in the last ~8 ky during the last sea level rise in a margin prone to frequent earthquake shaking of intermediate magnitude (~M<6.5) but also less frequent earthquakes of large magnitude. Actually, earthquakes of magnitude greater than 8 are known to have occurred in the historical past, with recurrence estimated to be larger than one thousand years.
- **Recurrence rate of tsunamigenic landslides in the Canary Islands is roughly 150 ky in the last 1.2 My**. The north-western slopes of Tenerife show evidence of mega-tsunamis generated by volcano flank failure. Analyses of the tsunami deposits demonstrate that two major tsunamis impacted the coasts of Tenerife 170 ky ago. The first tsunami was generated during the submarine stage of a retrogressive failure of the northern flank of the island, whereas the second one followed the debris avalanche of the subaerial edifice (named Icod collapse) and incorporated pumices from an on-going ignimbrite-forming eruption. Numerical simulations of failures on the northern flank of Tenerife confirm a 12-15 km^3 en masse failure of the subaerial flank. This is the first evidence of a coupled large explosive eruption (ignimbrite-forming) and a massive flank failure at an oceanic shield volcano. These results notwithstanding, such a scenario represents a low frequency hazard despite its high-magnitude.
- In the Ligurian Margin there are reports of tsunami waves following the main shock of earthquakes in 1564, 1818 and 1887. The tsunamigenic earthquakes of 1564, 1644 and 1818 allow for calculating a recurrence interval of ~100 y in the last 500 years. Extensive research off Nice showed widespread distribution of scars and turbidite deposits suggesting a **long history of MTDs associated with earthquakes that remains to be further investigated, including the tsunamigenic potential of individual events**.
- Paleoseismological studies off the **Algerian margin** allowed establishing the recurrence interval of earthquakes with a **mean recurrence interval of 250 years**, varying from 50 to 900 years and defining three shorter quiescence periods of seismicity lasting about 878, 721 and 485 years (7.1–6.2 ka BP, 4.6–3.9 ka BP, and 1.5–1 ka BP). It remains to be established the earthquake magnitude and their tsunamigenic potential. Nevertheless, these turbidites include the one left by the 2003 tsunamigenic

Mw 6.9 Boumerdes event in the coast of Algeria. Onshore SE Sicily, two sites investigated by coring suggest the **occurrence of extreme events with an abrupt change in depositional environment from lagoonal/alluvial to marine**. These events are interpreted as potentially related to a local earthquake or tsunami involving significant modification of the coastline. Taking into account detailed sedimentary analyses, foraminifera content and radiocarbon ages, an also previous works, such catastrophic deposit may correlate with the 365 AD Crete tsunami.

- **East of Sicily and Calabria** the number of historical tsunamigenic earthquake events, with a mean recurrence rate of 140 years, exceeds the number of turbidites found. The uppermost two turbidites relate to the 1908 Messina and 1693 Catania earthquakes, whereas another one seems to be related to a major Etna flank eruption and debris flow. This gives in an MTD recurrence rate of about 250 ky since the occurrence of the Augias megaturbidite and also for the last millennia, including triggering by both earthquakes and volcanic eruptions. **This shows that the geological record may underestimate tsunami frequency**.
- **In the Corinth Gulf, tsunamigenesis decreases from west to east** given that 12 out of 17 tsunamis and the most powerful ones were observed in the western part of the gulf, whereas only three waves were noticed in the central part. The eastern part is the less tsunamigenic, with only two minor events historically reported in AD 1898 and 1981.
- **Sedimentary evidence of the 1650 AD Kolumbo tsunami was found along the coast of Santorini Island**, in the Eastern Mediterranean Sea, at maximum altitudes ranging between 3.5 m a.s.l. (Perissa, southern coast) and 20 m a.s.l. (Monolithos, eastern coast), which correspond to a minimum inundation of 360 and 630 m, respectively. Tsunami deposits consist of an irregular 5 to 30 cm thick layer of dark grey sand that overlies pumiceous deposits erupted during the Minoan eruption, and are found at depths of 30-50 cm below the surface. Composition of the tsunami sand is similar to the composition of the present-day beach sand but differs from the pumiceous gravelly deposits on which it rests. Testing of different source mechanisms - i.e. earthquakes, underwater explosions, caldera collapse and pyroclastic flows- shows that the most probable source of the 1650 AD tsunami was a 250 m high water surface displacement generated by an underwater explosion.
- Paleotsunami records along the coast of Egypt were studied by means of 10 1.5 m deep trenches and 16 1 to 2.5 m long cores, which were described and logged in detail. Data collection includes X-ray radiographs, geochemical analyses, magnetic susceptibility measurement and radiocarbon dating needed for the identification of tsunami records. Dated charcoals ad shells in deposits above and below the catastrophic layers led to a **correlation with the 24 June 1870 (Mw 7.5), 8 August 1303 (Mw ~8) and 21 July 365 (Mw 8 – 8.5) major earthquakes that generated tsunamis leading to the inundation of Alexandria harbour**.

