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TSUNAMI EVACUATION PLAN FOR THE CITY OF TANGIER-MOROCCO BASED ON GIS TOOLS

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ABSTRACT

Morocco is located in convergence zone between two major plates, the Eurasian and the African plates. Moroccan coastal regions are prone to tsunami hazard caused by major earthquakes located along this boundary. The rapid growth of population and expansion in infrastructures and economic settlements in Moroccan coastal areas make them more vulnerable to tsunami threat. Tsunami evacuation plan is an important tool to mitigate the tsunami impact, it's the most efficient way to save human lives before the waves reach the hazard zone areas. In this study, we propose a tsunami evacuation plan for the city of Tangier-Morocco for horizontal evacuation. This plan is designed considering the tsunami threat from tsunamigenic source located in the SW Iberian margin and using the inundation maps of the worst case scenario to define the flooding area. The evacuation plan is elaborated through modeling evacuation routes using Closet Facility tool implemented in ESRIS's ArcMap 10.2 geographic information system (GIS) software. The proposed evacuation plan give valuable information to local government authorities and emergency managers in order to implement an official evacuation plan for Tangier city. It also provides practical support to increase community resilience.

***Keywords**: tsunami, worst case scenario, geographic information system (GIS), inundation map, evacuation plan.*

1. INTRODUCTION

Morocco is located near the Azores-Gilbraltar Fracture Zone (AGFZ), which marks the boundary of active tectonic interaction between the African and the Eurasian plates where major earthquakes can occur. The most destructive historical tsunamigenic earthquake near AGFZ occurred at 9:40 in the morning of 1 November 1775 (Fig.1). There were three distinct shocks over a ten minute period. The first shock was followed by an even more powerful second shock which destroyed many buildings in Lisbon and other cities in Portugal. According to reports, the tremors and ground motions lasted for three-and-one-half minutes. The first of the tsunami waves reached Lisbon about 40 minutes afterwards and in less than an hour reached Morocco. In Gibraltar, the sea rose suddenly by about two meters. The greater damage and casualties occurred on the western coast from Tangier, where the waves reached the walled fortifications of the town, to Agadir where the waters passed over the walls, killing many. The earthquake and the tsunami were particularly destructive in Morocco, where approximately 10,000 people lost their lives. Archival records document that the coastal towns of Rabat, Larache, Asilah, and Agadir (named Santa Cruz at that time) suffered much damage (Pararas-Carayannis, 2001). Another potential tsunamigenic area is south of the Gorringe bank near the Azores-Gibraltar fracture zone where an event occurred in 1969. It is expected that tsunamis will strike again Morocco, so a program pf preparedness is an absolute necessity.

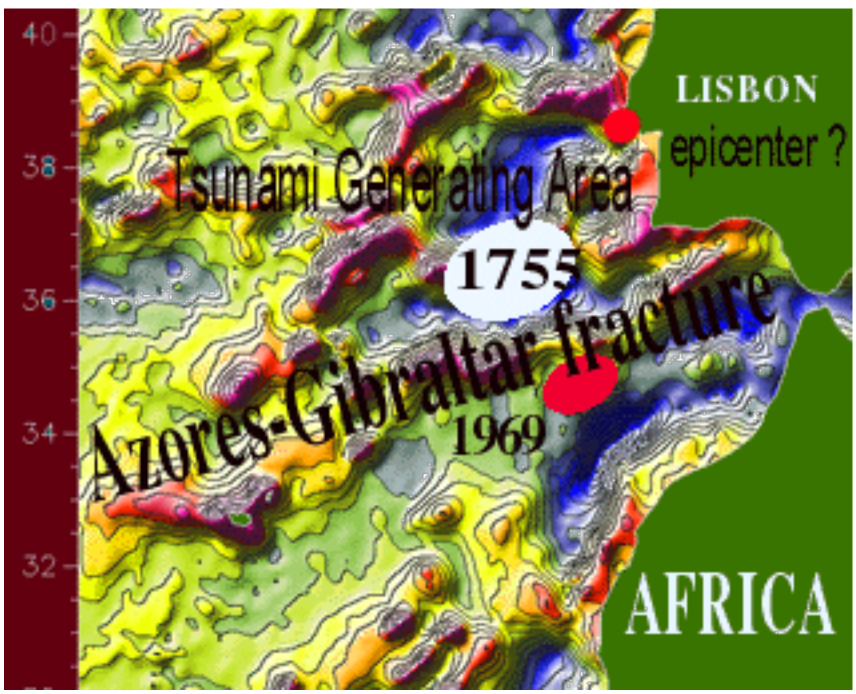

Fig.1 Generating Areas of the 1755 and 1969 tsunamis along the Azores-Gibraltar Fracture Zone (AGFZ) superimposed on bathymetry and gravity anomaly map (Source: Pararas-Carayannis, 2001)

A Tsunami Evacuation Plan is considered as a fundamental tool to mitigate the risk and save lives. Indeed, evacuation of vulnerable areas remains the most efficient action to save lives before the tsunami waves arrive. The Plan requires rapid evacuation of people from danger zones of coastal communities. The disastrous tsunami that struck the eastern coast of Japan on 11 March 2011, generated by the great Tohoku-Oki earthquake, (Mw 9.0), indicated that even the most protective tsunami structures (protective walls, fences, etc) were overtopped by waves (Pararas-Carayannis, 2011 a, b, 2014; Mas et al., 2012,). "Evacuation procedures" to a safer place provide the only effective way of moving people away from a potential danger area.

