Seismic risk assessment of Italian seaports using GIS technology: the ports of the Calabria Region

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SUMMARY:
The response exhibited by seaport structures to earthquakes has demonstrated their vulnerability under seismic loading. The evaluation of damage and risk scenarios represents the base for the development of mitigation strategies, plans of intervention and post-earthquake emergency management. In Italy, the Department of Civil Protection has funded a research project on seismic vulnerability and risk of national seaport structures. This paper shows the ongoing research, focusing on the features of a Geographic Information System (GIS) which collects data of the Italian major seaports, overall thirty. A GIS-based procedure for seismic damage assessment has been set up starting from the hazard definition accounting for contribution of site effects. Particular attention has been paid on liquefaction susceptibility evaluation. Damage to structures is assessed through fragility curves. Applications of the procedure are illustrated with reference to the seaports located in Calabria, the region with the largest seismic hazard of Italy.

Keywords: seaports; GIS technology; seismic damage assessment; liquefaction; Calabria.

1. INTRODUCTION

Seaports play a pivotal role in the policies of sustainable mobility, as critical points of connection that allow the transfer of goods and passengers, helping to increase the functionality of the general system of transportation. With over 80% of world merchandise trade by volume being carried by sea, maritime transport remains the backbone supporting international trade and globalisation. The importance of the sea and of the ship transportation is evident especially for those countries, such as Italy, with a particular geographical location and an extensive coastline. As a matter of fact, Italy stretches out into the Mediterranean Sea with a coastal development of more than 8000 km without comparison with the rest of continental Europe.

Worldwide, a large number of important maritime ports are located in active seismic regions, as for instance the Mediterranean area (e.g., Italy, Greece, Turkey, Algeria, etc.) or the circum-Pacific belt (the so-called “Ring of Fire”, e.g., California, Alaska, Peru, Chile, Japan, New Zealand, etc.). Historical earthquakes such as the Loma Prieta (USA, 1989), the Hyogoken-Nanbu (Japan, 1995), Tokachi-Oki (Japan, 2003) and the most recent events of Port-au-Prince (Haiti, 2010), Maule (Chile, 2010) and Tohoku (Japan, 2011) highlighted the seismic vulnerability of many existing port facilities, which suffered significant damage caused by ground shaking. Severe damage has been observed not only inside the epicentral area, but also at large distances where soil liquefaction and significant ground deformations occurred (Rathje et al., 2010; Bray and Frost, 2010). Offshore earthquakes can generate a further hazard, a seaquake, which can rapidly and violently inundate coastlines, causing damage and human losses, as during the Tohoku (Japan, 2011) earthquake.

In Italy, many of the major maritime ports, such as Gioia Tauro, Salerno, Catania, Ancona, just to name a few, are located in areas characterized by moderate to high seismicity. Therefore, the Italian Department of Civil Protection has funded a research project on seismic vulnerability and risk of

national seaport structures. Although the project is multi-disciplinary (EUCENTRE-PE d5, 2012), this paper focuses on the characteristics of the Geographical Information System (GIS), which represents the tool used to merge all available technical information of existing port structures. The data, acquired thanks to the collaboration of the Italian High Council of Public Works (Ministry of Infrastructures), are inserted into a GIS database which is continuously updated and improved. The GIS database includes thirty ports which corresponds to the most important Italian harbors located in areas of moderate to high seismicity. The collected and processed technical data of each seaport are shared with the Italian Department of Civil Protection through a complex WebGIS system architecture. The system is a robust and dynamic engine capable of processing basic information and compute newly-generated data such as seismic damage scenarios of seaport structures.
A GIS-based procedure for damage assessment of harbors has been set up starting from the definition of the hazard and accounting for contribution of site effects. A state-of-the-art methodology has been implemented to evaluate the liquefaction susceptibility and induced soil displacements. Damage to structures is assessed through the concept of fragility curves and expressed in terms of potential level of damage. Applications of the developed procedure are illustrated with reference to the port located in the area with the largest seismic hazard of Italy, the Calabria Region, involved by the Italian Department of Civil Protection in an emergency training program named “Calabria 2011” (program details at http://www.protezionecivile.gov.it/jcms/it/view_dossier.wp?contentId=DOS29163).