Figure 3: 10-cm-thick tsunami layer (white sand with mixed shells and gravels) in Marsah Matrouh (courtesy of Salama A. and Meghrahoui M.)

- Neotectonic numerical modelling of the Africa-Eurasia plate boundary west of Italy showed the need to consider an **Alboran micro-plate** between Africa and Eurasia. This three-plate model explains better than the two plates Africa-Eurasia configuration the geodetic data, the stress directions and seismicity.

The understanding of risk-driving tsunami sources focused in the study of the processes and mechanisms involved and in the mapping of those sources in the NEAM region. In that respect:

- ASTARTE **completed the first general assessment of potential tsunami sources in the NEAM region**, which were fed into GIS catalogues. The assessment included tectonic, landslide and volcanic sources. The goal of this task was to support tsunami hazard and risk assessment with full uncertainty treatment, also considering analyses of tsunami sensitivity to source parameter values.
- Some basic aspects of tsunamigenic earthquake mechanisms have been addressed through dynamic simulations of the seismic rupture and laboratory experiments, particularly focusing on the mechanisms of enhanced shallow slip in mega-thrust earthquakes, as observed for the 2011 Tohoku earthquake. As a result, a **computationally feasible strategy based on corrections to stochastic slip models has been proposed for inclusion in seismic probabilistic tsunami hazard assessment (SPTHA).**

3.2. Progress on numerical modelling

ASTARTE aimed at upgrading the modelling infrastructure by means of improved numerical computations, which are critical in all aspects of hazard assessment, uncertainty quantification and process simulation. They allow for evaluation of impact scenarios and for real-time data assimilation during the development of mega-events. The historical records of tsunami hazards in the NEAM region indicate complex interactions among source mechanisms, basin geometries and coastal infrastructures, rendering traditional database-assisted approaches to tsunami early warning questionable. Additionally, recent developments in detection technologies suggested a new computing paradigm for real-time hazard assessment for tsunami early warning. ASTARTE presented new methods for inverse modelling. These methods can help determining optimal sensor locations, as well as regions of influence to critical infrastructures.

- ASTARTE **completed a survey of advanced techniques for tsunami propagation**, inundation and source modelling, including software development.
- A **suite of new benchmarks for model validation** has been developed, based on laboratory experiments on marine structures commonly used in the Mediterranean Sea. The first one corresponds to a new experiment made in a long flume inspired on inspired on an analytical solution for run-up of an initial sine wave profile on a plane beach. The second one corresponds to experiments made on rubble-mount breakwaters. The third one is based on experiments on a 1:500 fjord model and provides a new benchmark for landslide tsunamis
- **Novel forecasting techniques, based on emulation** rather than simulation have been proposed and tested. The use of statistical surrogate models, also referred as statistical emulators, instead of the actual computer models constitutes a prominent solution. Statistical emulators form stochastic representations of the deterministic computer models used to simulate a physical process. Statistical surrogates can be used to assess uncertainty and conduct sensitivity analyses in short computational times.
- **New modelling techniques** included a discontinuous Galerkin approach for the simulation of inundation with non-linear shallow water equations, the representation of prognostic variables with monotone functions, and a nonhydrostatic correction for shallow water equations with quadratic vertical pressure profile and equivalence to Boussinesq-type equations.
- Finally, **instant simulation workflows**, based on cloud computing have been implemented prototypically. These include GPU-based computing devices and high performance FDTD kernel to solve shallow water equation

It is important to note that **the statistical emulator is a first of its kind in tsunami modelling**. While statistical emulation has been used in other fields, its application to tsunami forecasting was first tested and demonstrated within ASTARTE. Moreover, the Cloud Computing (instant computing) workflow is novel as well.

ASTARTE partner University of Hamburg demonstrated a generic approach utilizing a Python-based controller and cloud services for implementing a tsunami forecast workflow.

The implementation of a new non-hydrostatic projection for dispersive tsunami wave modelling demonstrated (also a first time) the equivalence of Boussinesq-type dispersive models and non-hydrostatic correction based models. The latter approach even allows for adaptive modelling of dispersive waves. This schema has been implemented in finite element and discontinuous Galerkin adaptive mesh tsunami models.

3.3 Progress on understanding tsunami coastal impacts

The massive devastation caused by the above-mentioned 2004 and 2011 major tsunamis showed the need to get a better understanding of tsunami impacts over coastal areas and on structures. ASTARTE aimed to assess the stability and performance of coastal defences and related structures in the NEAM region and to investigate the tsunami-induced morphological changes in coastal areas.

