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Real-time earthquake shake, damage, and loss mapping for Istanbul metropolitan area

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Abstract

The past devastating earthquakes in densely populated urban centers, such as the 1994 Northridge; 1995 Kobe; 1999 series of Kocaeli, Düzce, and Athens; and 2011 Van-Erciş events, showed that substantial social and economic losses can be expected. Previous studies indicate that inadequate emergency response can increase the number of casualties by a maximum factor of 10, which suggests the need for research on rapid earthquake shaking damage and loss estimation. The reduction in casualties in urban areas immediately following an earthquake can be improved if the location and severity of damages can be rapidly assessed by information from rapid response systems. In this context, a research project (TUBITAK-109M734) titled "Real-time Information of Earthquake Shaking, Damage, and Losses for Target Cities of Thessaloniki and Istanbul" was conducted during 2011–2014 to establish the rapid estimation of ground motion shaking and related earthquake damages and casualties for the target cities. In the present study, application to Istanbul metropolitan area is presented. In order to fulfill this objective, earthquake hazard and risk assessment methodology known as Earthquake Loss Estimation Routine, which was developed for the Euro-Mediterranean region within the Network of Research Infrastructures for European Seismology EC-FP6 project, was used. The current application to the Istanbul metropolitan area provides real-time ground motion information obtained by strong motion stations distributed throughout the densely populated areas of the city. According to this ground motion information, building damage estimation is computed by using grid-based building inventory, and the related loss is then estimated. Through this application, the rapidly estimated information enables public and private emergency management authorities to take action and allocate and prioritize resources to minimize the casualties in urban areas during immediate post-earthquake periods. Moreover, it is expected that during an earthquake, rapid information of ground shaking, damage, and loss estimations will provide vital information to allow appropriate emergency agencies to take immediate action, which will help to save lives. In general terms, this study can be considered as an example for application to metropolitan areas under seismic risk.

Keywords: Rapid response, Loss estimation and mapping, Shakemaps, Damage estimation, Real-time information, Istanbul city

Introduction

Rapid loss estimation after potentially damaging earthquakes is critical for effective emergency response and public information. The aim of the TUBITAK-109M734 research project "Real-time Information of Earthquake Shaking, Damage, and Losses for Target Cities of Thessaloniki and Istanbul," conducted during 2011–2014, was to establish rapid estimation of earthquake damages and casualties related to ground shaking in target cities of Thessaloniki and Istanbul, both of which have experienced devastating earthquakes (Zülfikar 2014). There is no doubt that efficient emergency response management immediately after an earthquake is an essential element of earthquake risk reduction. Research works (Coburn and Spence 2002) have shown that poor emergency response or a subsequent disaster can multiply the death toll of an earthquake by a maximum factor of 10. During the 1995 Kobe earthquake, natural gas could not be shut off in heavily damaged areas until 15 h after the event. The high

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number of casualties in Kobe is attributed to earthquake-triggered secondary events such as fire and explosions. During the 1999 Kocaeli earthquake, the central governing authorities were not aware of the severity and scale of the damage until several hours after the event. For the 2011 Van-Erciş earthquake, although an automated rapid response system was not in place, shakemaps and damage and loss estimation maps were obtained manually immediately after the earthquake information was received. In the view of above examples, there is no doubt that the presence of a real-time loss estimation application in metropolitan cities subject to earthquake hazards will provide immediate action and help to mitigate seismic risk during a potential future earthquake by providing rapid estimation of ground motion shaking maps and damage and loss assessments.

In 1994, the Federal Emergency Management Agency (FEMA) released a report (FEMA-249) outlining state-of-the-art methodology for earthquake loss estimation (FEMA 249 1994). The number of publications on the development of loss estimation methodologies and modeling increased significantly after the 1994 Northridge and 1995 Kobe earthquakes resulted in substantial economic losses. Methodological development of earthquake loss estimation was achieved at the regional scale by implementing HAZUS software (2003) in a cooperative work of National Institute of Building Sciences (NIBS) and FEMA. In addition, the Early Post-Earthquake Damage Assessment Tool (EPEDAT) was developed by EQE International (Eguchi et al. 1997) for the California region. In Japan, the Japan Meteorological Agency (JMA) developed a nowcast system for disseminating real-time information on the parameters of earthquakes, tsunami possibility, and seismic intensity at each observation station. A system for Real-Time Assessment of Earthquake Disasters in Yokohoma (READY), in operation since 1997, was developed to provide information on the spatial distribution of intensity and damage about 20 min after an earthquake. The rapid loss estimation systems currently used in Japan and Taiwan have been described by Yamazaki (2001) and Yeh et al. (2006), respectively.

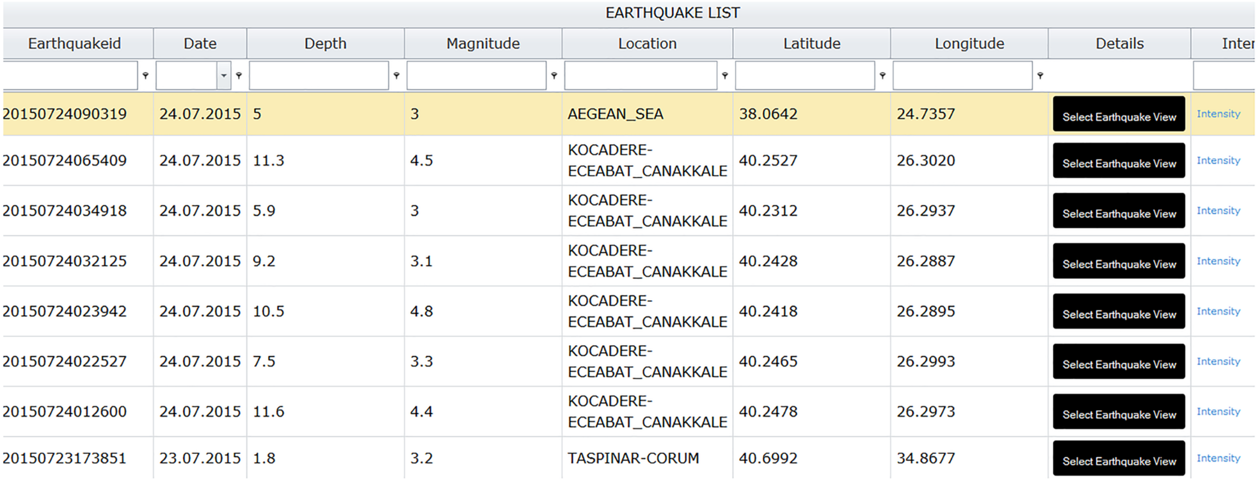
In Europe, post-earthquake response is coordinated at the national level by the individual civil protection agencies, although separate earthquake loss estimation (ELE) tools such as KOERILOSS, SIGE-DPC, ESCENARIS, SELENA, and DBELA (Strasser et al. 2008b) have been developed in various European countries. The OpenQuake engine is the seismic hazard and risk assessment software developed recently by the Global Earthquake Model (Silva et al. 2013). The EC-funded Network of Research Infrastructures for European Seismology (NERIES Project, 2010) project developed a rapid loss estimation tool known as Earthquake Loss Estimation Routine (ELER v3.1, 2010) to be used by European agencies such as the European Mediterranean Seismological Center (EMSC) for computing and broadcasting near-real-time earthquake loss estimates to the relevant emergency response institutions (Strasser et al. 2008a). In this study, the application of an earthquake rapid shaking map and loss estimation system for Istanbul city is introduced. The developed methodology consists of two modules of analysis: earthquake hazard assessment (EHA) and earthquake loss assessment (ELA). The EHA module produces ground shaking maps of intensity, peak ground acceleration (PGA), peak ground velocity (PGV), and spectral parameters at certain periods by using ground motion attenuation relationships; correlations among shaking intensity and PGA, PGV, and spectral parameters; and soil condition information. This module also uses the real-time ground motion information obtained by the strong motion stations distributed throughout the densely populated areas of Istanbul city. The ELA module uses ground motion information from the EHA module, grid-based demography, and building inventory data and provides damage and casualty information.