The present study proposes a simple methodology to evacuate effectively Tangier residents from tsunami prone areas to buildings, shelters and assembly areas in safe zones. Routes are modeled using Closet Facility tool implemented in ESRIS's ArcMap 10.2 geographic information system (GIS) software. This tool is used in network analysis in order to measure the cost of traveling between input sites (incidents) and locations (facilities). It's used for finding the locations based on the impedance chosen (time, distance etc...). In this study, we try to obtain the shortest path taking account the walking speed of evacuees and the capacity (width) of the road network. The Closet Facility tool, considered as macro-simulator approach, has the advantage to not require a lot of calculation and the results are easily exploitable in any Geographic Information System (GIS). The proposed map could be used by the local authorities in the process of evacuation in case of tsunami warning, it also helps to prepare and raise awareness among the populations living in tsunami hazard area.

2. BRIEF OVERVIEW OF TSUNAMI EVACUATION MODELING

In order to quantify the evacuation time, several studies have focused on developing different evacuation models. Pidd et al. (1996) distinguished two models to simulate tsunami evacuations: macro-simulators and micro-simulators. These models differ on spatial scale and variables taken into account. The macro-simulators have the interest of assessing "absolute" accessibility to refuge sites regardless of individual behavior, while the micro-simulators are considered as a dynamic approach, they try to assess "relative" accessibility taking into account human behavior with several individual characteristics and their interactions. However, we note the complementary of these two approaches.

The micro-simulator models require efficient capacity and very long calculation times, they are mainly applied in evacuations within buildings (malls, big hotels, stadiums ...) or in ships like the study conducted by Klüpfel et al. (2000). There are several types of micro-simulators models to simulate pedestrian evacuation in case of tsunami, the most known are: i) the "Multi-Agent System (MAS)" model; during the modeling, each agent maximizes his personal evacuation route to find the way of the faster evacuation. This method has been successfully applied to the town of Aonae (Okushiri Island, Hokkaido Japan) by Saito and Kagami (2004) using the software MAS (Multi Agent Simulator), to Padang city in Indonesia by Lammel et al. (2008) using MATsim (Multi-Agent Traffic simulation) software and recently to Arahama town located near the Sendai city, Japan by Mas et al. (2012). ii) the "Automate Cellular (AC)" model which was used for the first time in road traffic simulation by Nagel and Schreckenberg (1992). It is generally applied to model complex dynamic systems and iii) the "Social Force" model developed by Helbing and Molnar (1995). This model considers the behavior of each pedestrian which is affected by internal forces (the willpower to reach the destination) and by external ones due to others pedestrians (socio-psychological and physical influences) or to the obstacles present in his environment. The "SimWalk" is one of the software's based on "Social Force" model, it was applied by Steiner et al.(2007).

The macro-simulators models are used at more large scale. This approach has a static setting, it calculates the travel time in wide and open areas and describes each part of the space by attributes that take into account the speed of pedestrians. The approach, based on the shortest path theory associated with a GIS, was developed by Hamacher and Tjandra (2001), it has the advantage of not dealing with phenomena that are often random and complex.

This type of simulations are used to select large-scale evacuation routes. Several programs have been developed like : i) ETR (Evacuation Route Tools) that was developed as a part of the CRATER program (Coastal Risk Analysis and Environmental Remediation of Tsunamis, 2005) and which was applied in Thailand (Phuket Province and Phang Nga Province) ii) "Route Finder" was developed in MapInfo GIS platform. It has been widely applied in various places such as Indonesia in Mayotte (Leone et al. 2013), in the French Riviera (Sahal et al., 2013) and Martinique (Péroche et al., 2014). This application has the advantage of being easily transferable to different sites iii) "CASPER" (Capacity Aware Routing Evacuation Shortest Path) a tool developed for ArcGIS Network Analyst by (Shahabi and Wilson, 2014) and iv) least-cost-distance (LCD) model implemented in ArcMap, this model takes into account the slope and land cover of an area, it was applied in Aberdeen, Hoquiam, and Cosmopolis cities in the U.S. Pacific Northwest by Wood et al (2016) .

3. METHODOLOGY

Before launching the modeling of the shortest roads by "Closet Facility" tool, many GIS datasets should be configurated and created. These dataset are used as input, it includes many steps (Fig. 2);

Determination of danger areas and safe areas : danger areas correspond to the flooded areas estimated by tsunami hazard study. The inundated zone is the result of the determination of the potential of tsunamigenic sources and the use of numerical modeling. The obtained tsunami hazard map gives an idea of the limit of the inundated area which should be evacuated in case of tsunami warning. All areas located outside the inundation zone (generally located above than 20m) are considered as safe areas.

- Estimation of exposed population: to simulate the evacuation routes, it is essential to know the number of population (residents or not) present in the potential tsunami flooded zone and their distribution. The number of people to evacuate affects road capacity, also, locations of evacuees are taken as starting points for modeling.

Construction of road network dataset: the object of this step is to built a road network taking into account surface condition, slope, length and capacity of the paths (width). Road network is very essential for evacuation purposes since it will determine the movement of evacuees along the evacuation routes and also serves as connections to the evacuation building shelters.

Identification of assembly areas or evacuation building shelters: these buildings are selected according to the best practice guidelines set out in FEMA (2009). Building shelters or Assembly areas are chosen related to their locations, capacity, accessibility using the road network and the safety after a preceding local or regional earthquake.

