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Identification of elements at risk for a credible tsunami event for Istanbul

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Abstract. Physical and social elements at risk are identified for a credible tsunami event for Istanbul. For this purpose, inundation maps resulting from probabilistic tsunami hazard analysis for a 10 % probability of exceedance in 50 yr are utilised in combination with the geo-coded inventories of building stock, lifeline systems and demographic data. The built environment on Istanbul's shorelines that is exposed to tsunami inundation comprises residential, commercial, industrial, public (governmental/municipal, schools, hospitals, sports and religious), infrastructure (car parks, garages, fuel stations, electricity transformer buildings) and military buildings, as well as piers and ports, gas tanks and stations and other urban elements (e.g., recreational facilities). Along the Marmara Sea shore, Tuzla shipyards and important port and petrochemical facilities at Ambarlı are expected to be exposed to tsunami hazard. Significant lifeline systems of the city of Istanbul such as natural gas, electricity, telecommunication and sanitary and waste-water transmission, are also under the threat of tsunamis. In terms of social risk, it is estimated that there are about 32 000 inhabitants exposed to tsunami hazard.

1 Introduction

The city of Istanbul is under the threat of earthquakes expected to originate from the Main Marmara branch of the North Anatolian Fault System. In the Marmara region the earthquake hazard reached very high levels with 2 % annual probability of occurrence of a magnitude 7+ earthquake on the Main Marmara Fault (Erdik et al., 2004). Istanbul is the biggest city of the Marmara region as well as of Turkey with its almost 12 million inhabitants. It is home to 40 % of the industrial facilities in Turkey and operates as the financial and trade hub of the country. With the evidence of past earthquakes, the structural reliability of residential and industrial buildings, as well as that of lifelines including port and harbour structures in the country, is questionable (Erdik and Durukal, 2008; Durukal et al., 2008). These facts make the management of earthquake risks imperative for the reduction of physical and socio-economic losses. Yet the assets at risk along the shores of the city make a thorough assessment of tsunami risk essential. Important residential and industrial centres exist along the shores of the Marmara Sea. Particularly along the northern and eastern shores an uninterrupted settlement pattern with industries, businesses, commercial centres and ports and harbours in between is seen (Hancilar et al., 2008).

The population, structures, utilities, systems and socio-economic activities constitute the "elements at risk" in urban areas. The physical elements are the built environment such as buildings and lifelines. Demographic data represent the social elements at risk. The objective of the present study is to identify the elements at risk based on a probabilistic tsunami hazard assessment for Istanbul carried out by OYO Co. (2007). The paper encompasses three parts. In the first part, tsunamigenic seismic sources for the surrounding seas of Turkey and particularly for the Marmara Sea region are identified and a database for tsunamigenic seismic zonation is provided. In the second part, inundation maps resulting from probabilistic as well as deterministic tsunami hazard assessments are represented. The methodology for the identification of elements at risk and the results are presented in the last part.

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Fig. 1. Tsunamigenic seismic zonation map for Turkey. Zones are shown by green polygons and red dots represent the individual point sources as the epicentres of the earthquakes that produced tsunamis in the past.

Fig. 2. Tsunamigenic seismic zones (Zone 16 and 17) in the Marmara Sea region. Red dots represent the epicentres of historical earthquakes and the numbers just below or above them stand for the event's years. The fault segmentation model developed by Erdik et al. (2004) for the North Western, South Western and Marmara Sea strands of the North Anatolian Fault System is shown by dashed lines with the numbers of each segment (e.g., S1, S2 etc.).

2 Tsunamigenic seismic sources in the Marmara Sea region

There are two potential sources for tsunami generation in the Marmara Sea region: earthquakes and sub-marine landslides. As future earthquakes are expected to break segments of the North Anatolian Fault System, the possibility that tsunamis could be generated by the co-seismic displacement of the seafloor or by triggered sub-marine landslides should be considered (Hebert et al., 2005). It has been reported that the coasts of the Marmara Sea have been frequently struck by tsunamis; over 40 tsunamis could have occurred in the Marmara Sea between 120 and 1999 AD (Altinok et al., 2001a). The most recent event identified as a tsunami in the Marmara Sea was triggered by the 1999 Kocaeli Earthquake (Altinok et al., 2001b).

In the present study, only seismic sources are considered. A seismic source zone can be defined as a seismically homogenous area, in which every point within the source zone is assumed to have the same probability of being the epicentre of a future earthquake (Erdik et al., 2000). Seismic source zones can be determined by the help of a seismicity profile and the tectonic regime of the region under consideration. A seismic zonation map of Turkey and neighbouring regions is provided by Erdik et al. (1999, 2000). This map was adopted for the compilation of an inventory database for tsunamigenic seismic sources in and around Turkey. In the compilation process, the tectonics, seismicity and topography of the study region were checked with related literature (i.e., McKenzie, 1970; Barka and Kadinsky-Cade, 1988; Saroğlu et al., 1992; Barka and Reilinger, 1997; Armijo et al., 1999). Dominant faulting mechanisms, the dip angle, direction strike and rake angles were obtained through the searches of the CMT catalogue (http://www.globalcmt.org/CMTsearch.html). The Harvard CMT catalogue provides fault plane solutions for earthquakes with magnitudes greater than 5.0 in Turkey starting from 1976. Historical data provided in Ambraseys (2002), Altinok and Ersoy (2000), Altinok et al. (2001a, b, 2003), Yalciner et al. (2002) and Yolsal et al. (2007) on the past tsunami occurrences were utilised in the identification of seismic zones that have potential for tsunami generation. Only seismic zones that have produced earthquakes followed by a tsunami were included in the database. Hence, 26 zones were identified in total. Table 1 provides the minimum and maximum depths, expected seismogenic thicknesses and the associated faulting mechanisms for each zone. The zones are represented by polygons with up to eight vertexes with their corresponding geographical coordinates, i.e., latitudes and longitudes. The identified tsunamigenic seismic zones in the Marmara Sea region and partly in the Euro-Mediterranean and Black Sea regions are depicted in Fig. 1. For verification purposes, locations of the tsunamigenic sources, i.e., epicentres of historical tsunamigenic earthquakes, as provided by Y. Altinok (personal communication, 2010), are also illustrated in Fig. 1. Figure 2 represents a closer view on satellite imagery for the tsunamigenic seismic zones, namely Zone 16 and 17, in the Marmara Sea region. In this figure, an idealised fault segmentation model (Erdik et al., 2004) of the region as well as the epicentres of historical tsunamigenic earthquakes are also illustrated.

3 Inundation maps for Istanbul

Tsunami inundation maps show coastal land areas that become submerged during a tsunami. The area of land subject to inundation is a factor of (EERI, 2005):

Table 1. Tsunamigenic seismic zones in and around Turkey: a summary table representing kinematic parameters and geographical coordinates for each zone.

