# Earthquake and Tsunami-Induced Damage to Seaport Structures in Italy: Application of GIS for Risk Reduction and Monitoring

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**ABSTRACT:**

The presence of a seaport represents a remarkable, at times decisive, factor of development of a region and a fundamental element of politics for the sustainable mobility, able to produce a series of direct and indirect effects on the economy and on the social and environmental growth of the interested area. This consideration justifies the necessity of a high level of protection for the seaport structures. Experiences gained from some recent earthquakes (e.g. 1989 Loma Prieta in USA, 1995 Hyogoken-Nanbu and 2003 Tokachi-Oki in Japan, 1999 Kocaeli and Duzce in Turkey) have dramatically demonstrated the seismic vulnerability of these infrastructures and the severe damage that can be caused by ground shaking and tsunamis. In Italy, a country with an extensive coastline's length, a research project aimed at assessing the seismic vulnerability of Italian wharf structures was funded by the Italian Department of Civil Protection in areas characterized by medium and high seismicity. This paper shows part of the obtained results, with particular reference to the seismic risk management through an interactive, geographically referenced database (GIS). The impact of tsunamis on the shorelines will also be shown at the seaports of Ancona, Gioia Tauro and Messina in Central and Southern Italy.

**KEYWORDS:** Seaports, Geographic Information System, tsunamis, damage assessment, seismic risk, earthquakes, seismic hazard, seismic vulnerability

## 1. INTRODUCTION

A considerable part of the economy of many industrialized countries, included Italy, is based on the activities of export and import of commodities; a remarkable quote of these commercial trades is developed by the seaports, that also constitute crucial points of transit of millions of travellers every year. The interruption of functionality of port structures can have severe effects, at times devastating, on the economy of a nation.
The importance of seaports is mostly evident for a country such as Italy, that has a considerable coastal development and capability due to its strategic geographical position stretched out in the Mediterranean Sea.

According to the recently updated seismic hazard macrozonation map of Italy, many of the Italian seaports are located in zones characterized by moderate to high seismicity. Experiences gained from recent earthquakes (e.g. 1989 Loma Prieta in USA, 1995 Hyogoken-Nambu and 2003 Tokachi-Oki in Japan) have dramatically demonstrated the seismic vulnerability of seaport structures and the severe damage that can be caused by ground shaking. The poor performance exhibited by seaport structures in recent earthquakes has spurred an intense research activity worldwide for setting up methodologies and technical recommendations for a proper seismic design of new seaport structures and retrofit of existing facilities.
In Italy, the Department of Civil Protection has funded a research project meant to develop a methodology for the seismic design of new marginal wharves and assessment of existing structures at seaports located in areas characterized by medium and high seismic hazard. The first part of the project consisted in the implementation of a detailed census of the Italian major seaports which was carried out using purposely devised questionnaires aimed to identify the existing wharf typologies (Gentile & Lai, 2007).
In this research project, particular attention was given to three important seaports in Italy: Gioia Tauro and Messina in Southern Italy and Ancona in the Central part of the country. Gioia Tauro port is the first Italian harbor (Confetra, 2006) and among one of the first thirty in the world for number of containers. Ancona seaport, for which the data provided by the Port Authority for the year 2007 recorded a commercial traffic of over 9 million tons and a strong trend increment for goods of all categories, is classified among the first seaports of the Adriatic Sea for the

number of passengers, with more than a million and a half of transiting travelers. Ancona harbor has been selected for the definition of deterministic scenarios of seismic damage of the main seaport infrastructures (Pessina et al., 2008) and, together with the ports of Gioia Tauro and Messina, for the development of a pilot study for the application of probabilistic methods to the evaluation of tsunami impact on seaport structures.
This paper will illustrate part of the results of this research project. A special focus will be given to the tsunami-induced damage at the three above-mentioned seaports of Ancona, Gioia Tauro and Messina using Geographical Information Systems (GIS) techniques.