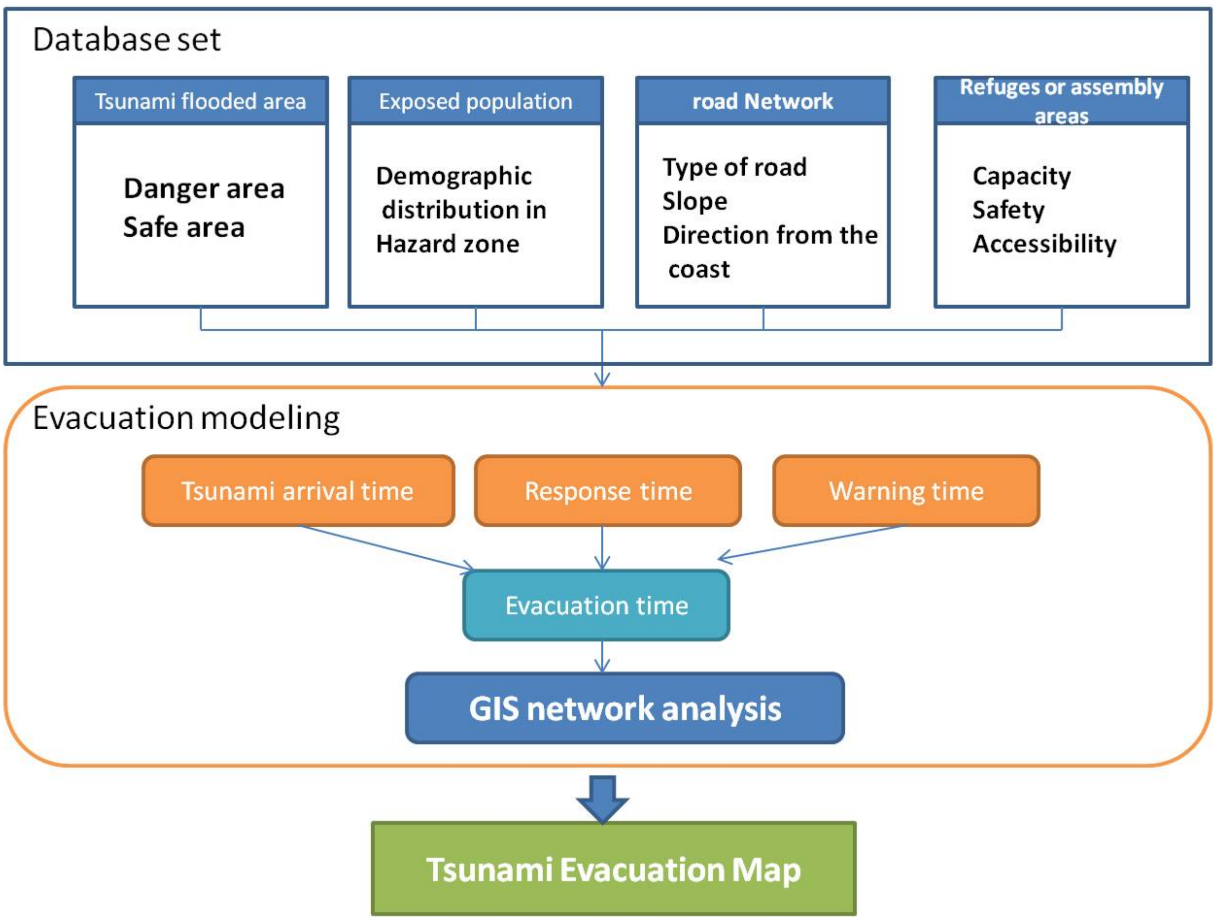

Figure 2: Flow chart indicating the methodology adopted for this study

4. STUDY AREA

The city of Tangier is located in the northern coast of Morocco with a population circa 948.000 according to population census of 2014. It lies at the western entrance to the Strait of Gibraltar where the Mediterranean meets the Atlantic Ocean (Fig. 3A). Its coastal zone covers an area of about 15 km long from west to the east. The city is knowing rapid development and modernization. the port city includes new tourism projects with many hotels and modern business centers. Tangier economy depends in general on tourism with nice beaches like Municipal, Malabata and Ghandouri beach (Fig. 3B), pedestrian avenues and terraces ranging front of the bay. The crowded beaches specially during summer months and the several seaside resorts increase the population exposure in Tangier city to tsunami threat. Until now this city doesn't has an official tsunami evacuation plan, this work could help emergency planners to adopt some evacuation routes after being validated.

Figure 3. Study area: (A) regional overview (B) Tangier map with principal locations as the city port, the ancient Medina and the important beaches.

4.1 EVACUATION AREA OR DANGER ZONE

The evacuation area corresponds to the expected extension of the flooding in land. The inundated area in Tangier is drawn based on deterministic approach, considering tsunami threat from the tsunamigenic sources located in the SW Iberian Margin. Modeling was applied for different scenarios based on the Most Credible Earthquake Scenarios (Tinti and Armigliato 2003), details of the sources are defined in ASTARTE-D8.8 (2015) (http://www.astarte-project.eu). The Cadiz Wedge Fault (CWF) with Mw=8.75 is considered the worst credible earthquake scenario, able to cause the higher impact tsunami for Tangier. The inundation map (Fig. 4) shows that over 6.2 km^2 of the coastal area is prone to inundation with maximum flow depths range from 0.1m to 10m. The highest inundation distances are mostly calculated in flat areas specialty along the rivers where the horizontal inundation exceeds 2.7 km. This penetration is due mainly to the low topography of these areas. This map shows also that horizontal inundation doesn't exceed 60 m from the shoreline at its east and west side due to the high topography of the hills that exceed generally 20 meters. The estimated inundated area is considered as danger zone', therefore all non-inundated zones could be considered as safe zones.