- ASTARTE conducted physical experiments to address the tsunami structure interaction on rubble mound breakwaters.
- ASTARTE developed new numerical models for simulating tsunami-induced flow, sediment transport, and consequent morphology of the seabed, spanning an impressive range of scales.
- ASTARTE refined computational fluid dynamics (CFD) modelling improved the understanding of sediment dynamics during the surge of tsunami-like breaking bores. Additionally, analysis of refined CFD applications led to the development of a new and simple engineering method for predicting tsunami-induced scours around monopile windfarm foundations.
- ASTARTE contributed to **improving knowledge on tsunami-structure interaction** with laboratory experiments on rubble mound breakwaters.
- ASTARTE tested tsunami-structure interaction with two different geometries: rubble mound breakwater - with and without crown wall, and two tsunami wave generation methods (solitary waves and steady currents).
- ASTARTE completed **analytical studies to address the tsunami-structure interaction** from an analytical point of view to assess the location of the damage within the structure, how the tsunami overflow can cause sliding of crown wall of the rubble mound breakwaters and damage in the rear slope, among others.
- ASTARTE used state-of-the-art numerical models to predict the morphological changes of the seabed caused by tsunami flow and sediment transport in Tangier test-site, in Morocco, and in the Belek area, in Turkey.
- ASTARTE addressed the response of basins and harbours (resonance effects, oscillations, currents, vorticity), including their interaction with nearby boundaries (bottom and shores of bays and semi-enclosed areas). The results obtained show that c**orners inside harbours are particularly critical locations for tsunami amplification**. In vortex currents, if the current is strong the sediment moves in wash load form but if the current is weak sediment motion is in bed load mode.

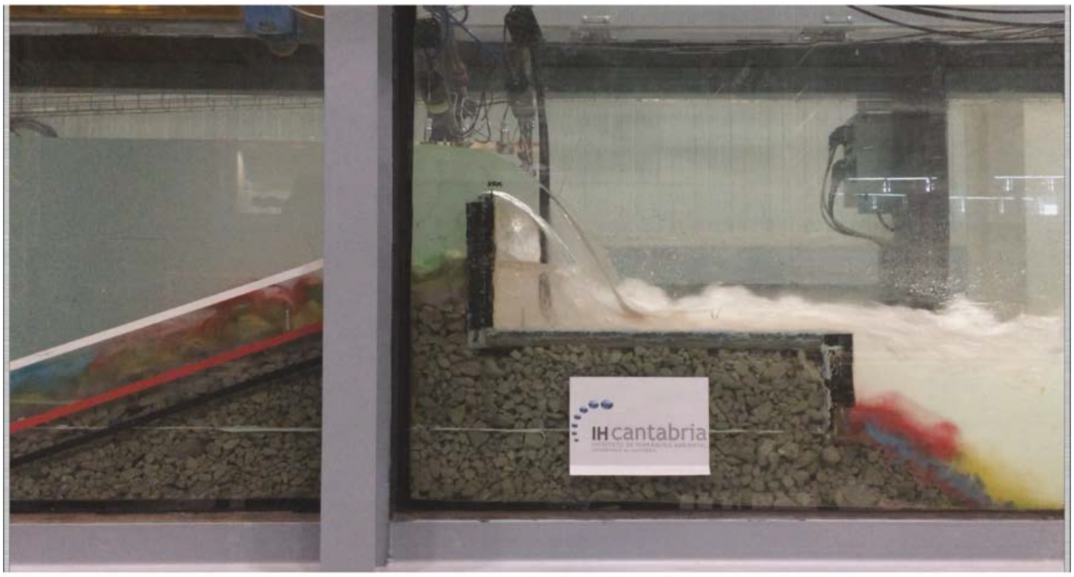

Figure 4 - Overtopping over a crown wall structure – experiment at University of Cantabria

3.4. Progress on tsunami detection and early warning

ASTARTE fostered the real-time mitigation through the improvement of existent TWSs. The ASTARTE project contributed to ameliorate the quality and in-time information to be provided to the populations at risk.

Two of the basic components of operational systems are the detection and the communication infrastructure needed to broaden the forecast and warning skills in the NEAM region. ASTARTE aimed to assess current and future operational infrastructures in the region and contribute to ameliorating early detection and forecasting capabilities concerning tsunami hazard. The small tsunami travel times to coast in most of the NEAM region requires fast evaluations of the tsunami source.

- ASTARTE developed a new database of the existing tsunami early warning relevant infrastructures in the NEAM region.
- ASTARTE reviewed the capabilities for tsunami source evaluation in the NEAM region. Moreover, ASTARTE made a **comprehensive comparison of the different methods in use to invert the seismic source** parameters from the seismic records. The results show that W-Phase, PDFM2, Isola and Kiwi perform similarly in most situations. Nevertheless, at global scale, it is well established that the most efficient method is the W-Phase for major earthquakes.
- ASTARTE partners of the operational tsunami warning centres of the NEAM region together with Intergovernmental Oceanographic Commission of UNESCO established **new decision matrices for different sub-basins** – North East Atlantic basin and Mediterranean basin.