## 2. USE OF GIS ENVIRONMENT AND TOOLS FOR SEISMIC RISK ASSESSMENT

Disaster can be defined as the onset of an extreme event (earthquake, tsunami, landslide, etc.) causing great damage or loss as perceived by the afflicted people. Disaster management involves three phases: *pre-disaster*, *during the disaster* and *post-disaster*. The *pre-disaster* phase consists of risk evaluation and reduction, risk monitoring and forecasting, use of Geographical Information Systems (GIS) to store, analyze and display geographic information for specific thematic scenarios. Geospatial information remains a key element also in the emergency phase, due to dynamic character of GIS, that allows to readily updating the available information, and its ability to yield new important information in a short amount of time. This is particularly effective for natural catastrophes such as earthquakes and tsunamis where the time of response to the emergencies is critical. GIS tools can provide answers to vital questions, such as the location of the most affected areas and how they can be reached (ESRI, 2006).

These disasters affect many regions of the world, however even though the problems faced by each nation are different, they find an ideal treatment in GIS environment. The geographic information may consist of a great variety of data sets, including natural and socio-economic information, each associated with a spatial coordinate system. The spatial referencing of the information permits the data sets to be linked. This overlay provides a powerful tool for analysis and integration of data sets from different sources. Using procedure of limited complexity, GIS tools allow the integration of different informative categories of georeferenced data and the creation of data models and maps, by providing particularly the possibility to:

- perform sophisticated queries on the represented real objects (on attributes, spatial and topological query) with the purpose to localize objects/elements of interest and to circumscribe areas of influence for various typologies of phenomena;
- associate to the geographical object various typologies of files (textual documents, images, web site links, etc.), that can be managed and visualized through specific queries functions of the object;
- rapidly update the available information through the use of advanced editing tools and the change/addition of themes inside the dataset or fields - textual, numerical or Boolean (presence/absence) - characterized by appropriate extension, inside the thematic layers;
- derive original data through tools of composition and elaboration of data information;
- define evolution scenarios (analysis of the type "*what if*").

A major objective of the research project funded by the Italian Department of Civil Protection, in the years 2007-2008, was the construction of a GIS-based database of technical data concerning the Italian major seaports located in medium-high seismicity zones. The technical data was mostly referring to wharf structures and to the elements, inside or connected to the seaport area, that are significant to seismic risk assessment. The seaports that were the objective of the study were the harbors of Ancona, Carrara and Livorno in Central Italy, and Naples, Salerno, Gioia Tauro, Augusta, Catania, Messina, Palermo and Trapani in Southern Italy.
The GIS database is based on technical data collected through a census carried out using purposely devised questionnaires (Gentile & Lai, 2007). The questionnaires consisted of a general part which included indicators defining the strategic role played by the seaport at the national level and a more specific section concerning relevant structural and geotechnical features affecting the seismic vulnerability of wharf structures. The census collected data spans from general information such as site identification and seismic classification, bathymetry, trade volume to more specific information such as wharf typology, geological, geotechnical and geomorphological data, type of

cranes, information on the structural and infrastructural elements inside the port areas. Moreover, probabilistic seismic hazard information was also included such as acceleration (DPC-INGV_S1, 2007) and displacement (DPC-INGV_S5, 2007) response spectra. Figure 1 shows acceleration and displacement response spectra for the harbors of Ancona, Gioia Tauro and Messina.