4.2 ESTIMATION OF THE EXPOSED POPULATION

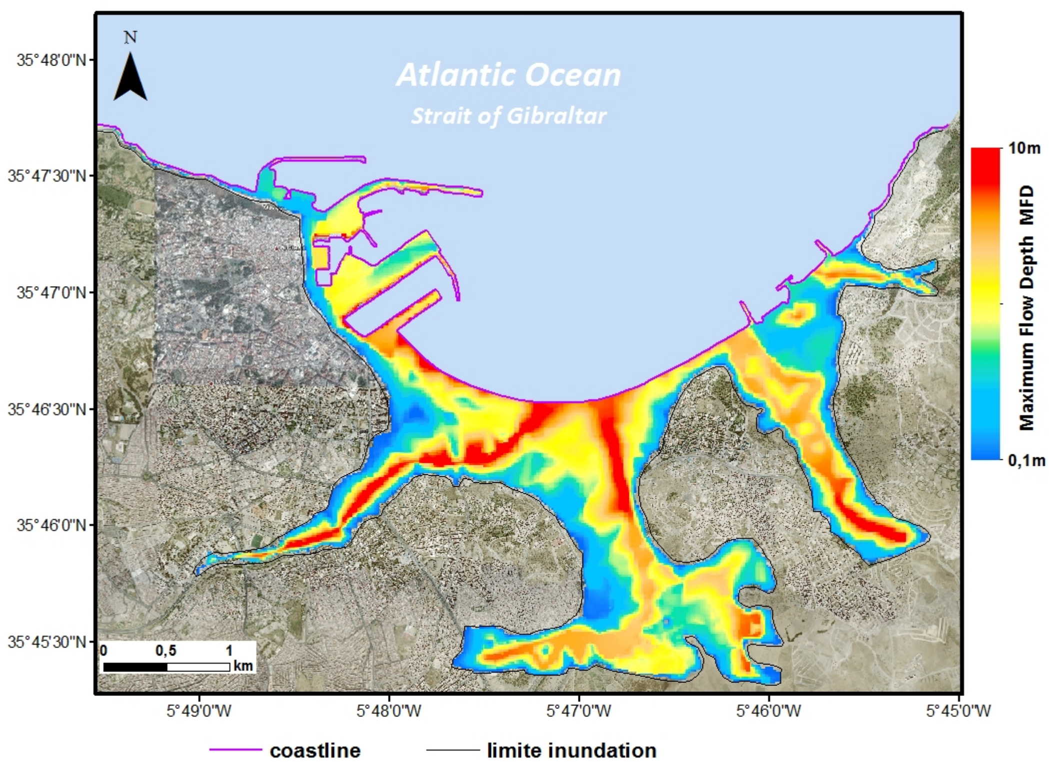

Figure 4: Inundation zone map for Tangier, simulation was based on the Cadiz Wedge fault source (ASTARTE-D8.8, 2015, http://www.astarte-project.eu)

To carry out the evacuation routes modeling, it is necessary to know the number of people (residents or not) located in the potential tsunami inundation zone and their distribution. For Tangier city, demographic data was provided by the institution "Haut Commissariat au Plan, HCP" collected during the general population census in 2014. This data provides a spatial distribution of the population by each district. Along the hazard zone, there are 63 districts divided in three communes (Fig. 5); Tangier-Medina, Charf-Souani and Charf-Mghogha. The Charf-Mghogha commune is the most populated with about 10000 residents, followed by Tangier-Medina commune with an estimated population of 3200. The Charf-Souani commune is the less populated with about 900 residents.For more complete database, and due to lack of official information related to the number of tourist visiting the beaches on high seasons, we added 3000 people (estimation of civil protection officer in Tangier) assumed as temporarily residents coming for work from outside of the hazard zone. They are supposed located, during the day and out of the high touristic season (summer), along the cornice and at the beaches (Municipal, Malabata and Ghandouri beaches, Fig. 3B). In total, the estimated population at the inundated area correspond to about 17100 people.

Ideally, people evacuate from each building block and try to take the shortest way to reach safe areas. In order to estimate the number of people to evacuate in each building block, we need demographic attributes at each residence. Due to the deficiency of these data, we start the modeling from the center of each district where evacuees are expressed in term of points. We note that, we ignored the different situations of evacuees (location inside or outside of buildings, activities, ...) since we used macro-simulator approach.

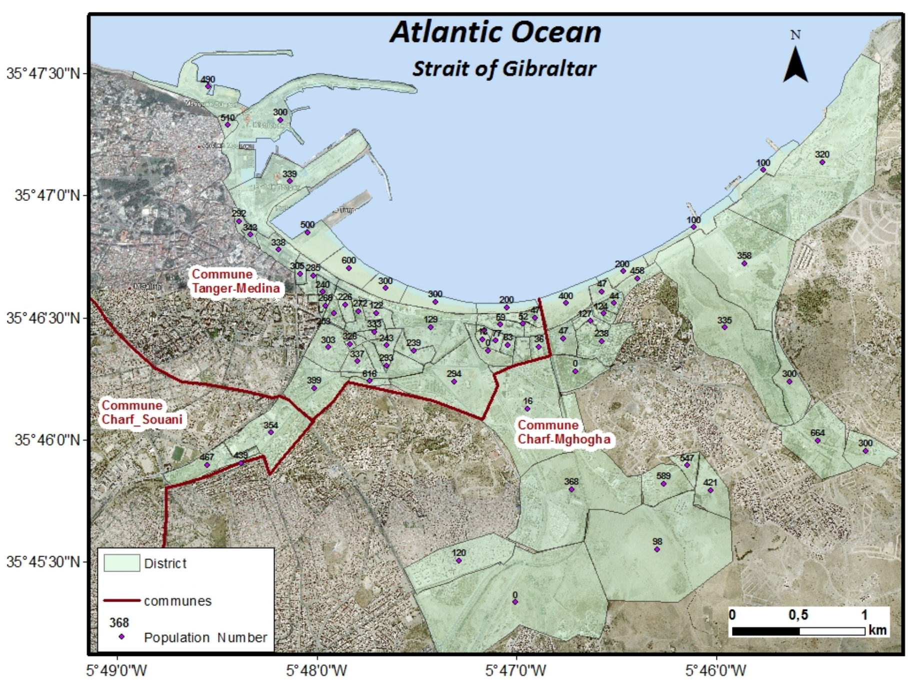

Figure 5: Spatial distribution of the population by district in Tangier flooded areas

4.3 ROAD NETWORK

Detailed road network is necessary to be implemented in the network modeling. We achieved a road network for coastal zone of Tangier which shows main roads that could be used as escape routes in case of tsunami (see Fig. 6).