From the operational point of view, the tsunami warning systems of the North East Atlantic and Mediterranean region would benefit with the installation of a network of cabled seafloor sensors.

3.5. Progress on tsunami hazard, vulnerability and risk assessment

ASTARTE explored new methods to cover the assessment chain from tsunami hazard to tsunami vulnerability and risk, and their application to the project's specific test sites in the NEAM region and, for some segments of the chain, to wide basins like the NE Atlantic and the Black Sea.

ASTARTE completed scenario-based (SBTHA) or SPTHA tsunami hazard assessment methods in several test sites of the project (Fig. 2).

ASTARTE performed **SBTHA for Nice and Heraklion test sites**, and SBTHA and 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 an *a priori* probability of each scenario), the probabilistic approach predicts the probability of flooding for a given exposure time. Both approaches considered only earthquake-induced tsunamis. SPTHA 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.

ASTARTE completed a basin wide PTHA for the North East Atlantic Basin and presented the results in terms of **probability hazard exceedance maps**. The seismic scenarios used in this study included a large number of tsunami sources from various potential tsunamigenic zones that include the SWIM, the Gloria Fault and the Caribbean Sea. The study uses 1 m and 5 m wave height thresholds and presents the probability that maximum wave heights exceed these threshold values during 100- and 500-year return periods. The probability that a maximum wave height exceeds 1 m in some coastal locations of the NE Atlantic reaches 60% in 100-year return period. The probability that a maximum wave height exceeds 5 m reaches only 15% in 100-year return period in a small number of coastal locations (e.g. Gulf of Cadiz) in the NE Atlantic. Considering 500-year return period, the 1 m tsunami probability of exceedance is 100% in various locations of the NE Atlantic, in particular the Gulf of Cadiz and the Azores coasts. However, the 5m tsunami probability of exceedance is about 50% in the Gulf of Cadiz. Coasts of South Portugal, NW Morocco and SW Spain are the most hazardous ones in the NE Atlantic. Seismic sources in the Caribbean arc might generate tsunamis that could impact the Azores Islands.

A major outcome of ASTARTE consists of the SPTHA study for the North Atlantic and Mediterranean basins that fostered the TSUMAPS-NEAM project (Probabilistic tsunami hazard maps for the NEAM region, http://www.tsumaps-neam.eu/), presently on-going, and derived mapping products. This project, funded by DG-ECHO, constitutes the first regional product on tsunami hazard for the NEAM region, representing an attempt to define and apply new standards in the optics of the Global Tsunami Model (GTM) (http://globaltsunamimodel.org).

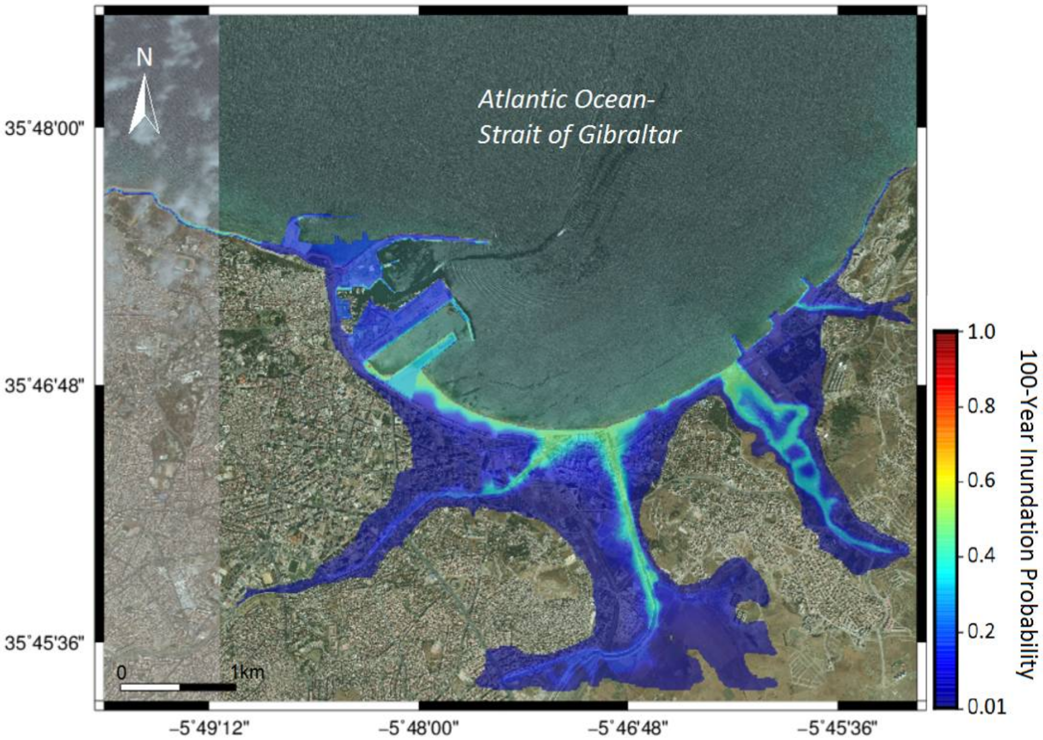

Figure 5 - Probability of tsunami flooding in Tangier – Morocco for a return period of 1000-year.

