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REL. I. E. F.

RELiable Information on Earthquake Faulting

Large Earthquake Faulting and Implications for the Seismic Hazard Assessment in Europe:
The Izmit-Duzce earthquake sequence of August-November 1999 (Turkey, Mw 7.4, 7.1)

Final Report

Partner 6 - UiB
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WP 6: Integration of multidisciplinary data for seismic hazard assessment
WP 9: Multidisciplinary seismic hazard assessment

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Summary

Within the framework of workpackage 6 (WP06: Integration of multidisciplinary data sets for seismic hazard assessment) of the RELIEF project, and as a part of workpackage 9 (WP09: Multidisciplinary seismic hazard assessment), seismic hazard assessment is performed using probabilistic and deterministic approaches. The final aim for these hazard studies is to implement the results in seismic risk assessment. The earthquake hazard in Istanbul is mainly controlled by the North Anatolian Fault (NAF) in the Marmara Sea, and contributions from other segments of the NAF in the region are assumed to be insignificant for the near future as both the eastern and the western parts of the Marmara Sea have experienced recent earthquakes (i.e. 1912 Ganos earthquake in the west and 1999 Izmit and Düzce earthquakes in the east). In this sense, probabilistic seismic hazard assessments conducted for the region are not sufficient to account for the expected earthquake threat in this mega-city with more than 12 million inhabitants. Deterministic ground motion simulations based on complex multi-asperity fault rupture scenarios, give a more realistic estimate of the ground motions from a future large earthquake in the Marmara Sea. In the present project we have therefore focused our efforts on the ground motion simulations using a hybrid method which gave important insights about the variability of ground motions in the metropolitan area of Istanbul and its surroundings. However, the assessment of uncertainties in the input parameters for ground motion simulations requires a careful understanding of the fault behaviour in the Marmara Sea. In order to address this problem, several input scenario models with various critical fault parameters are applied in ground motion simulations. The resulting ground motion distribution reveals the effect of fault behaviour as expressed by these critical parameters. The most influential parameters affecting the results are the location and size of the asperities, rupture initiation point, rupture velocity, rise time and stress-drop. Other important aspects of the fault behaviour are the geometry of the fault segmentation and linkage between the segments in individual earthquake ruptures.

The probabilistic as well as the deterministic approaches applied in this study both show significant levels of hazard in the Marmara region and especially in the metropolitan area of Istanbul. In general, ground motion distributions in the area based on deterministic simulations show a more complex pattern when compared to the probabilistic estimates (see RELIEF UiB Deliverables 18, 25 and 26). To estimate the seismic risk in Istanbul, the ground motion simulation results are combined with the existing vulnerability functions for different building categories and damage

maps are produced showing the distribution of collapsed buildings based on a scenario earthquake in the Marmara Sea (see RELIEF UiB Deliverable 27).

1. Introduction

Istanbul, with a population exceeding 12 millions, is considered one of the world's mega cities exposed to significant earthquake hazard. The disastrous consequences of the two large earthquakes at Izmit and Düzce in 1999 have highlighted the need for careful analysis of seismic hazard including local site effects, although the earthquake hazard in this region has been a topic of considerable interest for a long time. Recent results from several studies (e.g. Atakan et al., 2002; Erdik et al., 2003a; Erdik et al., 2004; Pulido et al., 2004), as well as the results presented in RELIEF deliverables 18, 25 and 26 show significant seismic hazard and emphasize the importance of earthquake preparedness and risk mitigation in the Istanbul metropolitan area and its rapidly growing surroundings.

The main objective of the workpackages 6 and 9 is to contribute to the detailed understanding of the seismic hazard in Istanbul and its consequences. The work started with standard probabilistic seismic hazard assessment (PSHA). However, during the project time the methods used in the seismic hazard analysis have evolved utilizing the results obtained in the paleoseismological analyses conducted within the framework of the RELIEF Project. The poissonian earthquake recurrence assumptions that were first applied, are substituted by renewal models. In addition, ground motion simulations based on a future scenario earthquake in the Marmara Sea are conducted using complex source models as input. Final goal of the present study is to demonstrate the effects of using a realistic scenario input from ground motion simulations to produce shake-maps and damage estimates.

2. Earthquake Hazard Assessment

Seismic hazard analyses for the Marmara region are conducted using two separate approaches. First the seismic hazard is estimated using the standard probabilistic methods including poissonian and renewal models. Secondly, ground motions are simulated based on various scenario earthquakes using complex physical source models. In the following, the main results from these methods are described.

A separate study was initiated in collaboration between INGV, Rome and UiB on establishing an attenuation relationship for the Marmara Sea region. This was conducted using ground motion scaling on small earthquakes (see RELIEF deliverable no. 18 for details; Akinci et al., in press). Figure 2.1 shows the comparison between the various attenutation relations for the region together with the relation obtained by Akinci et al (in press). In another study, the most significant earthquakes in the region are re-evaluated in terms of their magnitude and location by Ambraseys (2005). The following table (Table 1) summarizes all earthquakes with Ms≥7.0.

Table 1: The list of historical earthquakes (Ms≥7.0)
in the greater Marmara Region for the period 1500-2000.
Y: Year; M: Month; D: Day; OT: Origin Time; N: Latitutude N;
E: Longitude E; Ms: Surface wave magnitude

Y	**M**	**D**	**OT**	**N**	**E**	Ms
1509	09	10	2200	40.9	28.7	7.2
1556	05	10	2400	40.6	28.0	7.2
1625	05	18	2400	40.3	26.0	7.1
1653	02	22	0000	37.9	28.5	7.0
1659	02	17	1900	40.5	26.4	7.2
1672	02	14	0000	39.5	26.0	7.0
1719	05	25	1200	40.7	29.8	7.4
1737	03	06	0730	40.0	27.0	7.0
1766	05	22	0500	40.8	29.0	7.1
1766	08	05	0530	40.6	27.0	7.4
1829	05	05	1500	41.2	25.4	7.1
1855	02	28	0230	40.1	28.6	7.1
1894	07	10	1224	40.7	29.6	7.3
1912	08	09	0129	40.8	27.2	7.3
1928	04	18	1922	42.3	25.0	7.0
1944	02	01	0323	41.1	32.2	7.4
1953	03	18	1906	39.9	27.4	7.1
1957	05	26	0633	40.7	31.0	7.2
1967	07	22	1657	40.7	30.7	7.2
1999	08	17	0001	40.8	30.0	7.4
1999	11	12	1657	40.8	31.2	7.1

