Real-Time Mapping of PGA Distribution in Tehran Using TRRNet and peeqMap

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INTRODUCTION

Tehran megacity, the political and economical capital of Iran with population of more than eight million residents, is situated in the seismically active zone of Alborz. The seismicity pattern of this zone shows occurrence of large earthquakes in long time periods (Masson *et al.*, 2005). Several large earthquakes such as the 855 A.D. M_s 7.1, the 958 A.D. M_s 7.7, and the 1117 A.D. M_s 7.2 in the historical seismic catalog of Tehran and surrounding area proves that the city has a high level of seismic risk (Fig. 1). The last disastrous example among these earthquakes was in 1830, and the city is waiting for the next large earthquake (Ambraseys and Melville, 1982; Ashtari-Jafari, 2010). Several active faults surround Tehran including North Tehran fault, Eyvanekey fault, North and South Ray faults (Fig. 1). Apart from existence of several active faults around the city, fast growth of population and urbanization in previous decades, and lack of strong regulations for urban development increased the vulnerability of Tehran to moderate to large earthquakes (Amini-Hosseini *et al.*, 2009).

Mindful of the seismic risk faced by the city, the Tehran Rapid Response Network (TRRNet) has been installed in the Tehran metropolitan area in order to acquire real-time strong-motion data, to develop a strong ground motion database, and to improve microzonation as well as obtain effective information for the estimation of earthquake ground shaking and damage. This network consists of twenty strong-motion stations which have been established by the Iran Strong Motion Network (ISMN) department of Road, Housing and Urban Development Research Center in the frame of a pilot project for rapid assessment of ground-shaking parameters.

peeqMap software (http://www.peeqMap.ir, last accessed May 2013) developed by Sadeghi-Bagherabadi *et al.* (2010) is customized to be able to use the data obtained from TRRNet for mapping the distribution of peak ground acceleration (PGA) in Tehran. The peeqMap is able to extract the ground-motion parameters from recorded waveforms, and combine them with predefined seismological information (e.g., site effect factors and attenuation relationships) to determine the ground-motion maps at regional and local scales.

TRRNet, as a real-time strong-motion network, peeqMap software, and the map of the surface geology of the city are three fundamental ingredients toward generating a shakemap for Tehran. The ground-motion values obtained from the shakemap in combination with building inventory data can contribute to loss estimation and assessment of damage to the lifeline and utility networks, and for improving earthquake-hazard mitigation and rapid response (Sadeghi-Bagherabadi *et al.*, 2011).

DESCRIPTION OF TRRNET

Tehran Rapid Response Network (TRRNet) is composed of 20 three-component strong-motion stations installed in free-field sites. Table 1 lists the stations, their location and site classification. Currently, we have not performed any geophysical or geotechnical surveys for determining site condition for the TRRNet stations. However, the site classes given in the Table 1 are approximated according to the distribution of shear-wave velocity in the top 30 m (V_{S30}) presented by Shafiee and Azadi (2007; Fig. 2). This network covers an area of approximately 800 km^2 of Tehran. We could not array stations in a regular arrangement to achieve a specific pattern (e.g., circular, orthogonal, linear, elliptical) due to difficulties such as land acquisition and obtaining permission for installing stations in desired places, as well as problems of access to communication links. Thus, the stations are distributed randomly in the populated areas (Fig. 3). Recording stations of TRRNet are housed in a $120 \times 120 \times 120$ cm fiberglass shelter. The sensors are installed on a 0.3 m^3 reinforced concrete base at least 0.3 m into the soil.

The CMG-5TD instrument, which is a combination of the CMG-5T accelerometer and CMG-DM24 digitizer, is used at every station. The sensor has a wide dynamic range and the recording capability of $\pm 2g$ acceleration. The 24-bit digitizer converts analog to digital signals. It is able to save recorded ground motion for more than 300 hours onsite, and transfer the data with fireWire port. The global positioning system is installed in each station to guarantee the accuracy of time tagging. The stations equipped by Cisco 878 K9 integrated services router or Huawei AR 18-33 router for transmitting obtained data to the data center. Real-time IP packet transmission from stations to data center is done over Transmission Control Protocol/Internet Protocol (TCP/IP). All 20 stations in the TRRNet are connected to a data center using an