ASTARTE conducted vulnerability studies at local scale in most of the test sites (Fig. 2). Different methods were used for vulnerability assessment because of the different factors that might affect the vulnerability assessment procedure in every test site. The two main classes of structural vulnerability analysis currently in use can be distinguished in terms of qualitative and quantitative approaches. The qualitative methods generally characterize the exposure of structures to a hazard by means of attributes from territorial element inventories. Scores are assigned to some subjective criteria that 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 and structures, and mortality curves for individuals, which link damage and losses to values of tsunami parameters.

In Sines and Tangier test sites, ASTARTE completed building vulnerability assessments. 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, duly adapted to the classified constructions. The tsunami damage has been estimated considering six levels of damage (D1-Minor, D2-Moderate, D3-Major, D4-Complete, D5-Collapse, and D6-Washed away) and is depicted in vulnerability maps. Obviously, 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 play an important role in controlling tsunami vulnerability.**

For Colònia San Jordi site, both the basic framework for tsunami hazard assessment SCHEMA **(**SCenarios for Hazard-induced Emergencies Management, http://www.copernicus.eu/ projects/schema) and PTVA-3 (Papathoma Tsunami Vulnerability Assessment, version 3, https://www.nat-hazards-earth-syst-sci.net/9/1557/2009/nhess-9-1557-2009.pdf) 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 beachfront 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. In Siracusa and Augusta test sites ASTARTE concluded that **SCHEMA model tends to underestimate the damage level with respect to PTVA-3**.

ASTARTE conducted tsunami risk assessment studies that include evaluation of victims, fatalities and economic losses for some test sites. Tsunami risk studies in Heraklion test site shows the need to compute separately risk to buildings and risk to population. About risk to buildings it is easy to make an ex-ante calculation of the absolute economic (monetary) losses due to the needs for building replacement, either reparation or reconstruction. Moreover, ASTARTE used these examples to delineate guidelines on tsunami risk analyses and products.

ASTARTE implemented a general framework to treat uncertainties in the field of the probabilistic approach covering the analysis flow from hazard to risk. Such framework has been developed exploiting synergies with TSUMAPS-NEAM and STREST (Harmonized approach to stress tests for critical infrastructures against natural hazards) projects. A path for a systematic application has been devised as regards the hazards by establishing a **homogenized 4-step procedure to estimate probabilistic hazard** (probabilistic earthquake model, tsunami generation and modelling in deep water, shoaling and inundation, hazard aggregation and uncertainty quantification). The passage from the uncertainty associated with hazard to uncertainty associated with damage incurring to material assets and to people has been delineated.

ASTARTE developed an easy-to-use platform of hazard curves and maps in the NEAM region and implemented it as a prototype.

A GIS database collecting thematic maps computed in the frame of ASTARTE WP8 (From hazard to risk assessment) has been created.

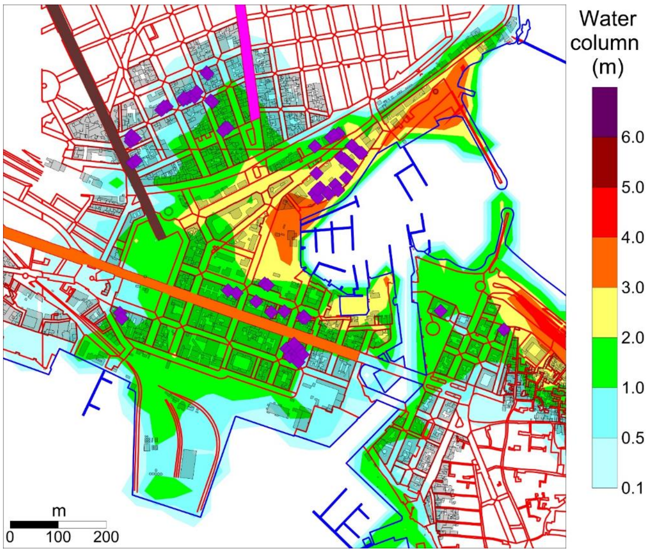

Figure 6 - Siracusa test site; Violet -diamond indicate buildings candidate as vertical shelters; Scale shows inundation depth

3.6. Progress on tsunami resilience in the NEAM region

ASTARTE shows that a **tsunami-related disaster is likely to occur in the NEAM region**. The high density of coastal population, especially in some areas, associated with the low level of preparation to react in case of a tsunami make the area highly vulnerable. Pure engineering approaches based on the construction of protection walls are expensive to build and maintain, and have a large environmental impact on the coastal environments. So, in most situations, **mitigation and adaptation must rely on planning instruments for coastal management and increased social resilience**.

