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Tsunami vulnerability and damage assessment in the coastal area of Rabat and Salé, Morocco

A. Atillah[1], **D. El Hadani**[1], **H. Moudni**[1], **O. Lesne**[2], **C. Renou**[2], **A. Mangin**[2], **and F. Rouffi**[2]

[1]Centre Royal de Télédétection Spatial, Rabat, Morocco
[2]ACRI-ST, 260 Route du Pin Montard, BP 234, 06904 Sophia-Antipolis Cedex, France

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Abstract. This study, a companion paper to Renou et al. (2011), focuses on the application of a GIS-based method to assess building vulnerability and damage in the event of a tsunami affecting the coastal area of Rabat and Salé, Morocco. This approach, designed within the framework of the European SCHEMA project (www.schemaproject.org) is based on the combination of hazard results from numerical modelling of the worst case tsunami scenario (inundation depth) based on the historical Lisbon earthquake of 1755 and the Portugal earthquake of 1969, together with vulnerability building types derived from Earth Observation data, field surveys and GIS data. The risk is then evaluated for this highly concentrated population area characterized by the implementation of a vast project of residential and touristic buildings within the flat area of the Bouregreg Valley separating the cities of Rabat and Salé. A GIS tool is used to derive building damage maps by crossing layers of inundation levels and building vulnerability. The inferred damage maps serve as a base for elaborating evacuation plans with appropriate rescue and relief processes and to prepare and consider appropriate measures to prevent the induced tsunami risk.

1 Introduction

The Moroccan Atlantic coast is highly exposed to tsunamis generated by submarine earthquakes like the 1 November 1775 event (El Mrabet 1991, Baptista et al..1998, Gutsher 2004, Zitellini et al., 2001, Kaabouben et al., 2009, Omira et *al.* 2009a, Omira et al., 2009b;). The study area of Rabat and Salé is particularly affected by tsunami hazard as reported by historical documents in which inundation related to the tsunami of 1755 reached a maximum distance of 2000 m inland and great damage had affected the town of Salé (Kaabouben et al., 2009). In Rabat city two hundred people were drowned (El Mrabet, 1991).

Moreover, this area is highly vulnerable because of its high population density, the presence of old centres with poorly resistant houses, and mainly because of the large flow of summer visitors on the two narrow beaches of Rabat and Salé with a maximum daily frequency of 75 000 and 13 000 persons, respectively (Direction of Ports and Direction of Risk Survey and Prevention, 2004). Furthermore, due to the development of the Bouregreg Valley into a large residential and touristic complex, the expected results of this study, designed to be used to identify potential zones at risk of flooding, could then be integrated into the new management planning.

This study focuses on the application of a common GIS approach for tsunami vulnerability and damage assessment on the Rabat and Salé sites performed within the framework of the SCHEMA project (Scenarios for Hazard-induced Emergencies Management)[1], aiming at using Earth observation data in order to develop and validate a simplified methodology to produce hazard, vulnerability and damage maps in case of tsunami events. The methodology seeks to quantify direct damage to buildings by combining tsunami hazard maps (maximum inundation depths) and building vulnerability maps.

The results are presented in the form of a series of vector maps of vulnerability classes and damage levels so they can be easily used or integrated into any GIS system of the end users. Both the methodology and the vulnerability maps have been validated by local end users. In fact, an atlas containing all maps representing tsunami hazard, building vulnerability and building damage levels and an associated questionnaire were sent to various local organisations dealing with disaster

Correspondence to: A. Atillah
(atillah@crts.gov.ma)

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crisis management (Civil Protection, Moroccan Red Crescent, Direction of Ports, Local Authorities, Insurance Companies, Environment Department, Ministry of Health, Universities and specialised institutes) to evaluate the approach and results. A national workshop for all these potential end users was organized in Rabat to discuss the relevance, the pertinence and the usefulness of these results. The users' feedback and suggestions were then taken into account to improve both the approach and the final maps.

2 State-of-the-art

A number of previous works to assess tsunami vulnerability has been carried out. The 2004 Indian Ocean tsunami generated much interest and numerous efforts are underway to assess the risk from tsunami. In this field, various approaches have been developed to assess the risk to coasts. The most commonly used method for assessing building vulnerability to damage from tsunami is the "Papathoma Tsunami Vulnerability Assessment" (PTVA) Model (Papathoma and Dominey-Howes, 2003; Papathoma et al., 2003; Dominey-Howes and Papathoma 2007; Dall'Osso et al., 2009a,b; Dall'Osso and Dominey-Howes, 2010). The PTVA model incorporates multiple vulnerability factors (building physical features, building environment and exposure to inundation) as attributes to calculate a Relative Vulnerability Index (RVI) score for every building within the flood area in order to assess both building and human vulnerabilities. In the absence of validated building fragility models, the weighting and ranking of attributes according to their importance in this model are subjective and based only on expert judgement (Dall'Osso and Dominey-Howes, 2010). Moreover, the potential inundation depth zone is not simulated but only identified as the area between the coastline and the 5 m contour (highest recorded tsunami) without taking in consideration tsunami source and offshore bathymetry. In this sense, the model was used to provide first-order assessments of building vulnerability to tsunami by establishing a GIS-based map and generating a primary database (Papathoma and Dominey-Howes, 2003; Papathoma et al., 2003).

Dominey-Howes and Papathoma (2007), testing and evaluating this method, proposed an improved version of the original PTVA model by refining attributes using field data from the Indian Ocean tsunami. The authors modified and detailed the attributes to estimate the Probability Maximum Loss (PML) for a tsunami.

Dall'Osso et al. (2009b) and Dall'Osso and Dominey-Howes (2010) proposed an enhanced version of the model (PTVA-3) introducing a multi-criteria approach in the ranking and weighting of the attributes based on the use of Analytic Hierarchy Process (AHP) in order to minimise the subjective nature of the ranking of attributes. Thus, the authors incorporated into the model the vulnerability of building elements due to their contact with water (intrusion water) as a new set of attributes to calculate the RVI of a building. The greatest limitation of this PTVA model as recognised by its designers is the large number of input data required that are often difficult to collect (Dall'Osso and Dominey-Howes, 2010). On the other side, vulnerability in this method is completely detached from the notion of hazard, thus independent from the flow height values or any other physical value describing the impact of the tsunami (Valencia et al., 2011).

Recently, a study of building vulnerability assessment of coastal zone of Casablanca (Morocco) was carried out by Omira et al. (2009b). The authors proposed a GIS approach to evaluate the impacts of tsunami on buildings based on the same principle of the PTVA model. Nevertheless, the work was not done for each building unit, but for whole block of buildings. Thus, one level of RVI was allocated to all buildings composing the block.

Other authors have developed different approaches for assessing building damage based on deriving empirical damage functions from field observations on the past tsunami events (Peiris, 2006; Leone et al., 2006; Ruangrassamee et al., 2006; Garcin et al., 2007; Reese et al., 2007; Leone et al., 2010). These approaches assume that damage is only due to hydrodynamic pressure generated by the water level of tsunami, ignoring other potential factors inducing damage to buildings. Thus, the damage level (resistance level of a building) is linked to the maximum inundation depth in order to obtain a logarithmic distribution. The water elevation criterion is considered the only reliable and uniform parameter of the tsunami magnitude to vulnerability functions on buildings and that can be observed or measured following all tsunami events. Nevertheless, the probabilistic approach proposed by Peiris (2006), despite its relevance, is more adapted to quantification by numbers of damage quantities by buildings stock, than to cartographic representation of ranges of damage probability requiring the use of sophisticated tools for its very random component (Guillande et al., 2009).

Regarding the SCHEMA project philosophy, the main purpose was to provide a simple and transferable method based on usual tools or functions of common GIS. Then, based on previous works of Leone et al. (2006, 2010); Koshimura et al. (2007) and Peiris (2006), an average damage approach is proposed that consists of the computation of the mean level of damages for different classes of buildings developing several new damages functions (Valencia et al., 2011).