Istanbul earthquake rapid response network

Strong ground motions in intensely populated metropolitan cities under seismic risk should be well monitored online. For this purpose, a dense strong motion network with 110 accelerometers was established in 2002 and was placed in populated areas of Istanbul within areas of approximately 50 km × 30 km for tracking strong motion activities. Currently, acceleration data obtained from this strong motion station network are transmitted online instantly to the main data server at Kandilli Observatory and Earthquake Research Institute (KOERI) by a 3G Global System for Mobile communications (GSM) network (KOERI 2013). Earthquake parameters of depth, magnitude, and epicenter location are computed automatically by the KOERI-Regional Earthquake-Tsunami Monitoring Center (RETMC 2015) and are displayed on the Web site of RETMC (http://www.koeri.boun.edu.tr/sismo/2/latest-earthquakes/list-of-latest-events/). Figure 1 shows a list of the latest earthquakes, and Fig. 2 shows the strong motion network in Istanbul. The aim of this study is to ensure that assessments of strong ground motion distribution can be made within a few minutes after an earthquake.

Methods

The main objective of the developed application is to determine the affected regions in Istanbul immediately following an earthquake event by mapping the distribution of ground motion parameters and estimating subsequent damage and loss. Shaking, damage, and loss maps



EARTHQUAKE LIST

Earthquakeid	Date	Depth	Magnitude	Location	Latitude	Longitude	Details	Inter
20150724090319	24.07.2015	5	3	AEGEAN_SEA	38.0642	24.7357	Select Earthquake View	Intensity
20150724065409	24.07.2015	11.3	4.5	KOCADERE-ECEABAT_CANAKKALE	40.2527	26.3020	Select Earthquake View	Intensity
20150724034918	24.07.2015	5.9	3	KOCADERE-ECEABAT_CANAKKALE	40.2312	26.2937	Select Earthquake View	Intensity
20150724032125	24.07.2015	9.2	3.1	KOCADERE-ECEABAT_CANAKKALE	40.2428	26.2887	Select Earthquake View	Intensity
20150724023942	24.07.2015	10.5	4.8	KOCADERE-ECEABAT_CANAKKALE	40.2418	26.2895	Select Earthquake View	Intensity
20150724022527	24.07.2015	7.5	3.3	KOCADERE-ECEABAT_CANAKKALE	40.2465	26.2993	Select Earthquake View	Intensity
20150724012600	24.07.2015	11.6	4.4	KOCADERE-ECEABAT_CANAKKALE	40.2478	26.2973	Select Earthquake View	Intensity
20150723173851	23.07.2015	1.8	3.2	TASPINAR-CORUM	40.6992	34.8677	Select Earthquake View	Intensity

Fig. 1 Real-time list of earthquakes (www.ew-istanbul.com)

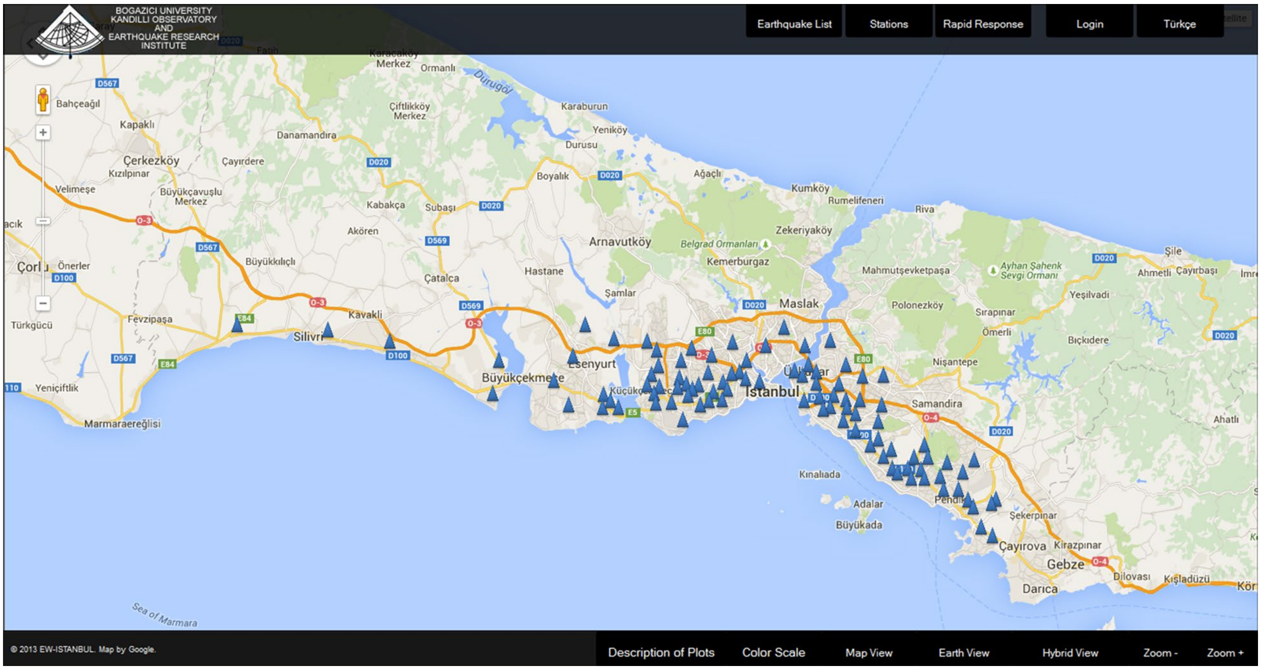


Fig. 2 Distribution map of the strong ground motion network throughout metropolitan Istanbul

are significant parts of the rapid response plans organized by rapid response rescue teams immediately after an earthquake. For the installation of the rapid response system application in Istanbul, three stages are followed: shakemapping, damage estimation, and loss estimation. All calculations in these three stages are performed in a grid-based environment. The necessary input for the calculations includes a fault database, grid-based local site conditions, building inventory, and demographic data for the specified region.

Site conditions

Within the TUBITAK 109M734 project, the site conditions for metropolitan Istanbul were evaluated by integrating several reference studies with the results of the Istanbul Metropolitan Municipality (IMM) microzonation project "Updating Probable Earthquake Losses for Istanbul" (IMM Report 2009). In this project, information on the average shear wave propagation velocity in the upper 30 m of the soil medium (V_{s30}) was obtained for each 250-m grid cell in populated regions of Istanbul. For the grid cells out of the IMM microzonation project area, regional geology units such as Quaternary, Tertiary, and Mesozoic (QTM) maps or topographic elevation data were utilized. The QTM map of Turkey created by General Directorate Mineral Research and Exploration (MTA) and the topographic slope-based V_{s30} map for the Euro-Med region created by Wald and Allen (2007) were implemented as reference studies within the project. Wald et al. (1999, 2006a, b) proposed a geology-based QTM map that classifies the soil into three different categories according to the V_{s30} velocity values. The QTM map of Turkey was prepared by grouping and digitizing 1:100,000-scaled surface geology maps of MTA (Zülfikar et al. 2007). In the QTM map, the shear wave velocity of the Quaternary (Q) sedimentary class is represented by V_s-333 m/s, whereas the Tertiary (T) soft rock and Mesozoic (M) hard rock classes are represented by V_s-406 and V_s-589 m/s, respectively.

Regarding the topographic elevation data, it is clear that topographic variations indicate near-surface geomorphology and lithology. According to Wald and Allen (2007), the slope of topography, or gradient, should be diagnostic of V_{s30} because more competent (high-velocity) materials are more likely to maintain a steep slope, whereas deep basin sediments are deposited primarily in environments with very low gradients. Based on this approach, the measured topographic slope (m/m) at each location is correlated with National Earthquake Hazards Reduction Program (NEHRP) V_{s30} boundaries (Federal Emergency Management Agency [FEMA] 222A 1994). The topographic slope at any site that falls within these ranges represents a V_{s30} that defines the median value of the NEHRP classes. In this study, for the regions in which microzonation study was not conducted, geological units, engineering surface geology, alluvial layer thickness, tertiary layer thickness, and wide-scaled artificial fill distribution information were evaluated in order to assign a V_{s30} value for each specified grid. For regions out of the microzonation project area, the relationship between V_{s30} value and geological formation depth, which was developed in the "Updating Probable Earthquake Losses for Istanbul" report (IMM Report 2009), was also considered. The integrated V_{s30} map for metropolitan Istanbul is given in Fig. 3.