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 and circulated to citizens. The resulting assessment allowed: (1) to evaluate the people's view of tsunami risk within a multi-risk approach, how recurrence and sources (links to ASTARTE WP2 - Long term recurrence of tsunamis- and WP3 - Tsunami sources and generation mechanisms-) are perceived, and which would be people's reaction face to a tsunami threat; (2) to estimate the level of customization needed and for the typologies of awareness and preparedness materials in each studied community; (3) to provide data for agent-based evacuation modelling. In total 1512 interviews were held in the different ASTARTE test sites. The conclusions that can be extracted vary according to each environmental setting, differences in coastal communities and levels of perception of tsunami risk and TEWSs.

In terms of *tsunami hazard awareness, knowledge of tsunami processes and risk perception* WP9 (Building tsunami resilient societies) pointed out several weaknesses in tsunami resilience, including **poor awareness of the tsunami hazard**, **poor knowledge on past tsunamis events** and of tsunami triggering and propagation processes, underestimation of tsunami threat on the Atlantic coasts in contrast with overestimation of tsunami height in the Western Mediterranean area. Additional weaknesses were identified in terms of *attitudes or response of the people exposed to tsunami threat* (**i.e. evacuation refusal**, search for confirmation from different sources before starting to evacuate, using own car instead of choosing pedestrian evacuation, etc.). Consequently, the leaflets developed in 6 of the ASTARTE test sites, and the sensitization movie on tsunami risk in Nice were aimed at certainly improving tsunami hazard knowledge, risk perception and responses of the people in case of tsunami threat.

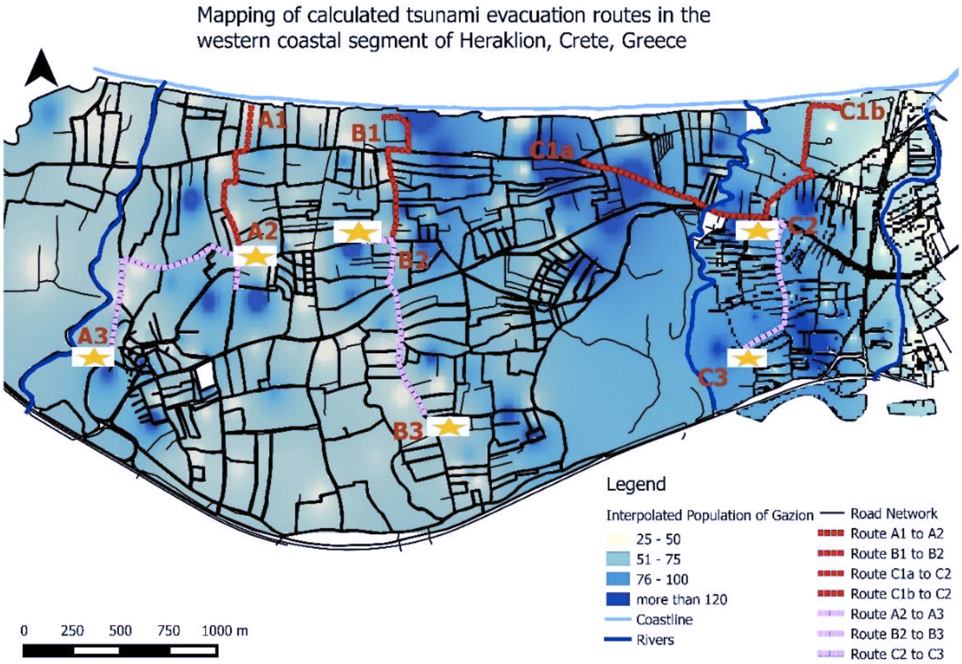

Figure 7 - Fastest evacuation routes in the area of Gazi, western segment of Heraklion Greece test-site

In terms of risk prevention and mitigation strategies, in-depth interviews with stakeholders revealed additional weaknesses, e.g. absence of official evacuation sites dedicated to tsunami hazard, inadequacy between earthquake official safety zones and safe areas for tsunami (e.g. Siracusa, Istanbul), lack of evacuation paths between low-lying beaches and higher areas, and poor awareness of the existence of a warning system. Results on the number of people to be evacuated, definition of tsunami safe areas and evacuation roads, and calculation of evacuation times should be considered critical for both local authorities and civil protection in order to address tsunami risk and associated contingency plans.