3 Brief review of SCHEMA project

SCEMA (www.schemaproject.or) is a research project conducted by a consortium of 11 organisms aiming at completing past and new research results dealing with several single hazard events in order to fulfil gaps and needs in terms of methodology assessing tsunami hazard and vulnerability in Europe as highlighted by the conclusions of the high level group on tsunami risks in Europe, based on the December

Asian disaster[2]. It intended to define vulnerability criteria and to provide a common methodology to produce hazard, vulnerability and impact maps related with the occurrence of tsunamis in the Mediterranean and NE Atlantic basins, using a combination of tsunami modelling, field surveys, earth observation and GIS data. The main issues addressed by SCHEMA was the clarification of concepts and building up a generic approach to assess vulnerability and risk with respect to tsunami hazard scenarios considering various spatial scales (large, regional or local). This should be accomplished in order to produce comprehensive documents and maps that end users could integrated in coastal management strategies[3]. The project mainly consisted of:

- Analysing performance and limitations of existing tsunami modelling to reproduce real cases of tsunami occurred in the past in order to assess the degree of uncertainties of results and to determine the local factors explaining the difference between models and real life (on the basis of the Dec 2004 Asia event);
- defining and extracting vulnerability and hazard level indicators, based on intrinsic vulnerability variables, (proprieties of buildings) and environment variables (density of buildings per unit area, road width, presence of floating objects, ...) using earth observation data;
- designing and developing a general methodology, in coordination with end-users, to produce scenarios impacts for tsunami, derived from hazards and vulnerability maps;
- validating the methodology on real life cases as observed during the recent tsunami in Asia;
- applying the prototype methodology to 5 test cases typical of different environments (Rabat-Salé Cities in Morocco, Setubal in Portugal, , Mandelieu in France, Catania in Italy and Balchik in Bulgaria) and proposing tsunami-based disaster scenarios involving earthquake and/or landslide events;
- providing relevant evacuation plans with or without early warning systems.

[2]Outcome of the Consultation Meeting on Tsunami Risk in Europe: status, Gaps and Needs Related to Early Warning Systems (28/02–02/03/2005–21/22/03/2005): tsunami research needs in Europe. (http://ec.europa.eu/research/environment/pdf/draft_final_document_en.pdf)

[3]SCHEMA project, Sixth Framework Programme Priority (Space) of the European Commission, Contract no. 030963: "Description of Work" (http://www.schemaproject.org/).

3.1 Outlines of SCHEMA methodology for building damage scenarios

Within the SCHEMA project a global common methodology has been designed and applied to the five test areas of the project. This methodology consists in modelling, for selected sources, potential scenarios of tsunami and aggregating them in order to produce a hazard map corresponding to the maximum values of inundation extent and depths. Then, this map is combined with a building vulnerability map to estimate damage scenarios using a damage matrix. A detailed description of the methodology used, based on deriving empirical damage functions, is given by Guillande (2009), Valencia (2011) and Tinti et al. (2010).

3.2 Building typology

In order to develop the SCHEMA approach based on damage functions, a building classification is proposed. This typology is principally derived from the works carried out by various authors on Banda Aceh (Leone et al., 2006) and Sri Lanka (Peiris, 2006 and Garcin, 2007) after the 2004 tsunami disaster. In this database, priority in analysis was given to constructions that were partially damaged and buildings with total destruction (thus, affected by the highest damage level) were ignored. Then, the existing building database was improved (completed, enlarged and adapted to local contexts) in order to firstly be more general by including at least the constructions modes present in the five test sites of SCHEMA and, secondly, to develop new damage functions for other classes of buildings. For example, buildings that completely collapsed have been identified using photo-interpretation of satellite images acquired before and after the tsunami event. Vulnerability classes were allocated to these buildings that may be associated with damage functions.

Depending on the structural characteristics of resistance of the buildings (intrinsic factors), a building typology has been defined containing five main classes (divided in subclasses) ranging from the most vulnerable buildings (A) to highly resistant buildings (E) (Table 1). Two other classes (F and G) representing others types of constructions (harbour, industrial buildings, historical buildings, ...) are not integrated in this study as there is no available assessment of the corresponding damage impact functions.

Knowing the damage levels of the building samples provided by a field survey, it has been possible to point out the buildings affected by the tsunami regarding the gradient of damage they suffered. Then, a discrete qualitative scale of damage levels classifying tsunami damage to buildings has been proposed, ranging from no damage (D0) to collapse (D5).

3.3 Elaboration of damage functions and associated damage matrix

Numerous authors have developed an approach deriving empirical damage functions starting from field observations for the estimation of building vulnerability (Leone et al., 2006, 2010; Peiris, 2006; Koshimura et al., 2007; Reese et al., 2007; Ruangrassamee et al., 2006). The approach proposed by the SCHEMA consortium, based on the previous works, suggests extracting fragility or damage functions for each building class using the building classes and damages levels defined above and a set of observations of maximum inundation depths observed on damaged buildings (Valencia et al., 2011). A logarithmic distribution function is obtained for each level of damage (Fig. 1). In this approach the damage level is linked to the maximum flow depth parameter supposed to be the demand parameter that governs the hydrodynamic forces causing damage to buildings. So, for each damage level there is a corresponding range of inundation depth (Guaraz et al., 2009).

To simplify the methodology, intervals of flow depth were generated for each building class. Then, for each interval of flow depth, the number of buildings suffering a certain level of damage was calculated and finally the weighted mean of damage level was computed for each building class. Unfortunately, the absence of samples representing building classes F and G in the SCHEMA database didn't permit computing the empirical functions of average damage.

Therefore, the enveloping curves for each building class, based on the extreme values of the weighted mean damage, were developed in order to take into account the worst cases of damage level for each class and to provide the starting threshold of damage for each building class (Fig. 1). This is, indeed, a conservative approach which tends to maximise the damage level for a range of water depth considered. For all curves, damage increases with flow depth.

In order to produce maps of the expected damage for different scenarios of tsunami using GIS interfaces, the continuous vulnerability functions were translated into damage matrixes (Table 2). For each building class, a given potential damage among the five levels defined above is associated with an interval of water depth.

3.4 Generation of building damage maps using GIS tool

Building damage maps are a basic element of damage scenarios. The SCHEMA common methodology of building damage maps through a GIS interface, consists of combining the simulated hazard map and the building map inventorying types of building vulnerability in the inundation area, and by making use of the damage matrix mentioned above. Thus, its application in any coastal area requires several steps (or inputs) that are illustrated in Fig. 2:

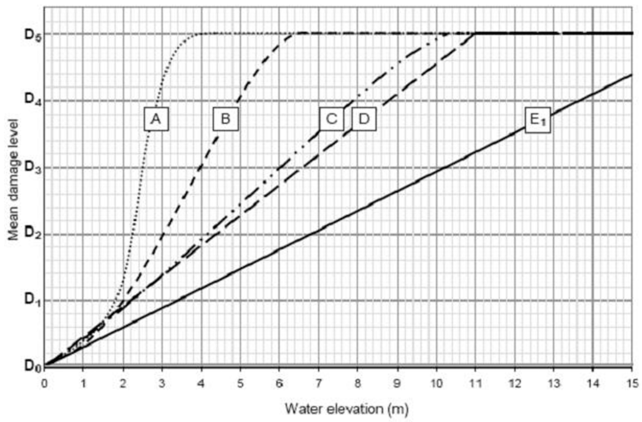


Fig. 1. Damage functions for buildings of classes A, B, C, D, E1 derived from experimental data from the area southwest of Banda Aceh (Sumatra, Indonesia) by GSC (Gardi et al. 2009).

1. Identification of the maximum inundation depth: in this study, the potential inundation zone is defined as the extreme inundation area generated by aggregation of flow depths resulting from all simulated potential tsunami hazard scenarios based on a set of selected and comprehensive sources. Indeed, the maximum inundation extent is the largest area inundated by the tsunami that results from adding together all the areas flooded by the various scenarios. Thus, local maps of the maximum tsunami height and inundation depth in the flooded zone resulting from this "aggregated scenario" are used to estimate building damages. This scenario corresponds, in fact, to the worst possible case of tsunami hazard scenario.

2. Establishing building vulnerability maps: according to the typology defined in SCHEMA, maps of classed buildings distribution within the inundation zone are achieved. Depending on its resistance proprieties, each building is assigned to one of five classes of vulnerability, ranging from the most vulnerable building (class A) to highly resistant buildings (class E).