Roads were digitized in Arc GIS from high resolution (40 cm) orthophotos (2009). In order to have more detailed road networks, missing roads were digitized from recent Google Earth images. The attributes related to the dataset network include for each path; name of major streets, length, capacity (width), traffic direction, restricted turns and special descriptions. Finally, the elaborated road network includes 1624 paths with 948 network connectivity (nodes).

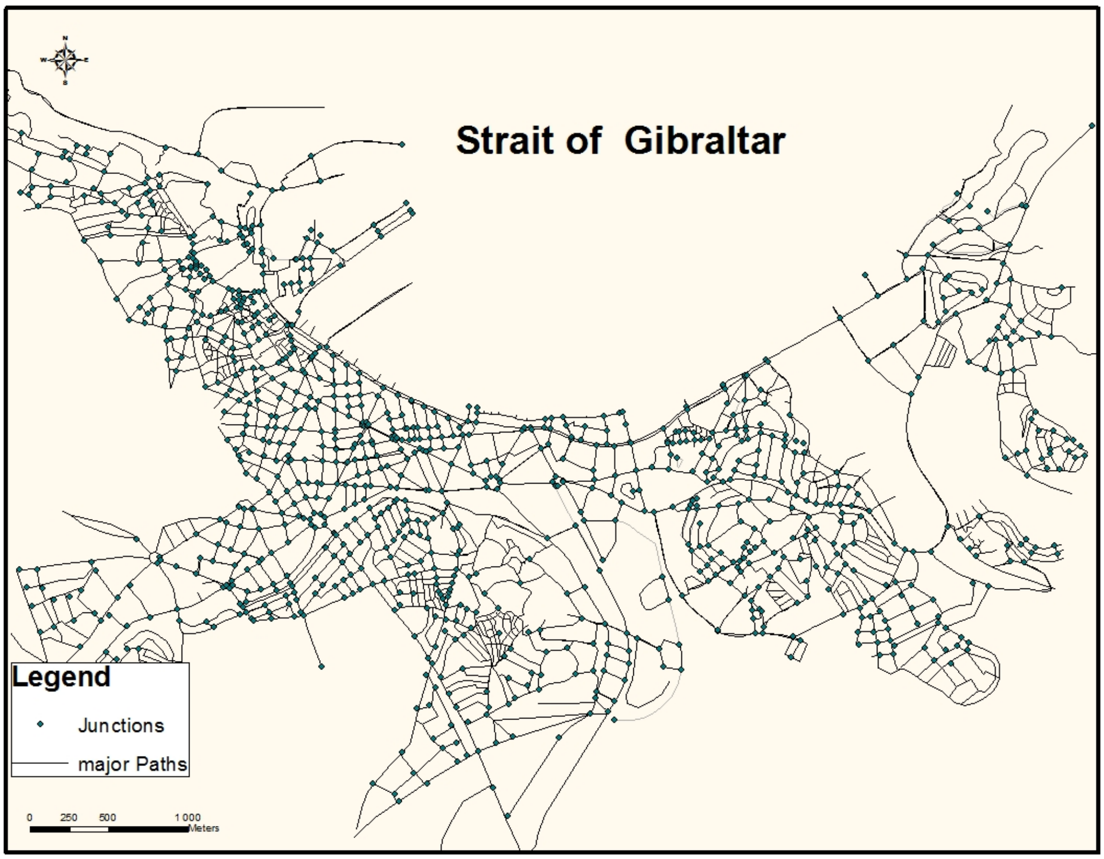

Figure 6: Road network in Tangier flooded zone

4.4 EVACUATION SHELTER BUILDINGS

Tsunami is an event who has long period to be occurred in Morocco, so, there are no buildings functioning specially as evacuation shelter buildings in Tangier. In this study, we tried to find suitable assembly areas or evacuation buildings shelters responding to different criteria such as location, accessibility, known by the population and capacity.

First, we identified several evacuation shelters buildings and assembly areas from recent Google Earth images, then we conducted a field survey to validate or exclude the identified sites. We finally retained 15 sites located not far to the inundated area, have easy access through the existing road network and are able to accommodate a large number of evacuees. Figure 7 illustrates the distribution of buildings shelters and assembly areas along the study zone.