ASTARTE developed a new tool for disaster management: FIND (Finding Inaccessible people in Natural Disasters) includes three components: FIND-Victim, FIND-RESCUER and FIND-Pro. FIND-Victim, is a smartphone application targeted at the general public, It senses people's smartphone activity and continuously and inconspicuously gathering location and aliveness indicators. This information is disseminated on a best-effort basis **through a peer-to-peer network of people's devices. The emergent network that is created requires no infrastructure**, relying solely in availability of neighboring devices, and human movement. This ad hoc opportunistic network is designated FIND-Service and constitutes one of the non-interactive subsystems. FIND-Victim is available for download at Google Play for Alpha testers that can subscribe at http://accessible-serv.lasige.di.fc.ul.pt/~find. The network subsystem is automatically installed as well as services for simulation and alert registration and specific messaging applications. The second component, VICTIM-Rescuer, is a tablet application provides a visualization map where volunteers can directly track the data provided by the victims' devices. Besides the location, it shows aggregation and history of the victims' aliveness data thus informing the volunteers about the people's conditions in their vicinity. The third component, FIND-Pro, is a web application which allows authoritative rescuers to access the server's data, enabling them direct their actions based on local knowledge which they otherwise wouldn't have access to.

ASTARTE objectives and results are aligned with the Sendai Framework for Disaster Risk Reduction 2015-2030 (http://www.preventionweb.net/files/43291_sendaiframeworkfordrren.pdf), namely with priority actions 1, 2 and 4 (Table 1):

Sendai Framework for Disaster Risk Reduction	ASTARTE
Priority 1 - Understanding disaster risk Disaster risk management should be based on an understanding of disaster risk in all its dimensions of vulnerability, capacity, exposure of persons and assets, hazard characteristics and the environment. Such knowledge can be used for risk assessment, prevention, mitigation, preparedness and response.	Improved knowledge on long-term recurrence of tsunamis and their generation mechanisms. New studies on hazard vulnerability and risk assessment available to civil protection and local authorities. Improved knowledge on the performance of coastal and harbour protection structures under tsunami impact.
Priority 2. Strengthening disaster risk governance to manage disaster risk Disaster risk governance at the national, regional and global levels is very important for prevention, mitigation, preparedness, response, recovery, and rehabilitation. It fosters collaboration and partnership.	Contribution to the implementation of the national and regional TEWSs in the NEAM region (NEAMTWS) under the umbrella of the Intergovernmental Oceanographic Commission of UNESCO. Development of new numerical tools for tsunami early warning and forecasting. Development of a new tool for disaster management, named FIND (Finding Inaccessible people in Natural Disasters).
Priority 4. Enhancing disaster preparedness for effective response and to "Build Back Better" in recovery, rehabilitation and reconstruction The growth of disaster risk means there is a need to strengthen disaster preparedness for response, take action in anticipation of events, and ensure capacities are in place for effective response and recovery at all levels. The recovery, rehabilitation and reconstruction phase is a critical opportunity to build back better, including through integrating disaster risk reduction into development measures.	Assessment of preparedness skills, resources and attitudes residents and visitors of the ASTARTE test sites. With this work ASTARTE concluded that several weaknesses exist concerning tsunami resilience. The populations of the North East Atlantic and Mediterranean basins reveal a low level of **awareness of tsunami hazard** and a **poor knowledge on past tsunamis events. Also, these populations** underestimate tsunami threat but they overestimate tsunami heights.

Table 1. Alignment of ASTARTE objectives and results with the Sendai Framework for Disaster Risk Reduction.

4. Expected Results and their social and economic impact

Tsunamis are high-impact natural disasters. 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 different test sites vulnerable to tsunami impact generated by different source mechanisms: earthquakes, landslides and volcanic eruptions. These sites covered a broad range of values at risk namely: buildings and other infrastructure, industrial facilities, harbors, road network, fisheries, aquaculture and tourist areas. Therefore the results obtained in these test sites can be extended to the whole North East Atlantic and Mediterranean basin.

ASTARTE improved knowledge on tsunami generation involving novel empirical data and statistical analyses so that the long-term recurrence of large events in sensitive areas of the North East Atlantic and Mediterranean basins can be established. ASTARTE revised the seismic and tsunami catalogues of the NEAM region. Moreover, ASTARTE produced a public Georeferenced database of tsunami deposits and Mass Transport Deposits for the North East Atlantic and Mediterranena region. This database is open access to the scientific community and can be updated and expanded in the future beyond the number events that are presently there.

ASTARTE produced guidelines for tsunami source harmonization. These guidelines are intended to assist tsunami modelers in choosing appropriate source models and properly documenting their use, with a focus on tsunami modelling for tsunami hazard assessment, and tsunami forecasting in tsunami early warning).

ASTARTE developed new numerical techniques for tsunami simulation concentrating in real-time simualtion codes, novel statistical emulations and refined methods for the assessment of tsunami hazard, vulnerability, and risk. These tools are available for real time tsunami simulation codes in use in the operational tsunami warning centers of the North East Atlantic and Mediterranean region.