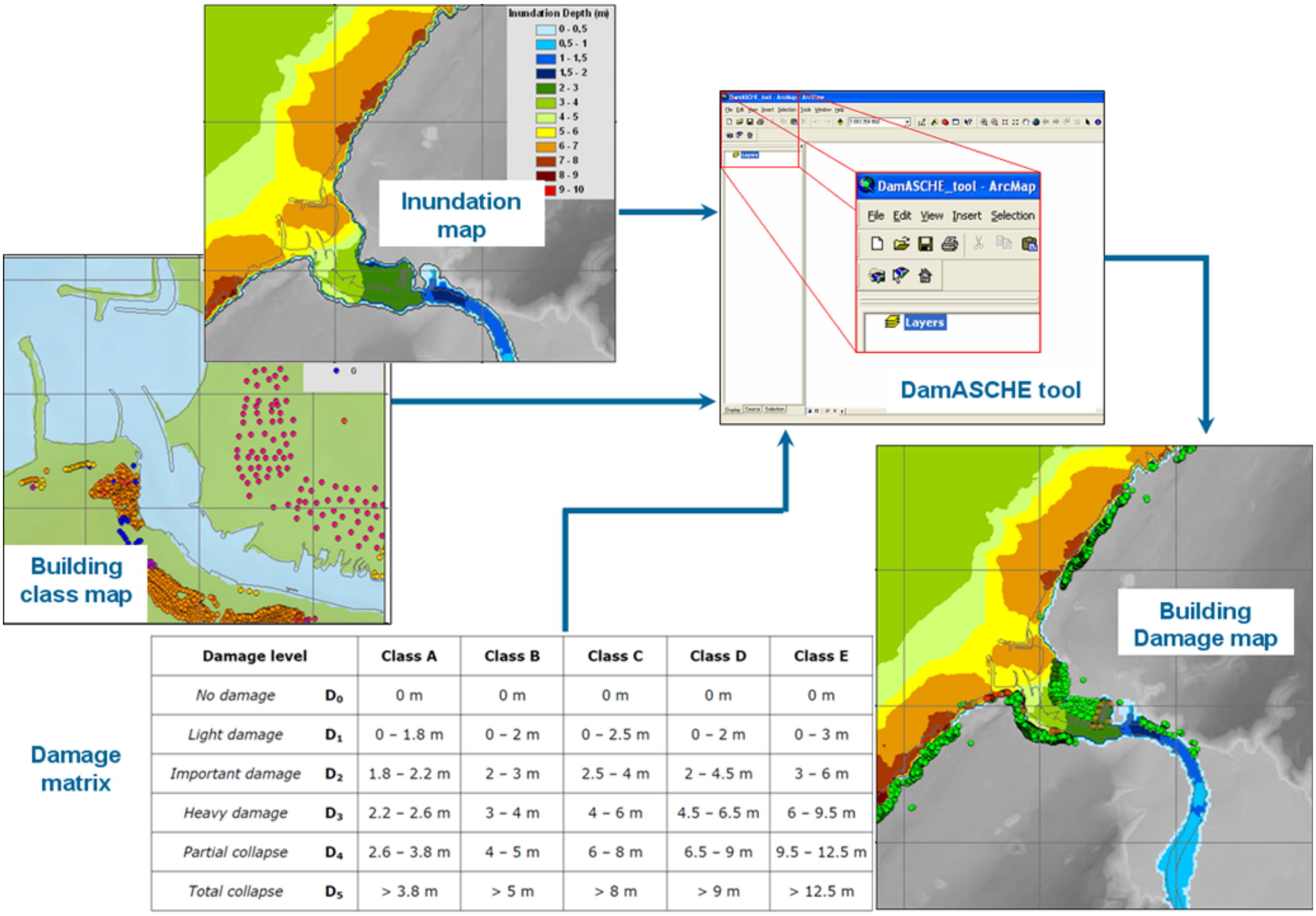
3. Deriving maps of damage scenarios: damage levels are calculated for individual buildings included in the building vulnerability map. The level damage for each building is estimated by crossing information from the map of the inundation depth resulting from the aggregated scenario with the distribution of buildings resulting from the building inventory. This combination is handled through a specific GIS application "DamASCHE tool" that has been developed by Geosciences on the ArcGIS (ESRI) platform during the SCHEMA project. This tool uses the damage matrix that provides the expected level of damage for each building according to its vulnerability class and the estimated inundation depth at its location (Table 2). The result is

Table 1. Building classification based on primary (intrinsic) factors of vulnerability (SCHEMA project).

Structural characteristics of resistance	Class/ subclass	Building types	Height/ storeys
I. Light constructions	A1	Beach or sea front light constructions (Bungalows) (*Wooden, timber, glass and clay materials*	0 to 1 floor Rarely 2
	A2	Very light constructions: Shantytown as set of huts very rudimentary, with fragile materials: wood, clay, timber, slabs of zinc	0 floor
II. Masonry constructions, not reinforced concrete	B1	Concentrated constructions not reinforced: *wooden, timber and clay materials* (old centre houses, uncontrolled buildings, rural houses...	1 to 2 floors
	B2	Brick not reinforced, cement mortar wall, fieldstone, masonry	1 or 2 floors
	C	Individual buildings, villas: *Brick with reinforced columns and masonry filling*	1 or 2 floors
	D	Large villas or collective building, residential or commercial buildings: *concrete not reinforced*	1 to 2 floors
III. Reinforced concrete constructions	E1	Residential or collective structures or offices, car parks, schools: *reinforced concrete, steel frame*	0 to 3 floors
	E2	Residential or collective structures or offices, car parks, schools, towers: *reinforced concrete, steel frame*	> 3 floors
IV. Other constructions	F	Harbour and Industrial building, hangar: *reinforced concrete, steel frames*	Undifferentiated
	G	Other, administrative, historical, religion buildings	Undifferentiated

Table 2. Damage matrix obtained for building vulnerability derived from the vulnerability functions and adopted in SCHEMA project.

Damage level		Class A	Class B	Class C	Class D	Class E_1
No damage	D_0	0 m	0 m	0 m	0 m	0 m
Light damage	D_1	0–1.8 m	0–2 m	0–2.5 m	0–2 m	0–3 m
Important damage	D_2	1.8 – 2.2 m	2–3 m	2.5–4 m	2–4.5 m	3–6 m
Heavy damage	D_3	2.2–2.6 m	3–4 m	4–6 m	4.5–6.5 m	6–9.5 m
Partial collapse	D_4	2.6–3.8 m	4–5 m	6–8 m	6.5–9m	9.5–12.5 m
Total collapse	D_5	> 3.8 m	> 5 m	> 8 m	> 9 m	> 12.5 m



Damage level		Class A	Class B	Class C	Class D	Class E
No damage	D_0	0 m	0 m	0 m	0 m	0 m
Light damage	D_1	0 – 1.8 m	0 – 2 m	0 – 2.5 m	0 – 2 m	0 – 3 m
Important damage	D_2	1.8 – 2.2 m	2 – 3 m	2.5 – 4 m	2 – 4.5 m	3 – 6 m
Heavy damage	D_3	2.2 – 2.6 m	3 – 4 m	4 – 6 m	4.5 – 6.5 m	6 – 9.5 m
Partial collapse	D_4	2.6 – 3.8 m	4 – 5 m	6 – 8 m	6.5 – 9 m	9.5 – 12.5 m
Total collapse	D_5	> 3.8 m	> 5 m	> 8 m	> 9 m	> 12.5 m

Fig. 2. Global scheme of the common methodology developed during SCHEMA project summarising the steps *to produce damage maps.*

presented as a GIS layer (map) providing quantitative description of damage levels to buildings ranging from no damage to collapse.

It should be noted here that this is a simplistic and transferable approach to assess damage levels produced by the worst-case credible aggregated scenario. Even if we admit that it uses limited physical attributes, its application to various sites differing from each other (at least in terms of tsunami data, tsunami sources, coastal and urban environment, economical, social and cultural conditions) has been constituted a good validation test for it. Therefore, it is also an operation that can be handled automatically in any GIS environment.