In order to quantify the uncertainties associated with the probabilistic methods, two separate studies are conducted for the Marmara region. One study focuses on the effects of differences in source and the other on the attenuation models. Additionally PSHA is conducted using both a poissonian and renewal (time dependent) recurrence model. Results from these studies show significant differences in the absolute ground motion values, however the distribution is relatively similar for the case of the poissonian models. Significant differences also exist in the distribution of ground motion values when the poissonian PSHA results are compared with the time dependent models. The uncertainties associated with the ground motion simulations are quantified by comparing various input scenarios with respect to a "standard scenario" as described in RELIEF Deliverable # 25. Comparisons indicate clearly that critical parameters such as the rupture initiation point, rupture velocity, rise time and the stress drop have significant effect on the resulting ground motions.

2.1. Probabilistic Seismic Hazard Analysis (PSHA)

The first study follows the methodology used by Atakan et al. (2002). The probabilistic seismic hazard analysis was performed using 12 different input models, based on a combination of three earthquake source models and four attenuation relations. The three earthquake source models were one based on a standard poissonian assumption (Cornell, 1968) and two based on a renewal model (McGuire, 1993) assuming a 'characteristic earthquake' (Schwartz and Coppersmith, 1984; Youngs and Coppersmith, 1985). In the renewal models, the time elapsed since the last event is incorporated, recognizing that the stress accumulation and release process on faults is cyclical (McGuire, 1993). In each of these models, four different attenuation relations were applied. These are from Ambraseys et al. (1996), Boore et al. (1997), Campbell (1997) and Sadigh et al. (1997). The results of these seismic hazard computations are presented in detail in RELIEF UiB Deliverable 18. In Figure 2.1.1, the PSHA results using a renewal model are given in terms of peak ground accelerations (PGA) corresponding to the 10 % probility of exceedence for the next 50 years. The distribution of the PGA values indicates a significant level of hazard for Istanbul and the surrounding areas.

2.2. Ground Motion Simulations

Ground motions were simulated using a number of earthquake scenarios in the Marmara Sea and were compared to a 'standard' scenario. The various scenarios (16 in total) are defined by changing the critical source parameters one at a time to see their influence on the simulated ground motions. This provides important information about the sensitivity of the ground motions to the different source parameters and reveals the most critical ones. In the standard scenario, the location and dimensions of the rupturing fault are defined by considering the local tectonics and seismicity. We assume a combined rupture of the Central Marmara Fault (CMF) and North Boundary Fault (NBF) segments of the North Anatolian Fault (NAF). A total fault length of 130 km is used, which is confined to the area between the 1999 Izmit rupture to the east and the 1912 Ganos rupture to the west. We assume a fault width of 20 km in agreement with the depth of the seismogenic zone as indicated by the depth distribution of seismicity (Gurbuz et al., 2000). The fault plane solution used is the one of Pulido et al. (2004) with pure right-lateral strike-slip faulting along the CMF and an oblique-normal mechanism along the NBF. Two asperities are defined covering 22% of the fault plane following the empirical results of Somerville et al. (1999). These are located near the intersection of the CMF and NBF segments. This area has previously been suggested to be a seismic gap (Gurbuz et al., 2000), characterized by its low seismicity. The seismic moment released by the scenario earthquake is 2.0 x 10^{20} Nm, which is an average value of the seismic moments estimated by different authors for the 1999 Izmit earthquake (Pulido et al., 2004). The velocity model used in the modelling is the one used for routine location of earthquakes in the region. For the cut-off frequency f_{max} we use a value of 10 Hz, which is also the upper frequency limit of the calculations. In practice this implies that the high-frequency decay of the ground motion is mainly controlled by attenuation.

For the standard scenario, the rupture initiation point is located at the westernmost edge of asperity 1 (Figure 2.2.1). This is believed to be a likely location since the boarder regions of asperities represent significant changes in physical properties of the fault and thereby zones of weakness. Based on seismic moment, fault area and asperity area, the stress drop is calculated based on the relations of Das and Kostrov (1986) and Brune (1970) following Pulido et al. (2004). Rupture velocity and rise time are taken from Pulido et al. (2004) for the standard scenario. The regional attenuation is defined in terms of Q. For the standard scenario we have used the "Low Attenuation Model" of Pulido et al. (2004). The source parameters of the standard scenario are summarized in Table 2. It should be noted that the standard scenario is considered as a conservative approximation.

Table 2: Source parameters for the standard scenario.

Seismic moment	$M_0 = 2.0 \cdot 10^{20}$ Nm
Strike / Dip / Slip - CMF segment	81.5 / 90 / 180
Strike / Dip / Slip - NBF segment	110 / 90 / -135
Average stress drop	5.0 MPa
Asperity stress drop	10 MPa
Rise time	3.0 s
Rupture velocity	3.0 km/s
f_{max}	10 Hz
Q	$100 \cdot f^{1.5}$

Based on the ground motion simulation results for the standard scenario, the effect of a M=7.5 earthquake in the Marmara Sea on the city of Istanbul is significant with the largest ground motions occurring in the southern and southeastern parts of the city (Figure 2.2.1). Here, ground accelerations at the level of 0.5g can be expected at bedrock level. These acceleration levels are in general slightly larger than those expected based on the PSHA results.

Based on the standard scenario, we have changed source parameters one by one in order to test the effect on the ground motions. The parameters, which have been tested, are: low-frequency attenuation (Qp and Qs), high-frequency attenuation (Q), rise time, rupture velocity, rupture initiation point and stress drop. In Figure 2.2.2, the effect of variation in rupture velocity is shown as an example in terms of difference maps between the standard scenario and the tested scenarios. For the complete set of parameter sensitivity results the reader is referred to RELIEF UiB Deliverable 26 (see also Sørensen et al., in review – a). Most critical parameters are found to be the rupture initiation point, rupture velocity, rise-time and the stress-drop. In general, even though the level, distribution and spectral values of the ground motions differ significantly, the response spectra are consistent (Figure 2.2.3), showing the usefulness of ground motion modeling in estimating a realistic hazard for Istanbul and hence in risk mitigation efforts despite the large uncertainties involved.