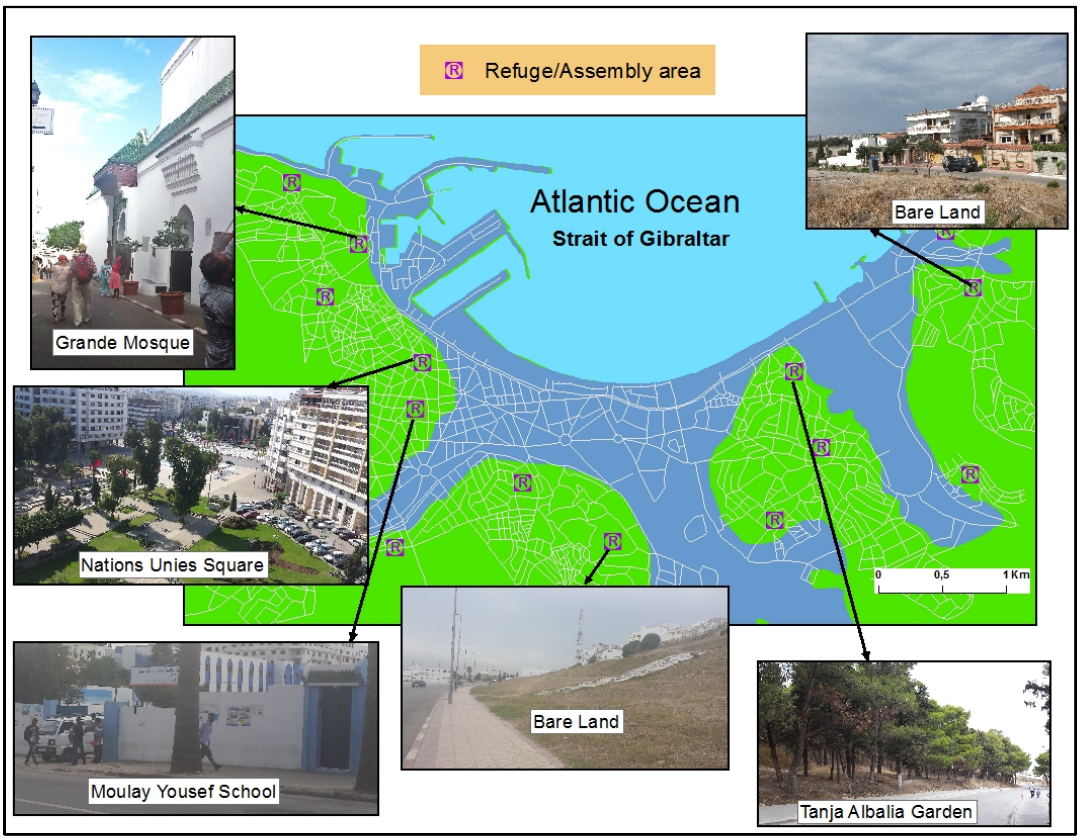

Figure 7: Map indicating the location of evacuation shelters buildings/ assembly areas with some photos

These sites corresponds to: i) evacuation shelters buildings; as Mosques (Grande Mosque, Mosque Assouriyine) or schools (Moulay Youssef school, Roi Fahd school and Sakia El Hamra school). They are able to shelter the evacuees for a considerable period since they have appropriate infrastructures (rooms, drinking water, electricity...) and ii) assembly areas like; public gardens (United Nations garden, Tanja Al Balia garden) or high topography areas (forest or bare land), these areas could accommodate evacuees temporarily. The total capacity of the proposed refuge sites seems to be sufficient in case of a real threat because it exceeds 17100 people estimation. The proposed assembly areas or evacuation building shelters should be validated by the local authorities before adopting an official evacuation map.

5. TSUNAMI EVACUATION MODELING

The principal action of an evacuation is to ensure that, in case of risk, people move from a relatively danger zone to safer places via routes that are free from significant danger. Furthermore, the main goal of evacuation is to save lives.

NTHMP (2001) explained that there are two methods to evacuate people from tsunami hazard zones; a) Horizontal evacuation; when evacuees move from the hazard zones to the safer areas or higher grounds (hills) located out of the inundation area; b) Vertical evacuation; when threatened community evacuate to nearby higher floors of tsunami resistant buildings. Vertical evacuation is needed for near-source generated tsunamis which there is not enough time between warning and the arrival of the first tsunami wave.
To achieve a good modeling of evacuation routes some parameters should be taking account.

5.1 SPEED OF EVACUEES

According to the Intergovernmental Oceanographic Commission report (IOC, 2008); to ensure safe evacuation, several risk management programs prohibit residents to evacuate by their personal vehicles for all types of disasters. In the case of a local tsunami where the source is close to the coastal zones, the waves could arrive in 30 minutes or less after the trigger of the earthquake. Threatened persons are encouraged to walk to safe areas because in such cases, the use of vehicles can not only block the roads but constitute a real menace to people life.

In this study, evacuation was assumed to be performed by walking. As the network analysis is based on time traveling, we have defined two more parameters; the speed of pedestrians and topography (slope). These parameters are considered able to influence the movement of evacuees along the routes before reaching the selected safe areas.

Pedestrians speed was identified from available bibliographic references. Dewi (2012) used for modeling evacuation routes in the coastal area of Cilacap (Java, Indonesia), the walking speed equal to 0.751 m/s. To model the behavior of persons in Arahama locality (District Miyagi, Japan) during the evacuation, Mas et al (2012) suggested an average speed of 1.1 m/s and a maximum speed of 1.33m/s. Scheer et al. (2012) consider an average human speed of 1 m/s while in ground where it is difficult to move as beaches, a speed of 0.5 m/s is proposed. Gonzalez Riancho et al. (2013), considered for modeling the evacuation in the coastal area of El Salvador, two types of pedestrian velocity; the rapid one 1m/s for adults and the slow one 0.7m/s for children, elder, and disabled people . A "comfortable" pedestrian speed without interaction with other people or with physical barriers of 1.3 m/s was adopted by Sahal et al (2013) and applied to pedestrians evacuation at Côte d'Azur (France).

According to these different studies, the proposed pedestrian speed vary from 0.5 m/s to 1.33 m/s. In this work and since we don't know the pedestrian velocity for people living in Tangier, we adopted an average speed, therefore, the value of pedestrian speed taken is 1.03 m/s.

Tangier is a city with many slopes, we assume that this situation will decelerate the evacuation, that why a correction of walking speed based on the slope is necessary. To calculate the slopes from the DEM (10m) used in tsunami modeling, we took in account the difference in altitude between the lowest points considered as origins and the high points considered as destinations. New values of pedestrian speed were calculated on the basis of the coefficients reduction proposed by Laghi et al. (2006, see Table1). The road network has been divided into 16 classes of slopes extracted from DEM with a range of 3%, we obtained 16 classes of corrected speeds values varying from 1.03 m/s to 0.10m/s.

5.2 ESTIMATED TSUNAMI ARRIVAL TIME (ETAT)

The Estimated Tsunami Arrival Time (ETAT) is the time required for the first tsunami wave to travel from its source to a certain point in the coast (IOC, 2008). It is defined as the time that elapsed between the end of the earthquake and the arrival onshore of the first wave of the tsunami.

The estimated tsunami arrival time may vary from minutes to several hours depending on the type of tsunami which can be local, regional or transgenic. The first wave of local tsunami may hit the coastal area in a few minutes after the earthquake and can have important damage to coastal areas. On the other hand, distant tsunamis can travel for hours before striking coastal areas. The type of tsunami will determine the time required to alert the population in order to evacuate.