4 Case study: costal area of Rabat and Salé

4.1 Tsunami Hazard Assessment (purpose of Renou et al., 2011)

To generate the aggregated scenario as described above, two selected seismic sources have been used to simulate tsunami hazard scenarios on the coastal area of Rabat and Salé. One is the historical Lisbon earthquake source (magnitude M_w 8.5 to 9) that occurred in 1755 generating a devastating tsunami (Baptista et al., 1998; Gutscher, 2004; Zitellini et al., 2001) (Worst case scenario) and the second is the historical Portugal earthquake that occurred in 1969 ($M_s = 7.9$) producing a moderate scenario with a small amplitude tsunami (Fukao, 1973; Guesmia et al., 1998; Gjevik et al., 1997).

In this study, the tsunami propagation from the source to the coast was simulated through TIDAL software (a general-purpose software tool for fluid flow, heat and mass transfer problems in shallow water bodies) using nested models at three different scales: large (oceanic propagation level), regional and local, with grid resolutions of 3.7 km, 50 to 250 m (irregular grid) and 20 m, respectively. Scenario modelling has been performed both at Low Tide (LT) and High Tide (HT) conditions. However, coping with unavoidable uncertainties resulting from computations and related to various parameters' uncertainties (sources, quality of the simulation model, accuracy of topographic and bathymetric data), the amplitude of the initial wave height has been increased

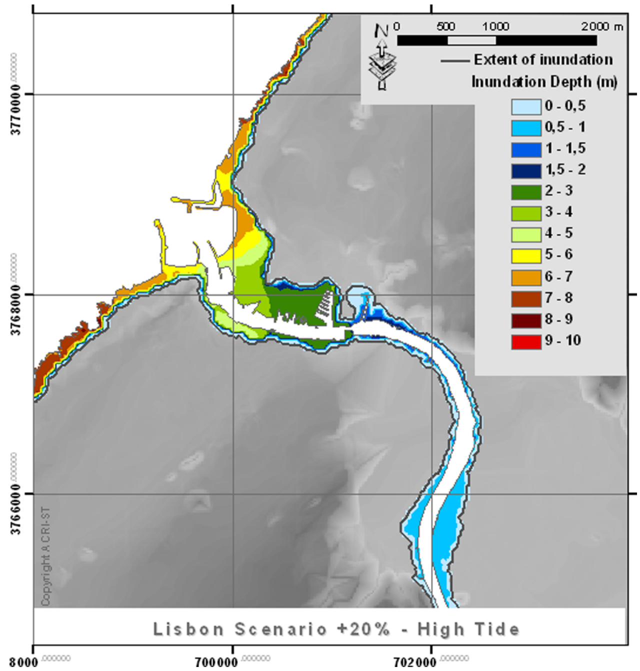


Fig. 3. Inundation depth for tsunami triggered by earthquakes (Aggregated scenario) for coastal area of Rabat and Salé.

arbitrarily by 20% to produce final hazard maps that correspond to an "augmented scenario" representing the worst possible case scenario. Thus, for a hazard map,the extreme value of inundation extent and inundation depths for each position on it are selected and computed for the two individual scenarios of tsunamis at HT + 20 % to get the worst case situation.

Figure 3, representing the local map for the aggregated scenario mainly dominated by the scenario associated with the 1755 earthquake source (augmented and at high tide condition), displays the distribution of maximum values of inundation depth and maximum values of inundation extent in the coastal area of Rabat and Salé and along the Bouregreg river. It shows that inundation depths are globally situated between 6 and 8 m except the southern part of Rabat (left bank) and the extreme North of Salé (right bank) that are affected by the highest values (8–9 m). In the flat topography area of Salé located north of the Bouregreg River, the values are smaller (2 to 5 m) due to the effect of many breakwaters newly constructed to protect the new residential and touristic complex, under construction, from marine waves. The maximum inundation depth decreases then gradullay when entering deeper in the estuary.

4.2 Building vulnerability assessment

4.2.1 Classification of building vulnerability to tsunami

It has been shown that in the coastal zone exposed to tsunami inundation, the buildings and infrastructure are not uniformly at risk within the flood zone (Papathoma and Dominey-Howes, 2003; Papathoma et al., 2003; Dominey- Howes and Papathoma, 2007). The probability of damage is related both to vulnerability (structural capacity to resist) and to the wave energy. In other words, damage level to buildings depends on building type and on inundation depth (Tinti et al., 2010). Thus, individual buildings will interact differently with a tsunami depending on a number of parameters (Papathoma and Dominey-Howes 2003; Papathoma et al., 2003; Dominey-Howes and Papathoma, 2007). Various factors (primary and secondary) that affect the resistance of the building interact to produce a net level of building vulnerability.

The vulnerability criteria used to classify buildings in this study are defined as "intrinsic factors" or elements at risk that influence its vulnerability (resistance properties of the building) such as type of construction material, height and number of floors, design and architecture of the building, type of foundations, etc. (Table 1). However, in reality, numerous other factors composing the building environment but which are not building properties strictly speaking, interact to produce a pattern of vulnerability that varies spatially and temporally (Papathoma et al., 2003; Ruangrassamee et al., 2006; Saatcioglu et al., 2005; Ghobarah et al., 2006; Reese et al., 2007). This second group of factors are more difficult to quantify and a review of the literature reveals limited examples of their influence, qualitatively or quantitatively (empirical or mathematical formulation (Papathoma and Dominey-Howes, 2003; Dominey-Howes and Papathoma, 2007; Dall'Osso et al., 2009; Omira et al., 2009; Dall'Osso et al., 2010). These "external factors" of vulnerability (ground properties, building age, type of soil, orientation, sea proximity, presence of obstacles, floating objects, vicinity of rivers or channels...) that may modify the damage is quite difficult to estimate in our method based on damage curves calculated from real cases observed before and after the tsunami event. Thus, at this stage of the work, they have been used only in a qualitative way and for descriptive purposes.

In other words, despite this limitation and in order to make our approach simpler and more generic and transferable, we consider that the intrinsic properties of buildings are more important than factors related to the building environment to assess building damages.

Thus, each type of construction is classified into a main class with a possible division into subclasses. This classification is then adapted to the Rabat-Salé area to take into account local building characteristics and can be seen in Table 1. We added two classes considering the particular urban characteristics of Rabat and Salé (shantytown huts, old centre houses, rural clay houses without any reinforcement, etc. . . .) (Fig. 4).

4.2.2 Use of earth observation data for building detection and classification

A new generation of satellites, offering a sub-metric spatial resolution, permits the identification and extraction of various elements of the urban environment. They are particularly useful in the analysis of the spatial distribution of different building characteristics, since image analysis and processing methods have been developed at object level rather than at pixel level, exploiting both spectral and structural features and elements of the objects. Indeed, if in low-resolution, the objects disappear and become part of the texture, in high resolution, the shape features and the spatial relations between objects are exploited (Guray et al., 2007). In this way, building vulnerability can be easily assessed thanks to visual recognition of building elements in optical images. Indeed, the differentiation between different building classes is quite possible thanks to the shapes of the buildings and colours of roofs, easily differentiated on high space resolution images.

In this case, two high resolution Quick Bird images (0.60 cm), acquired in 2007 and 2008 (Fig. 5), were largely used to extract building units and to identify their level or class of vulnerability according to the typology described above. A third image of GEO EYE1 satellite (0.50 cm) acquired in July 2010 is also used to update the building database, mainly the new constructions of Bouregreg Valley. Nevertheless, automatic processing based on the ratio of spectral bands, segmentation or various classifications has not been applied because of the complexity of our urban landscape that makes it difficult for a numerical process to extract urban units from a remotely sensed image. The completely automated extraction techniques are still encountering problems and are undertaken at an elementary level due to various factors such as geometry noise induced by variation in space scales and the level of details of elements composing urban areas, the problem of shadow which induces confusion in definition of building outlines, roads and bridges and variation of illumination conditions and building density (Lau Bee Theng, 2006). The Building extraction methods are more limited in the case of anarchical buildings in informal settlement areas (Ruther et al., 2002) because of their difference in terms of building materials, shapes, sizes and orientations as compared to structured buildings.