3. Local Site Effects

Seismic hazard analysis results obtained for bedrock conditions need to be modified taking into account the local site effects. In this regard, the areas susceptible for site amplifications are mapped in Istanbul in previous studies (e.g. JICA, 2004; Ansal et al., 2004). Within the framework of the RELIEF Project a pilot study at Ataköy was initiated with the aim of demonstrating the importance of the site effects and a possible implementation to hazard assessment. In the following, a short summary of the ongoing efforts in Istanbul in general, as well as the main results from the Ataköy study, are presented.

3.1. Site Effects in Istanbul

Previous studies of local site effects, following the 1999 Izmit and Düzce earthquakes, have focused mainly on the Avcilar district of western Istanbul (e.g. Özel et al., 2002; Tezcan et al., 2002), and on the city of Adapazari in the east (e.g. Bakir et al., 2002; Komazawa et al., 2002; Sancio et al., 2002; Beyen and Erdik 2004 and Ansal et al., 2004), which experienced significant damage mainly due to site effects. In both areas, the presence of soft sediments in basin structures has caused strong amplifications of earthquake ground motions during past earthquakes.

As for the city of Istanbul, possible effects of local geological variations have been studied in several microzonation studies (e.g. JICA, 2004; Eyidogan et al., 2000; Ansal et al., 2004). The geological map showing the distribution of main units indicates that there are significant differences in both the age and the composition of these units. In a recent study, Birgören et al. (2004) found amplification levels up to a factor of 7 for some geological formations at 1 and 3 Hz frequencies, based on spectral ratios of records from a M=4.2 earthquake (Figure 3.1.1). More recently, Sørensen et al. (in review - b), have studied the local site effects in Ataköy using a 3-D FD-scheme. This is described in a separate section below.

In order to estimate the site effects present at all rapid response (RRS) station sites of the Istanbul earthquake Early Warning and Rapid Response System (IEEWRRS), a comprehensive microtremor survey was conducted by Kandilli Observatory and the Earthquake Research Institute KOERI (Özel et al., 2005). In general, peaks observed on some of the sites agree with the standard spectral ratios observed on the 16 May 2004 (Mw=4.2) earthquake record. The peaks observed around 1.0 – 1.5 Hz is probably associated with the Bakirköy formation. Similar results were obtained in other studies (e.g. Eyidogan et al., 2000; Sørensen et al., in review).

3.2. Site Effects in Ataköy

As part of the RELIEF project, workpackages 9 and especially 6, a detailed study of the local site effects in Istanbul, with special emphasis on the Ataköy area, has been initiated. During this study, several approaches are followed in order to estimate the site effects. These can be grouped into two categories; one empirical and the other synthetic.

Regarding the empirical data, both microtremors and local earthquakes of moderate magnitudes (weak motion) have been used. Microtremor data have been collected and H/V spectral ratios have been calculated for a number of sites covering mainly two geological formations. Weak motion data have been collected on a temporary network of three broadband seismic stations, and spectral ratios relative to a bedrock site have been calculated in order to find information about frequencies where significant amplification occurs. In addition, synthetic models for the area have been developed both in 1D and in 3D and the results are compared to the empirical data.

Regarding the frequency content of the site effects, the clear peaks observed in the microtremor data around 1 Hz are comparable to 1D and 3D synthetic results. 3D synthetic results give an insight to the complexity of the site response, especially for higher frequencies where lateral variations become more visible. In this respect the response of alluvial deposits is clearly visible at frequencies higher than 2 Hz (Figure 3.2.1). Regarding the amplification factors, the different methodologies predict different values. The empirical data (microtremor and weak motion) have significantly higher amplification levels when compared to the synthetic data (1D and 3D). Increasing the ground motion level from weak to strong motion causes a general decrease in the amplification levels due to non-linearity. Our results on the amplification factors show increasing levels from microtremors to weak motion and decreasing levels from weak to strong motion. In combination, the applied methods complement each other and provide reliable information about the local site effects in Ataköy. These results have also implications for the southwestern parts of the city of Istanbul built on similar formations.

4. Seismic risk

There are a number of ongoing efforts in Istanbul aiming to improve earthquake prearedness and risk mitigation. In the RELIEF Project, two recent examples are considered relevant with regard to the implementation of our results. The first one of these is a joint effort on the Earthquake Master Plan for Istanbul (IBB, 2003) by the Istanbul Metropolitan Municipality and the four major Universities in Turkey. The second is the recently installed Istanbul Earthquake Early Warning and Rapid Response System - IEEWRRS (Erdik et al., 2003b).

In order to provide an overview of the possible damage due to a scenario earthquake, the ground motion simulations are computed for the IEEWRRS station sites and then converted to response spectra. These results are used as the hazard input to risk computations, where they are combined with the vulnerability functions established for different building categories. Risk computations are performed in frequency ranges corresponding roughly to the most common height categories of building stock in Istanbul (i.e. 1-4, 4-8 and >8 floors). The vulnerability functions and the methods of damage computations based on rectangular cells are developed by KOERI.

4.1. Damage maps for Istanbul based on ground motion simulations

Based on the results of ground motion simulations, a preliminary damage distribution map is produced using the already established IEEWRRS procedures. The results are presented in terms of collapsed buildings (Figure 4.1.1). The distribution clearly shows that there is a significant risk posed on several locations within the metropolitan area of Istanbul. The highest values are obtained in locations where both hazard and the vulnerability function are high. Examples are locations such as Fatih and Zeytinburnu, which have dense building structure and relatively high vulnerability functions. In general it can be seen that the total number of collapsed buildings is much larger in the SW part of the city on the European side when compared to the SE part on the Asian side. Clearly, the damage is gradually reduced when moving towards north.