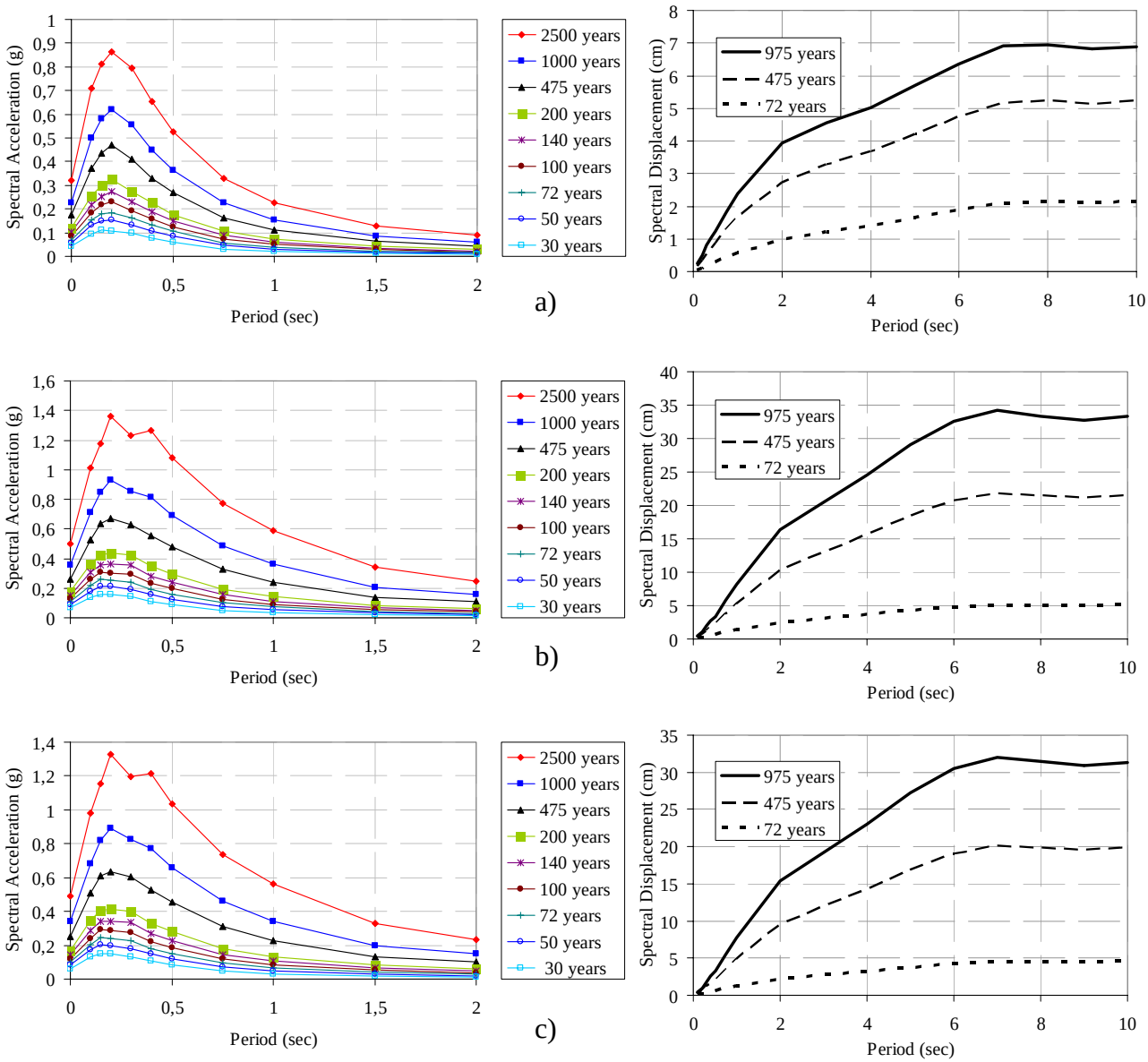


Figure 1 Response spectra of acceleration (left hand side) and displacement (right hand side) for different return periods for three Italians seaports: Ancona (a), Gioia Tauro (b) and Messina (c) (from http://www.mi.ingv.it/).

The collected information have been organized in an interactive, geographically referenced database which also includes data obtained from processing the primitive information such as risk and damage scenarios and independent calculations to assess local site effects and tsunami hazard. The objective of this GIS database was the assessment and mitigation of seismic risk as well as the planning of actions during the emergency. The completeness and the accuracy of the database determined the quality of the subsequent analyses. The GIS software used for the analyses is ESRI ArcGIS-ArcINFO 9.0. The structure used to obtain a high degree of data organization is the Personal Geodatabase, inside which it was possible to insert punctual, areal or linear vectorial data, raster data, charts, but also rules and topological relationships among the represented real objects.