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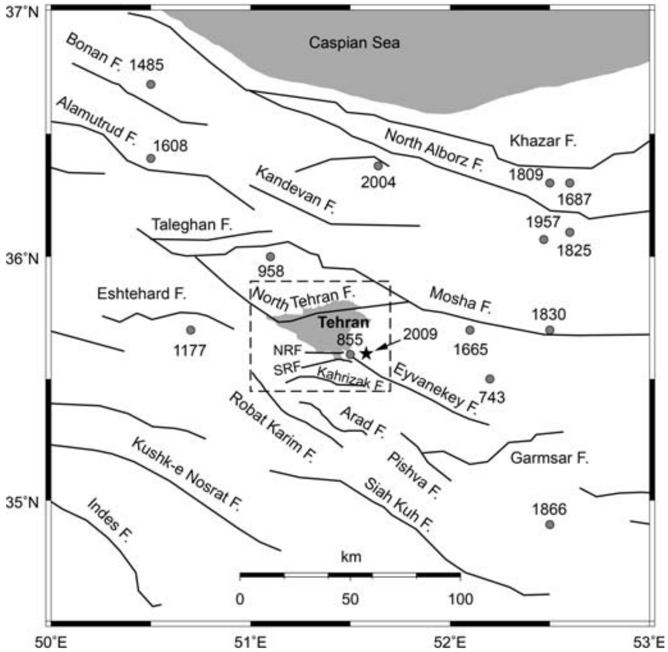


▲ **Figure 1.** Map showing major active faults (Hessami *et al.*, 2003), and seismicity around Tehran. Circles, epicenters of M_s >6 earthquakes; numbers, the year of earthquake occurrence. The historical earthquakes are from Ambraseys and Melville (1982). Star, the epicenter of the 17 October 2009 (M_w 4.0). NRF and SRF in the dashed square area, closely surrounding the city, refer to South Ray fault and North Ray fault, respectively. Topographic contours at 200 m intervals of the boxed area are shown in Figure 3.

Internet Protocol/Multi-Protocol Label Switching (IP/MPLS) network with hub-and-spoke topology over Single-pair High-speed Digital Subscriber Line (SHDSL). The advantage of MPLS mechanism as a pocket-switched network is its independence on a particular data link layer technology. The bandwidth of each station link is 64 kb/s, and in the data center the 2 mb/s bandwidth is used to receive the total 20 × 64 kb/s bandwidth of transferred data from all 20 stations simultaneously. The dial-up modem is also connected to the dataloggers and is used as a backup data-communication line. The sampled signals achieved from stations in real time, are being continuously stored in ASCII format in the data center, which is located in the ISMN building next to the TH001 station (Fig. 3).

It is worth mentioning that apart from 20 stations of TRRNet, there are 30 free-field strong-motion stations of ISMN with SSA-2 or CMG-5T accelerometers in Tehran and its suburbs (Fig. 3). The data acquisition at these 30 stations is not real time; it is performed manually or by dial-up connections following triggering by an earthquake. Waveforms recorded by these stations could be used as complementary information for determination of source and shaking parameters during the first few hours of an earthquake. The earthquake of 17 October 2009 (M_w 4.0), southeastern of Tehran, could be considered as a case (Hamzehloo *et al.*, 2009; Sadeghi *et al.*, 2010; Vasheghani-Farahani and Zare, 2011). The TH008, TH009, and TH013 are three stations of TRRNet that were operational when the earthquake occurred. The recorded signals of this event are the only reliable and significant data registered by TRRNet stations until now. In addition to three stations of TRRNet, 12 other strong-motion stations of ISMN, including eight SSA-2 and four Guralp sensors, were triggered by this event (Fig. 4). The source parameters of 17 October 2009 earthquake are determined using all records by Sadeghi *et al.* (2010).