2. USE OF GIS TECHNOLOGY AND TOOLS FOR SEISMIC RISK ASSESSMENT

Management of disasters such as earthquakes involves three major phases: pre-disaster, co-disaster and post-disaster. During the pre-disaster phase, risk monitoring and forecasting use geographical information systems to store, analyze and display georeferenced information and potential damage scenarios. GIS remains a key instrument also in the emergency phase due of its dynamic character that allows to readily update the available information and its ability to produce new processed data in a short amount of time. Especially, when natural events like earthquakes occur and time to respond is crucial, GIS tools can provide answers to vital questions, such as where the most affected areas are and how they can be reached. Despite these disasters affect many regions of the world and the problems faced are different, they find in GIS an ideal tool of treatment.

2.1. GIS technology to manage port facilities data

The GIS database includes all the major Italian seaports located in medium to high seismicity areas. An additional adopted selection criterion is the importance of the port for the purpose of civil protection in the emergency planning and managing phases in case of an earthquake. Thirty is the total number of ports under investigation (see Fig. 2.1 a): Ancona, Augusta, Bari, Barletta, Carrara, Castellammare di Stabia, Catania, Catanzaro, Civitavecchia, Corigliano, Crotone, Formia, Gaeta, Gela, Gioia Tauro, Livorno, Manfredonia, Messina, Milazzo, Napoli, Palermo, Pozzallo, Reggio Calabria, Riposto, Salerno, Siracusa, Torre Annunziata, Trapani, Vibo Valentia and Villa San Giovanni. The GIS database is continuously updated to include all available technical information regarding the selected seaports. The technical data of the port structures are acquired in purposely devised and calibrated questionnaires that the port authorities are asked to fill in. The question themes are organized as check lists, in order to create a basic and standard database that can be integrated in different time steps with the introduction of further data. The questionnaires are organized in three parts. The first general part of the technical card includes indicators which define the strategic role played by the port at national level. The second part of the questionnaires concerns relevant structural and geotechnical features affecting the seismic vulnerability of wharf structures. Recently, the questionnaire has been integrated to obtain information about port security management according to Italian legislation (Bozzoni et al., 2010).

The GIS platform is the key instrument used to merge collected data such as property surveys, facility base maps, soil-boring data, buildings plans and facility as built-drawings, referenced and tied together using a georeferenced spatial context thus creating a geographic port data framework (Wright and

Yoon, 2007). The spatial georeferencing of the information permits the link among various datasets. The overlay of data provides a powerful tool for the analysis and integration of datasets from different sources. GIS tools allow also the creation of data models and maps, specifically providing the opportunity of:

- updating the available information by changing/adding themes within a set of data through the use of advanced editing tools. For example, information regarding new port facilities, added in the new regulatory plan for the expansion and renovation of the port area, can be easily included within the database;
- associating multi-category, multi-layered, dynamic, non-spatial information with spatial information; files of various typologies (e.g., textual documents, images, etc.) can be linked to a georeferenced object and may be visualized through specific querying functions, which allows to jointly assess the various factors that contribute to the seismic risk in the port area;
- performing sophisticated queries (on attributes and spatial features) to the represented georeferenced objects with the purpose to localize elements of interest and circumscribe areas of influence for various typologies of phenomena (e.g., zone with high soil liquefaction potential);
- processing the information to derive new original data through tools of composition;
- computing evolution and queries scenarios (“what if” analysis) in order to identify in the short term anomalies and situations that require urgent actions to mitigate the seismic risk in port areas.