Such a work was however achieved by a photo interpretation method using standard keys (colour, structure, texture, form, size, shadow). The digitization of homogeneous building units is considered as the most suitable technique of extraction of urban elements using high-resolution images. So, individual buildings or houses are totally or partially identified by their roof brilliance (depending on roof covering materials), but also by their shadows characterised by low radiometric values, their shapes (building geometry), their size (small, large), their structures (flat, slope,), their textures (rough, smooth. . .) and their form describing the outlines of the building (Lau Bee Theng, 2006; Ruther et al., 2002; Wang Ziyu et al., 2004).

Unfortunately, this manual method presents some limitations in our area accentuated by some specific and local urban characteristics. For example, it was very difficult to identify individual building units both in old centres and shantytowns because of the very small size of houses in these areas and the absence of large streets separating blocks of houses. Only blocks of homogeneous houses are distinguished using high space resolution images.

Other complementary data were used for extraction of building vulnerability factors like urban and cadastral plans informing about the types of constructions and the height of buildings (number of floors). In order to take into account some future urban developments, mainly those related to the new management project of the Bouregreg Valley, the building database was completed by data on future developments of the Bouregreg Valley recovered from new and planned buildings documents from the Bouregreg Management Agency. Field surveys were carried out to validate the EO results and to obtain much complementary information, such as the number of storeys, the design and the age of buildings and possible information about construction materials and types of foundations, but also to locate emergency services and critical building structures (such as hospitals, schools, mosques. . .).

4.2.3 GIS database for building vulnerability assessment

In our study and in order to meet the requirements of the SCHEMA methodology, a GIS database of building maps describing the levels of building vulnerability in the potential flood zone has been produced in the form of point features. Each building or house is represented by a point and attributed to a class of vulnerability. Regarding the difficulty of identifying each individual building or house in shantytown and the old centre areas using EO images, the polygon form has been developed and then converted into sets of points regularly but arbitrarily distributed within the polygon.

Figures 6a and b illustrate the distribution of buildings within the inundated areas of Rabat and Salé according to their level of vulnerability to the tsunamis. Along about 9.5 km of coastal areas centred on the Bouregreg River and 9 km along the river, 897 individual buildings and houses of various types are located within the expected inundated area associated with a worst case tsunami scenario. They also reveal that most buildings potentially affected are situated south of Bouregreg River belonging to the Rabat district. The urban area of Salé town, mainly the ancient Medina, has a low tsunami hazard area thanks to its relatively long distance

Fig. 4. Examples of constructions of Rabat and Salé representing various classes of building vulnerability.

from the coast and river and to the higher elevation of the urban area, mainly towards the north of the old centre (except the new buildings located in the flat part of the Bouregreg Valley forming the new development project).

The analysis of the distribution of buildings using vulnerability criteria in the coastal area prone to tsunami flooding (Table 3) shows that the study area is characterised by a wide range of construction types. It shows also that almost half of the buildings composing this impacted urban area belong to the vulnerable class B (409 units). The high number of this type of constructions is due to housing composing the old centre of Rabat. It is noted here that some old buildings of this homogeneous district belong to class C (yellow colour), and are more resistant, because of restoration work aimed at reinforcing building structures. The second class in terms of building numbers (146 units) is formed by the category C composed of individual residential buildings and villas built with brick with reinforced columns and masonry filling. They are concentrated in the western part of the Bouregreg Valley. The buildings of Class E comprise 115 units and are in the third range. These types of well-reinforced constructions are concentrated on the north side of the Valley in the framework of the new project management of this area.

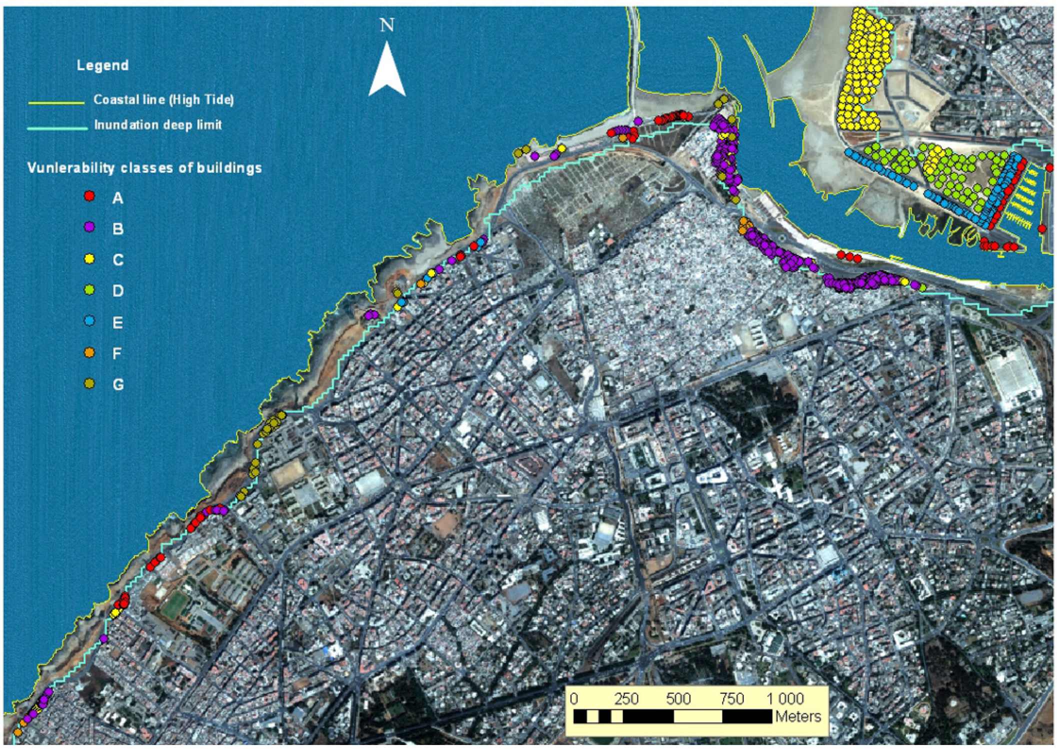
The highly vulnerable buildings (class A), 85 units, are located around the New Marina in the Bouregreg Valley and close to Rabat beach. They mostly represent restaurants and cafés with very light constructions (glass, wood...). The remaining constructions of this class are huts of the Shantytown of the Akkari quarter in the south of the area. The Table 3 (Repartition of buildings according to thier calss of vulnerability in the impacted area of Rabat and Sal) should be inserted here somewhere

4.3 Damage assessment maps

Figure 7a and b show the damage maps of the impacted area of Rabat and Salé, obtained by crossing the building class map with the inundation map and using the damage matrix. They indicate the expected damage level of each building. Table 4 summarizes the distribution of buildings by degree of damage.

The results reveal that 349 buildings will suffer from minor or insignificant damages (D1). These “safe buildings” represent more than 38 % of the buildings included in the flooded area and could be used as evacuation shelters. The majority of them are well constructed and located in the Bouregreg Valley development project and correspond to resistant buildings (Classes D and E) or in the high part of the medina of

Fig. 5. QuickBird image acquired in November 2008 (Rabat and Salé centres).



(a)

Fig. 6a. Spatial distribution of building vulnerability in the potential inundated area of Rabat and Salé (1755 Lisbon Scenario) (Rabat Side).