Shaking maps

The current Istanbul Earthquake Rapid Response Network provides the real-time ground motion information obtained by the strong ground motion stations

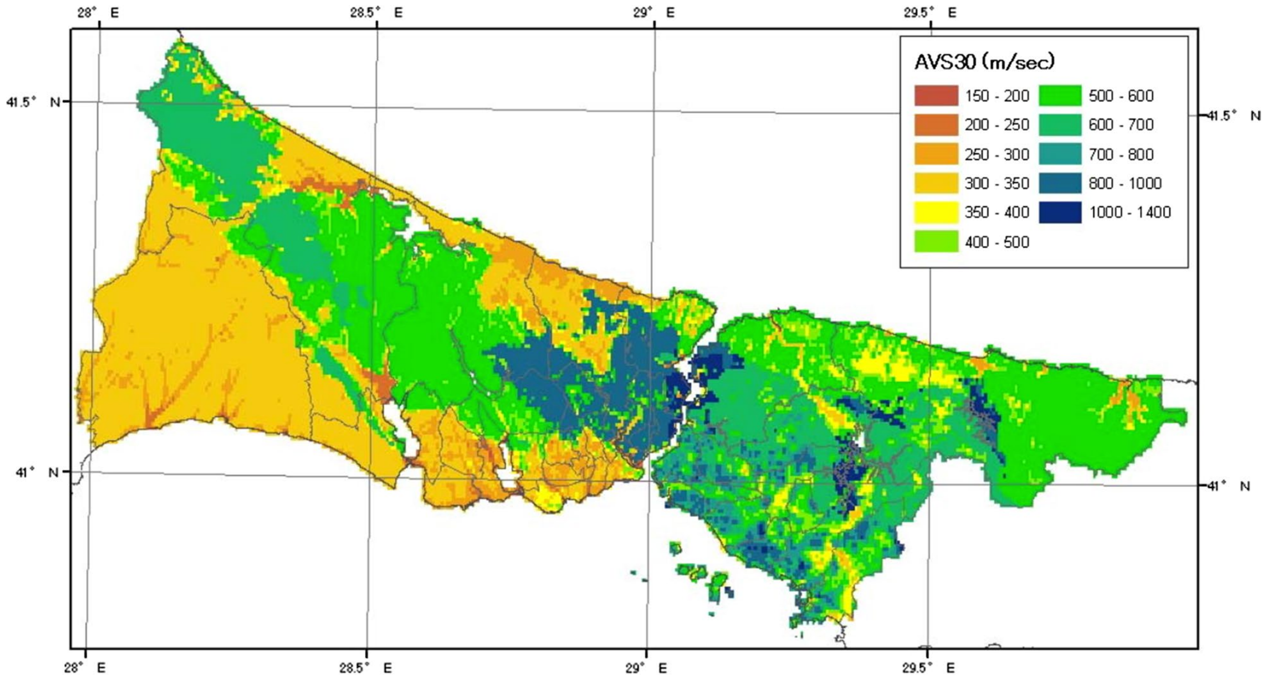


Fig. 3 Integrated V_{s30} map for metropolitan Istanbul; V_{s30} information for each 250-m grid in populated regions of Istanbul according to the Istanbul Metropolitan Municipality (IMM) Microzonation project (2009)

distributed throughout densely populated areas of Istanbul. After the occurrence of an earthquake, acceleration data obtained from this network and the earthquake information computed by RETMC are instantly transmitted online to the main data server at KOERI. The rapid response application checks the earthquake list through the RETMC Web site every 20 s to check for the occurrences of new earthquakes. The occurrence of an earthquake triggers the computation module of the installed rapid response application to estimate ground motion, building damage, and casualty distribution. The input data for the computation in the hazard module are magnitude, epicenter location, epicenter depth, and, if available, actual station records of the event obtained from the earthquake list at the RETMC Web site, which is similar to the US Geological Survey (USGS) ShakeMap strategy (Wald et al. 1999, 2003, 2006b). The automated solution of the hazard module checks the fault database of the region and attributes the event to the closest fault segment if present; otherwise, point source calculation is conducted until the source information is obtained.

Two different ground motion prediction equations (GMPEs) are used for the ground motion parameter distribution maps. In the selection of GMPEs, studies on the evaluation of available GMPEs using the National Strong Ground Motion Network Data of Turkey were considered. Kamer and Zülfikar (2011) evaluated available GMPEs with the records obtained from National Strong Ground Motion Network Data of Turkey between 1976 and 2011 for M2.2–M7.4 events. In the view of this study, the Boore and Atkinson (2008) approach was chosen for the events of $M \geq 5.0$; that of Ozbey et al. (2004), which was developed for only aftershocks of 1999 earthquakes (Kocaeli $\mathrm{Mw} = 7.4$ and Düzce $\mathrm{Mw} = 7.1$), was chosen for the events of $M < 5.0$.

According to the specified GMPE and intensity approach, the PGA, PGV, and intensity distribution maps (shakemaps) are computed automatically.

Building inventory and population

Within the TUBITAK 109M734 project, the building inventory for the Istanbul metropolitan area was updated by GIS service provided by the GRM Company (2015). At the beginning of the project, the grid-based building inventory was compiled by using the year 2000 Turkish Statistical Institute (TUIK) Building Census. The TUIK record, numbering 724,623, included information on the construction year, number of floors, and building construction type. In the later stage of the project, the district-based building inventory of Istanbul, which was developed by IMM in 2002 within the JICA project (Istanbul Disaster Prevention/Mitigation Base Plan Work including Seismic Microzonation, 2002), was integrated with the existing TUIK inventory (JICA-IMM 2003). The new inventory was finalized into 0.005° grids by using the IMM 5747 administrative borders produced by using the 2008 building line geometries of 1/1000-scaled existing maps. The number of total records of this produced dataset was 1,163,383. Additional information on the building inventory updating process can be found in the TUBITAK 109M734 project report. The building distribution for the IMM is shown in Fig. 4.

For the population inventory, Istanbul 5747 border district–rural population data from the Istanbul governorship including the number of people based on the IMM 5747 148 district–rural border were used. The total population was 12,572,852. Existing maps for the year 2008 were used for the calculations of night population. The number of floors point building data and IMM 5747 district–rural population data was spatially joined, and district–rural ID and district–rural total population values were assigned to each floor point dataset. The daytime and nighttime population distributions for the Istanbul metropolitan city are shown in Figs. 5 and 6, respectively.

In the building damage estimation, 57 building classes used for the Istanbul metropolitan area were adopted from HAZUS-MH (FEMA 2003) depending on the information for construction year, number of floors, and building construction type.

Damage estimation method

The spectral acceleration–displacement-based vulnerability assessment methodology was utilized to estimate the building damage. Different methods in ELER are used for this purpose. In this real-time damage estimation application, the coefficient method (CM) defined in the FEMA-356 document (ASCE 2000) and later modified by ASCE/SEI 41-06 (2007) was used. As mentioned in the building inventory and population section above, for real-time application of the damage estimation module, the building and population data consist of grid (geocell)-based urban building and demographic inventories.

The CM utilizes a displacement modification procedure in which several empirically derived factors are used to modify the response of a linearly elastic, single-degree-of-freedom (SDOF) model of the structure. This modification, presented as a nonlinear static analysis procedure in FEMA-356 (2000) and FEMA-273 (1997), essentially modifies the linear elastic response of the equivalent SDOF system by multiplying it by a series of coefficients to generate an estimate of the target displacement, or performance point. The coefficient method was critically evaluated in FEMA-440 (2005), and the results were reflected in ASCE/SEI 41-06 (2007).

Application of the spectral capacity-based vulnerability assessment requires the provision of spectral displacement, which defines the threshold of a particular damage state and the standard deviation of the natural logarithm