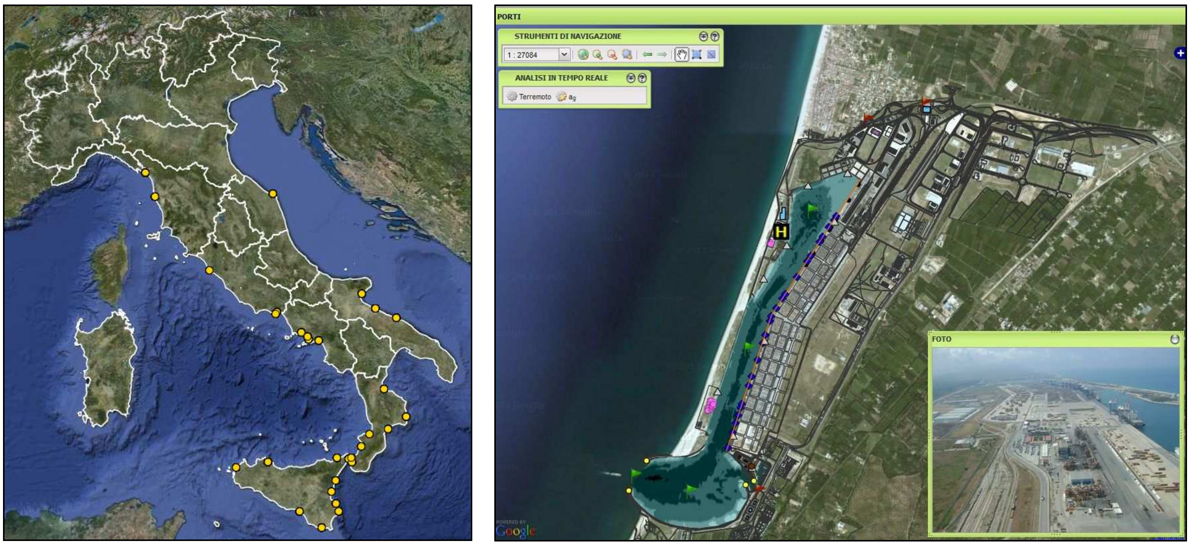
The adopted GIS software is ESRI ArcGIS 9.1. The spatial information is encoded in the geographic information system through two main types of data: vector data and raster. The vector mapping is particularly suited to the representation of data that vary discretely, such as the location of soil-boring or the representation of transport infrastructures within the port system (power lines, water lines, etc.). The adopted vector data format is the shapefile, developed and regulated by ESRI and issued substantially as open source in order to increase interoperability among ESRI and other GIS systems. The raster map is more suited to the representation of data which vary continuously, such as the maps that represent the settlements induced by soil liquefaction in the port area. Raster and vector data coexist and complement each other increasing the system capabilities.

2.2. The WebGIS platform of the Calabrian seaports

Data, information and results of calculations can be made available and searchable online through the development of specific functionalities with appropriate WebGIS applications. The GIS platform of seaports is integrated and harmonized with all the services that EUCENTRE is developing for the Italian Department of Civil Protection as GIS databases useful to asses seismic risk of Italian strategic buildings (e.g., schools, hospitals), lifelines and dams. The complex WebGIS Architecture, whose creation is currently underway, allows a homogenous and composite flow of information to the Department of Civil Protection.

Specifically, the WebGIS platform provides for the seven ports under investigation of the Calabria Region a database with geological, geotechnical and bathymetric data and information on the structural and infrastructural elements of the seaport system. Thanks to the support of the Italian Department of Civil Protection and the Italian High Council of Public Works (Ministry of Infrastructures), reconnaissance surveys were carried out in order to acquire technical data concerning the ports of Gioia Tauro, Reggio Calabria, Vibo Valentia, Crotone, Corigliano, Villa San Giovanni and Catanzaro. The visit at each port allowed also a direct view of the strategic port elements, whose technical data have been kindly provided by the port authorities.

The collected data concerning the Calabrian seaport structures have been processed and organized in the WebGIS platform, where the following pieces of information are now available: digital and georeferenced general plan view of the port and its bathymetry; technical data related to the wharf structures (e.g., structural typology, state of repair, constitutive materials); data from geotechnical investigation performed in the port area; availability of backup areas suitable for civil protection purposes in case of an earthquake (e.g., existence of emergency zones to be allocated to host tent camps for displaced persons); port accessibility (e.g., inlet, access ways linking the port area to roads and railways, helicopter landing pads); port facilities and infrastructures of strategic importance (e.g., bunkering facilities, storage sites of dangerous goods); tsunami hazard maps developed by the University of Bologna (EUCENTRE-PE d5, 2012). Fig 2.1 b shows an extract of the WebGIS platform for the port of Gioia Tauro.



a) **b)**

Figure 2.1. Extracts of the WebGIS platform: a) Italian seaports under investigation (overall thirty ports); the port of Gioia Tauro with in evidence the general plan view of the port, the bathymetry, the access points to the port area, port facilities and infrastructures of strategic importance for civil protection purposes

The WebGIS platform of the maritime ports allows to consider and evaluate jointly the different factors that contribute to seismic risk in the port area, providing also the possibility to identify the vulnerable structural and infrastructural elements of the harbour system. Thus, this platform is the ideal tool to assess the seismic risk of maritime port facilities.