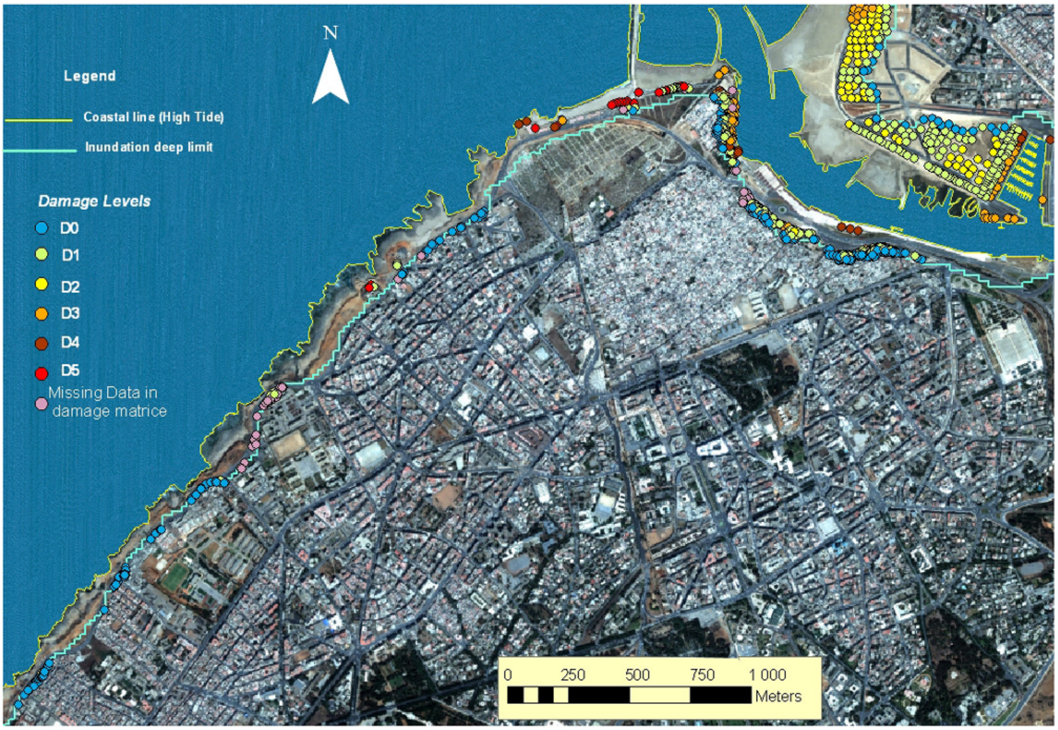
(b)

Fig. 6b. Spatial distribution of building vulnerability in the potential inundated area of Rabat and Salé (1755 Lisbon Scenario) (Salé side).

Table 3. Repartition of buildings according to their class of vulnerability in the impacted tsunami area of Rabat and Salé.

Vulnerability Class	A	B	C	D	E	F	G	Total
Building number	85	409	146	84	115	12	46	897
%	9.5	45.6.	16.3	9.4	12.8	1.4	5.1	100

Rabat affected by minimum water depth even though they belong to the vulnerable category (class B). Then, 72 of them should expect important damages (D2) such as collapse of parts of wall sections or panels. Damage may be limited to the first floor without affecting the structural integrity of the building. It largely concerns the E-class buildings which are



(a)

Fig. 7a. Map displaying levels of damage of buildings within the Rabat Salé inundated area (Aggregated Scenario) (Rabat Side).

Table 4. Number of buildings per level of damage expected in the zone potentially flooded by tsunami along the coasts of Rabat and Salé.

Level of damage	D_1	D_2	D_3	D_4	D_5	Missing Information on damage matrix or in the hazard parameter	Total
Number of buildings	344	72	90	15	19	357	897
%	38.3	8.1	10.0	1.7	2.1	39.8	100

concentrated mainly in the flat area of the Valley. Otherwise, 89 buildings will suffer from heavy damage (D3) including structural damage that could affect the building stability (out-of-plane failure or collapse of masonry, partial collapse of floors, excessive scouring and collapse of sections of structure due to settlement). Some of these buildings are highly vulnerable buildings from category A and B and are located in various places of the study area like around the Marina and within the Rabat old centre. This level of damage also affects some buildings from category C concentrated in the extreme western part of the Valley. We also note that only 15 buildings are threatened by strong damages (D4) compromising the structural integrity of the building, or as partial collapse of the building. It is mostly the vulnerable class A or B buildings located respectively along the river and within the ancient Medina of Rabat. Finally, the most devastating impacts such as total collapse are forecast to affect 19 units forming the first line of buildings overlooking the sea and spreading along the coast, within the highly flooded zone. They are poorly constructed (class A) and mainly concentrated along the Rabat beach.

4.4 Secondary vulnerability factors potentially increasing/decreasing intensity of destruction and accessibility

A map of additional potential criteria influencing building vulnerability has been produced using a Quick Bird image (Figs. 8a and b). It concerns secondary or external factors characterising the environment in the vicinity of a single building or block of buildings that could intensify or reduce the level of damage estimated through the damage function described above. It should be noted that despite some attempts to measure physically the action of the impact of

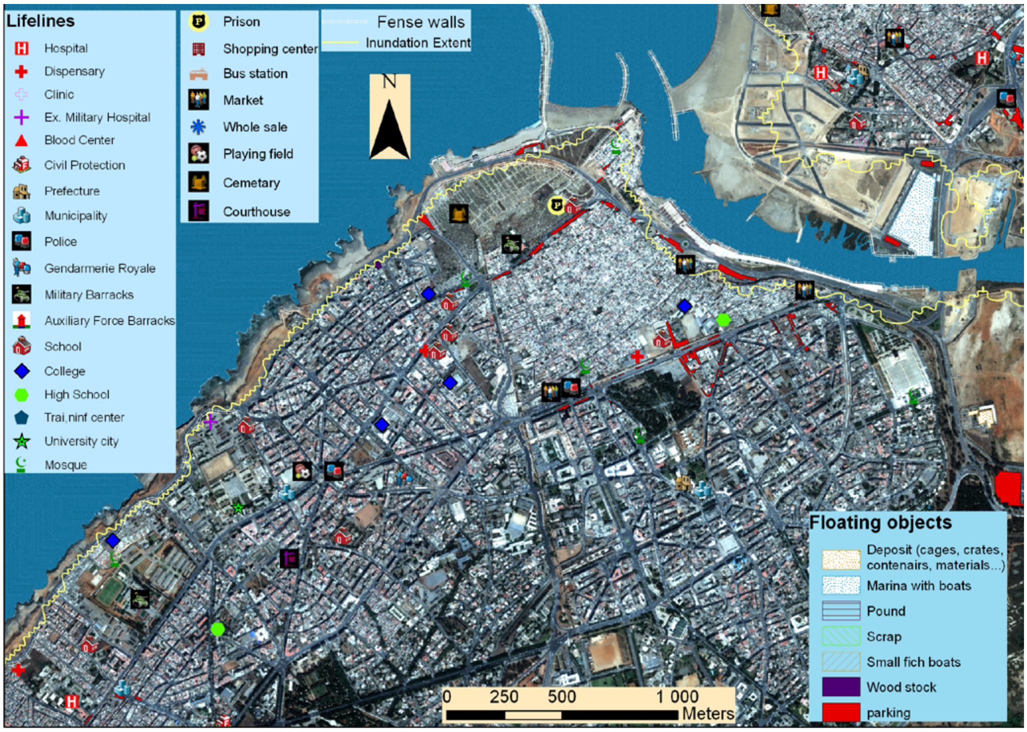
(b)

Fig. 7b. Map displaying levels of damage of buildings within the Rabat Sale inundated area (Aggregated Scenario) (Salé Side).

floating debris on buildings (Yeh et al. 2005), there is no known empirical method or formulas at present, based on fragility curves, quantifying the additional effect of such potential factors on damage affecting individual buildings and translated into predictive law. Without details on the impacting object and the impacted wall or structural element, no real assessment of playing forces and resistance, and, thus, assessment of their damage level is possible (Guillande et al., 2009). Therefore, it appears unrealistic to develop complex damage functions to calculate the expected effects of those factors present in the vicinity or close to one or more buildings. The approach only consists in identifying and mapping them independently as additional information helping to apprehend the degree of risk in case of their presence.

Figures 8a and b depict various potential additional factors characterising the environment of buildings. The main external factors mapped here are floating objects (parked cars or cars on coastal roads, boats in marinas, deposits of various material, scrap) that could be moved by the wave and intensify impacts on buildings located in front of them. On the other hand, many fence walls and breakwaters protecting coastal areas are located in various places of the coastal line. These obstacles can break the wave and reduce the intensity of the flow force and therefore decrease the impact on buildings (Dall'Osso et al., 2009a).