5. Concluding remarks

Based on our analyses of the earthquake hazard in Istanbul and the surrounding areas we can draw the following conclusions:

- Seismic hazard assessment based on ground motion simulations are more appropriate when compared to the probabilistic seismic hazard assessments, since the expected hazard for the city of Istanbul is controlled by the NAF in the Marmara Sea where the next large earthquake is expected to occur.
- Ground motion simulations using physically based complex earthquake source models provide a more detailed picture of the ground motion distribution in the area when compared to the PSHA.
- Based on ground motion simulation results for the standard scenario, the effect of a M=7.5 earthquake in the Marmara Sea on the city of Istanbul will be significant with the largest ground motions occurring in the southern and southeastern parts of the city. Here, ground accelerations at the level of 0.5g can be expected at bedrock level. These acceleration levels are in general slightly larger than those expected based on the PSHA results.
- The largest uncertainty associated with the PSHA is due to the choice of the attenuation relationship for the Marmara Sea region. The resulting hazard levels vary depending upon the chosen relationship. Other sources of uncertainties are those associated with the seismic source zonation as well as the choice of the earthquake recurrence models.
- The level and distribution of modeled ground motions by hybrid simulations are highly dependent on the input source parameters and these uncertainties should be taken into account when applying modeling results. In this respect modeling for both 'worst-case' and 'best-case' scenarios provide the upper and lower bounds on the expected ground motions. Stress drop, rise time, rupture velocity, and rupture initiation point are the most significant parameters in terms of variations in ground shaking levels. However these parameters have their effect in different frequency bands and the engineering significance therefore varies. Our efforts in the future should focus on understanding the accuracy of the most critical parameters influencing the ground motion, namely the rise time, rupture velocity, rupture initiation point and the stress drop.

- From an engineering point of view, stress drop and rupture initiation point are the most important input parameters since these have a large effect on the ground shaking level at frequencies of engineering interest.
- Even though the level, distribution and spectral values of the ground motions differ significantly, the response spectra are consistent, showing the usefulness of ground motion modeling in estimating a realistic hazard for Istanbul and hence in risk mitigation efforts despite the large uncertainties involved.
- The site effect analyses conducted in Ataköy area, indicate that there exist clear amplifications along the alluvial and fluvial deposits associated with the N-S running river systems. These amplifications are observed at frequencies around 3-5 Hz and in addition, amplification (though less significant) around 1 Hz is inferred which is attributed to the response of the Bakirköy formation.

Implementation of the ground motion simulations to calculate the seismic risk in the area is conducted as a pilot study for demonstrating the effects of ground motion simulations on damage. The preliminary results show clearly that the strong ground motion simulations based on realistic earthquake scenarios when combined with vulnerability functions provide a good estimate of the expected level of risk in Istanbul. These results would be important with regard to the ongoing efforts of risk mitigation in the metropolitan area in terms of strenghtening the critical buildings such as hospitals and schools as well as planning activities for future settlements in Istanbul.

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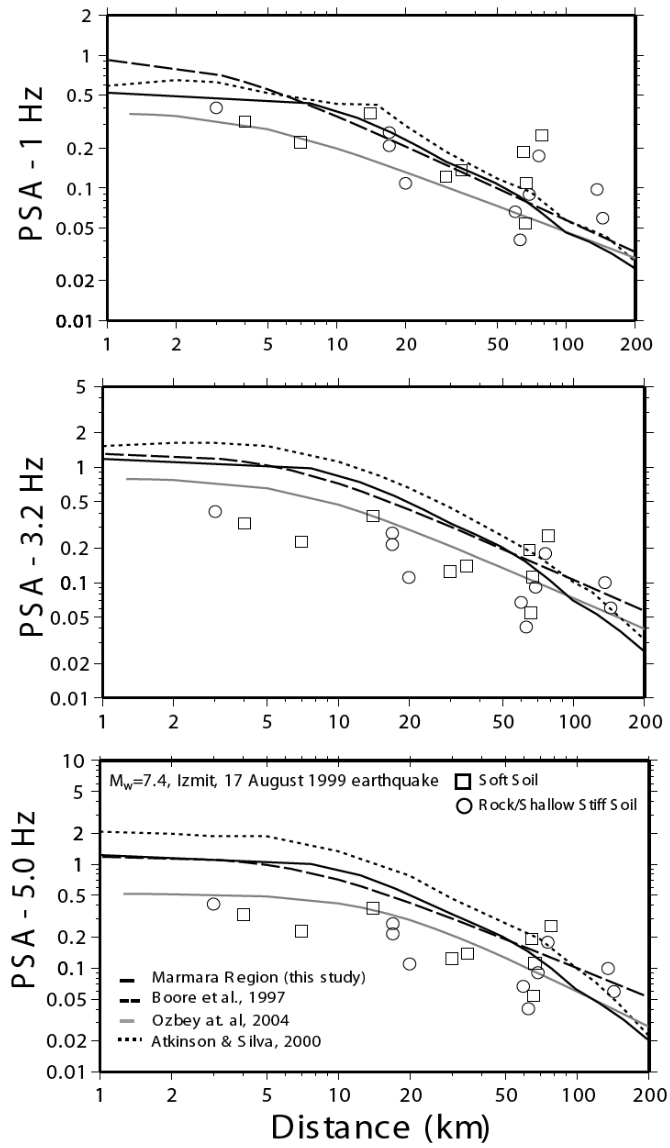

Figure 2.1. Comparison of different estimates of PSA (g) at frequencies of 1.0, 3.0 and 5.0 Hz in the Marmara region as obtained by using the empirical relationships by Ozbey *et al*., (2004, dotted), Boore *et al*., (1997, gray line) and Atkinson and Silva (2000, short dashed); dark solid line indicate PSA computed by Boore's program SMSIM (Boore, 1996). Curves are computed for Mw 7.4 and compared to the observed values of PGA (at soft, stiff and rock sites) during the 17 August 1999, Mw =7.4, Izmit earthquake. (From Akinci et al., in press).