To simulate arrival time of the first tsunami wave to reach the Moroccan coasts, we used the TTT (Tsunami Travel Times). The TTT maps are obtained using TTT software (figure 8), this program calculates the first arrival travel times with global bathymetry grids for a tsunami generated in a given source. For Tangier, calculation was based on two tsunami scenarios, the Horseshoe fault (HSF) and the Cadiz Wedge fault (CWF), details of the sources are given in ASTARTE-D8.8 (2015) (http://www.astarte-project.eu).

Results showed that the first wave of the tsunami will reach the Tangier coastal area in 0.9 hour (54 minutes) for the HSF scenario and in 0.8 hours (48 minutes) for the CWF scenario. As we are interested of the worst case scenario, we considered the shortest time of

48 minutes corresponding to the estimated tsunami arrival time. This time gives an idea to the available time for the threatened population to evacuate tsunami hazard zones.

Table 1: Evacuation speed correction based on the slope (Laghi et al., 2006).

Slope	Speed value	Slope	Speed value
0 - 3	100%	***24-27***	25%
3-6	85%	***27-30***	20%
6-9	70%	***30-33***	15%
9-12	55%	***33-36***	14%
12-15	45%	***36-39***	13%
12-18	40%	***39-42***	12%

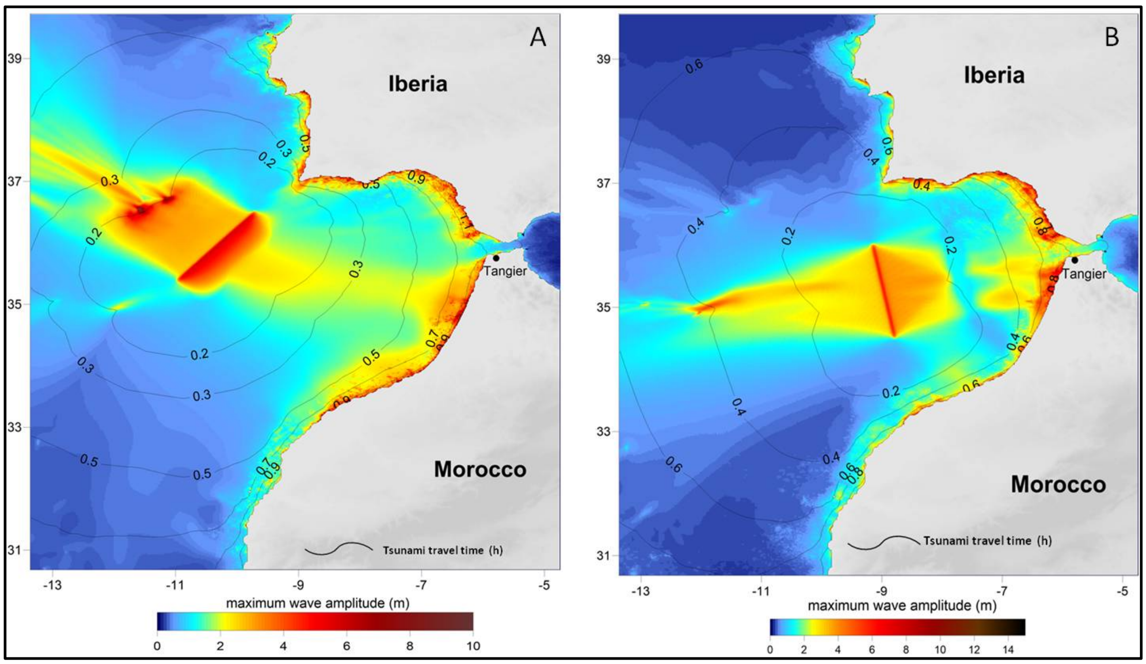

Figure 8: Simulation of the first tsunami arrival time to Moroccan coasts using TTT software for two tsunami scenarios, A) the Horseshoe fault (HSF) and B) the Cadiz Wedge fault (CWF).

5.3 EVACUATION TIME (ET)

Evacuation Time (ET) is the time that the alerted population need to reach a secure area (refuge site) before the first tsunami wave arrive. The evacuation time can vary according to the type of tsunami from several minutes to hours. In order to define the evacuation time (ET) for Tangier, we used the formulae proposed by Dewi (2012):

$$ET = ETAT - WT - RT$$

ETAT: Estimated Tsunami Arrival Time (48mn)
WT: Warning Time
RT: Response Time of the population

Warning Time (WT) is defined as the time required to tsunami warning center to take the decision to disseminate the information to the authority. Generally, a threatened community is considered timely warning when the alert time is less than 15 min. For our study, we considered the warning time proposed by Omira et al. (2009). These authors suggested that for ensuring the best evacuation for the city of Tangier, the minimum warning time should be between 20 and 30 minutes. In our study, we decided to take an average value of 25minutes as Warning Time (WT).

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Response Time (RT) of evacuees depends on the degree of awareness of the threatened population. It's preferable that people leave the danger area immediately after an official warning. However, in most of time , people don't evacuate even the authorities suggest to do it. Mas et al. (2012) reported that the survey conducted in Miyagi, Iwate and Fukushima after the Tohoku-Oki tsunami and which concerned 870 survivors, showed that only 57% have evacuated immediately after the earthquake and 37% have taken more time to evacuate. Suppasri et al.(2013) reported that a survey accomplished after the same tsunami in Kamaishi and Natori cities (Japan) shows that 60% of 113 interviewees in Kamaishi evacuated less than 10 minutes while in Natori only 30% of 105 interviewees evacuated between 20 and 30 minutes. For Tangier, the population response time is supposed to be 10 minutes, it it's an optimistic estimate due to the low level of awareness of Tangier population.

After given values to the three factors that seem influence the evacuation time (ET) which are; the estimated tsunami arrival time (48 minutes), the warning time (25 minutes) and population response time (10 minutes), the calculated evacuation time (ET) is 13 minutes.