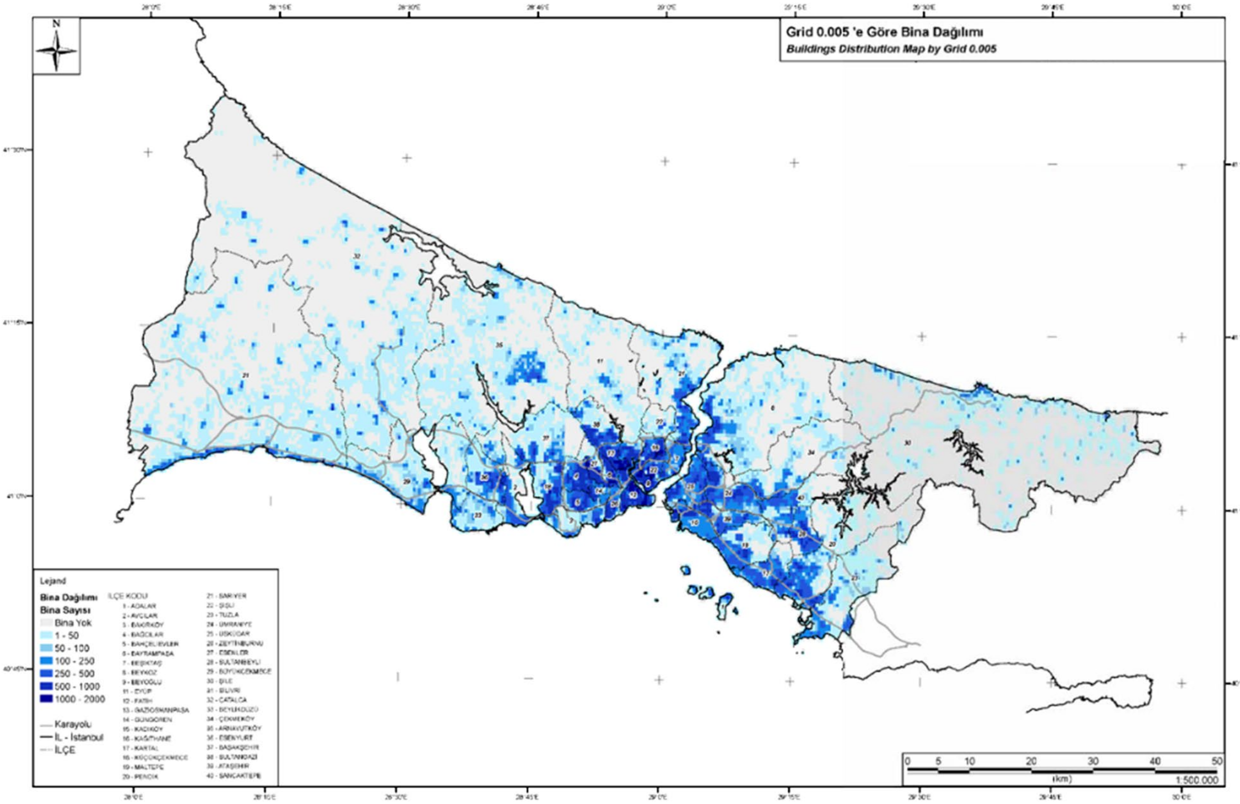


Fig. 4 Building distribution for metropolitan Istanbul

of the spectral displacement values for different model building types. In addition, the damage states are needed for the assessment of damage predictions for buildings, casualties, and socioeconomic losses owing to structural damage. "No," "Slight," "Moderate," "Extensive," and "Complete" damage states for each building model type are adopted in the Damage Estimation Routine of the rapid response application.

To estimate the performance of a group of buildings of a particular class under given ground shaking conditions, the spectral response of the building at the performance point for the standard building of that class is used in conjunction with a set of fragility curves for that class. This estimates the probability of any particular building exceeding each of the damage states after shaking at any given spectral response level.

The fragility curves represent the probability-based relationship between the expected response and the performance limits in terms of the cumulative density function of the probability of exceeding specific damage limit states for a given peak value of a seismic demand. If structural capacity and seismic demand are random variables that roughly conform to either a normal or lognormal distribution, then, following the central limit theorem, it can be shown that the composite performance outcome will be lognormally distributed. Therefore, the probabilistic distribution is expressed in the form of a so-called fragility curve given by a lognormal cumulative probability density function.

Loss estimation method

Although some studies on the building damage–casualty relationship for past Turkish earthquake events in national and regional levels were conducted within the TUBITAK 109M734 project, HAZUS-MH methodology was applied in the automatic routine for casualty estimation. In order to estimate the casualties depending on the damage estimation routine, the probability of each building damage state, information on population distribution by time, building general occupancy class, building type, and damage state (D1—slight, D2—moderate, D3—extensive, D4—complete, D5—complete with collapsed structural damage) are defined. The event tree for casualty estimation used in the automatic procedure as proposed by HAZUS-MH is shown in Fig. 7. The injury severity level proposed in the methodology is shown in Table 1.

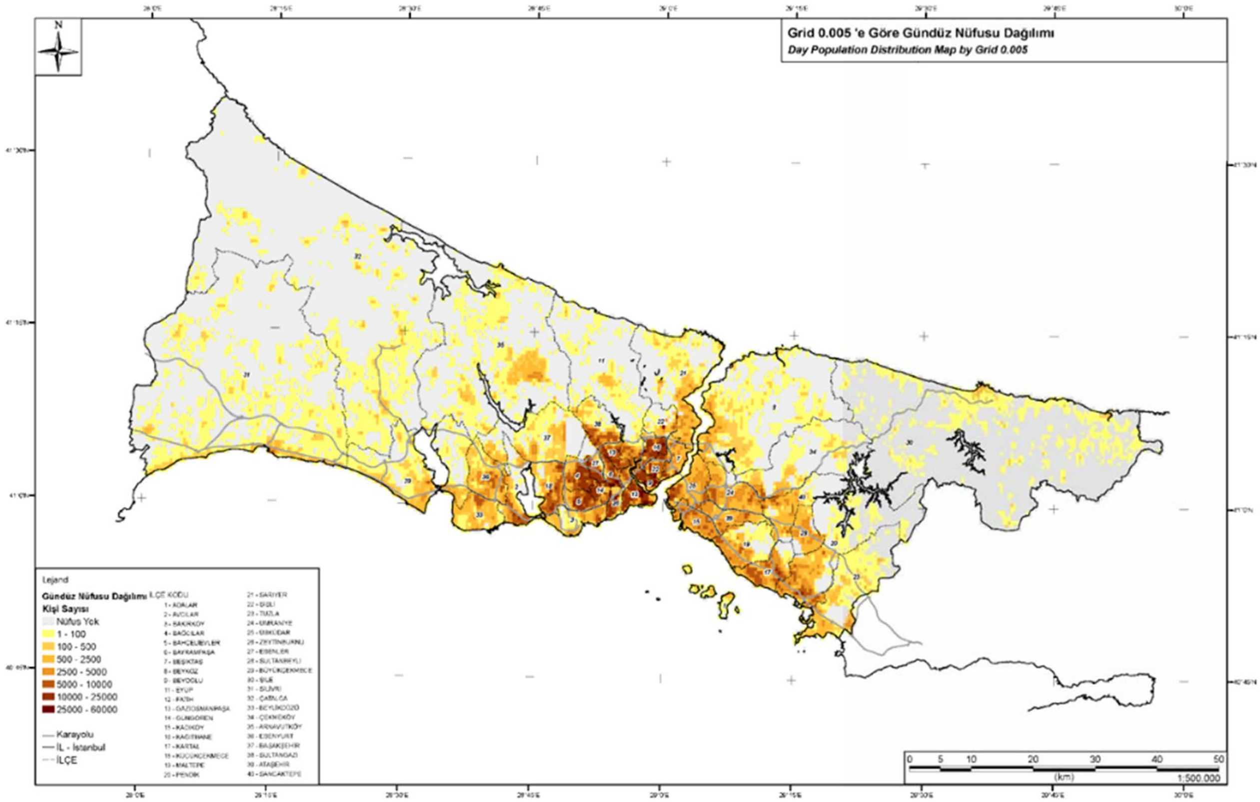


Fig. 5 Daytime population distribution for metropolitan Istanbul

Results and discussion

Because the Istanbul metropolitan area is under high seismic risk, prediction of damage and casualty distributions throughout the European and Asian sides is an essential requirement for a rapid response system. Through this project, installation of the rapid response application for Istanbul was achieved successfully following the steps mentioned above.

A flowchart showing the operation of the rapid response system is given in Fig. 8. As is illustrated in the figure, the rapid response system constantly checks an earthquake list for new earthquake activity. If activity larger than M4.0 is detected, distance from the epicenter is determined. If the definitions of magnitude and distance range are met, the application generates shakemaps with the available GMPEs and reads the data from stations to calculate ground motion parameters PGA, PGV, PSA02, and PSA10 as input data. Then, by using the input data, it prepares an XML file to run ELER. The output figures are then instantly sent to the interested agencies.