The GIS database included data related to the extension of the area of flood and to the height of anomalous waves caused by the seaquakes (run-up) at the seaports of Ancona, Gioia Tauro and Messina using the results of a study performed by the Department of Physics of the University of Bologna. Furthermore, the database included also the results obtained from analyses performed by the Italian Institute of Geophysics and Volcanology, section of Milan (http://www.mi.ingv.it/; EUCENTRE-PE5, 2008) with calculation of ground shaking and damage scenarios of the seaport structures at the harbor of Ancona.

### *2.1 Tsunami-hazard and damage assessment*

Under particular conditions, the seismic events can produce further catastrophes events of secondary origin, but not of secondary importance. These are for instance the tsunamis, trains of anomalous waves that cause a quick and violent flood of the coast that are hit, causing amplified devastating property damage, injuries and loss of life.

Tsunami generated from earthquakes in Chile (1960) and Alaska (1964) caused damage not only in the immediate vicinity of their source but also travelled across the Pacific Ocean and cause major devastation at far-field locations such as Japan, Hawaii and at the West Coast of the United States. Likewise, the 2004 Indian Ocean tsunami caused significant damage near its source in northern Sumatra, but also propagated across the Indian Ocean to impact the coasts of Thailand, Sri Lanka, India and several other countries (Dale and Flay, 2006). In Tokachi-Oki event (2003), that affected a 400 km-wide area along the coastal areas of southern and south-eastern Hokkaido Island, the primary event produced tsunami run-ups along the shoreline of southern Hokkaido that reached maximum heights of 4 meters in the areas of Taiki and Erimo (EERI, 2003).

Since the seaquakes are rare events, the tsunami catalogues contain in general a limited number of events. This fact makes difficult and often even impossible the application of statistical methods for the assessment of the probabilities of occurrence and the impact of tsunami phenomena. Difficulty is even greater if the impact assessment concerns specific areas of limited size, but having strategic importance to the economic, social and environmental conditions, such as urban areas, industrial districts, commercial zones and port areas.

It is well known that the majority of seaquakes have seismic origin and the earthquake catalogues contain data sets that are more complete in comparison to the catalogues of tsunamis, both because the frequency of earthquakes occurrence is higher, and because the networks of seismic monitoring are much more dense and efficient than the analogous networks specifically designed to monitor seaquakes. Therefore, the application of statistical methods or probabilistic-deterministic hybrid methods for the assessment of the probability of earthquakes occurrence usually lead up to relatively reliable results. Unfortunately this is untrue for tsunamis.

A possible strategy for the assessment of the impact of tsunami having seismic origin on the shore structures, is founded upon a three-step process:

1. assessment of the probability of occurrence of tsunamigenic earthquakes;
2. assessment of the corresponding probability of tsunami occurrence;
3. assessment of the tsunami impact on a specific shoreline.

The first step makes use of the same statistical methods adopted in seismology and focus on the tsunamigenic potential sources (see Figure 2). The second step is based on the accepted theory that the seismic tsunami genesis is essentially due to the vertical displacement of the sea bottom caused by an earthquake, and it is connected to the use of deformation models that calculate the co-seismic surface movements starting from the focal parameters of the seismic source. The third step is connected to the propagation of the seaquake from the source zone to the target object of investigation and combines purely hydrodynamic calculations (i.e. the propagation of the waves of tsunami up to the coast) to engineering and/or social and environmental assessments such as the evaluation of the maps of flood and the impact of the tsunami waves on structures built in the coastal belt and to people.

At the present time this approach is widely used worldwide in a variety of versions according to specific applications (Geist and Parsons, 2006; Annaka *et al*., 2007). It has been introduced relatively recently, just around twenty years ago. Applications of such methodology limited to the first two steps to the Italian coasts can be found in the works by Tinti (1991a) and Tinti (1991b) where the probability of occurrence of seaquakes and the potential of different tsunamigenic sources was assessed. A more complete application of the method which includes also the third step, to the coastlines of Southern Calabria and Eastern Sicily is reported in the works by Tinti (2004), Tinti *et al*. (2005a) and Tinti *et al*. (2005b) who evaluated the impact of seismically-induced seaquakes in terms of maximum expected run-up on the shoreline for a return period of 475 years.