On the same figure, the main lifeline and critical infrastructures like emergency services (hospitals and medical centres, police offices, fire station), buildings with a



(a)

Fig. 8a. Location of floating objects, fences, walls and lifeline infrastructure (Rabat Side).

possible high concentration of people (schools, mosques, prisons, market) or administrative buildings are also represented. All these critical infrastructures require special protection because they must remain functional after the disaster (Dall'Osso et al., 2009b). The identification of their distribution in the impacted area is also very useful information for the generation of tsunami prevention land mitigation measures, including evacuation maps" (Dall'Osso and Dominey-Howes, 2010).

5 Discussion

Applying the SCHEMA approach for assessing the vulnerability and damage of buildings by tsunami in the coastal area of Rabat and Salé provided very interesting results in terms of hazard, vulnerability and damage scenarios. These outputs can be used by various end users as first order assessments of building vulnerability to aid to:

– Design appropriate measures of tsunami prevention and mitigation in order to enhance tsunami risk reduction strategies (protection work to protect exposed populations, evacuation of sites prone to disaster) and develop building codes and regulations to prepare relevant urban planning and land use zoning policies (land management and urban planners).

– Prepare emergency risk plans including evacuation plans (Civil security organisations, rescue planners).

– Prepare populations and rescue teams to deal with such events (local authorities and public safety policy makers).

– Identify spatial distribution of potential flooded areas, vulnerable buildings and potentially damaged buildings (Insurance companies).

It is important to keep in mind that the assessment of damage induced by tsunami scenarios is based on the use of vulnerability matrixes or functions to carry out a relation between the magnitude of the phenomena and the damage expected. Nevertheless, this method has the drawback of being certainly conservative and exaggerating the damage level. Indeed, these functions do not only represent the damage due to hydrodynamic forces of the tsunami, but they result from cumulated effects induced by multiple factors (debris and floating objects effects, effects of earthquake on the studied area, scouring and erosion effects, etc.) whose damaging impact is too complex to be separately modelled and integrated in a single model (Valencia et al., 2011). Therefore, it is admitted that this is a simplistic approach which incorporates all physical effects in a single parameter and its results could suffer certain constraints and limitations mainly due to:

– The uncertainty of results of tsunami modelling that could be induced by the difficulty to locate the potential

(b)

Fig. 8b. Location of floating objects, fences, walls and lifeline infrastructure (Salé side).

tsunami source and/or by the low accuracy of inputs used (bathymetry and topography).

– The restriction of the building vulnerability classification to only inherent building properties passing over external or environmental factors which are used here only as indicative purposes;

– the difficulty of distinguishing between some proposed building classes (example C and D) on the base of primary factors of vulnerability;

– the missing information in the damage matrix concerning the building class F and G which did not allow calculating scenarios.

Lastly, despite these limitations and compared with other approaches more complex and in the absence of any information at all, this method has the merit of being simple and easily usable and transferable to other coastal areas for assessing tsunami damage scenarios and producing at least first basic information on the expected impacts of tsunami hazard. We must also remind the reader that the same methodology has been applied to five different sites with various building environments, social and cultural conditions and economical contexts which constituted a good validation test for it. In addition, in the case of our study area, all the results were presented to local users from various organisations dealing with risk management. Indeed, completing a specific questionnaire, the users evaluated the relevance, the pertinence and the usefulness of both methodology and results. The users' feedback and suggestions during a local SCHEMA workshop organized in Rabat were then taken into account to improve both the approach and the final maps.

6 Conclusions

In this study we applied a simple but integrated GIS methodology for building vulnerability and impact assessment on the coastal area of Rabat and Salé (Morocco) exposed to tsunami hazard. The approach uses earth observation data to quantify direct damages to buildings by combining tsunami hazard maps (maximum inundation depths) and building vulnerability maps. The tsunami hazard assessment is based on individual worst-case credible scenarios traduced in an "aggregated scenario". The vulnerability analysis aiming at identifying elements exposed to tsunami allows classifying individual buildings into main classes of vulnerability according to their internal levels of resistance. A vulnerability building database is then generated on the study area that could be regularly updated in case of new urban developments. One of the foundations of the method is also the development of damage functions linking depth inundation level to possible level of damage for each building on a scale of damages from D0 (no damage) to D5 (collapse).

The results obtained for Rabat and Salé highlight quite different vulnerable building areas according to the depth of inundation and resistance of buildings. Therefore, the most vulnerable buildings that expect heavy damages are mainly located in the ancient medina and along the Rabat beach. These preliminary results could be used as a baseline for the preparation of a viable evacuation plan with or without any warning system.

Finally, even if we admit that our approach suffers from certain constraints and limitations as mentinned above, it definitely has the benefit of being simple and easily usable and transferable to other coastal areas to depict potential maximum damage level expected for tsunami scenarios. Indeed, the use of the GIS application (DAMASHtool) developed for this purpose requires only two main inputs: the tsunami inundation depth and the inventory building vulnerability.

As perspectives, further investigations are needed to improve the SCHEMA methodology, mainly the consideration of others factors to better evaulate building damage. The secondary or external factors related to the buiding environment that aggravate or minimise damages have to be integrated into the model to produce the final maps of damage. Moreover, it will be important also to evaluate damage levels expexcted for other infrastructures composing the lifelines system, in addition of building. The vulnerable critical infrastructures have to be protected to keep them functional in order to ensure a minimum of basic services after the disaster.

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References

Baptista, M. A., Miranda, P. M. A., Miranda, J. M., and Mendes-Victor, L.: Constrains on the source of the 1755 Lisbon tsunami from numerical modelling of historical data on the source of the 1755 Lisbon tsunami, J. Geodynamics, 25, 159–174, 1998.

Dall'Osso, F. and Dominey-Howes, D.: Public assessment of the usefulness of "draft" tsunami evacuation maps from Sydney, Australia - implications for the establishment of formal evacuation plans, Nat. Hazards Earth Syst. Sci., 10, 1739–1750, doi:10.5194/nhess-10-1739-2010, 2010.

Dall'Osso, F., Gonella, M., Gabbianelli, G., Withycombe, G., and Dominey-Howes, D.: A revised (PTVA) model for assessing the vulnerability of buildings to tsunami damage, Nat. Hazards Earth Syst. Sci., 9, 1557–1565, doi:10.5194/nhess-9-1557-2009, 2009.

Dall'Osso, F., Gonella, M., Gabbianelli, G., Withycombe, G., and Dominey-Howes, D.: Assessing the vulnerability of buildings to tsunami in Sydney, Nat. Hazards Earth Syst. Sci., 9, 2015–2026, doi:10.5194/nhess-9-2015-2009, 2009.

Direction of Ports and Direction of Risk Survey and Prevention: Surveillance de la qualité des eaux des baignades de al zone atlantique du Nord du Maroc : Mai 2003–Février 2004, 52 pp., Morocco, 2004.

Dominey-Howes, D. and Papathoma, M.: Validating a tsunami vulnerability assessment model (the "PTVA Model") using field data from the 2004 Indian Ocean tsunami, Nat. Hazards, 40(1), 113–136, 2007.

El Mrabet, T.: La seismisité historique du Maroc Thèse d'état de 3éme cycle, Faculté des letters et des Sciences et Humaines, Université Mohammed V, Rabat, 291 pp., 1991 (in arabic).

Fukao, Y.: Thrust faulting at a lithospheric plate boundary, the Portugal earthquake of 1969, Earth Planet. Sc. Lett., 18 pp., 205–216, 1973.

Garcin, M., Prame, B., Attanayake, N., De Silva, U., Desprats, J. F., Fernando, S., Fontaine, M., Idier, D., Lenotre, N., Pedreros, R., and Siriwardana, C. H. E. R.: A Geographic Information System for Coastal Hazards. Application to a pilot site in Sri Lanka

(Final Report), BRGM Open file BRGM/RP-55553-FR, 124 pp., 2007.

Gardi, A., Valencia, N., and Sheer, S.: WP3.3 – GIS conceptual model and processing for production of elements required for test sites scenarios, Deliverable 3.1 part II, SCHEMA project, 2009.

Gauraz, A. L., Valencia, N., Koscielny, M., Guillande, R., Gardi, A., Leone, F., and Salaün, T.: Tsunami damages assessment: vulnerability functions on buildings based on field and earth observation survey, Geophys Res Abstr., 11, EGU2009-5785, EGU General Assembly, Vienna, Austria, 2009.