November 27, 2013, Mw4.7 Marmara Ereglisi earthquake

On November 27, 2013, an earthquake occurred offshore of Marmara Ereglisi in the northwest Marmara Sea (latitude: 40.851, longitude: 27.9198). The magnitude of the earthquake (Mw) was 4.7, and the hypocenter depth was 9.6 km. Because the magnitude is relatively small, it is convenient to assign a point source for the earthquake. In this section, the GMPEs utilized in the rapid response system are compared. As mentioned in the previous section titled "Shaking maps" section, in the rapid response system, Ozbey et al. (2004) GMPE is used for $M < 5.0$ events, and Boore and Atkinson (2008) GMPE is used for $M \geq 5.0$ events. The V_{s30} map of the Istanbul metropolitan area, which was obtained for each 250-m grid in the populated regions, was used for soil amplification. Detailed information on the V_{s30} map is given in the "Site conditions" section above. With the contribution of actual strong ground motion data from the Rapid Response Station Network of Istanbul, bias-corrected PGA, PGV, PSA02, and PSA10 distribution maps were obtained for Marmara regions by considering the Ozbey et al. (2004) GMPE (Figs. 9, 10). In Figs. 11 and 12, a comparison of PGA, PGV, PSA02, and PSA10 distribution maps is shown by considering the Boore and Atkinson (2008) GMPE. As shown in Figs. 9 and 11, the GMPE of Ozbey et al. (2004) computed similar acceleration values as those from actual stations. The GMPE of Boore and

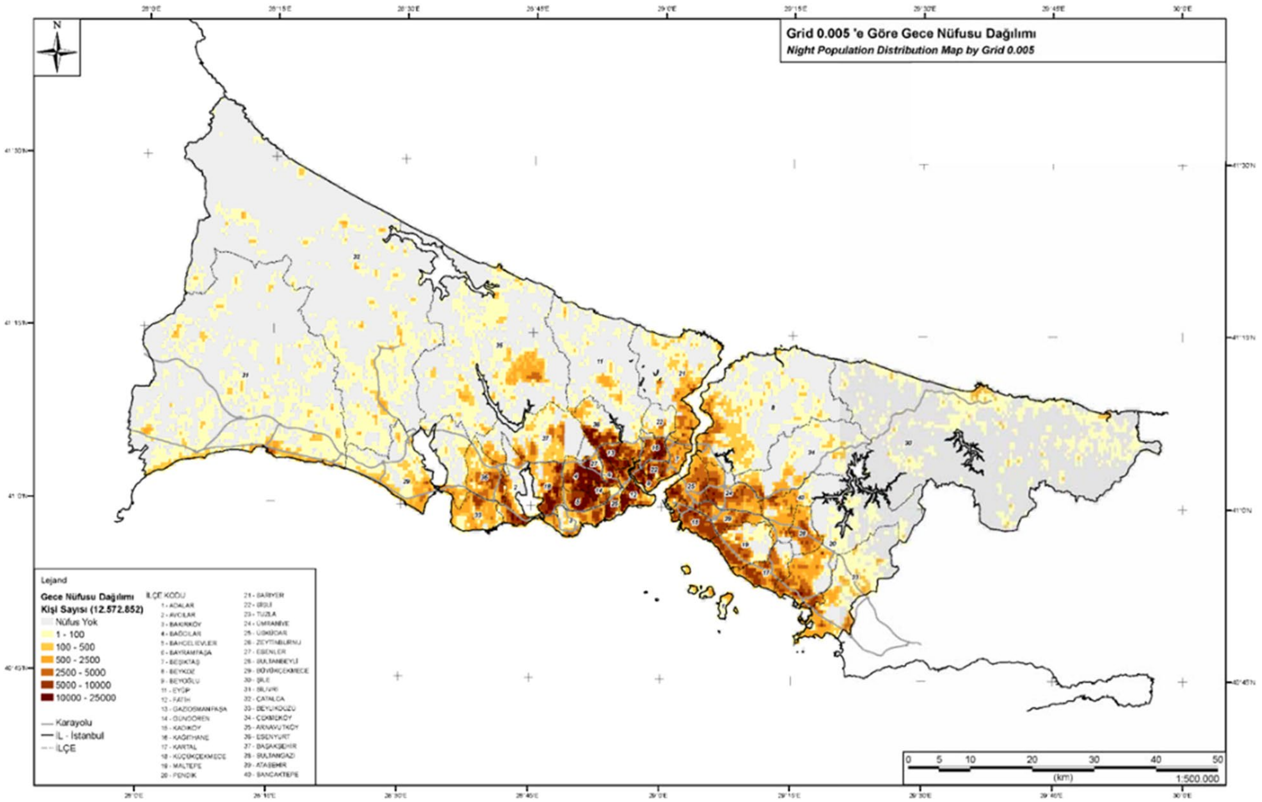


Fig. 6 Nighttime population distribution for metropolitan Istanbul

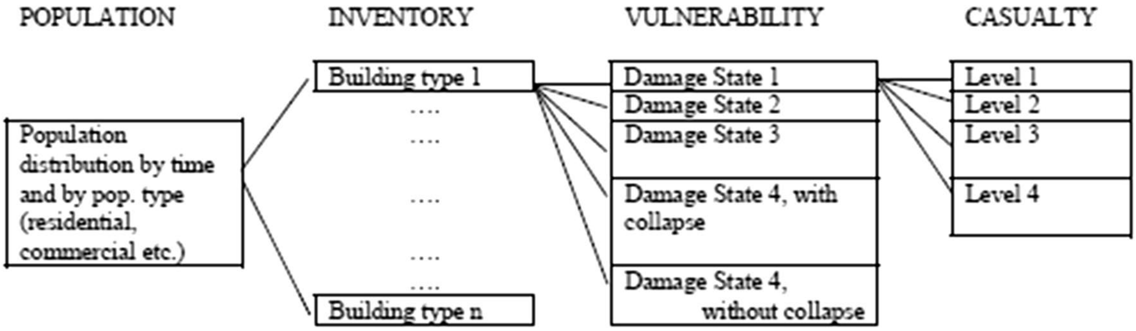


Fig. 7 Event tree used for the estimation of casualties (Source: HAZUS-MH-FEMA 2003)

Table 1 Descriptions of injury severity levels

Injury severity	Injury description
Level 1	Injuries requiring basic medical aid without requiring hospitalization
Level 2	Injuries requiring medical care and hospitalization that are not expected to progress into a life-threatening status
Level 3	Injuries that pose an immediate life-threatening condition if not treated adequately and expeditiously. The majority of these injuries are attributed to structural collapse and subsequent collapse or impairment of the occupants
Level 4	Instantaneous death or mortal injury

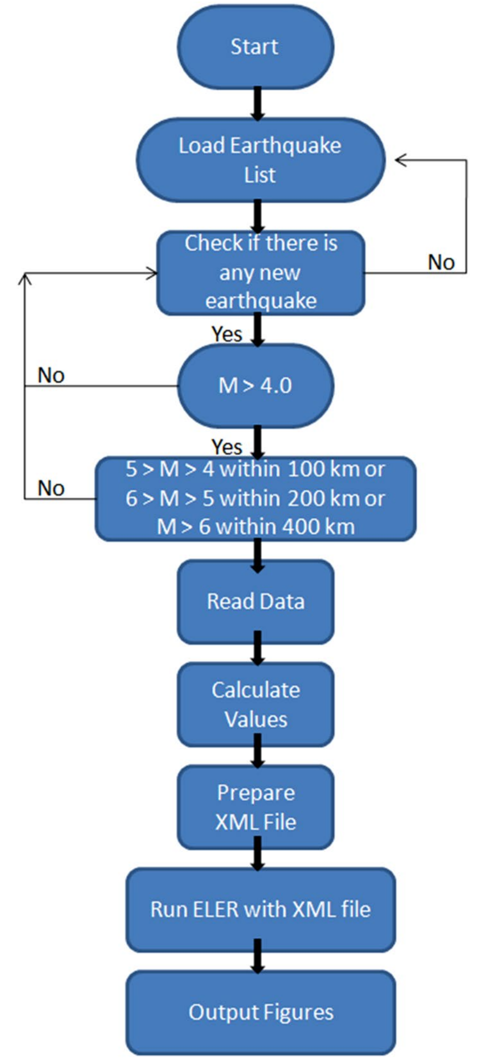


Fig. 8 Flowchart of the operating rapid response system

Atkinson (2008) computed higher PGA values than those actually recorded.

Daily real-time earthquake scenarios

The configured application of the real-time rapid response system generates a scenario earthquake in the Marmara region every day and generates PGA, PGV, intensity, PSA02, PSA10, and damage and casualty distribution maps. Then, the application automatically sent the created shakemaps and damage distribution maps to IMM and the Governorate of Istanbul and Army Commandership. The aim of these daily running earthquake scenarios is to test the application and operability of the system. Shakemaps for a scenario earthquake run for the Istanbul metropolitan area by the application are presented in Figs. 13, 14, 15, 16 and 17.