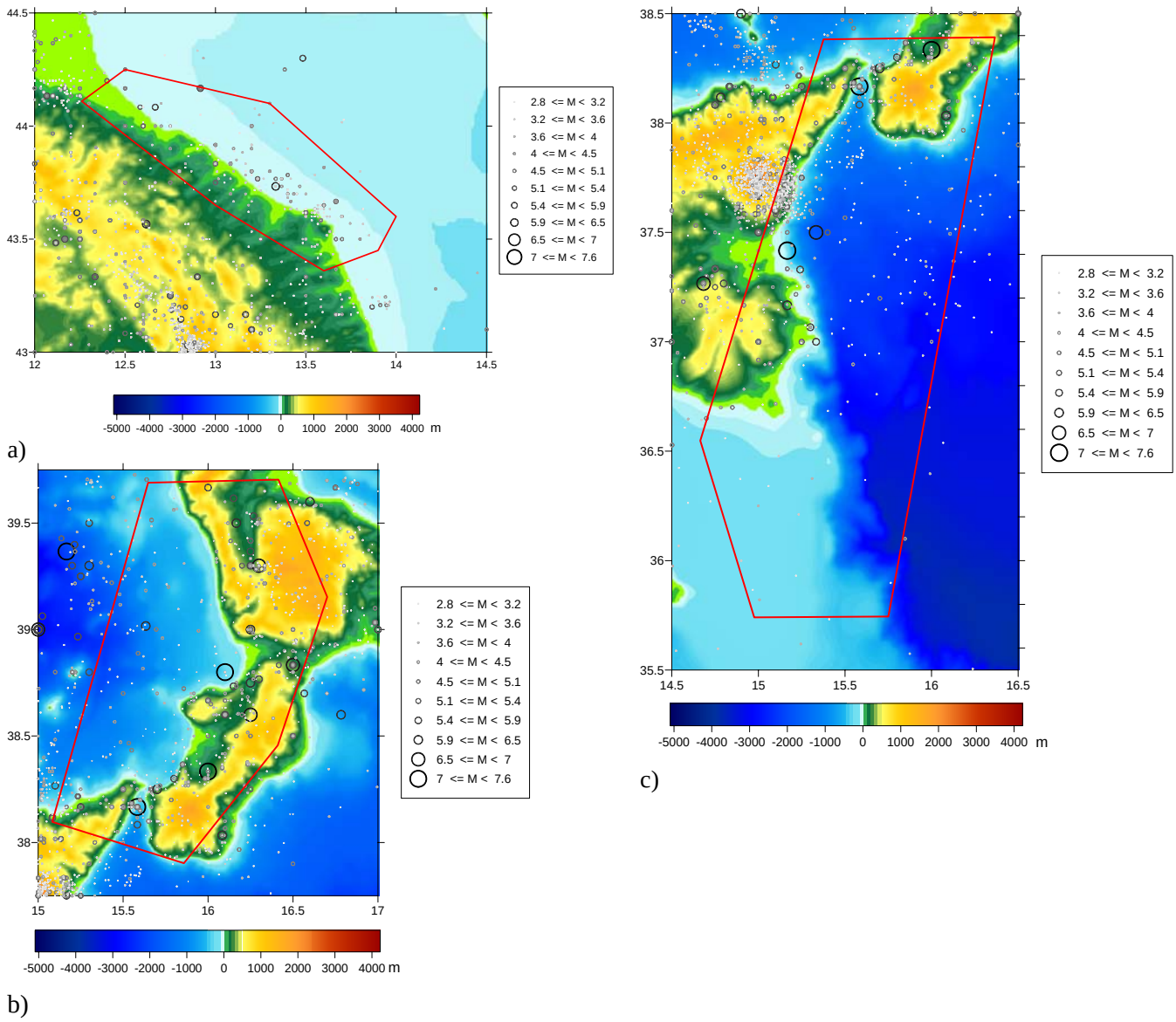


Figure 2 Tsunamigenic seismic sources considered for the ports of Ancona (a), Gioia Tauro (b) and Messina(c).