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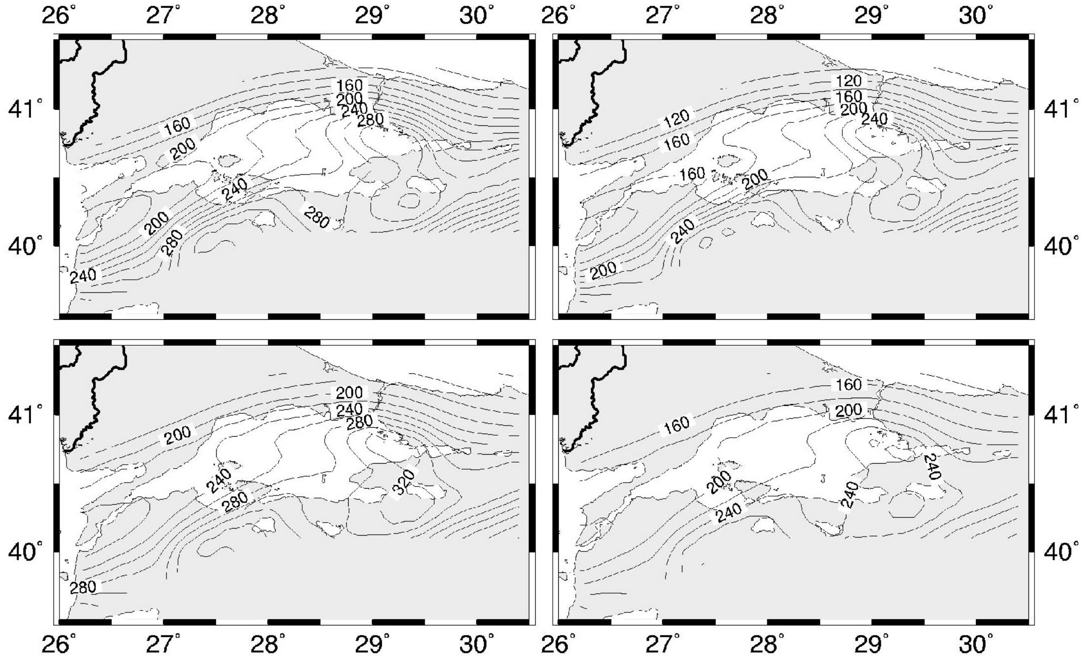

Figure 2.1.1. Distribution of PGA (in cm/sec^2) using Model 3 (Time dependent with fine zonation) with the four different attenuation relations. Upper-left is using Sadigh et al. (1997) relation. Lower-left is using Ambraseys et al. (1996) relation. Upper-right is using Campbell (1997). Lower-right is for Boore et al. (1997). Note that the highest PGA values are obtained when using the Ambraseys et al. (1996) relation.

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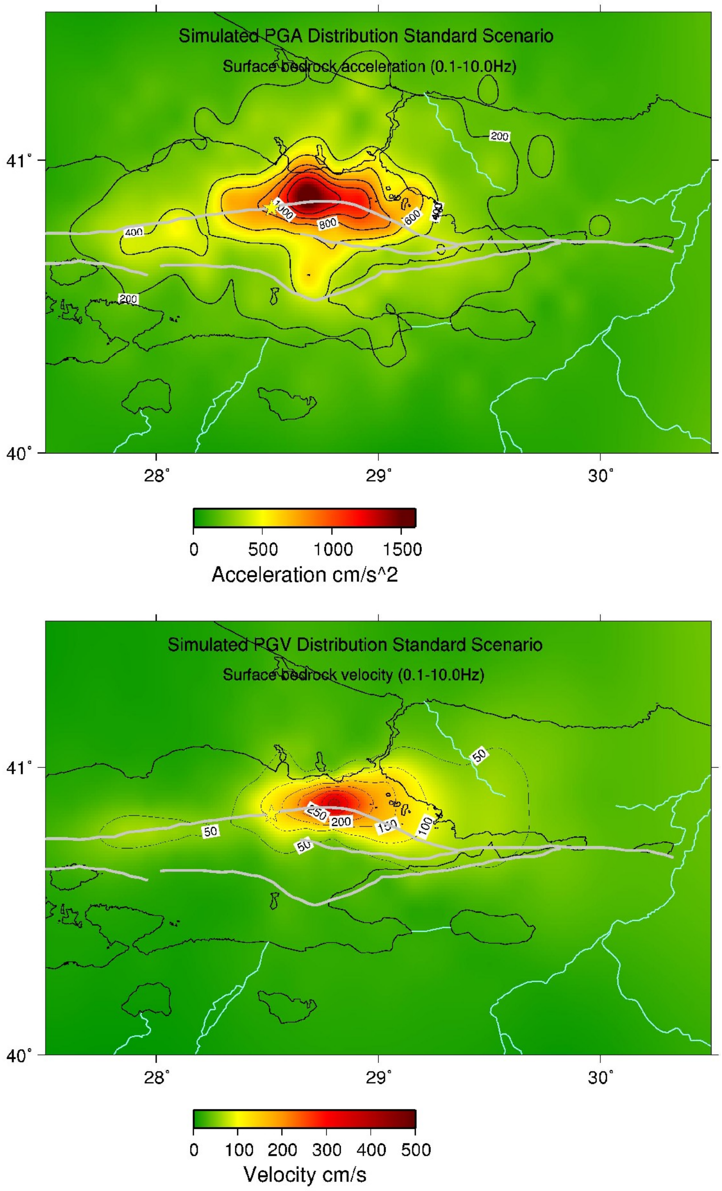

Figure 2.2.1. Ground motion simulation results based on the "standard" scenario presented in terms of peak ground accelerations (PGA) **(top)** and peak ground velocities (PGV) **(bottom).**