Zone No.	Zone ID	Min. Depth (km)	Max. Depth (km)	Thickness (km)	Kinematics	LatV1 LonV1	LatV2 LonV2	LatV3 LonV3	LatV4 LonV4	LatV5 LonV5	LatV6 LonV6	LatV7 LonV7	LatV8 LonV8
1	Z10	5	40	35	right-lateral strike slip	40.694 26.075	40.307 26.218	40.161 25.774	39.989 25.012	38.97 23.748	39.075 23.497	39.416 23.174	40.31 24.847
2	Z12	10	170	160	–	36.736 26.571	36.097 26.983	36.097 26.445	36.322 25.376	37.314 23.635	38.108 24.215	37.228 25.205	36.831 26.024
3	Z13	5	100	95	–	35.829 26.95	34.628 27.501	34.159 26.75	33.99 24.802	34.726 22.905	35.784 23.775	35.422 24.977	35.518 25.94
4	Z14	8	30	22	normal	38.527 26.592	38.22 26.351	38.222 26.094	38.217 25.826	38.203 25.06	38.587 24.999	38.61 25.824	38.599 26.006
5	Z15	8	30	22	normal	38.83 26.829	38.527 26.592	38.848 25.532	38.937 25.279	38.947 25.295	39.046 25.431	39.129 25.62	– –
6	Z16	8	30	22	right-lateral strike slip + normal	40.878 31.886	40.616 31.902	40.561 29.223	40.649 27.674	40.307 26.218	40.694 26.075	40.975 27.678	40.822 29.275
7	Z17	6	30	24	right-lateral strike slip + normal	40.549 31.106	39.953 28.47	40.032 27.981	39.046 25.431	38.651 24.833	38.984 24.141	39.557 24.761	40.561 29.223
8	Z20	6	30	24	left-lateral strike slip	39.637 28.324	37.928 26.962	38.22 26.351	38.527 26.592	38.83 26.829	39.68 27.496	– –	– –
9	Z22	8	30	22	normal	37.879 29.931	37.631 29.577	37.77 28.692	38.086 28.725	38.305 28.44	38.424 27.357	38.83 27.68	38.564 28.907
10	Z23	8	30	22	normal	38.086 28.725	37.77 28.692	37.751 28.448	37.657 27.676	37.499 27.011	37.881 26.558	38.002 27.274	38.063 27.932
11	Z24	8	30	22	strike slip, normal	37.668 27.786	37.204 28.705	37.162 28.621	37.028 27.324	37.499 27.011	37.657 27.676	– –	– –
12	Z25	8	170	162	normal	37.204 28.705	37.094 28.922	36.722 28.49	36.325 27.953	36.089 27.524	35.902 27.106	36.736 26.571	37.028 27.324
13	Z26	8	100	92	left-lateral strike slip with normal component	36.722 28.49	35.863 29.172	35.255 28.293	34.628 27.502	35.828 26.948	35.902 27.106	36.089 27.524	36.325 27.953
14	Z27	8	60	52	left-lateral strike slip with normal component	38.427 30.654	38.123 31.241	37.624 30.455	36.709 29.598	35.863 29.172	36.722 28.49	37.094 28.922	37.879 29.931
15	Z28	8	110	102	strike slip	37.783 30.692	36.561 31.03	35.412 31.874	35.695 31.007	35.863 29.172	36.709 29.598	37.23 30.028	– –
16	Z29	10	70	60	strike slip, thrust	35.412 31.874	33.994 31.609	34.8 26.694	34.841 28.592	34.312 26.999	34.475 27.308	35.863 29.172	35.695 31.007
17	Z30	10	40	30	strike slip, thrust	35.024 33.377	34.011 33.556	33.936 33.102	33.88 32.09	33.994 31.609	35.412 31.874	35.141 32.309	35.029 32.86
18	Z31	10	40	30	–	36.456 35.986	35.684 35.807	34.687 35.631	34.173 34.454	34.011 33.556	35.024 33.377	35.315 34.277	35.945 35.383
19	Z32	8	130	122	strike slip, thrust	36.974 36.288	36.456 35.986	35.141 32.309	37.783 30.692	38.123 31.241	37.878 31.579	37.772 31.419	35.598 32.937
20	Z33-1	–	–	–	thrust and normal	41.884 44.587	41.554 43.477	41.665 42.121	41.289 40.424	41.621 40.282	41.727 40.882	41.994 41.471	42.148 43.245
21	Z33-2	–	–	–	thrust and normal	41.621 40.282	41.289 40.224	41.282 38.089	41.97 35.762	42.337 35.981	41.66 37.308	41.642 37.7	41.518 39.968
22	Z33-3	–	–	–	thrust and normal	42.337 35.981	41.97 35.762	42.334 34.26	42.091 32.876	41.37 30.916	41.633 30.96	42.241 32.655	42.523 33.948
23	Z33-4	–	–	–	thrust and normal	41.633 30.96	41.37 30.916	41.422 29.556	42.31 28.365	43.303 28.877	43.316 29.139	42.303 28.717	41.685 29.783
24	Z38	8	45	37	left-lateral strike slip	37.715 35.876	37.163 36.447	36.974 36.288	36.723 35.93	36.323 35.366	36.873 34.656	37.048 34.887	37.369 35.35
25	Z40	–	–	–	left-lateral strike slip	35.684 36.466	33.091 36.12	30.073 35.762	30.126 34.947	34.691 35.636	35.684 35.807	– –	– –
26	Z41	8	30	22	left-lateral strike slip + normal	37.6 36.785	37.1 37.02	35.684 36.466	35.684 35.807	36.065 35.895	36.456 35.986	36.974 36.288	37.163 36.447

- distance of shoreline from the tsunami-generating source;
- earthquake magnitude (primarily related to the earthquake source);
- duration and periods of the waves;
- run-up elevations (height above sea level likely to be flooded);
- tide level at time of occurrence;
- direction of shore with respect to propagated waves;
- topography of the seabed in the vicinity (bathymetry).

This section provides a brief summary of the probabilistic and deterministic tsunami hazard studies where the tsunamigenic seismic sources described in the previous section were utilised. Probabilistic inundation maps for a credible tsunami event on the coastal lines of Istanbul are also represented.

Probabilistic tsunami hazard analyses and inundation mapping for Istanbul were performed by OYO Co. (2007) for Istanbul Metropolitan Municipality in the framework of the project entitled "Simulation and Vulnerability Analysis of Tsunamis Affecting the Istanbul Coasts". For

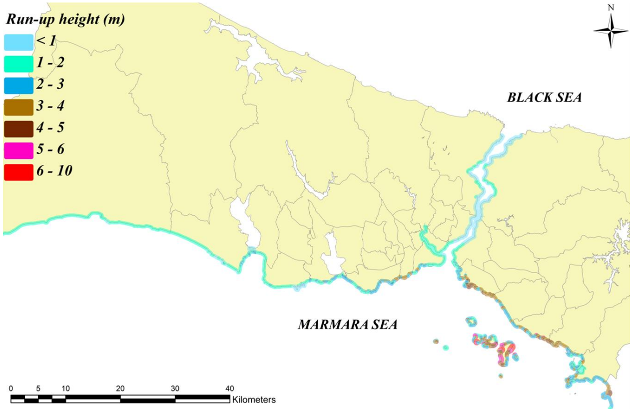

Fig. 3. Maximum run-up heights resulting from the probabilistic simulations for 10 % probability of exceedance in 50 years.

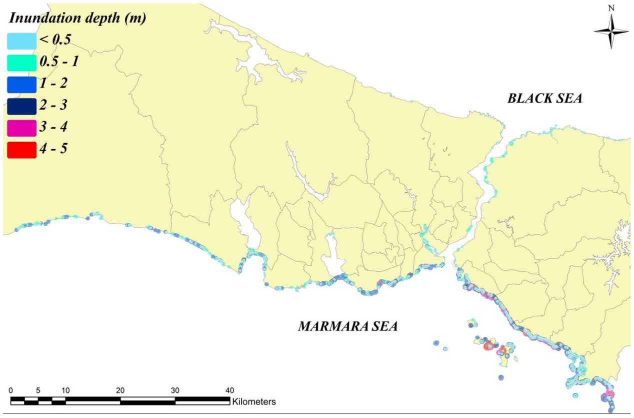

Fig. 4. Maximum inundation depths resulting from the probabilistic simulations for 10 % probability of exceedance in 50 years.

the assessment of tsunami hazard for a 10 % probability of exceedance in 50 yr, OYO Co. conducted 42 simulations by utilising 150-m-resolution bathymetry-topography data for the Marmara Sea region and 50-m-resolution was adopted for the better characterisation of the area covering the fault segments which were considered to produce the expected magnitude 7+ earthquake. In each simulation, not only different rupturing cases of individual fault segments and/or simultaneous rupturing of several segments were considered, but also cascade and no cascade models were taken into account. The reader is referred to OYO Co. (2007) and http://www.ibb.gov.tr/en-US/SubSites/IstanbulEarthquake/Pages/TsunamiHazardAnalysis.aspx for further information on the probabilistic hazard study. Maximum run-up heights and maximum inundation depths as the outcome among 42 simulations are mapped in Figs. 3 and 4, respectively. The results show that the eastern coasts of Istanbul are more hazardous than its western coastline. The highest run-up height exceeding 9 m is expected in the Prince Islands. Kartal and Kadıköy are the next hazardous areas on the Asian side. On the European side, run-up heights up to 3 to 4 m are expected in Bakırköy and Zeytinburnu districts. The inundation at the south of the Küçükçekmece Lake is remarkable. The maximum inundation distance from the coast reaches about 600 m. The coastline of Kadıköy and the coast from Kartal to Tuzla are also expected to suffer run-ups for 100 to 300 m.