3. GIS-BASED PROCEDURE FOR THE SEISMIC DAMAGE ASSESSMENT OF SEAPORT

Damage assessment of seaports under seismic loading is of fundamental importance due to their strategic role: any disruption in the activities of port infrastructures may lead to significant economic losses and can hamper the response and recovery efforts following a natural disaster. In the present paper, a GIS-based procedure for the evaluation of seismic damage which includes the assessment of the seismic hazard, vulnerability and exposure of seaport structures will be outlined. Fig. 3.1 schematically shows the flow-chart of the procedure. It is important to point out that all the steps of the procedure can be carried out at various levels of complexity, applying more sophisticated algorithms and approaches depending on the availability and quality of the data. Damage scenarios is computed in the GIS environment integrating the adopted procedure through the coupling with external programs purposely developed. Furthermore, the possibility to share the GIS platform with the DPC through the WebGIS Architecture constitutes a key instrument for the development of seismic risk mitigation and prevention strategies.

3.1. Seismic hazard assessment

Seismic damages observed at seaports are due to different types of hazard namely ground shaking, liquefaction, soil settlements and, for strong earthquakes, surface fault rupture. Thus, the developed procedure involves: seismic hazard assessment for standard site conditions; local ground response analyses; evaluation of liquefaction susceptibility and induced displacements.

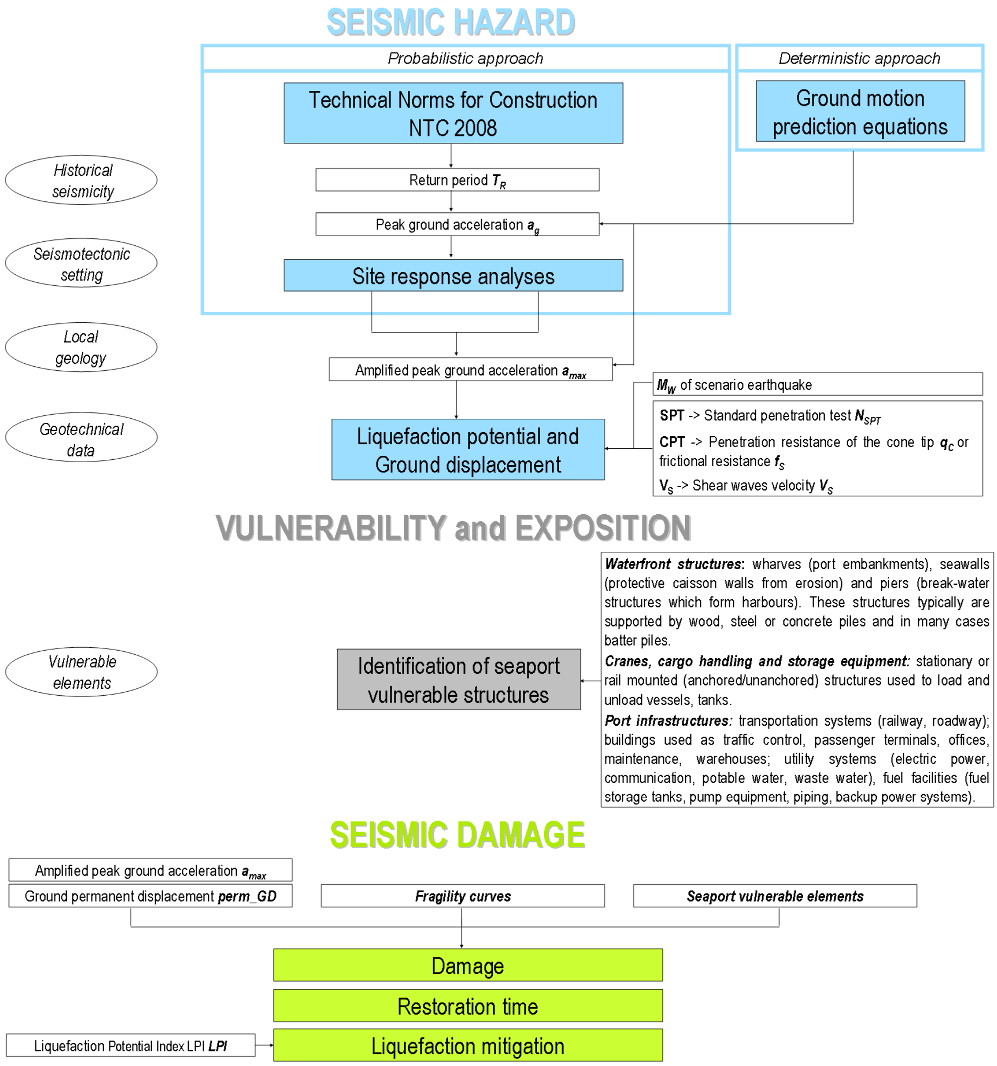


Figure 3.1. Flow chart of the procedure for damage assessment of seaport structures