ASTARTE results on physical experiments on tsunami impact on coastal structures focused typical harbor protection structures of the ports of the North East Atlantic and Mediterranean basin, namely the effectiveness of the existing breakwaters in the region. ASTARTE results go beyond the lifetime of the project and will serve as the basis for recommendations and guidelines not only for tsunami Eurocodes but worldwide.

ASTARTE contributed to the implementation of new tsunami early warning tools. This work was developed back to back with the existent National and Regional Tsunami Warning Centers of the NEAM region. The present design of the North East Atlantic Mediterranean Tsunami Warning System developed under the umbrella of Intergovernmental Oceanographic Commission, benefits from the incorporation of most of these achievements. ASTARTE results on fast seismic sources contribute to ameliorate the quality and in-time information provided to the endangered populations. All these outputs focus the safety of citizens will benefit from ASTARTE the scientific and technological skills and results.

ASTARTE research on tsunami hazard, vulnerability, and risk assessment will support coastal management activities and decision makers so that sustainability and resilience of coastal communities could be increased. For the first time in Europe, and very likely globally, ASTARTE conducted a coordinated effort to test different methods for tsunami hazard assessment. In particular, ASTARTE community developed methods for Probabilistic Tsunami Hazard Assessment. This work fostered the new map TSUMAPS – NEAM a Probabilistic Tsunami Hazard (PTHA) maps for the North East Atlantic and Mediterranean region: This is the first homogeneous long-term probabilistic map of earthquake-induced tsunamis for the coastlines of the Europe produced for Directorate-General for European Civil Protection and Humanitarian Aid Operations.

ASTARTE produced a Pilot Analysis Support Platform tool that permits a quantitative analysis of hazard and risk curves, probability and hazard/risk maps. It has been conceived in such a way to be usable by both scientists and risk managers and to allow also non-experts to access the results easily.Moreover, ASTARTE developed a dynamic GIS Data Base of tsunami risk products. This database is intended to be used by stakeholders – coastal mangers and local authorities. The layers contained in the database for the differenttest sites are intended to help them to understand the different level of risk at the test sites. This is a dynamic database - open access that can be updated and expanded in the future.

ASTARTE experience on test sites reveal that the level of awareness of the local populations and tourists to tsunami hazards is low. The work in test-sites reveal the need of official tsunami evacuation sites and the definition of evacuation paths between the beach and higher areas. These results go beyond these test sites and constitute a valuable information for civil protection and local authorities in the North East Atlantic and Mediterranean basins.

The scientific results of ASTARTE project are widely spread in the tsunami scientific communnity. The scientific production of ASTARTE includes more than 90 scientific papers in ISI journals and hundreds of oral and poster presentations in international meetings. For the general public ASTARTE published an article in the European Union's Research and Innovation Magazine, Horizon, published the article 'Scientists investigate how to defend Europe against tsunamis' which features work on the pro-ject ASTARTE written in collaboration with ASTARTE researchers.

ASTARTE conducted a large number of dissemination activities, ASTARTE was presented in World Conference on Disaster Risk Reduction organized by UNISDR which took place in Sendai, Japan on March, 14-18 2015. Several initiatives were organized back to back with the Intergovernmental Coordination Group of IOC - UNESCO for the implementation of the North East Atlantic and Tsunami warning System

The joint ASTARTE-PEARL-TANDEM summer school organized under the umbrella of the 7FP projects ASTARTE and Pearl in collaboration with TANDEM project funded by Agence National de Receherche (France) took place in the Technical University of Crete. This event put together researchers from different fields of tsunami science and extreme coastal events. The goal was the trainning of young researchers with participation of 28 undergraduate or graduate students and 17 lecturers. The summer school contributed to the participants' knowledge on coastal hazards, both theoretically and methodologically, with emphasis on coastal disaster resilience. The programme covered subjects from different areas of expertise, thus introducing and exploring the diversity of natural hazards linked to coastal flooding. The program included two field trips where the students had direct contact with local authorities.

Tsunamis know no borders, making international cooperation key for deeper political and public understanding of risk reduction measures. As a result, the United Nations General Assembly has made 5 November into World Tsunami Awareness Day, with the first edition in 2016. ASTARTE partners were deeply commited in the activities of the Tsunami Awarenness day.

FIND - Finding Inaccessible people in natural disasters is a new software for disaster management developed by ASTARTE, which goes beyond the lifetime of the project.

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Attached documents : Furthermore, project logo, diagrams or photographs illustrating and promoting the work of the project (including videos, etc...), as well as the list of all beneficiaries with the corresponding contact names can be submitted, provided the consortium ensures that all necessary authorisations have been obtained and that the publication of the information by the Commission does not infringe any rights of third parties (e.g. commercial interests, including intellectual property, or privacy and the integrity of the individuals, in particular in accordance with Community legislation regarding the protection of personal data).

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