Conclusions

This paper presents the outcome of the nationally funded project "TUBITAK-109M734, Real-Time Information of Earthquake Shaking, Damage, and Losses for Target Cities of Thessaloniki and Istanbul." Within the project, the existing IERRS algorithm for Istanbul was improved, and a new algorithm, ELER, was adopted; the latter was developed during the EC-FP6 NERIES project. The procedures of automated shakemapping and damage and loss estimations were described in detail. The improved IERRS has real-time data transmission ability from the densely distributed strong motion network throughout metropolitan Istanbul and generates real-time maps of intensity, PGA, PGV, PSA02, PSA10, and damage and loss distribution maps. It should be noted that the aim of this study is to describe the structure of a rapid response system, which has an important role in transmitting earthquake information to related emergency response agencies to facilitate their actions immediately following the event. This automation system is important because it gives reliable information as soon as possible. The reliability of the shaking maps depends on the information from ground motion stations and local site condition through the grid-based V_{s30} parameter. In the damage and loss estimations, updated building inventory and demography information are crucial. Because the numbers of strong motion stations and their distribution are not sufficient for generating maps of ground shaking for the entire Istanbul metropolitan area, the use of GMPEs is necessary. For $M < 5.0$ and $M \geq 5.0$ events, the regional GMPE of Ozbey et al. (2004) and the Boore and Atkinson (2008) GMPE were utilized, respectively. For the damage and casualty estimations, although several approaches are mentioned in the literature, proper methods for the automated system have been chosen. The accuracy of the information first delivered can be increased in the offline mode combined with the results of other approaches.

For the damage estimations, 57 building classes were adopted from HAZUS-MH (FEMA 2003) depending on the information of construction year, number of floors, and building construction type. The ASCE/SEI 41-06 coefficient method approach was utilized for calculating

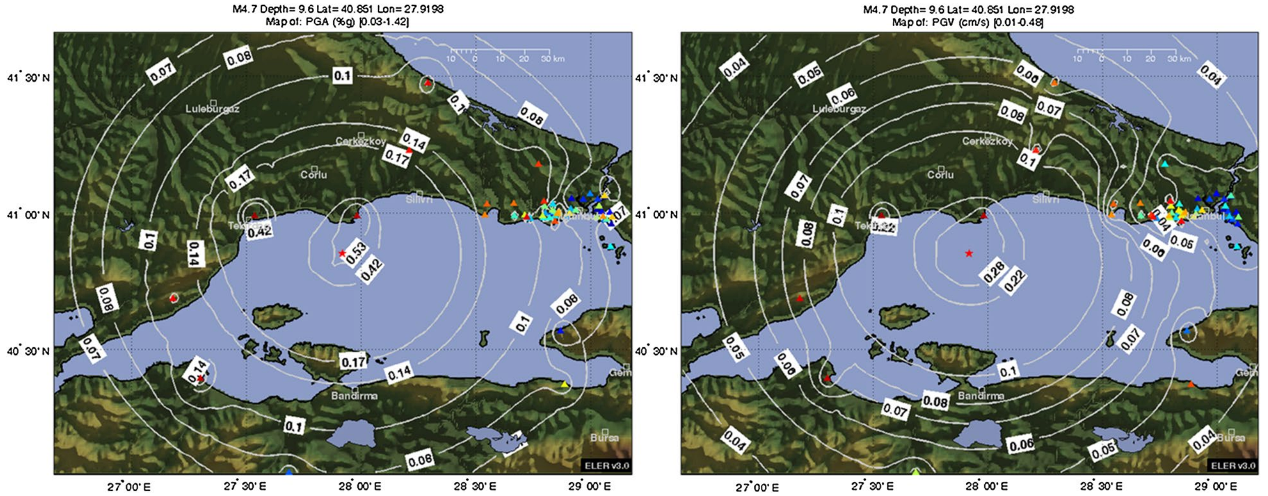


Fig. 9 PGA and PGV distribution maps obtained for the M4.7 Marmara Ereglisi earthquake based on the GMPE of Ozbey et al. (2004) after bias correction of phantom stations by real stations

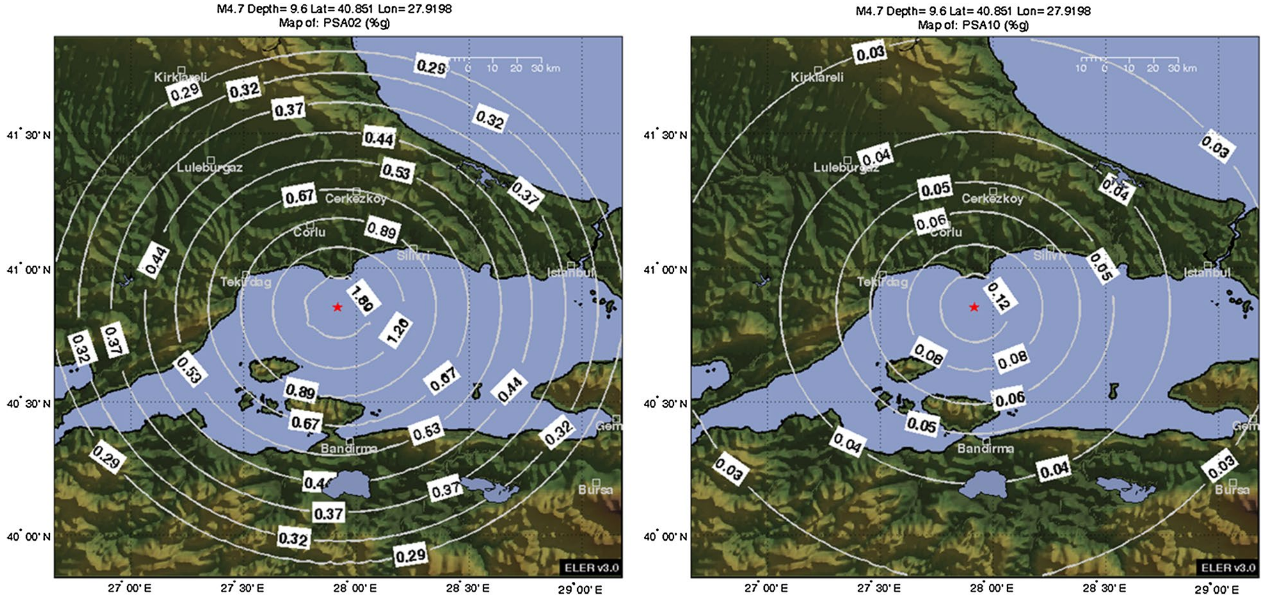


Fig. 10 PSA02 and PSA10 spectral acceleration distribution maps for the M4.7 Marmara Ereglisi earthquake based on the GMPE of Ozbey et al. (2004)

spectral displacement under certain acceleration rates. For the loss estimation, HAZUS-MH methodology was applied, and the loss was described by using four levels of injury severity.

The real-time shakemaps of the November 27, 2013, M4.7 earthquake in the Marmara Sea were presented. A scenario earthquake simulation for metropolitan Istanbul was conducted, and shakemaps and damage maps were presented. In order to check the operability of the system, a daily scenario earthquake was simulated, and distribution maps were generated and automatically transmitted by the system to relevant agencies.