3.1.1. Severity of seismic ground motion

Concerning the severity of ground shaking, both probabilistic and deterministic approaches have been considered. In Italy, the probabilistic seismic hazard was assessed by the National Institute of Geophysics and Volcanology (http://esse1.mi.ingv.it/) in terms of both uniform hazard acceleration and displacement spectra. This study was used in the current Italian technical norms for construction (NTC, 2008; Circolare NTC, 2009) to prescribe the seismic action. A fundamental step in the application of the probabilistic approach is the definition of the return periods to be used for seaport structures. For port facilities, limit states to be considered according to the technical norms are the Damage Limit State (SLD) and the Life Saving Limit State (SLV), characterized by probabilities of exceedance respectively of 63% and 10% in a reference period given by the product of the service life of the structure by an importance factor. Since in the current Italian legislation seaports are considered strategic structures, they are attributed with a reference period of 100 years. Hence, the computed return periods for the above two limit states turn out to be 100 and 950 years. To have a comparison with international recommendations, an investigation has been carried out by consulting relevant documents available in the literature on this subject (e.g., Werner, 1998; PIANC, 2001; Pitilakis et al. 2006, POLA, 2007). Werner (1998), PIANC (2001) and POLA (2007) indicates substantially two reference return periods for the seismic action, 75 and 475 years. Pitilakis et al. (2006) suggest that in case of strategic structures such as seaports the seismic hazard assessment should be performed for return periods of 100, 475, and 950 years. In light of this, three return periods has been considered: 100, 475 and 950 years. Thus, the definition of the seismic action is consistent with the requirements contained in the current Italian legislation and in the most important international references.

As an alternative to the probabilistic approach, the seismic action has been also defined using a deterministic approach based on Ground Motion Prediction Equations (GMPEs) accurately selected for the sites under consideration. Following this method, the parameters required to use the adopted GMPEs can be defined using the Italian Database of Individual Seismogenic Sources (DISS v.3.1.1, 2010, http://legacy.ingv.it/DISS), integrated in the WebGIS platform. Alternatively, the earthquake scenario was defined by the magnitude-distance pair computed from deaggregation of the probabilistic seismic hazard study (Spallarossa and Barani, 2007). In the framework of "Calabria 2011" program, a simplified procedure has been implemented using the selected GMPEs in order to develop, "real time", seismic damage scenarios for wharf structures, with minimal data requirement. The methodology, fully automated and integrated in the WebGIS, requires, as input data from the user, the major seismological characteristics of the event available in the immediate aftermath of the earthquake (further details in EUCENTRE-PE d5, 2012).

3.1.2. Site response analysis

While the deterministic approach, through the GMPEs, provides an estimate of peak ground acceleration for either rock or soil conditions, in the probabilistic approach the ground motion was predicted for stiff ground and level surface topographic conditions.

For the evaluation of site effects, the NTC (2008) allows the use of a simplified approach by applying the provided amplification factors (S_S for the litho-stratigraphic effects) which modify the shape and the amplitudes of the ordinate of the elastic response spectrum. Alternatively, it is possible to evaluate the litho-stratigraphic effects by specific site response analysis, that require spectrum-compatible acceleration time histories recorded on rocky sites selected from accredited strong motion databases. This type of analysis is based on an adequate knowledge of the geotechnical soil properties, from in situ and laboratory tests, that allows the definition of a suitable soil geotechnical model. If the hypothesis of vertically propagating seismic waves through horizontally layered soil deposits is verified, a one-dimensional (1D) model can be assumed for the evaluation of litho-stratigraphic amplification. Several codes are available to perform this kind of analyses (e.g., SHAKE2000, EERA, STRATA, ProShake, DEEPSOIL, etc.). The quality and completeness of the data used to construct the soil model strongly affect the reliability of the results. The implemented procedure includes the opportunity to perform 1D fully stochastic site response analysis that allow to assess the sensitivity of results to both epistemic and aleatory uncertainty of soil model parameters as well as the variability of seismic input (see the application carried out, in the project, for the port of Salerno in EUCENTRE-PE d5, 2012). In case of more complex soil configuration, for which a 1D model is not appropriate, more sophisticated and refined models (i.e., two-dimensional or three-dimensional) are to be used.