Piatenesi and Romano (2009) and Roger et al. (2009) conducted deterministic tsunami hazard assessments for Istanbul within the activities of the EC FP6 project entitled “Tsunami Risk and the Strategies for the European Region-TRANSFER (http://www.transferproject.eu/)”. Piatenesi and Romano (2009) studied a worst-case scenario event to take place in zone Z16 (see Table 1) on fault segment S6 (see Fig. 2). They reported that the eastern shores of Istanbul will likely be more affected than its western shores. The wave heights on the eastern shorelines reach about 2.5 m while they are about 1 m on the western shores. Tuzla area on the eastern shores is identified as the most affected zone; the inundation height reaches about 3 m. Roger et al. (2009) studied five earthquake scenario cases for the modelling of tsunami hazard in Istanbul. They selected fault lines within zone Z16 corresponding to the fault segments S5, S6, S7, S8, S9 and S10 (see Fig. 2). They found that the whole shoreline of Istanbul is exposed to important tsunami heights (often exceeding 2 m) and the eastern shores are more impacted than the western shores. They also identified the most hazardous areas as the area between the Marmara Sea and the Küçükçekmece Lake, and the coasts along the Kartal-Pendik-Tuzla line exposed to tsunami heights possibly greater than 3 m and to important local inundations. It is seen that both deterministic tsunami hazard assessments for Istanbul produce inundation results highly comparable to those of the probabilistic analyses.

4 Exposure assessment

Methods for tsunami risk assessment generally include hazard identification and characterisation, assessment of exposure data and risk characterisation. Risk is defined as the probability of harmful consequences, or expected losses (deaths, injuries, property, livelihoods, economic activity disrupted or environment damaged) resulting from interactions between hazards and vulnerable conditions determined by physical, social, economic and environmental factors or processes, which increase the susceptibility of a community to the impact of hazards (UN/ISDR, 2004). Tobin and Montz (1997) give a definition of exposure as the measure of a population at risk. This definition typically refers to the spatial coincidence of a resource (e.g., a structure) and a hazard (e.g., tsunami). It is a spatial attribute and does not include the quality of the resource in question (e.g., building code level of a structure) or efforts already in place to minimize future losses (e.g., flood insurance, evacuation routes) (Wood and Stein, 2001). Elements at risk are the social and physical elements exposed to a hazard and usually include population, buildings, lifeline systems, transportation systems and infrastructures. For a general building stock the following parameters affect the damage and loss characteristics: structural (system, height and building practices), non-structural elements and occupancy (such as residential, commercial and governmental) (Hancilar et al., 2010). Comprehensive information on tsunami risk assessment methodologies can be found in Jelinek and Krausmann (2008); they denote that the literature on tsunami risk assessment is very limited compared to other natural hazard risk such as earthquakes, floods or landslides. In this section, the methodology for the identification of elements at risk is described and the results are presented.

4.1 Methodology

Tsunami vulnerability of the society as well as of the built environment has just been made evident again by the catastrophic tsunami which struck the Japanese coastlines after the Great East Japan Earthquake of moment magnitude 9.0 on 11 March 2011. As of 16 May 2011 the Japanese government communicated that the number of fully or partially collapsed buildings, essentially all due to the tsunami, is 126 800. According to Chock (2011), the cost of the damage and economic losses had reached about 309 billion US Dollars and the total number of fatalities and missing people was estimated at about 24 000. Chock (2011) also reported that the tsunami had imposed different types of loads on the buildings, including hydrostatic and hydrodynamic forces, debris damming and debris impact forces and scouring effects, which were sufficient to cause structural failures of low- to mid-rise buildings of any structural material. The need for credible fragility models and laboratory data to understand the interaction of tsunami with the built environment has been mentioned by different researchers and studies, e.g., Grundy et al. (2005); Bernard et al. (2007). Dall'Osso et al. (2009) stated that no robust, well-constructed and validated building fragility model for assessing the vulnerability of buildings to tsunami had been developed yet. One of the recent studies on the derivation of structural fragility curves by the help of visual inspection of high-resolution satellite images taken before and after the 2004 Indian Ocean tsunami has been carried out by Suppasri et al. (2011). In order to make a preliminary investigation of the vulnerability of coastal areas to tsunami, a model, which is called "Papathoma tsunami vulnerability assessment model-PTVAM", was developed by Papathoma et al. (2003). The PTVAM was organised within a GIS framework to allow rapid data entry and visualisation of changing vulnerability by considering the production of new maps and was designed to be sensitive and capable of examining vulnerability at high resolution scales, i.e., at building to building scale (Dominey-Howesi and Papathoma, 2007). In this model a number of parameters/attributes which influence the vulnerability of buildings to tsunamis are identified, including but not limited to: number of stories, description of ground floor, building material, construction year and design code. Vulnerability of individual buildings is evaluated by considering the contributions made by those attributes. Concerning the social vulnerability, PTVAM estimates the number of people per building by taking into account population densities during the night and day times as well as in the summer and winter. The PTVAM requires that once data for physical and social elements at risk with pre-defined attributes are ready, they need inputting into the GIS environment and merged with inundation maps.

For the identification of socio-economic elements within the inundation zones on the shorelines of Istanbul, a similar methodology to PTVAM was followed. First, the building inventory data were classified and a unified database was compiled in GIS environment. Second, the unified inventory database was combined with the inundation maps and, buildings lying within the inundated areas were counted. The GIS-based data for the building stock of Istanbul were obtained from the Istanbul Metropolitan Municipality (IMM-2009). Inundation maps resulting from the probabilistic tsunami hazard study by OYO Co. (2007) were used (Figs. 3 and 4).

The building inventory data were processed and classified in terms of structural system types, number of stories, building usage functions and existence of basement floors. The classification includes:

- Structural System Types: reinforced concrete, masonry, steel and precast
- Number of Stories: low-rise (1–4), mid-rise (5–8) and high-rise (>8)
- Building Function and Usage: residential, commercial, public (schools, hospitals, governmental buildings, religious buildings, sports facilities), industrial, infrastructure (car parks, garages, fuel stations, electricity transformer buildings)
- Existence of Basement Floor(s)

According to this classification, low-rise and mid-rise reinforced concrete frame buildings constitute about 75 % of the building stock in Istanbul. The same building taxonomies utilised in the studies of seismic loss estimation for Istanbul (KOERI-2002, IMM-2009 and Erdik et al., 2011) were adopted in the classification presented in this study. In this way, and considering that the credible tsunami will strike the city after an earthquake and damage to the buildings will primarily be associated with damage due to seismic action, it is aimed to provide a consistent database for future steps of tsunami loss assessment, i.e., computation of tsunami vulnerability functions. Although seismic fragility/vulnerability functions and conversion rates, in terms of repair-cost ratios, of physical damage to financial loss are available for the

Table 2. Number of buildings within the inundation zone with respect to structural system types, height-wise classification and usage functions.