PEEQMAP: SOFTWARE FOR PRODUCING EMERGENCY EARTHQUAKE MAPS

Shakemaps depict the spatial distribution of ground-shaking parameters such as PGA, peak ground velocity, and response spectral ordinates in desirable frequencies. Such maps can be used as rudimentary information for estimation of damages and losses after catastrophic earthquakes. The shakemap concept was originally conceived by Wald *et al.* (1999). They developed software called ShakeMap® for applying the procedure proposed in their seminal paper for southern California. The latest versions of the ShakeMap® package are currently functional in U.S.A., Italy, southeastern Alps, and Switzerland (Wald *et al.*, 2006; Wiemer *et al.*, 2007; Cua *et al.*, 2008; Michelini *et al.*, 2008; Moratto *et al.*, 2009; Worden *et al.*, 2010). The most recent version of the U.S. Geological Survey (USGS) ShakeMap tool uses the approach developed by Worden *et al.* (2010). In this approach, a weighted interpolation scheme combines instrumental peak ground motions with estimated ground motions based on the inverse of their uncertainty, and also allows for usage of intensity data in addition to ground-motion data.

Although, the scientific field of generating shakemaps traditionally has been based on the technique of Wald *et al.* (1999), in recent years different methodologies have been developed that are incorporated in a substantial number of different software programs (Bartlakowski *et al.*, 2006; Convertito *et al.*, 2009).

Being aware of the consequence of accurate ground-shaking estimation, the Earthquake Research Center of Ferdowsi University of Mashhad (EQRC) has developed software to calculate and display the distribution of ground-shaking parameters in urban and regional scales using data obtained from seismic networks. This software is termed peeqMap (Producing Emergency EarthQuake MAPs).

It should be noted that the core of the ShakeMap® (Wald *et al.*, 1999) was adapted for peeqMap. However, the algorithm of peeqMap benefits from the existing methodologies used in a number of urban and regional shakemaps around the world (e.g., Ontario in Canada, and Campania in southern Italy). The equation of rapid magnitude estimation, developed by Babaei *et al.* (2010), is implemented in peeqMap that allows users to determine the magnitude of moderate to large earthquakes using strong-motion records. Intensity analysis procedures as

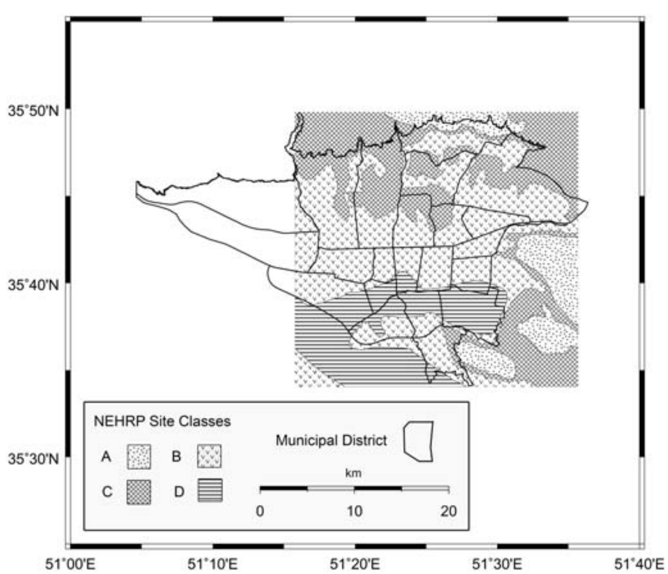
Table 1
TRRNet Station Codes, Locations, and Site Classes*

Station Code	Latitude (°N)	Longitude (°E)	Elevation (m)	Location	NEHRP Site Class
TH001	35.741	51.364	1413	Building and Housing Research Center	B
TH002	35.739	51.585	1514	Abbaspour University of Technology	C
TH003	35.801	51.396	1720	Shahid Beheshti University	B
TH004	35.735	51.386	1410	University of Tehran, Department of Physics	C
TH005	35.697	51.332	1185	Geological Survey of Iran	C
TH006	35.746	51.504	1332	Iran University of Science and Technology	C
TH007	35.741	51.392	1503	Alzahra University	C
TH008	35.647	51.399	1122	Bahman Artistic Cultural Center	D
TH009	35.704	51.351	1215	Sharif University of Technology	C
TH010	35.593	51.428	1062	Shahr-E-Rey Government	C
TH011	35.779	51.491	1510	Sahid Rajaee Teacher Training University	B
TH012	35.683	51.411	1177	City Park	C
TH013	35.764	51.410	1480	K. N. Toosi University of Technology	C
TH014	35.720	51.381	1283	Tarbiat Modares University	C
TH015	35.604	51.305	1135	Chahar Dange Sheriffdom	D
TH016	35.754	51.283	1407	2nd Sub_Region of Region 5 of Tehran Municipality	C
TH017	35.725	51.244	1296	2nd Sub_Region of Region 22 of Tehran Municipality	C
TH018	35.790	51.320	1405	Science and Research Branch of the Islamic Azad University	B
TH019	35.676	51.262	1189	Fayazbakhsh Hospital	C
TH020	35.652	51.468	1147	Khavaran Artistic Cultural Center	D