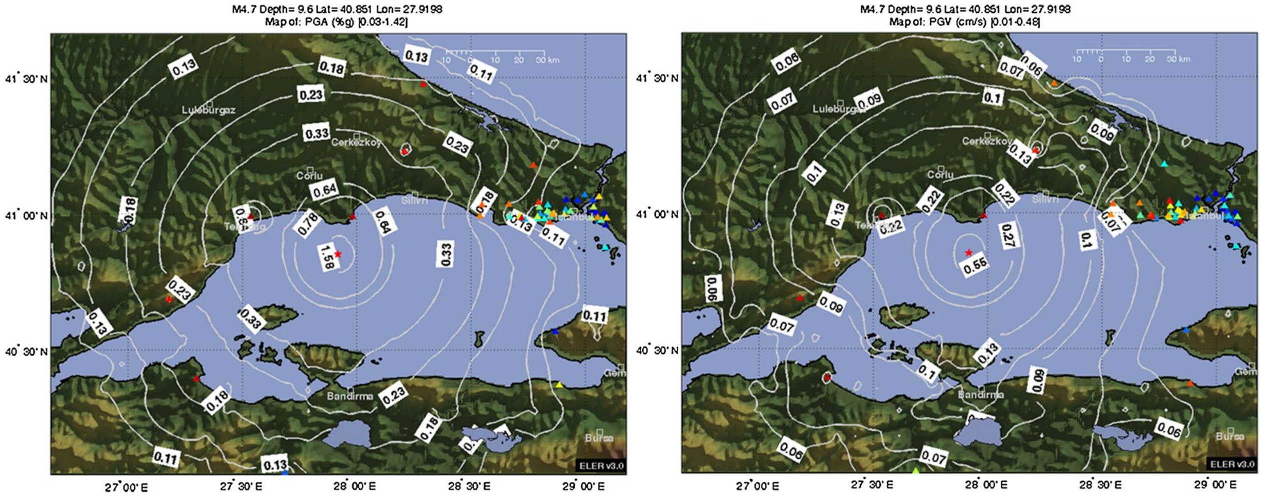


Fig. 11 PGA and PGV distribution maps obtained for the M4.7 Marmara Ereglisi earthquake based on the GMPE of Boore and Atkinson (2008) after bias correction of phantom stations by real stations

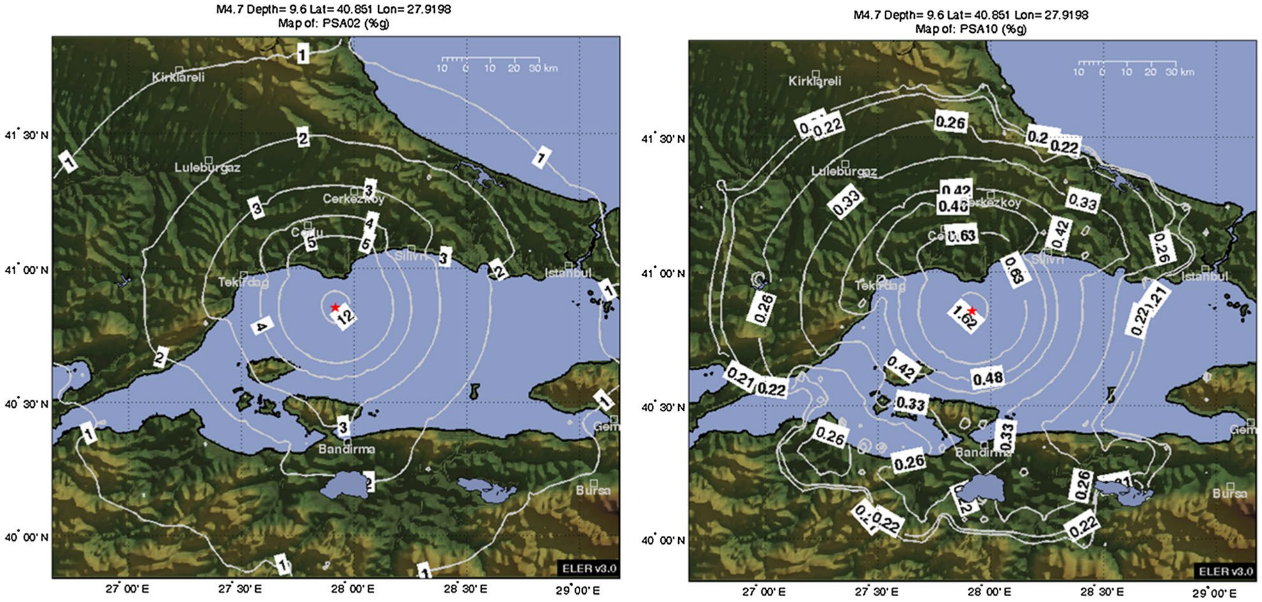
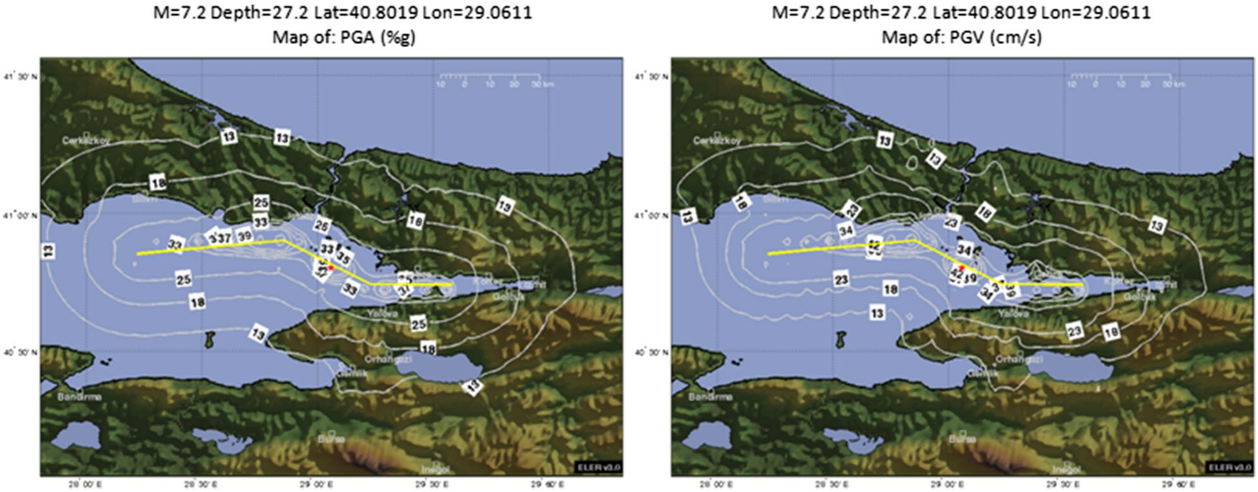


Fig. 12 PSA02 and PSA10 spectral acceleration distribution maps for the M4.7 Marmara Ereglisi earthquake based on the GMPE of Boore and Atkinson (2008)


M=7.2 Depth=27.2 Lat=40.8019 Lon=29.0611
Map of: PGA (%g)

M=7.2 Depth=27.2 Lat=40.8019 Lon=29.0611
Map of: PGV (cm/s)

Fig. 13 PGA and PGV distribution maps obtained for an M7.2 scenario earthquake in the Marmara Sea based on Boore and Atkinson (2008)

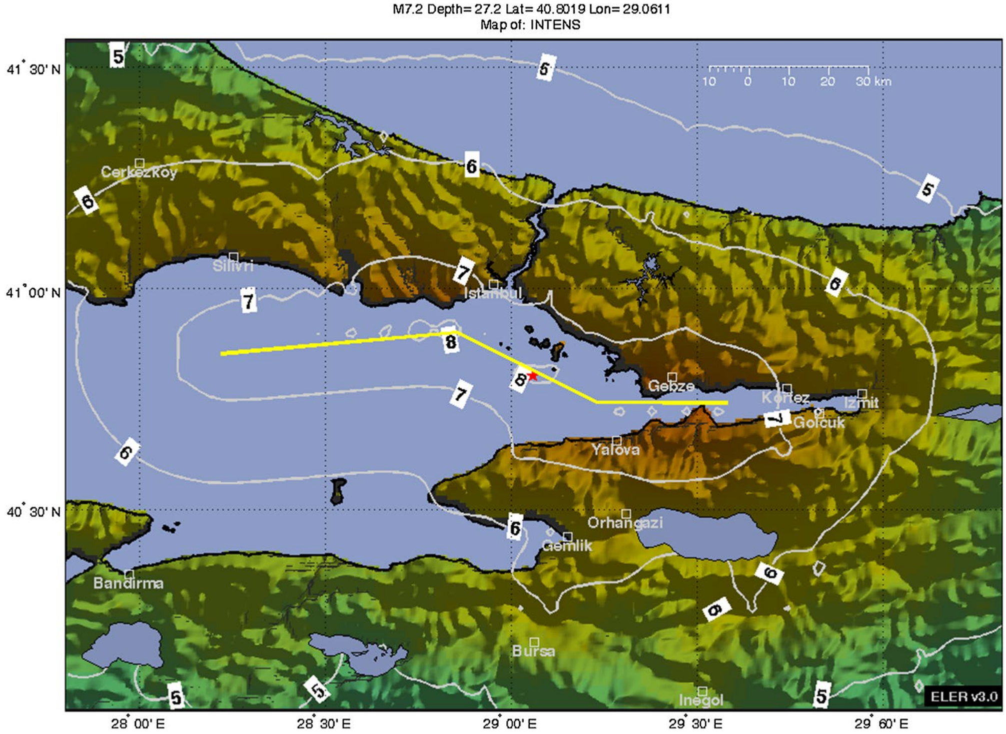

M7.2 Depth= 27.2 Lat= 40.8019 Lon= 29.0611
Map of: INTENS

Fig. 14 Intensity distribution maps obtained for an M7.2 scenario earthquake in the Marmara Sea based on Boore and Atkinson (2008)