The method was applied for the first time in this study to assess tsunami impact in geographically limited areas such as harbors, which often have the peculiarity of complicated geometries that impose the use of sophisticated tools for the calculation of the field of local waves from the hydrodynamic simulation point of view. If in many circumstances the effects of a seaquake can be calculated through simplified hydrodynamic models or even by means of empirical or semi-empirical formulas, in case of complex geometries it is necessary to use numerical models on high resolution grids since seaport structures include various elements such as wharves, piers, breakwaters, offshore seawalls some located in minor basins and channels of access.

The study focused on the harbors of Gioia Tauro, Messina and Ancona and it was conducted for 475 year return period. For each port the expected maximum and minimum elevation of the sea level has been defined. The first datum allows the computation of the extension of flood in the port areas, while the second datum allows to identify the areas that can temporarily dry up because of the draw back of the sea produced by the tsunami. Moreover, a comparison between the two maps allows an estimation of the variability of the sea level produced by the seaquake. Many Italian seaports are affected by tsunamigenic earthquakes generated from both local and remote sources. A

result that has emerged from the study is that the worst scenario for the harbors of Ancona, Gioia Tauro and Messina is that produced by local sources. The reasons are due to the properties of wave propagation that are strongly affected by the bathymetric features of the basin in which they travel, and also to the co-seismic effects of the earthquakes that produce subsidence of the coastal zones and thus great exposure to the attack of tsunamis.
For this analysis, a hybrid probabilistic-deterministic method was adopted where the assessment of earthquake occurrence was performed using purely statistical techniques whereas the calculation of tsunami waves was carried out by means of numerical simulation. Obviously the analysis focused on earthquake-induced tsunami and thus doesn't take into account tsunami generated by other phenomena such as submarine landslides and volcanic eruptions.

The results of the study, calculated on a high resolution (8 m) numerical grid, shows that the seaport of Messina is expected to be affected by a remarkable rise and lowering of the sea level for a 475 year return period with a variation of several meters (see Figure 2). The effect of the tsunami could thus be devastating for the port structures. A large tsunami is also expected at the harbor of Gioia Tauro even though characterized by smaller run-ups (1-2 m). However, it should be remarked that the resolution used for the grid (200 m for every cell) is inadequate for the seaport and this is due to lack of more detailed information of the harbor. It is believed that a more accurate representation of the harbor through a denser and higher resolution grid of calculation would have shown the excitation of the fundamental mode of oscillation of the port with the corresponding increase of wave amplification and therefore of the expected values of run-ups for the considered return period.
The seaport of Ancona is located in front of a limited number of tsunamigenic faults. The results of the analyses confirms that this harbor is well protected, considering that the maximum and minimum elevations of the sea level are smaller than one meter, while higher values are predicted in the East zone outside the seaport (see Figure 3).

More detailed information about the results of the study which include also calculation of the damage scenarios of the seaport structures at the harbor of Ancona and a thorough description of the GIS database can be found in the reference document EUCENTRE-PE5 (2008).

## 3. CONCLUDING REMARKS

Earthquake-induced tsunamis are capable of causing a substantial amount of damage and devastation. However, tsunami-induced damage can be minimized through land use planning and measures for risk mitigation and monitoring. The GIS technology is a valid tool in the assessment of seismic and tsunami-related risk, before, during and after a catastrophic event occurs, because of its abilities of integration, updating and processing of technical information. In association with other techniques, GIS can be a powerful tool for the evaluation of the vulnerability of elements at risk in seaport areas and to seismic risk assessment. The final goal is to improve seismic performance of port structures and reduce casualties related to earthquake and tsunami events. This paper has shown some of the results that were obtained by applying GIS technology for seismic and tsunami-related risk assessment at the seaports of Ancona, Gioia Tauro and Messina ports in Italy.