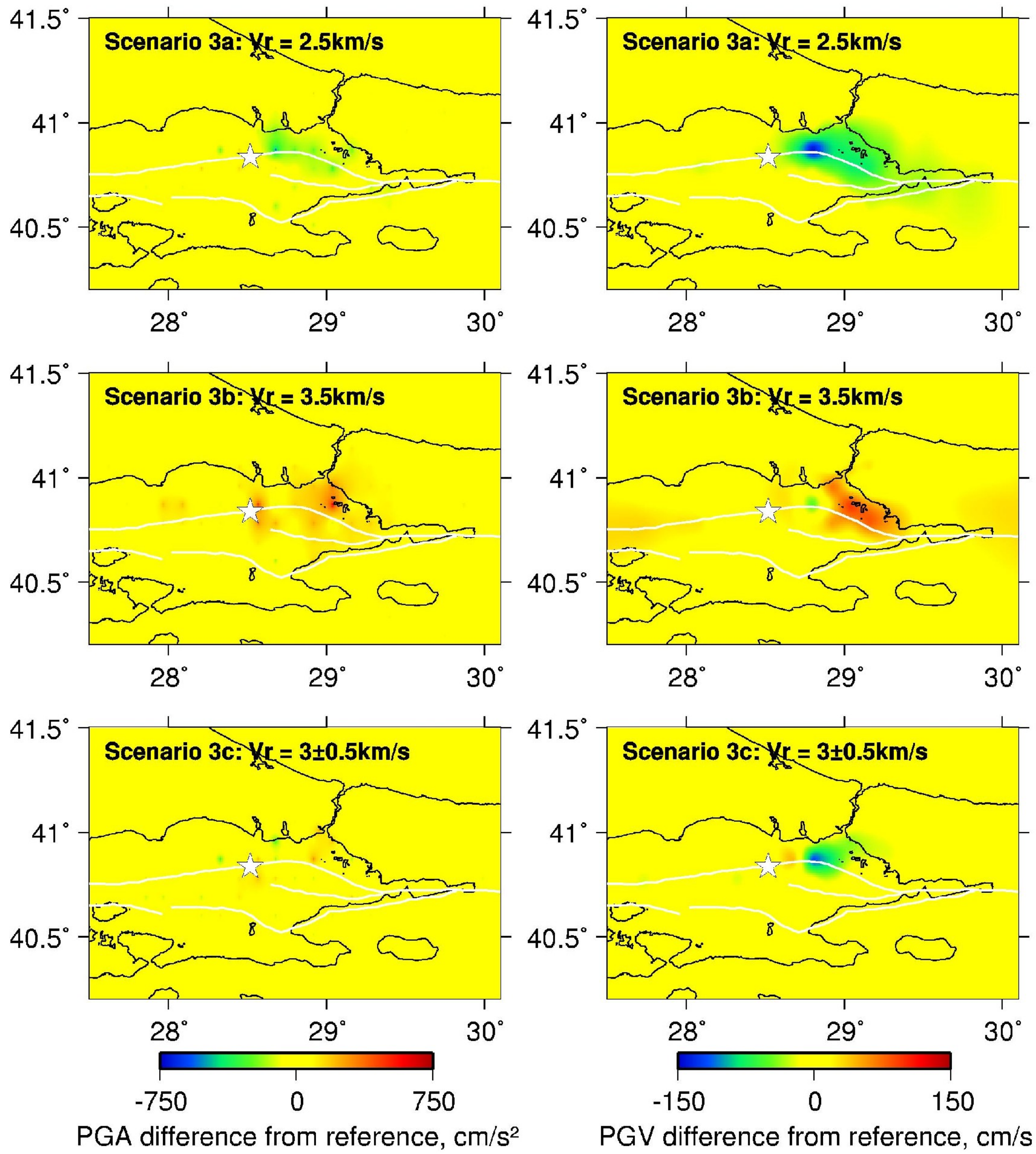

Figure 2.2.2. Effect of rupture velocity variation on ground motion simulation results. The maps are given as difference between the tested parameter and the “standard” scenario results.

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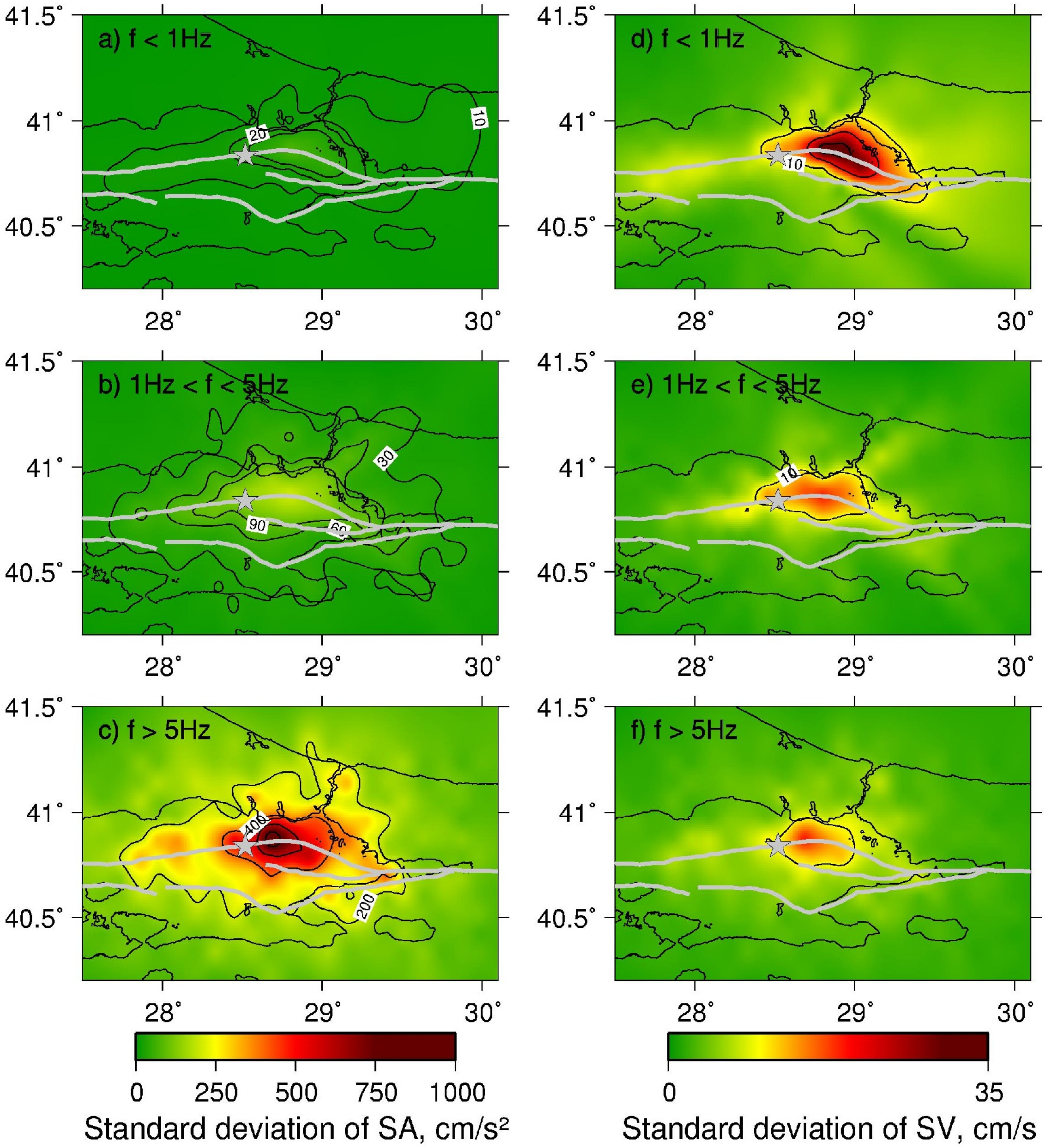