6. RESULTS AND DISCUSSION

In this study, we used the Closest Facility tool to obtain the most efficient time to go to the nearest evacuation shelter points. While solving the analysis, restrictions attributes including capacity limits of the paths or high degrees of the slope were chosen to prohibit some evacuees to traverse certain roads in order to avoid pedestrian congestion.

After solving the routes, the results are displayed in a graphic layers map. Figure 9 demonstrates an evacuation plan with the position of horizontal shelters and assembly areas. The areas to evacuate (danger) are displayed in blue color whereas the refuge zones (safe) in green, the evacuation roads are represented in different colors according to the calculated evacuation travel time.

Modeling results suggest that the total of the study area could be evacuated in less than 25min. The minimum time modeled for evacuation is 3.05 min whereas the maximum time needed to be in a safe place is 25 min. Also the capacity of the proposed shelters seems to be sufficient because at the end of the modeling all the threatened population have reached the safe areas.

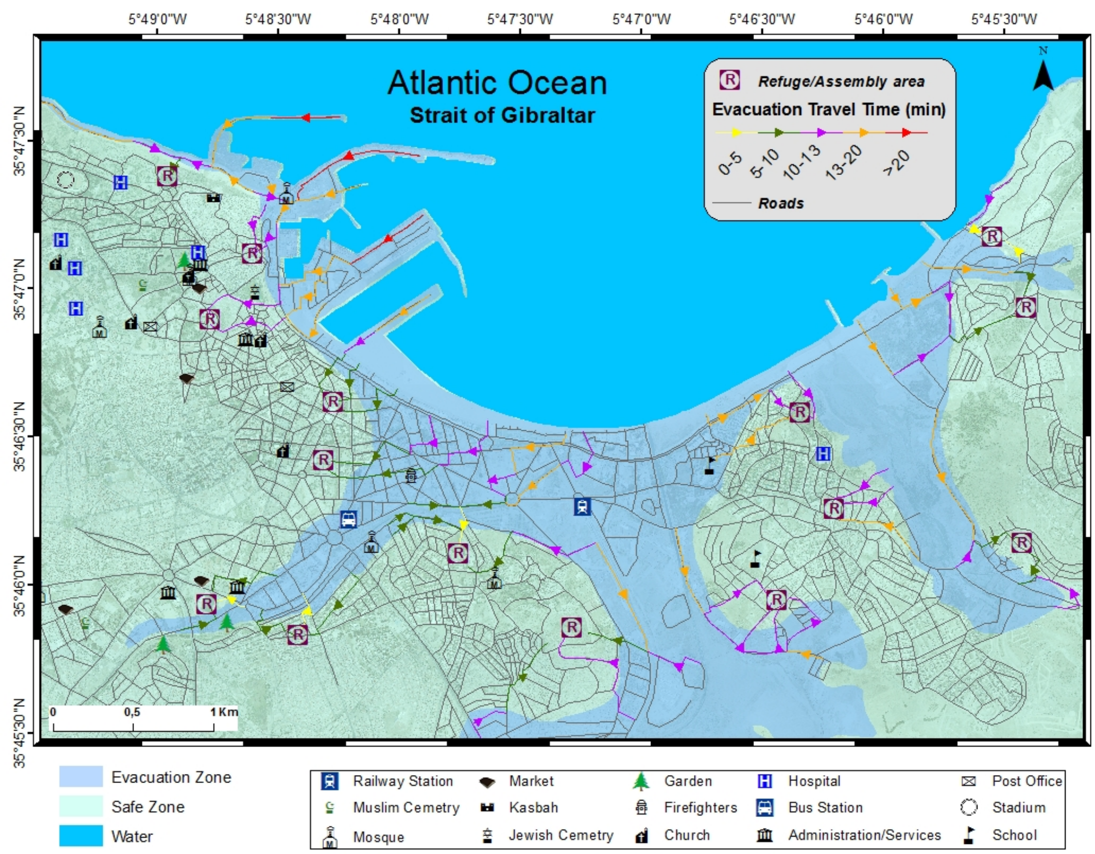

Figure 9: The proposed tsunami evacuation plan for Tangier city.

The results suggested that nearly 72% of the threatened population (12312 evacuees) could be sheltered in less than the calculated Evacuation Time ET (13 min). The remaining population (4788 evacuees) with evacuation travel time larger than 13 min are susceptible to the coming tsunami waves. For this part of the community, vertical evacuation refuges or shelters in the flooded area could be proposed for hosting temporarily these evacuees.
Also, if we want to have more time to evacuate, it is necessary that population react properly in a short of time. Awareness campaigns, distribution of brochures and training exercises are very useful to increase community resilience. These actions permit to explain to the potentially affected population the best attitude to take in case of tsunami warning

and when an earthquake is felt, threatened people should immediately evacuate to high areas or vertical shelters without waiting for an official warning from local authorities.

7. CONCLUSIONS

This study proposed a tsunami evacuation plan for the city of Tangier-Morocco. Evacuation modeling based on GIS tools was applied to find the most effective routes taking into account the shortest travel time to evacuate hazard zones in case of tsunami during the low season. Modeling was achieved using detailed input data of road network, evacuation building shelters or assembly areas and spatial distribution of the population in the hazard zone. Results are presented in an evacuation plan in which the escape routes, safe locations and assembly points are clearly marked. The proposed map need to be validated by local authorities and emergency planners in order to produce an official evacuation plan for Tangier city.

Many advances could be carried out in future studies; detailed data of the local population will help to consider building blocks as origin points for modeling. This will make the model more realistic since it represents the real condition where people start moving from. We recommend for next works, to take into account the high variation of daily or seasonal touristic fluctuations; several evacuation scenarios could be implemented by varying the number of population (day/night, high/low season) or the profiles of people (adults, children, and disabled).

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