Structural system type	Height	Residential	Commercial	Industrial	Public	Infrastructure
Reinforced concrete	Low-rise	1513	361	10	72	13
	Mid-rise	369	135	1	7	–
	High-rise	19	–	–	–	–
Masonry	Low-rise	391	133	14	35	–
	Mid-rise	7	4	1	1	–
	High-rise	–	–	–	–	–
Steel	Low-rise	–	10	11	2	–
	Mid-rise	–	–	–	–	–
	High-rise	–	–	–	–	–
Precast	Low-rise	2	6	2	3	–
	Mid-rise	–	–	–	–	–
	High-rise	–	–	–	–	–
Unknown	Low-rise	618	348	217	140	21
	Mid-rise	22	28	13	2	–
	High-rise	4	–	–	–	–
Total		2945	1025	269	262	34

buildings in Istanbul, there are currently no tsunami vulnerability and loss functions, neither empirically nor analytically derived. Since the present study only deals with exposure assessment and there is no estimation of physical tsunami damages to buildings, total monetary value of the exposed buildings was calculated as an indicative figure. Based on number of stories and structural system classification, a unit value in terms of construction costs by taking into account the construction practices in Istanbul, as provided in Durukal et al. (2006), was assumed for each class and then, it was multiplied by the number of buildings.

For the estimation of the social exposure, the number of people was calculated based on the number of exposed buildings (IMM-2009). The data from the 2009 Population Census were utilised in combination with the database of the Istanbul Metropolitan Municipality, IMM 5747 Mahalle- Koy-Nufus – Population Data for Districts, Sub-Districts and Villages. These data were spatially joined with the number of floors at each exposed building to estimate the number of people residing in each building.

4.2 Results

The built environment on the shorelines of Istanbul exposed to tsunami inundation, that results from a probabilistic hazard assessment for 10 % probability of exceedance in 50 yr, consists of residential, commercial, industrial, public (governmental/municipal, schools, hospitals, sports and religious), infrastructure (car parks, garages, fuel stations, electricity transformer buildings) and military buildings as well as piers and ports, gas tanks and stations, urban elements (recreational facilities). In the forthcoming sections, spatial distributions of the physical elements, i.e., buildings, lifeline systems, piers and ports, and other buildings and structures, as well as the population exposed to tsunami hazard are mapped. A preliminary estimation of the monetary values of the exposed buildings is provided.

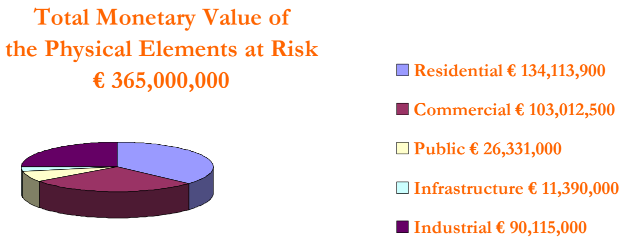

Fig. 5. Estimated total monetary value of the buildings within the inundation zone.

4.2.1 Buildings and population

Total number of the exposed buildings within the inundation zone was estimated at 4922. The breakdown of the buildings, with respect to previously defined classification system, is given in Table 2. This table includes only the buildings for which at least two attributes of the classification system are known. The estimated total monetary value of the exposed buildings is 365 million Euros. The pie chart in Fig. 5 represents the distribution of this value for different building classes. The number of exposed people was estimated at about 32 000. The spatial distribution of the number of exposed population is shown in Fig. 6.

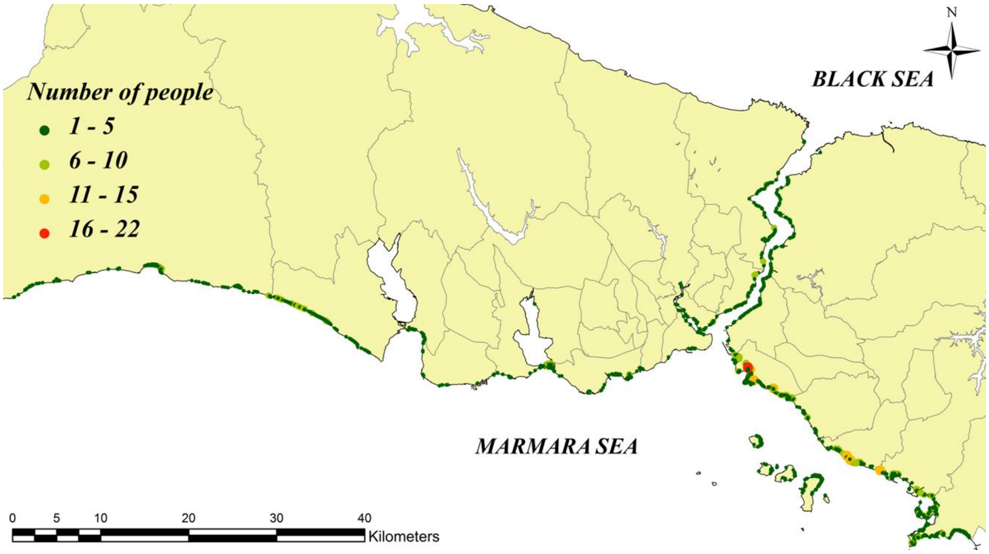

Fig. 6. Spatial distribution of the number of people residing in the exposed buildings.

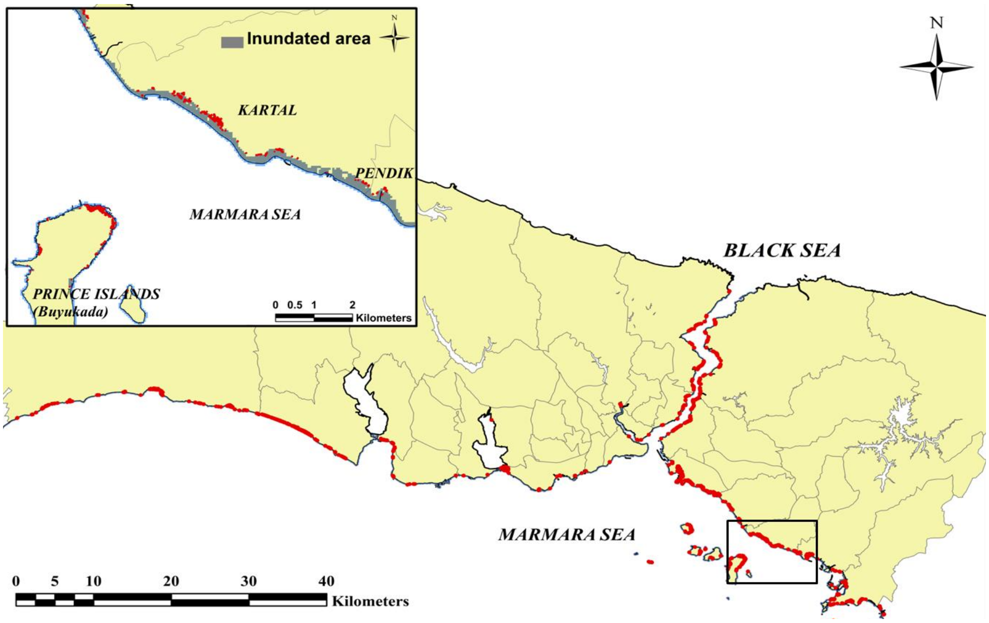

Fig. 7. Spatial distribution of the residential buildings at risk: buildings highlighted by red. Embedded frame: a closer view of the inundated areas where the residential buildings are densely located.

The building stock along the inundation zone consists mostly of residential buildings. The spatial distribution of residential buildings within the inundation zone is shown in Fig. 7. The majority of the residential buildings are located on the Prince Islands, the east coast of the Marmara Sea as well as in Büyükçekmece district on the western coasts. Commercial buildings are the second largest group in the building stock and they are located mostly on the eastern coasts of the Marmara Sea. The spatial distribution of commercial buildings within the inundation zone is shown in Fig. 8. The eastern coasts of the Marmara Sea as well as Beyoğlu, Fatih and Beşiktaş districts on the European side are dense locations for public buildings. The distribution of public buildings within the inundation zone is shown in Fig. 9. The industrial buildings are mostly located in Tuzla Bay area and their spatial distribution within the inundation zone is shown in Fig. 10. The infrastructure buildings identified within the inundation zone spread throughout the city; their spatial distribution within the inundation zone is given in Fig. 11.