Figure 2.2.3. Distribution of the standard deviation for spectral accelerations **(left)** and spectral velocities **(right)** for selected frequency bands for the 16 scenarios modeled based on response spectra calculated at each simulation site.

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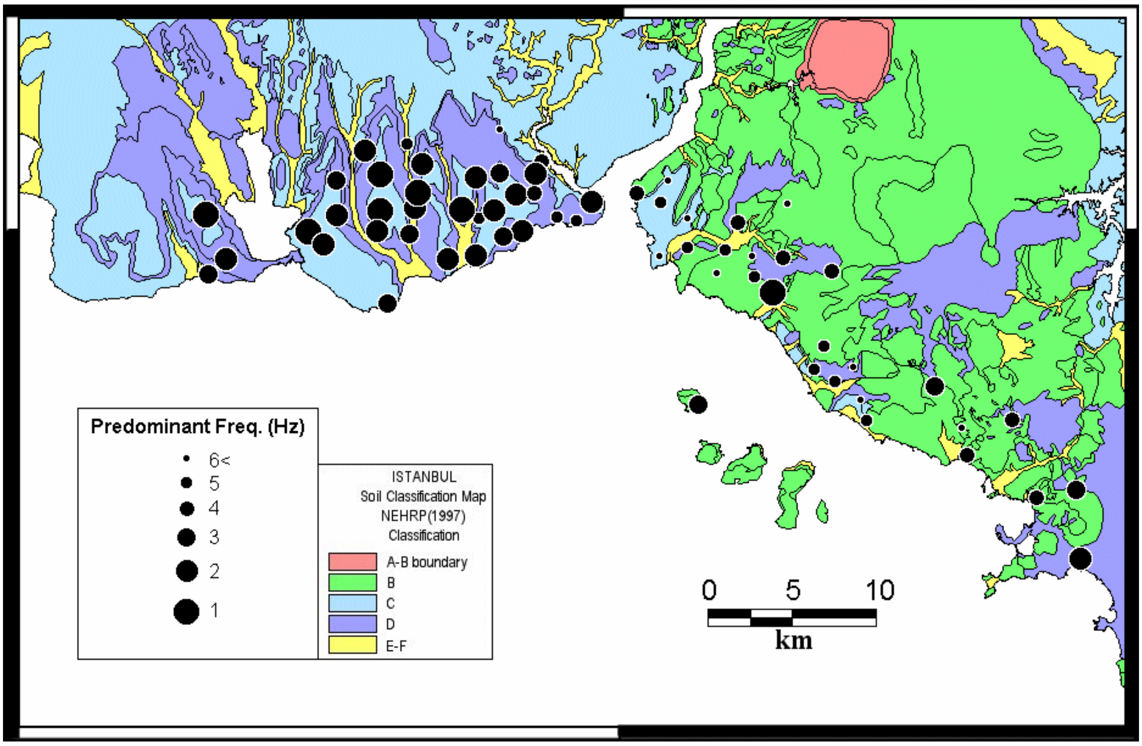

Figure 3.1.1. Predominant frequencies of the RRS sites based on the H/V spectral ratios of the May 16, 2004 earthquake records. Soil classification is based on the NEHRP (1997). Note that the soil classes D, E and F show lower frequencies. (From Birgören et al., 2004).