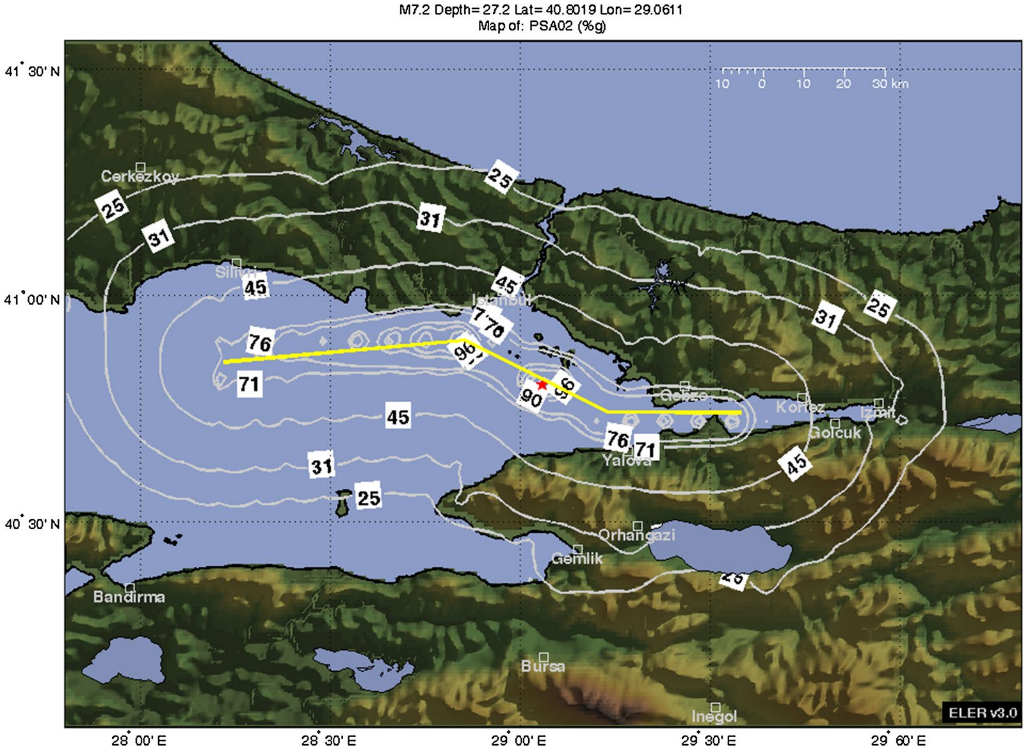


Fig. 15 PSA02 spectral acceleration distribution map obtained for an M7.2 scenario earthquake in the Marmara Sea based on Boore and Atkinson (2008)

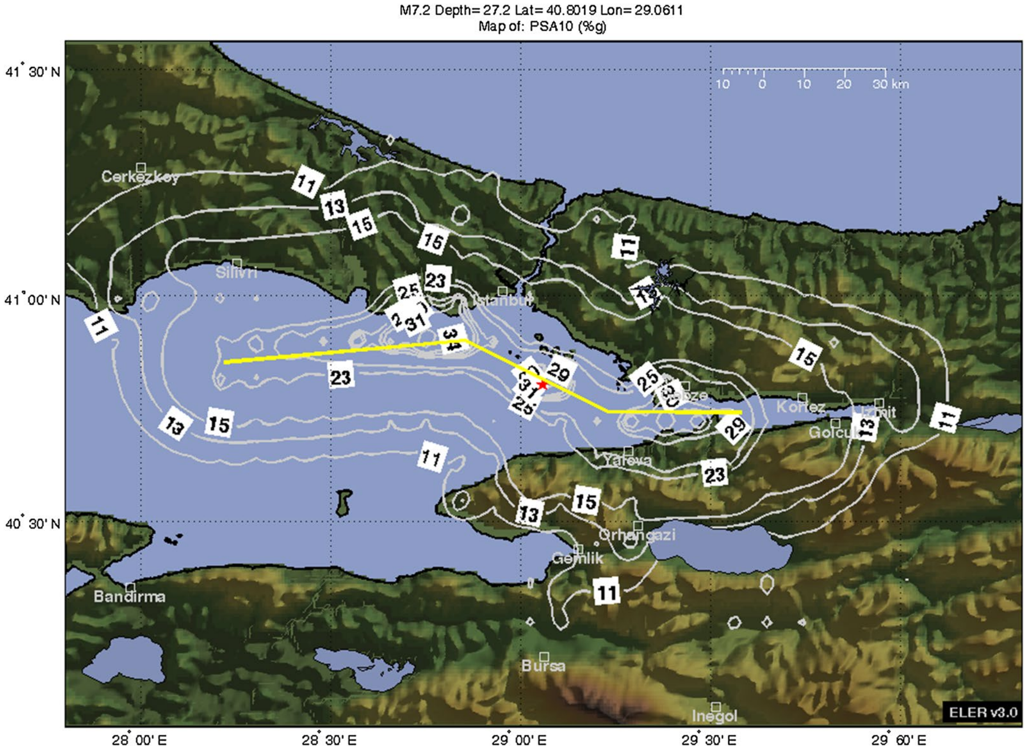


Fig. 16 PSA10 spectral acceleration distribution map obtained for an M7.2 scenario earthquake in the Marmara Sea based on Boore and Atkinson (2008)

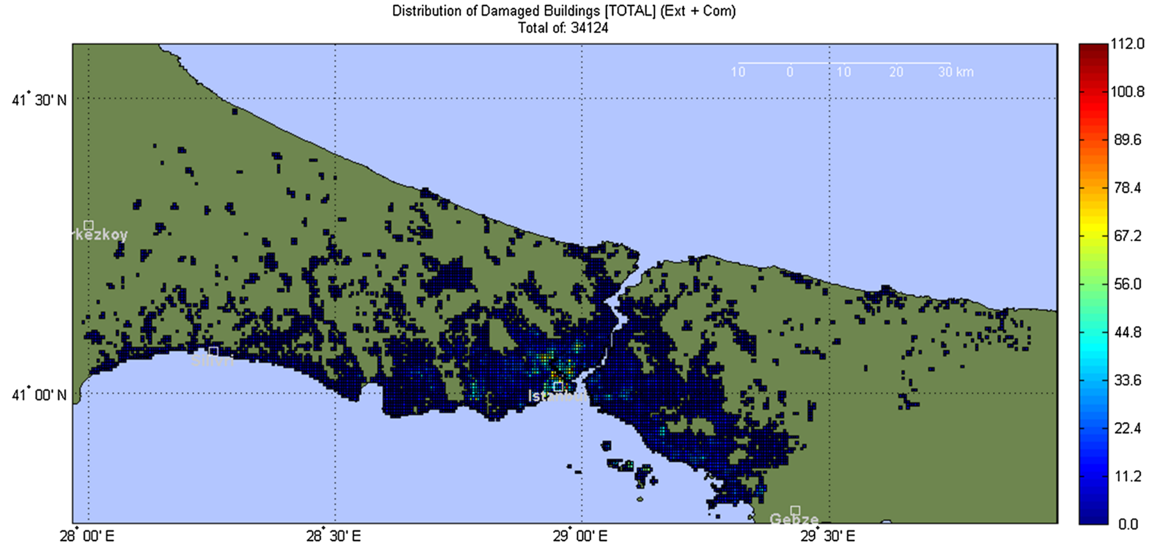


Fig. 17 Extensive and complete damage distribution maps obtained for an M7.2 scenario earthquake in the Marmara Sea

Although this study describes the earthquake rapid response system and its algorithm in the Istanbul metropolitan area, it is believed that similar systems can be deployed in other regions with high seismic risk.

Authors' contributions

The authors' contributions to the manuscript are described below for each author by stating their initials: ACZ drafted the manuscript, integrated hazard and risk studies, and formed the automated system by choosing the appropriate hazard and risk methods. NOZF applied scenario studies, obtained the results, and helped to draft the manuscript. ST provided real-time data transmission and parameter computation for the automated system. ME was the advisor of the project and guided the authors to form the automated system. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

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