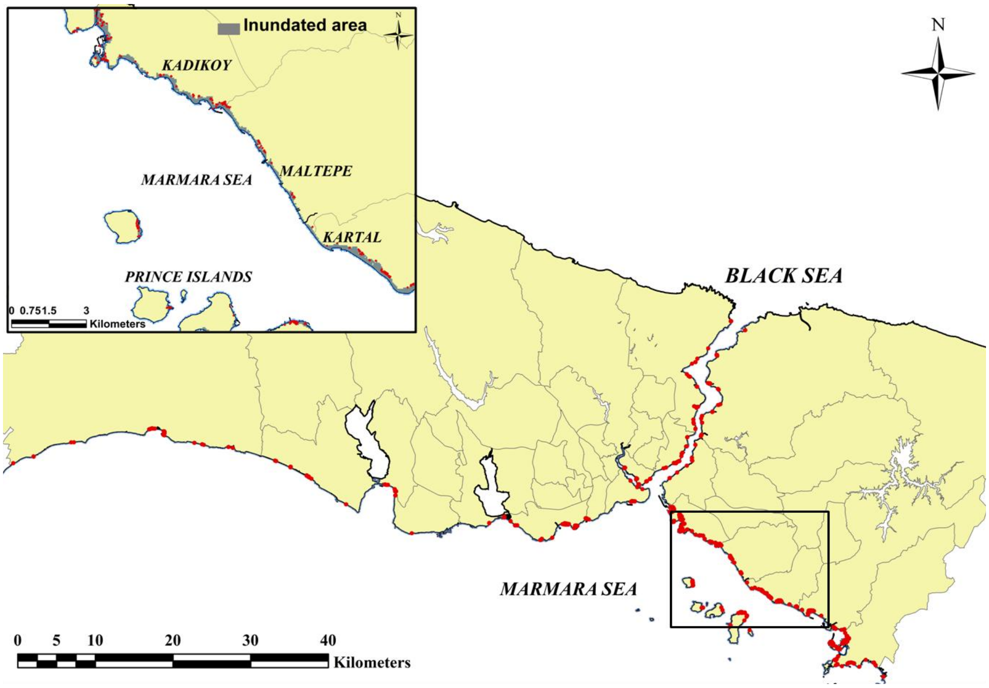

Fig. 8. Spatial distribution of the commercial buildings at risk: buildings highlighted in red. Embedded frame: a closer view of the inundated areas where most of the commercial buildings are located.

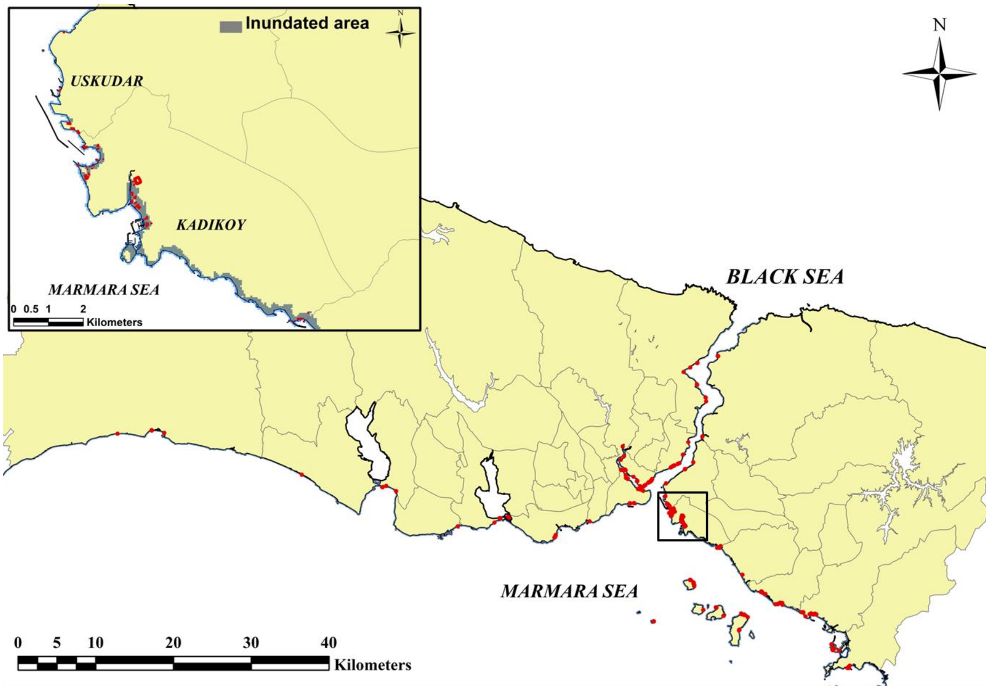

Fig. 9. Spatial distribution of the public buildings at risk: buildings highlighted in red. Embedded frame: a closer view of the inundated areas where most of the public buildings are located.

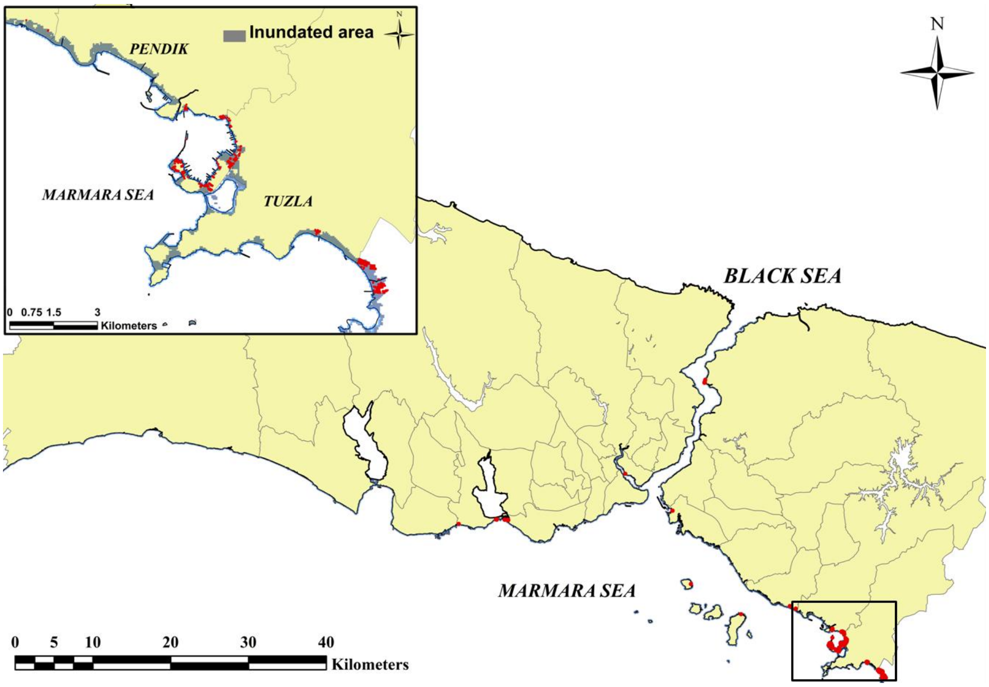

Fig. 10. Spatial distribution of the industrial buildings at risk: buildings highlighted in red. Embedded frame: a closer view of the inundated areas where most of the industrial buildings are located.