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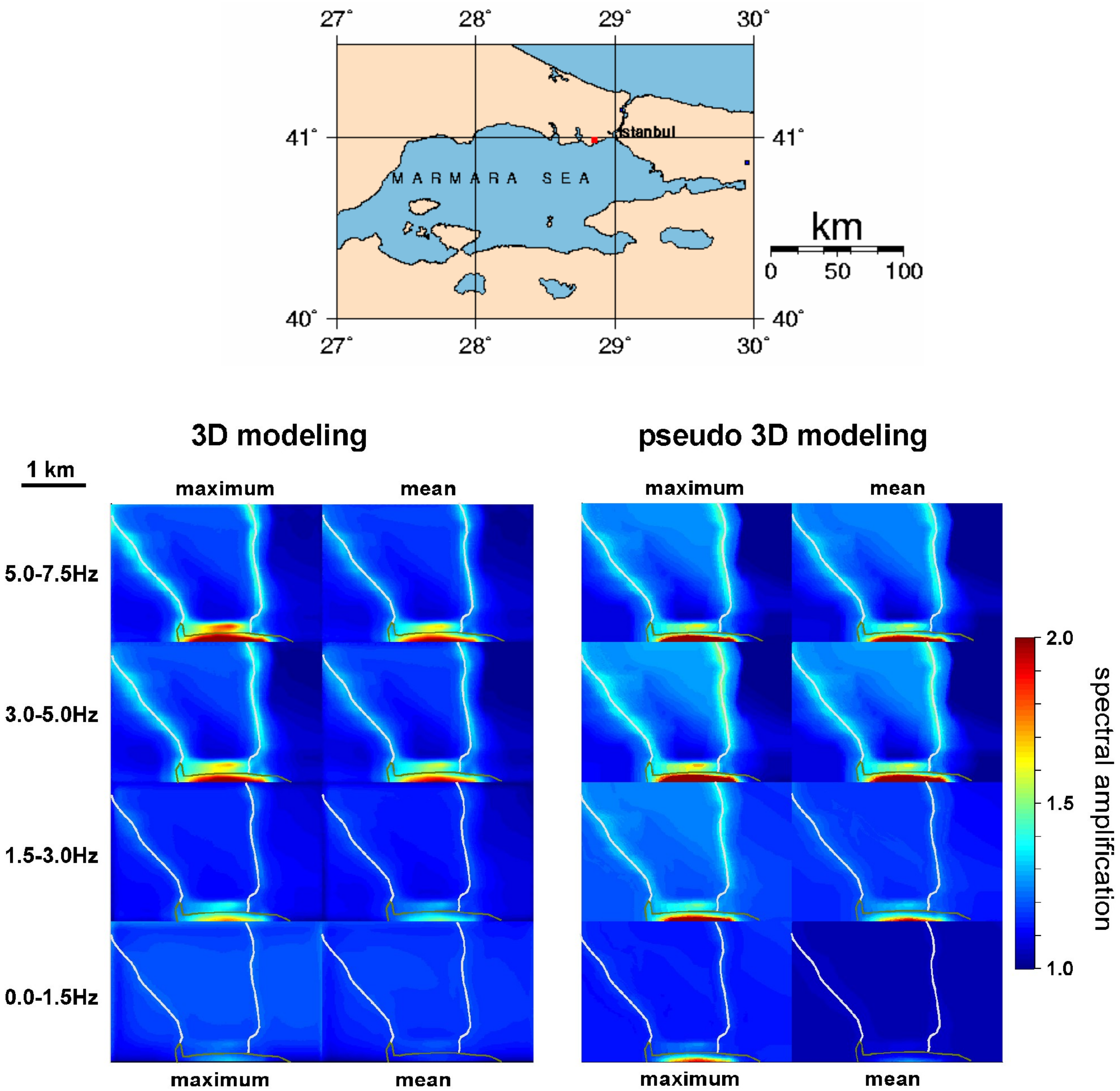

Figure 3.2.1. The spectral amplifications in the Ataköy area, shown in various frequency bands. The color code indicates the absolute level amplification factors. The maps shown on the left are the results from the 3D-modeling. The maps on the right are from pseudo 3D-modeling. Index map shows the location of Ataköy (red dot).

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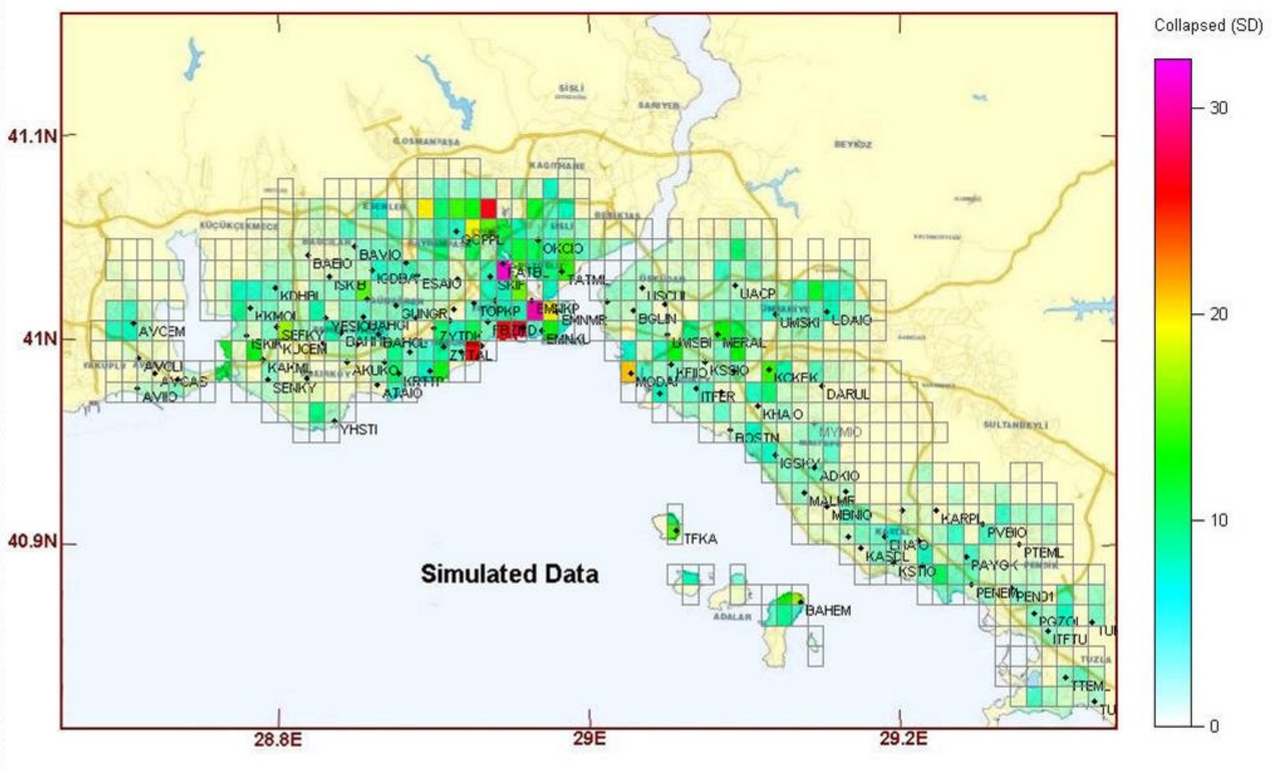

Figure 4.1.1. The spatial disrtibution of earthquake damage in Istanbul in terms of collapsed buildings.