3.1.3. Evaluation of liquefaction susceptibility

Liquefaction risk has been recognised as one of the most significant seismic geotechnical hazards for an harbor area (Rathje et al., 2010; Bray and Frost, 2010). Therefore, particular attention has been paid on the assessment of seismic soil liquefaction potential. The evaluation of liquefaction susceptibility is performed in several stages that include: preliminary geological/geotechnical assessment of the site; quantitative estimate of liquefaction potential; development of mitigation programs, if required.

Concerning site assessment, a detailed summary of available methods that can be used to characterize shallow marine sediments at seaports is illustrated in Bozzoni et al. (2010). Data of seaports under investigation, acquired and collected in the GIS database, are the basis for the geological and geotechnical characterization at the harbor sites.

The assessment of liquefaction potential was carried out using empirical correlations linking liquefaction capacity to field-measured penetration resistance or low-strain stiffness. The field tests, upon which the method of empirical correlations is based, have now reached a sufficient level of maturity as to represent a reliable tool (Youd et al., 2001). For sites in Italy, they include the standard penetration test (SPT), the cone penetration test (CPT) and direct measurement of in situ shear wave velocity V_S (Lai et al., 2009). SPT and CPT are generally preferred due to the extensive databases and experience. The oldest, and still the most widely used of these, is the SPT. In general, the methods based on empirical correlations should be used with the awareness that the obtained predictions can be considered valid only in first approximation. Therefore, an in-deep study has been undertaken to identify the most suitable approaches to evaluate liquefaction potential taking into account advantages and disadvantages of each adopted method.

An ad hoc procedure has been implemented in GIS environment using the selected liquefaction triggering methodologies based on STP data. Two different approaches has been applied: the deterministic approach, based on the concept of factor of safety (F_S) and the probabilistic approach, for which the liquefaction potential of a soil is described in terms of probability of liquefaction (P_L). Furthermore, the implemented methods allow both a punctual assessment of susceptibility to liquefaction at different depths, through the definition of F_S and P_L profiles with depth, and a global estimate of the incidence of the phenomenon by the Liquefaction Potential Index LPI, proposed by Iwasaki et al. (1978), and the Liquefaction Severity Index LSI, introduced by Yilmaz (2004). Simplified approaches have been adopted for the evaluation of liquefaction-induced soil settlements and lateral displacements.

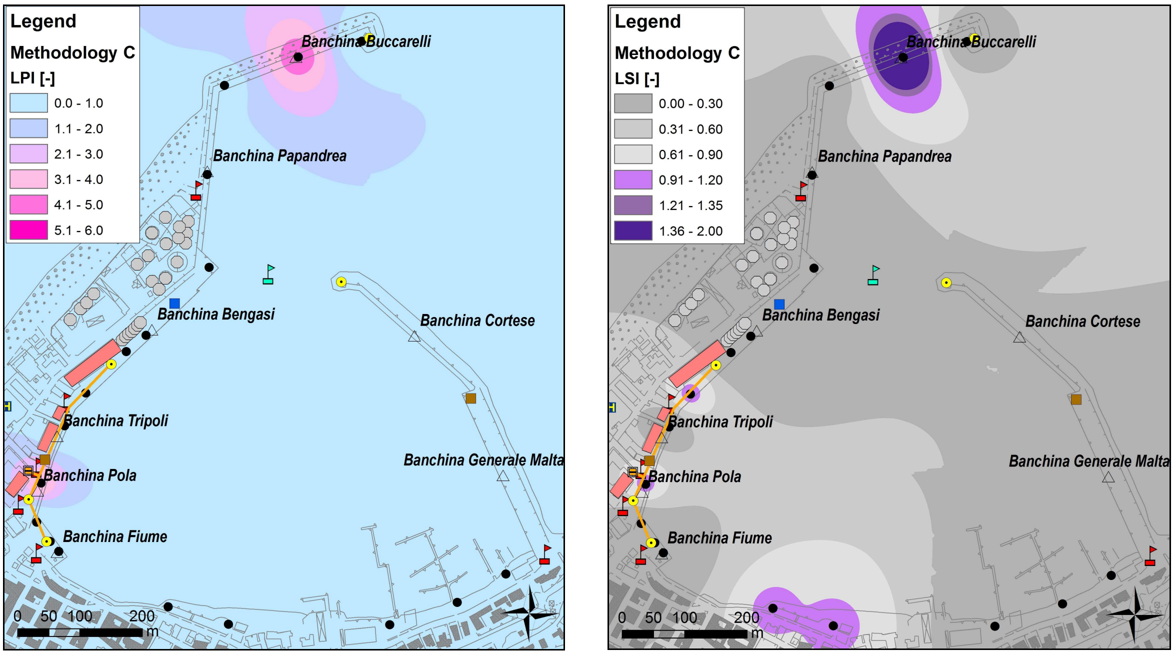
Three computation methodologies, named Methodology A, Methodology B and Methodology C, have been implemented basing especially on Lai et al. (2009), Idriss and Boulanger (2008) and Seed (2010) recommendations. Each methodology permits to compute the following parameters: factor of safety, probability of liquefaction, LPI, LSI, vertical settlements and lateral spreading. The Methodology A includes the widely employed methods (e.g., Youd et al., 2001). The recent monographs of Idriss and Boulanger (2008) and Seed (2010) highlighted that the most negative aspect of such methods consists in using databases which are not updated with recent data. Seed (2010) criticized also several formal aspects contained in the monograph of Idriss and Boulanger (2008). In particular, he argued that the results obtained by applying the methods developed by Idriss and Boulanger (2008) are highly unconservative and suggested the use of the procedure set up by Cetin et al. (2009), who proposed a probabilistic approach based on advanced Bayesian methods for the evaluation of liquefaction potential and soil settlements.