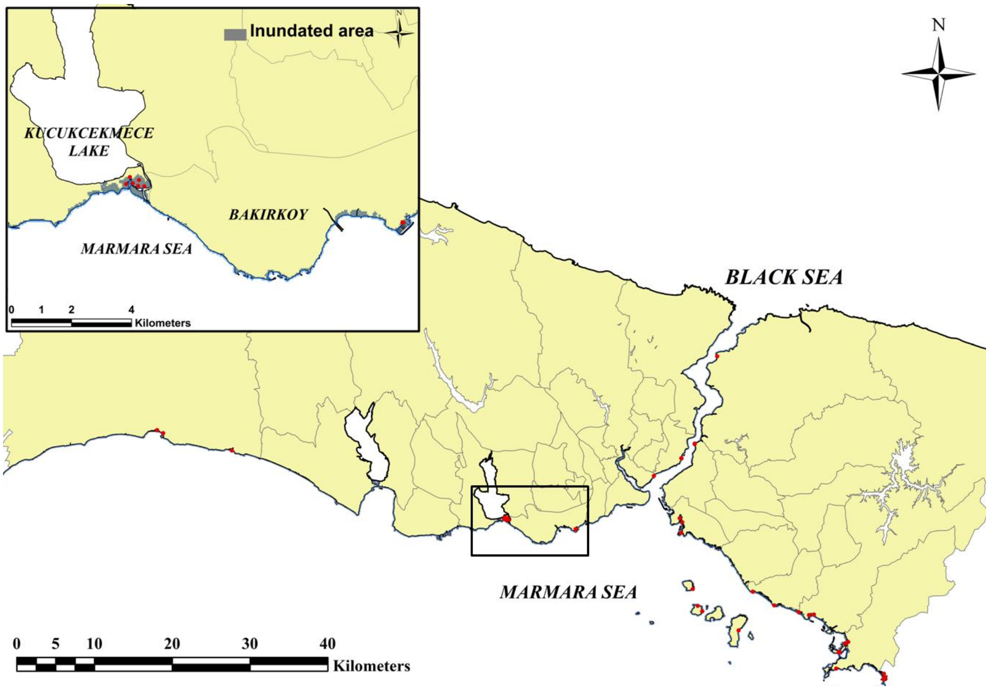

Fig. 11. Spatial distribution of the infrastructure buildings at risk: buildings highlighted in red. Embedded frame: a closer view of the inundated areas where most of the infrastructure buildings are located.

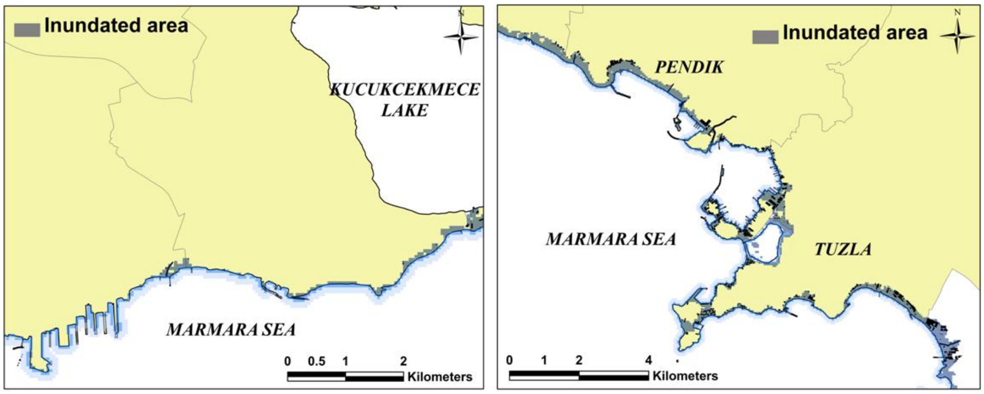

Fig. 12. Inundated areas within two important industrial/commercial zones of Istanbul. Left panel: Ambarlı Port area and its vicinity, Right panel: Tuzla Bay area and the Tuzla shipyards.

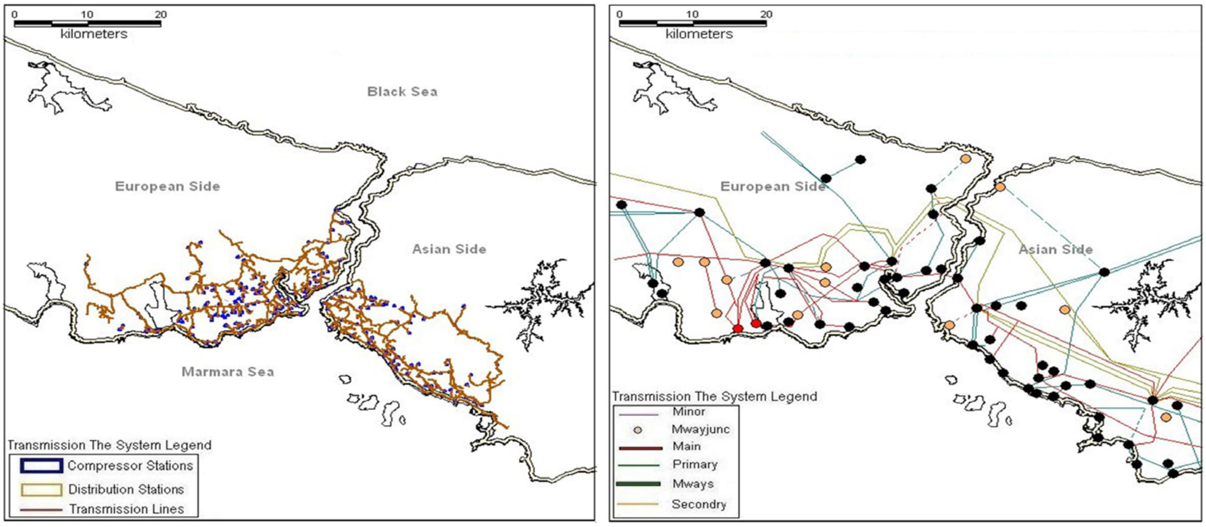

Fig. 13. Natural gas transmission network (left) and electricity network (right). A uniform, 600 m-width buffer zone which corresponds to the maximum inundation distance from the coastline is also shown (modified after KOERI, 2002).

4.2.2 Piers and ports, other buildings and structures

It was identified that there are 44 small and large piers and ports within the inundation zone. Besides, two important commercial/industrial facilities are exposed to tsunami inundation:

- The Ambarlı Port and Petrochemical Filling Facilities (Fig. 12): it should be noted that Ambarlı is the second largest port after Pire in the region of the Eastern Mediterranean and Black Sea.
- The Tuzla Shipyards (Fig. 12): there is a total of 36 companies actively working in Tuzla Bay area.

It was also identified that there are 17 fuel stations and tanks and 198 military buildings within the inundation zone. The military buildings are located next to the Tuzla Bay area. Ambarlı and Tuzla are the two areas in Istanbul already recognised as particularly vulnerable to earthquake hazard (Durukal et al., 2008).