Ghobarah A., Saatcioglu, M., and Nistor, I.: The impact of the 26 December 2004 earthquake and tsunami on structures and infrastructure, Eng. Struct., 28, 312–326, 2006.

Gjevik, B., Pederson, G., Dybesland, E., Miranda, P. M., Baptista, M. A., Heinrich, P., and Massinon, B.: Modelling tsunamis from earthquake sources near Gorringe Bank southwest of Portugal, J. Geophys. Res., 102(C13), 27931–27949, 1997.

Guesmia, M., Heinrich, P. H., and Mariotti, C.: Numerical simulation of the 1969 Portuguese tsunami by a finite element method, Nat. Hazards 17, 31–46, 1998.

Guillande, R., Kocielnym, Salaün, T., Atillah, A., and Ribeiro, J.: SCHEMA Delivarable 2.1: Generic aspects and rules on vulnerability evaluation: Definition of tsunami vulnerability criteria (primary, secondary) and damage Classification of the building vulnerability as regards to tsunami hazard, 85 pp., www.schemaproject.org, 2009.

Guray, E. and Loménie, N.: Extraction of Cartographic Objects on High Resolution Satellite Images for Object Model Generation, Hal-00136179, 1–12 March, 2007.

Gutscher, M. A.: What caused the Great Lisbon earthquake?, Science, 305, 1247–1248, 2004.

Kaabouben, F., Baptista, M. A., Iben Brahim, A., El Mouraouah, A., and Toto, A.: On the moroccan tsunami catalogue, Nat. Hazards Earth Syst. Sci., 9, 1227–1236, doi:10.5194/nhess-9-1227-2009, 2009.

Koshimura, S.: Tsunami vulnerability assessment for the city of Banda Aceh using the tsunami numerical model and the post-tsunami survey data. Proceedings of the IUGG XXIV General Assembly, Perugia, Italy, 2–13 July, 2007.

Lau Bee, T.: Automatic Building Extraction from Satellite Imagery, Engineering Letters, 13:3, EL_13_3_5, http://www.engineeringletters.com/issues_v13/issue_3/EL_13_3_5.pdf, last access: 4 November 2006, 5 pp., 2000.

Leone, F., Denain, J. C., Vinet, F., and Bachri, S.: Analyse spatiale des dommages au bâti de Banda Aceh (Sumatra, Indonésie): contribution à la connaissance du phénomène et à l'élaboration de scénarios de risque tsunami, Scientific report of Tsunarisque (2005–2006) programme, 2006.

Leone, F., Lavigne, F., Paris, R., Denain, J.-C., and Vinet, F.: A spatial analysis of the December 26th, 2004 tsunami-induced damages: Lessons learned for a better risk assessment integrating buildings vulnerability, Appl. Geogr., doi:10.1016/j.apgeog.2010.07.009, 2010.

Omira, R., Baptista, M. A., Miranda, J. M., Toto, E., Catita, C., and Catala, J.: Tsunami vulnerability assessment of Casablanca-Morocco using numerical modelling and GIS tools, Nat. Hazards, Springer, The Netherlands, doi:10.1007/s11069-009-9454-4, 2009a.

Omira, R., Baptista, M. A., Matias, L., Miranda, J. M., Catita C., Carrilho F., and Toto E.: Design of a Sea-level Tsunami Detection Network for the Gulf of Cadiz, Nat. Hazards Earth Syst. Sci., 9, 1327–1338, 2009b, http://www.nat-hazards-earth-syst-sci.net/9/1327/2009/.

Papathoma, M. and Dominey-Howes, D.: Tsunami vulnerability assessment and its implications for coastal hazard analysis and disaster management planning, Gulf of Corinth, Greece, Nat. Hazards Earth Syst. Sci., 3, 733–747, doi:10.5194/nhess-3-733-2003, 2003.

Papathoma, M., Dominey-Howes, D., Zong, Y., and Smith, D.: Assessing tsunami vulnerability, an example from Herakleio, Crete, Nat. Hazards Earth Syst. Sci., 3, 377–389, doi:10.5194/nhess-3-377-2003, 2003.

Peiris, N.: Vulnerability functions for tsunami loss estimation. First European conference on Earthquake Engineering and Seismology (a joint event of the 13th ECEE and 30th General Assembly of the ESC), Geneva, Switzerland, Paper number 1121, 2006.

Reese, S., Cousins, W. J., Power, W. L., Palmer, N. G., Tejakusuma, I. G., and Nugrahadi, S.: Tsunami vulnerability of buildings and people in South Java - field observations after the July 2006 Java tsunami, Nat. Hazards Earth Syst. Sci., 7, 573–589, doi:10.5194/nhess-7-573-2007, 2007.

Renou, C., Lesne, O., Mangin, A., Rouffi, F., Atillah, A., El Hadani, D., and Moudni, H.: Tsunami hazard assessment in the coastal area of Rabat and Salé, Morocco, Nat. Hazards Earth Syst. Sci., 11, 2181–2191, doi:10.5194/nhess-11-2181-2011, 2011.

Ruangrassamee, A., Yanagisawa, H., Foytong, P., Lukkunaprasit, P., Koshimura, S. and Imamura, F.: Investigation of tsunami-induced damage and fragility of buildings in Thailand after the December 2004 Indian Ocean Tsunami, Earthq. Spectra, Special Issue III, 22, S377–S401, 2006.

Ruther, H., Hagai, M. M., and Mtalo, E. G.: Application of Snakes and Dynamic Programming Optimization in Modeling of Buildings in Informal Settlement Areas, ISPRS J. Photogramm., 56, 269–282, 2002.

Saatciouglu, M., Ghobarah, A., and Nistor, I.: Performance of structures in Thailand during the december 2004 great Sumatra earthquake and Indian ocean tsunami, Earthq. Spectra, Special Issue III, 22, S355–S375, 2005.

Scheer, S., Guillande, R., Koscielny, M., Ranguelov, B., and Silva, A.: WP2.2 Definition of tsunami vulnerability criteria (primary, secondary) and damage, deliverable 2.1, SCHEMA project, www.schemaproject.org, 2009.

Tinti, S., Tonini, R., Bressan, L., Armigliato, A., Gardi, A., and Guillande, G.: Handbook on Tsunami Hazard and Damage Scenarios, SCHEMA (Scenarios for Hazard-induced Emergencies Management), Project no. 030963, Specific Targeted Research Project, Space Priority, IRC Scientific and technical Report (www.schemaproject.org), 2010.

Valencia, N., Gardi, A., Gauraz, A. L., Leone, F., and Guillande, R.: New tsunami damage functions developed in the framework of SCHEMA project: application to Euro-Mediterranean coasts, Nat. Hazards Earth Syst. Sci., submitted, 2010.

Wang, Z., Wenxia, W., Shu He, Zhao, Xiuwan, C.: Object-oriented classification and application in land use classification using SPOT-5 PAN imagery, Geoscience and Remote Sensing Symposium, IGARSS '04, Proceedings, IEEE International, 5, 3158–3160, 2004.

Yeh, H., Robertson, I., and Preuss, J.: Development of Design Guidelines for Structures that Serve as Tsunami Vertical Evacuation Sites, Washington division of Geology and Earth Resources, Open File Report, 2005–4, 42 pp., 2005.

Zitellini, N., Chierici, F., Sartori, R., and Torelli, L.: The tectonic source of the 1755 Lisbon earthquake, Annali..di..Geofisica 42(1), 49–55, 1999.

Zitellini, N., Mendes, L.A., Cordoba, D., Danobeitia, J., Nicolich, R., Pellis, G., Ribeiro, A., Sartori, R., Torelli, L., Bartolome, R., Bortoluzzi, G., Calafato, A. Carrilho, F., Casoni, L., Chierici, F., Corela, C., Correggiari, A., Della Vedova, B., Gracia, E., Jornet, P., Landuzzi, M., Ligi, M., Magagnoli, A., Marozzi, G., Matias, L., Penitenti, D., Rodriguez, P., Rovere, M., Terrinha, P., Vigliotti, L. and Zahinos Ruiz, A., Source of 1755 Lisbon earthquake and tsunami investigated, EOS 82, No .26, 285–291, 2001.