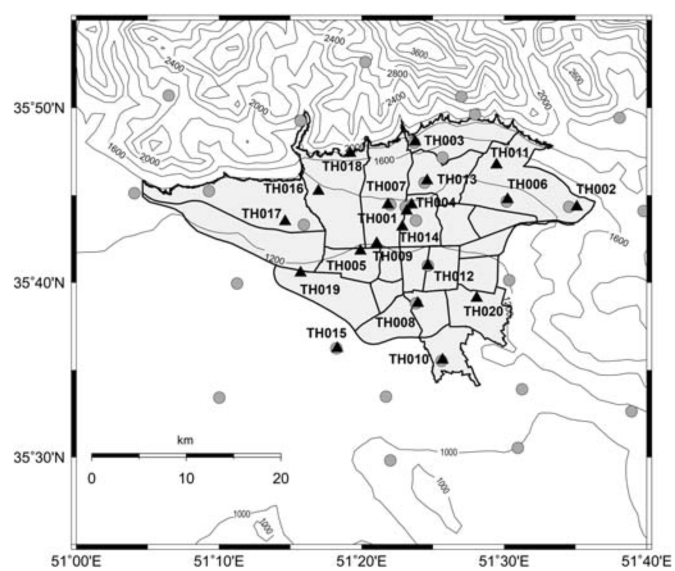
*The V_{S30} map is used for the site classification (see Fig. 2 and Table 3).

proposed by Worden *et al.* (2010) are not included because no real-time intensity data is currently available for Iran.

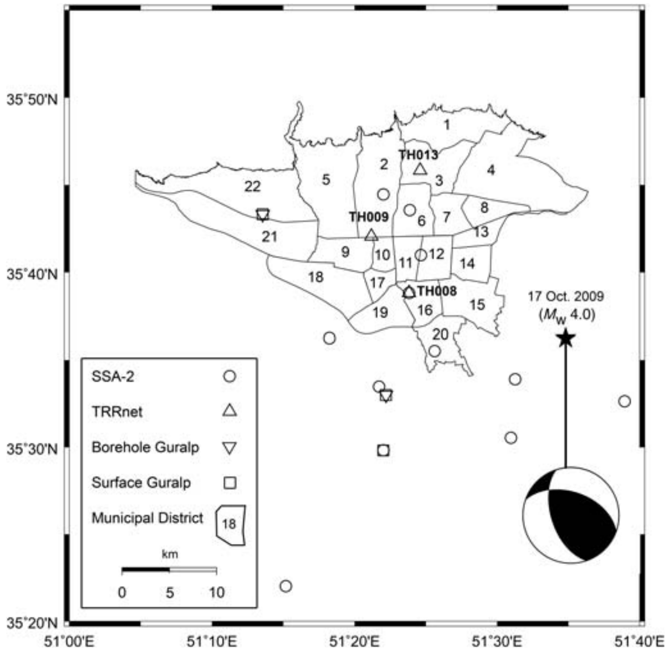
We describe the procedure employed in peeqMap for generation of shaking maps by data retrieved from regional and urban seismic networks. According to Wald *et al.* (1999), the main steps of producing shakemaps can be listed as: (1) Collecting peak ground motions of available stations on the network; (2) magnitude and location determination and



▲ **Figure 2.** Distribution of V_{S30} in Tehran based on the NEHRP site classification (Shafiee and Azadi, 2007).



▲ **Figure 3.** Tehran municipal district borders, free-field strong-motion stations in the city and its suburbs including triangles with station codes, 20 stations of TRRNet; and circles, other free-field stations of ISMN, overlaid on the topographic contour map.



▲ **Figure 4.** Tehran municipal districts and their numbers; black star, epicenter, and recording stations of 17 October 2009 earthquake (M_w 4.0). The focal mechanism is from Sadeghi *et al.* (2010).

estimation of strong motion in the rock site located in areas far from the recording stations; (3) site effect correction and interpolation of recorded and estimated values for a fine grid of points; (4) modifying values in the fine grid network based on the site conditions.