LPI and LSI with the values of vertical settlements and lateral displacements are used for the creation of liquefaction hazard maps in GIS environment. Liquefaction continuous maps (raster) are particularly useful for the decision makers during the phases of emergency response planning and mitigation prioritization. Mitigation strategies to be proposed when required, are those described in Idriss and Boulanger (2008) and Lai et al. (2009).

The assessment of the susceptibility to liquefaction for the port areas of Vibo Valentia, Crotone and Reggio Calabria was carried out by applying all three methodologies described above. Fig. 3.2 shows digital and georeferenced maps, obtained in GIS environment, which represent the values of LPI (Fig. 3.2 a) and LSI (Fig. 3.2 b), computed at the port of Vibo Valentia for the return period of 950 years, applying the Methodology C. Maximum values of LPI and LSI are reached in a limited area of the port, at "Banchina Buccarelli". The LPI values are less than 6, therefore, on the basis of the correlations proposed in the literature between LPI and ground failure levels (Lai et al., 2009), the liquefaction failure potential can be considered low. Fig. 3.2 b shows that the LSI parameter is less than 1.35 in the largest part of the port area, thus the liquefaction failure potential is low (Yilmaz, 2004). The use of liquefaction digital and georeferenced maps not only provides a representation of the geographical variability of the phenomena within the harbour area under invesigation, but also allows to extrapolate the input data necessary to estimate the damage to the port structures.

3.2. Vulnerability and damage of port facilities

Harbours represent complex systems of elements with different features and vulnerability and during an earthquake various facilities can be damaged, from wharves with their supporting systems to superstructures and utilities. Port facilities can be classified into three main categories (see Fig. 3.1): waterfront structures (i.e. wharves, seawalls); cranes, cargo handling and storage facilities; port infrastructures, such as transportation systems and utility systems.



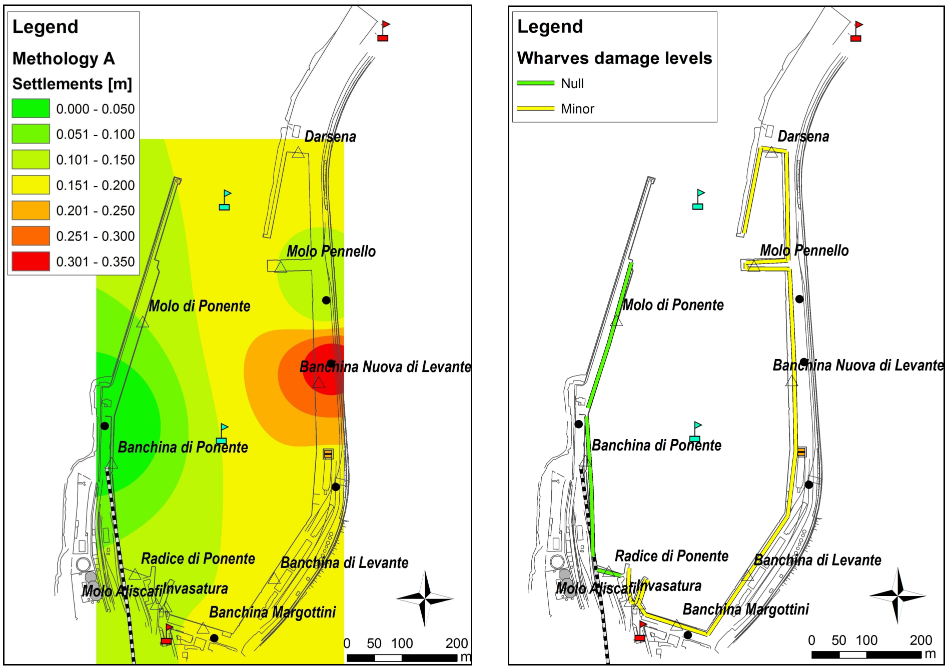
a) b)