4.2.3 Lifeline systems

The inventory database for the lifeline systems of Istanbul, i.e., natural gas network, sanitary and waste-water transmission systems, electricity network, telecommunication stations and transportation network, was the one used in KOERI-2002 study. It was not possible to spatially join the inventory data with the inundation maps because of different formats and conversion errors. In order to present indicative maps of exposed elements, a uniform, 600 m-width buffer zone which corresponds to the maximum inundation distance from the coastline was shown with the spatial distribution of the components of each lifeline system. It can be seen

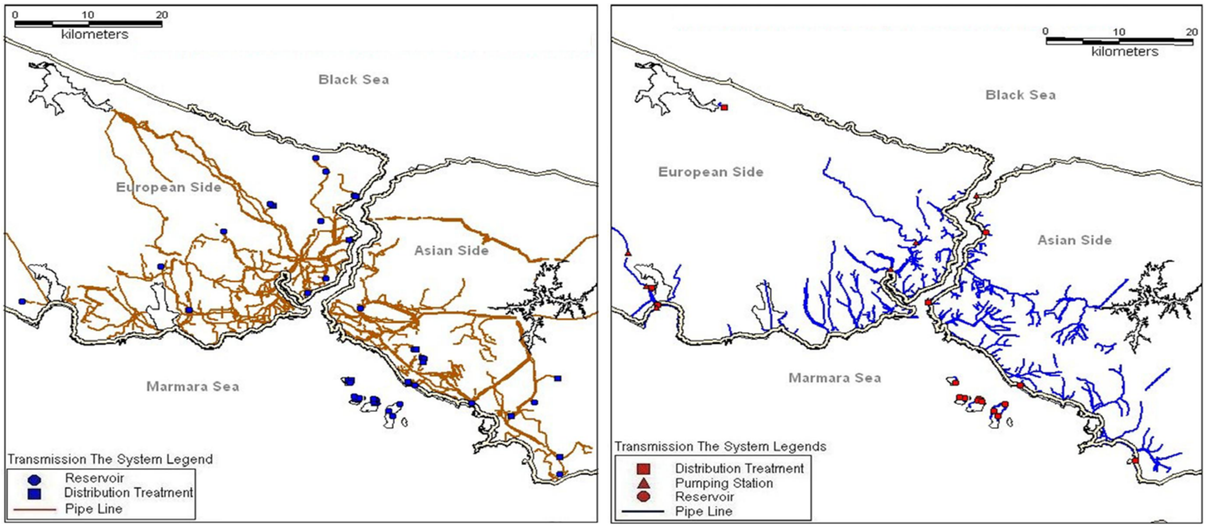

Fig. 14. Sanitary water transmission system (left) and waste-water transmission system (right). A uniform, 600 m-width buffer zone which corresponds to the maximum inundation distance from the coastline is also shown (modified after KOERI, 2002).

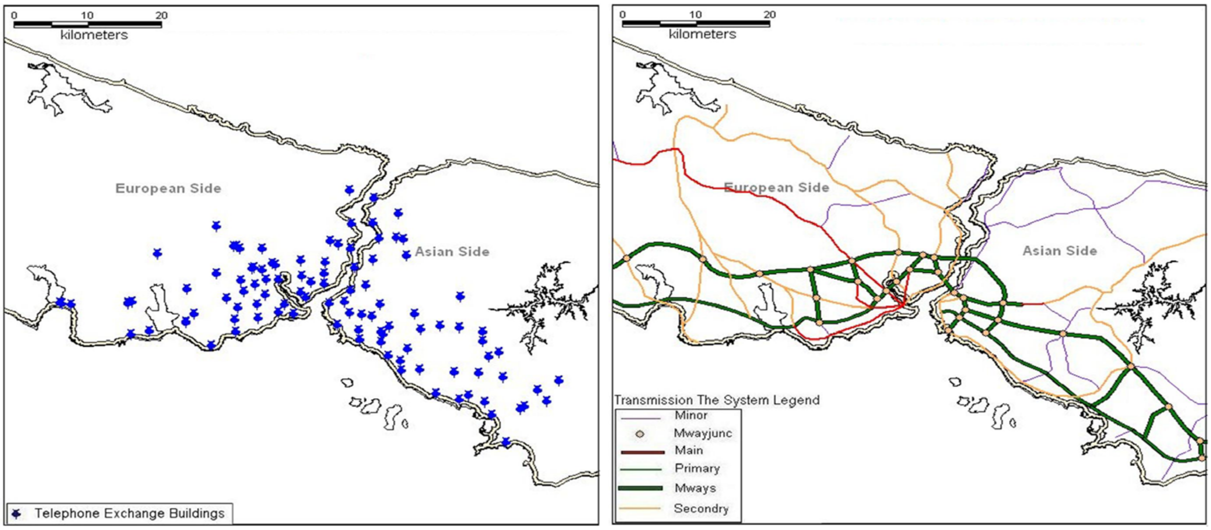

Fig. 15. Telecommunication buildings (left) and transportation network (right). A uniform, 600 m-width buffer zone which corresponds to the maximum inundation distance from the coastline is also shown (modified after KOERI, 2002).

that transmission lines and compressor stations of the natural gas network spread throughout both the western and eastern coastlines (Fig. 13). Most part of the transformer stations of electricity network exposed to tsunami hazard is located along the eastern coasts (Fig. 13). The reservoir stations of the sanitary and waste-water transmission systems are mostly located on the eastern shorelines as well as on the Prince Islands which are very close to the Main Marmara Fault System (Fig. 14). Some of the telecommunication buildings and secondary roads as well as some parts of the motorway lying between the Marmara Sea and Küçükçekmece Lake are also identified within the inundation zone (Fig. 15).

5 Concluding remarks

Tsunamigenic seismic sources for the surrounding seas of Turkey and particularly for the Marmara Sea region are provided and identification of physical and social elements at risk for a credible tsunami event for Istanbul is addressed. Based on the results of previous probabilistic and deterministic tsunami hazard assessments where tsunamigenic seismic sources provided herein were considered, it can be said that the eastern coasts of Istanbul are more hazardous than the western coastlines. At this point, it should be kept in mind that numerical modelling and hazard assessment considering sub-marine landslides, which are the non-seismic tsunamigenic sources in the study region, might result in different inundations on the shorelines of the city.

The built environment on the inundated coasts of Istanbul comprises residential, commercial, industrial, public (governmental/municipal, schools, hospitals, sports and religious), infrastructure (car parks, garages, fuel stations, electricity transformer buildings) and military buildings as well as piers and ports, gas tanks and stations, urban elements (recreational facilities). Total number of the exposed buildings and the number of inhabitants are estimated at 4922 and 32 000, respectively. The estimated total monetary value of the exposed buildings is 365 million Euros. Low-rise and mid-rise reinforced concrete frame buildings constitute about 75 % of the building stock in Istanbul. Regarding the relatively better structural resistance of those buildings comparing to wooden or adobe constructions, this can be considered as an advantage under the actions to be imposed by the credible tsunami event. On the other hand, a relatively high number of people reside/work in those multi-story buildings; this can increase the social vulnerability, especially for a daytime tsunami event. Significant lifeline systems for the city of Istanbul such as natural gas, electricity, telecommunication and sanitary and waste-water transmission as well as the important port and petrochemical facilities at Ambarlı and the Tuzla shipyards are also under the threat of tsunami inundation. It can be expected that economic losses due to business interruption and non-structural damage, i.e., damage to equipment and contents, in the industrial and infrastructure facilities will be higher than those resulting from structural damages in the buildings.

The aim of the project entitled “Simulation and Vulnerability Analysis of Tsunamis Affecting the Istanbul Coasts” by Istanbul Metropolitan Municipality was to produce a tsunami hazard map in order to assess tsunami risk and its impacts on Istanbul and to perform the necessary analyses for proper land use and development of strategies for mitigation of the possible effects of tsunami on Istanbul shorelines. The present study takes the efforts one step further by identifying the elements at risk in the framework of EC FP6 project entitled “Tsunami Risk and the Strategies for the European Region-TRANSFER”. The study also underlines the significance of well-classified inventory databases in the risk assessment. The provided unified inventory data can be used for further steps in a tsunami loss assessment study for Istanbul. The exposed building data might be utilised for the derivation of tsunami fragility functions. The results of the study certainly help create more public awareness, might contribute to the risk mitigation efforts and may also provide useful information for the development of proper land use plans.

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References

Altinok, Y. and Ersoy, Ş.: Tsunamis observed on and near the Turkish coast, Nat. Hazards, 21, 185–205, 2000.

Altinok, Y., Ersoy, Ş., Yalçıner, A. C. , Alpar, B., and Kuran, U.: Historical tsunamis in the Sea of Marmara, in: Proceedings of the International Tsunami Symposium, Seattle, Washington, USA, 527–534, 2001a.