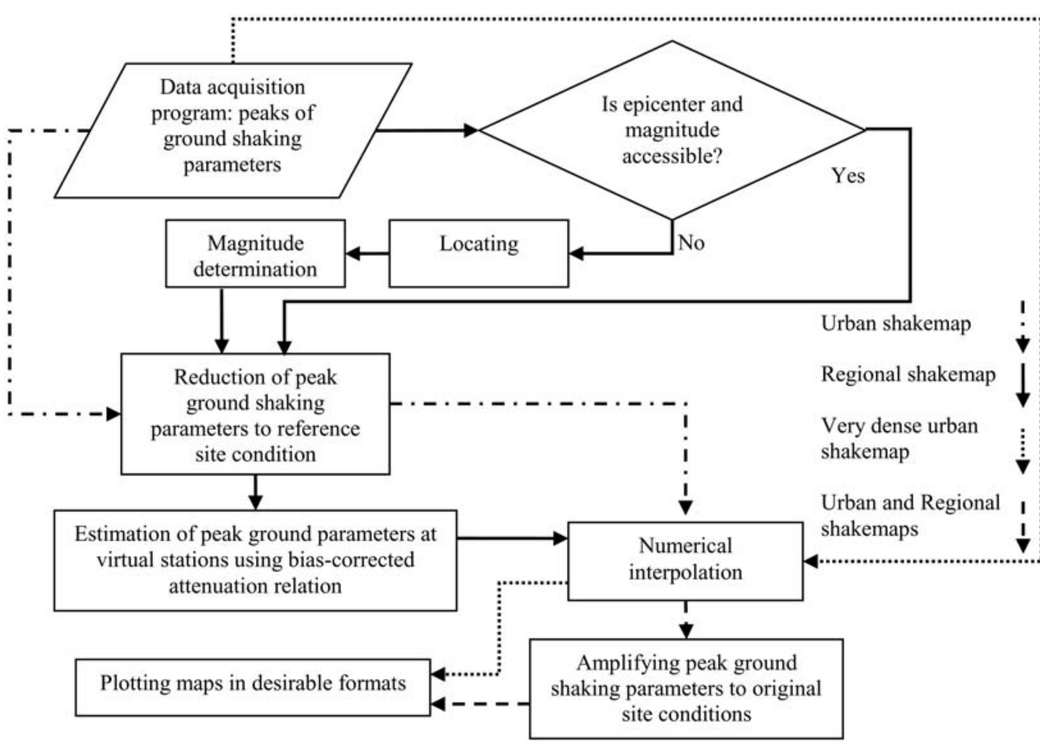
In principle, peeqMap consists of three modules for producing shaking maps based on data obtained from very dense urban, urban, and regional seismic networks. The main distinction between applied procedures in these modules is in the density of seismic networks. Regardless of the module used, users have to supply a number of input files, which contain the necessary input data in advance (e.g., site correction factors and geographical position of recording stations).

Regional Shaking Maps

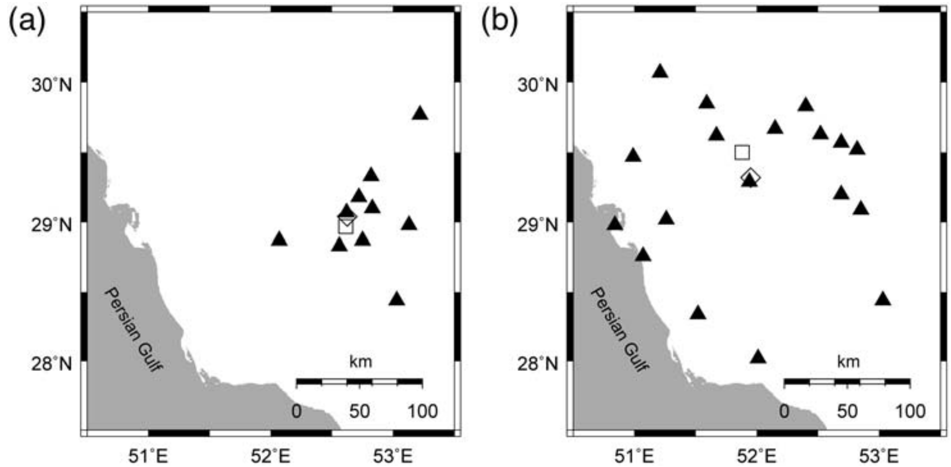
As shown in Figure 5, the first step in the procedure of generating a shakemap is extracting peak ground-shaking values from recorded signals. This part of the program could be customized in order to use recorded signals in different formats and types of recording, such as continuous or triggered.