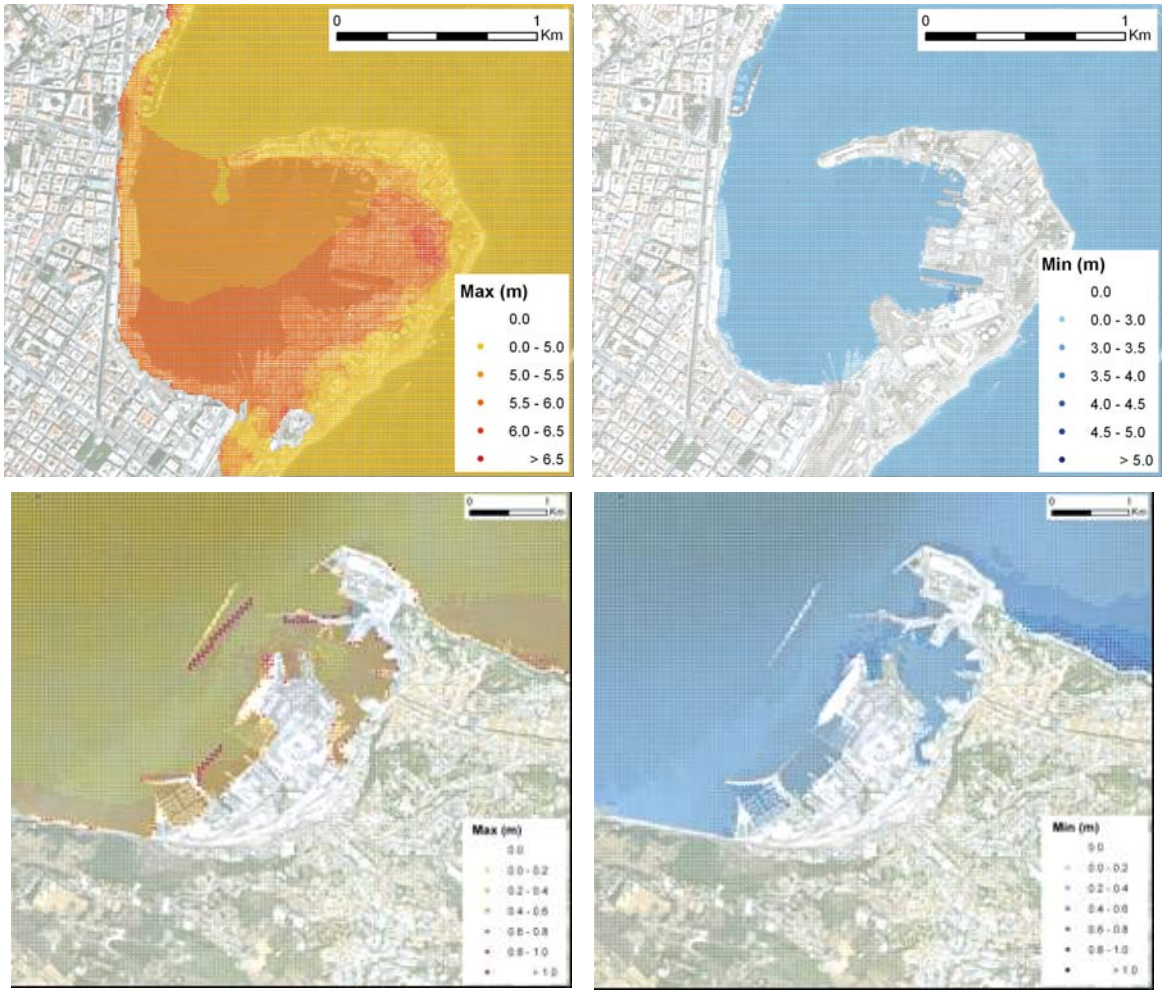


Figure 3 Maximum and minimum expected values of run-up for the seaports of Messina (upper part) and Ancona (lower part) for a return period of 475 years.

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