Figure 3.2. Digital and georeferenced GIS maps which represent the values of LPI (a) and LSI (b) computed at the port of Vibo Valentia applying the Methodology C for the return period of 950 years.

Damage to harbour components is classified into five levels: slight/minor, moderate, extensive and complete. Damage to each component is estimated by vulnerability curves defined as (cumulative) lognormal distribution functions, which provide the probability of exceeding different levels of damage as a function of a specific ground motion parameter. Vulnerability of seaport structures has been calculated by using empirical fragility curves following the standard procedure proposed in HAZUS (NIBS, 2004) which is supported by data and results collected and revised in the European projects RISK (Pitilakis et al., 2006) and LESSLOSS (Faccioli, 2008). Although the procedures for damage assessment implemented in HAZUS are based on American and Japanese data, a study by Kakderi et al. (2006) showed that these databases can be reasonably used, to a first approximation, also in the European context. Different ground motion parameters are used depending on the typology of the structure: permanent ground displacement for waterfront structures, railways, storage and fuel facilities; peak ground acceleration for cranes; peak ground velocity or peak ground strain for buried pipelines; other ground motion parameters for different specific components (NIBS, 2004, Pitilakis. et al., 2006). In HAZUS no distinction is made between different kinds of waterfront structures (i.e. wharves, piers, seawalls) and types of ground displacement. Research projects are currently underway to define ad hoc fragility curves; for instance, in the European framework, REAKT project (http://www.reaktproject.eu/) has, among others, the objective of developing time-dependent fragility functions for critical structures and infrastructures, such the ones located in the port system.

Damage state is expressed in terms of percentage of non-functionality which is estimated as the probability of a structure to reach at least a moderate level of damage (Pachakis and Kiremidjian, 2004). This parameter is of relevant importance since the consequences of seismic damages are not only related to life safety and repair costs of the structures, but also to interruption of port serviceability in the immediate aftermath of an earthquake. On the other hand, the time required for restoration of damaged structures constitutes the basis to estimate economic and social losses.

Fig. 3.3 b shows an example of seismic damage scenario for wharf structures computed at the port of Reggio Calabria for the return period of 950 years. The damage levels for wharves have been evaluated using HAZUS fragility curves, which require as input data the ground permanent displacement, assumed equal to the estimated vertical settlements, represented in the GIS map of Fig. 3.3 b. From the GIS map, it is possible to extract the values of the settlements for the points at which the port structures of interest are located. The wharf structures are represented as linear elements, purposely discretized in segments of some tens of meters in order to take into account the geographical variability of the input parameter to fragility curves. On the basis of the results obtained applying the three methodologies implemented for the liquefaction potential assessment, higher values of vertical settlements are reached in the eastern part of the port area, specially at “Banchina Nuova di Levante”, where the maximum settlements are 35 cm. This is the reason why the expected damage level at wharves located in the eastern part of the Reggio Calabria port is minor (see Fig. 3.3 b).



a) **b)**

Figure 3.3. Digital and georeferenced GIS maps which represent the values of vertical settlements (a) and the damage level estimated for the wharf structures (b) at the port of Reggio Calabria for 950 years.

4. CONCLUDING REMARKS

The paper illustrates the ongoing research project funded by the Italian Department of Civil Protection on seaport seismic vulnerability and risk assessment. A pivotal aim consists in the creation of a georeferenced WebGIS database of the major Italian seaports located in moderate to high seismic zones. This article focuses on the main features and capabilities of this tool able to transform the multitude of heterogeneous datasets concerning port facilities into interactive and intelligent map-based visuals. The WebGIS platform represents a valid support to decision makers for the purpose of civil protection, being the corner stone of a multi-disciplined approach to mitigate the seismic risk in port areas. A GIS-based procedure for seismic damage assessment of seaports has been set up starting from the definition of the hazard and accounting for contributions of both site effects and liquefaction susceptibility. Some applications of the set up methodology have been illustrated with reference to the seaports located in Calabria.

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