Altinok, Y., Tinti, S., Alpar, B., Yalçıner, A. C., Ersoy, Ş., Bortolucci, E., and Armigliato, A.: The tsunami of August 17, 1999 in İzmit Bay, Nat. Hazards, 24, 133–146, 2001b.

Altinok, Y., Alpar, B., and Yaltirak, C.: Sarkoy-Murefte 1912 Earthquake’s tsunami, extension of the associated faulting in the Marmara Sea, Turkey, J. Seismol., 7, 329–346, 2003.

Ambraseys, N. N.: Seismic sea-waves in the Marmara Sea region during the last 20 centuries, J. Seismol., 6, 571–578, 2002.

Armijo, R., Meyer, B., Hubert, A., and Barka, A.: Westwards propagation of the North Anatolian Fault into the Northern Aegean: Timing and kinematics, Geology, 27, 267–270, 1999.

Barka, A. and Kadinsky-Cade, K.: Strike-slip fault geometry in Turkey and its influence on earthquake activity, Tectonics, 7, 663–684, 1988.

Barka, A. and Reilinger, R.: Active tectonics of the Eastern Mediterranean: Deduced from GPS, neotectonic and seismicity data, Ann. Geofis., X2, 587–610, 1997.

Bernard, B., Dengler, L., and Yim, S.: National Tsunami Research Plan: Report of a workshop sponsored by NSF/NOAA, NOAA Technical Memorandum OAR PMEL-133, 135 pp., available at: http://nctr.pmel.noaa.gov/pubs.html, 2007.

Chock, G.: The Japan Tohuku Tsunami of March, 2011 – Part 1: Preliminary observations of effects on buildings, Struct. Mag., 28–29, August 2011.

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.

Dominey-Howesi, 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, 113–136, 2007.

Durukal, E., Erdik, M., Sesetyan, K., and Fahjan, Y.: Building loss estimation for earthquake insurance pricing, in: Proceedings of the 8th US National Conference on Earthquake Engineering, San Francisco, California, 18–22 April, USA, 2006.

Durukal, E., Erdik, M., and Uckan, E.: Earthquake risk to industry in Istanbul and its management, Nat. Hazards, 44, 199–212, 2008.

EERI Quake'06 Champaign: Tsunami fact sheet, Local Government Committee, Northern California Chapter of the Earthquake Engineering Research Institute available at: http://www.eerinc.org/ (last access: 4 July 2010, February 2005.

Erdik, M. and Durukal, E.: Earthquake risk and its mitigation in Istanbul, Nat. Hazards, 44, 181–197, 2008.

Erdik, M., Biro, Y., Onur, T., Sesetyan K., and Birgoren, G.: Assessment of earthquake hazard in Turkey and neighboring regions, Ann. Geofis., 42, 1125–1138, 1999.

Erdik, M., Durukal, E., Birgören, G., Biro, Y., and Sesetyan, K.: A probabilistic seismic hazard assessment for Turkey in connection with the improvement of natural hazard insurance and disaster funding strategy (TEFER) Project, Part I: Tectonics, seismicity and seismic source zonation, Technical Report, Bogazici University, Istanbul, 2000.

Erdik, M., Demircioglu, M., Sesetyan, K., Durukal, E., and Siyahi, B.: Earthquake hazard in Marmara Region, Turkey, Soil Dyn. Earthq. Eng., 24, 605–631, 2004.

Erdik, M., Sesetyan, K., Hancilar, U., and Demircioglu, M.: Chapter 6: Earthquake risk assessment of an urban area (Istanbul), in: Hazard and Risk Management, edited by: Ashtiany, M. and Scawthorn, C., Springer, submitted, 2011.

Grundy, P., Thurairaja, A., and Walker, G.: Some reflections on the structural engineering aspects of tsunami, in: Proceedings, Australian Earthquake Engineering Society, Albury, New South Wales, 2005.

Hancilar, U., Durukal, E., Zulfikar, C., Erdik, M., Demircioglu, M. B., and Kariptas, C.: Tsunami impact and risk assessment for Istanbul, in: Proceedings of European Geosciences Union General Assembly, Vienna, Austria, 2008.

Hancilar, U., Tuzun, C., Yenidogan, C., and Erdik, M.: ELER software – a new tool for urban earthquake loss assessment, Nat. Hazards Earth Syst. Sci., 10, 2677–2696, doi:10.5194/nhess-10-2677-2010, 2010.

Hebert, H., Schindele, F., Altinok, Y., Alpar, B., and Gazioglu, C.: Tsunami hazard in the Marmara Sea (Turkey): A numerical approach to discuss active faulting and impact on the Istanbul coastal areas, Mar. Geol., 215, 23–43, 2005.

IMM-2009: Updating the estimations of the probable earthquake losses in Istanbul, Istanbul Metropolitan Municipality (IMM) – Directorate of Earthquake and Ground Investigation, OYO International Co., GRM Inc., Boğaziçi University- Kandilli Observatory and Earthquake Research Institute, Istanbul, 2009.

Jelinek, R. and Krausmann, E.: Approaches to tsunami risk assessment, JRC Scientific and Technical Reports: EUR 23573 EN, European Commission Joint Research Centre, Institute for the Protection and the Security of the Citizen, Ispra, Italy, 2008.

KOERI 2002: Earthquake risk assessment for Istanbul Metropolitan Area, Bogazici University, Kandilli Observatory and Earthquake Research Institute, Istanbul, Rep. no. 16, available at: http://www.koeri.boun.edu.tr/depremmuh/EXECENG.pdf (last access: 22 March 2010), 2002.

McKenzie, D. P.: Plate Tectonics of the Mediterranean Region, Nature, 226, 239–243, 1970.

OYO International Co.: Simulation and Vulnerability Analysis of Tsunamis Affecting the Istanbul Coasts, Final Report to Istanbul Metropolitan Municipality, Directorate of Earthquake and Ground Investigation, Istanbul, 2007.

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.

Piatanesi, A. and Romano, F.: Flooding maps in the Marmara Sea by INGV in Deliverable D8.1. EC FP6 TRANSFER Project – Tsunami Risk and Strategies for the European Region, 2009.

Roger, J., Labbé, M., and Hébert, H.: Deliverable D7.2: Inundation maps for the Sea of Marmara by CEA-DASE. EC FP6 TRANSFER Project – Tsunami Risk and Strategies for the European Region, 2009.

Saroglu, F., Emre, O., and Kuscu, I.: Active fault map of Turkey, Mineral Research and Exploration General Directorate of Turkey, 1992.

Suppasri, A., Koshimura, S., and Imamura, F.: Developing tsunami fragility curves based on the satellite remote sensing and the numerical modeling of the 2004 Indian Ocean tsunami in Thailand, Nat. Hazards Earth Syst. Sci., 11, 173–189, doi:10.5194/nhess-11-173-2011, 2011.

The Global Centroid-Moment-Tensor (CMT) Project: Harvard University, CMT catalogue web search, available at: http://www.globalcmt.org/, 2010.

Tobin, G. and Montz, B.: Natural Hazards, Guilford Press, New York, 388 pp., 1997.

UN/ISDR: Living with risk: a Global Review of Disaster Reduction Initiatives. International Strategy for Disaster Reduction. Geneva, UN Publications, 2004.

Wood, N. And Stein, D.: A GIS-based vulnerability assessment of Pacific Northwest ports and harbours to tsunami hazards, in: Proceedings of International Tsunami Symposium (ITS 2001), Session 1, 1–13, 2001.

Yalciner, A. C., Alpar, B., Altinok, Y., Ozbay, I., and Imamura, F.: Tsunamis in the Sea of Marmara: Historical Documents for the Past, Models for Future, Mar. Geol., 190, 445–463, 2002.

Yolsal, S., Taymaz, T., and Yalciner, A. C.: Understanding tsunamis, potential source regions and tsunami prone mechanisms in the Eastern Mediterranean, The Geodynamics of the Aegean and Anatolia, The Geological Society, London, Special Publication, 201–230, 2007.