Location and magnitude of earthquakes can be considered as appropriate parameters for triggering peeqMap. However, for local and regional networks that record continuous signals without automatic event detection, the methodology of Kaka and Atkinson (2006) is incorporated into the program to detect events based on exceeding specified ground-motion amplitudes at a predefined number of stations within a particular time window.

Although it is preferable to accept a precise location and magnitude of earthquakes determined by other locating programs, if they are not available the method of Kanamori (1993) will be applied to estimate them after event detection.



▲ **Figure 5.** The flowchart of peeqMap for producing very dense urban, urban, and regional shakemaps.



▲ **Figure 6.** Filled triangles, recording stations; square, epicenter; and diamond, strong-motion centroid of the (a) 20 June 1994 M_w 5.9 Zanjiran earthquake and the (b) 6 May 1999 M_w 6.2 Baladeh earthquake.

This method determines the location of the strong-motion centroid (SMC) by nonlinear fitting of a bivariate regional attenuation relation to the PGA values. Figure 6 shows the location of the epicenter and the centroid determined for two events that occurred in the Zagros seismic zone of Iran. The two events are the M_w 5.9 Zanjiran earthquake of 20 June 1994 and the M_w 6.2 Baladeh earthquake of 6 May 1999. The estimated SMC magnitudes as well as the distance between the SMC and the epicentral location of these events are listed in Table 2.

For strong-motion waveforms recorded in Iranian plateau, the program estimates the moment magnitude of the events precisely using an attenuation relationship between total effective shaking and epicentral distance (Babaei *et al.*, 2010). The total effective shaking parameter is calculated by time integration of the absolute amplitude values of the three components of accelerograms over the strong shaking duration (Wu and Teng 2004). Application of the total effective shaking parameter significantly improved the estimation of magnitude for events occurred in Iran by comparison with SMC magnitude (Table 2).

Following determination of the location and magnitude of an earthquake, the peak ground-motion values are scaled according to a common reference site by applying empirical amplitude-dependence factors (Borcherdt, 1994). At the next stage, a magnitude-versus-distance ground-motion prediction equation (GMPE) is used for estimation of ground motion in areas of sparse station coverage. According to Wald *et al.* (2006), the quantities obtained from GMPEs should be bias-corrected to decrease the uncertainty of the estimation. The bias correction factor (BF) obtained from equation (1) is multiplied to computational values to result bias corrected peak ground motions in uniformly spaced virtual stations:

$$BF = \frac{\sum_{i=1}^{n}\left(\frac{\mathrm{PGP}_i - \mathrm{PGP}_{i\mathrm{att}}}{\mathrm{PGP}_{i\mathrm{att}}}\right)}{n}, \tag{1}$$

where PGP_i is the observed peak value of ground-motion parameter at the i-th station. $\mathrm{PGP}_{i\mathrm{att}}$ is estimated value at the i-th station by a GMPE, and n is the number of recording stations. The predefined distance between virtual stations is used to form a coarse grid of estimation points. Phantom stations, which are closer than a specified distance to instrumental recording stations, are removed from the initial arrangement.

Table 2
Comparison of the USGS Source Parameters with Source Parameters Estimated by Strong-Motion Centroid (SMC) for the Two Studied Earthquakes

Earthquake	Date (yyyy/mm/dd)	USGS Latitude (°N)	USGS Longitude (°E)	SMC Latitude (°N)	SMC Longitude (°E)	USGS Magnitude	SMC Magnitude	TES Magnitude*	*d*E (km)†
Zanjiran	1994/06/20	28.968	52.614	29.041	52.625	5.9	6.4	5.8	5.0
Baladeh	1999/05/06	29.501	51.880	29.321	51.950	6.2	6.0	6.2	21.8

Source: http://earthquake.usgs.gov/earthquakes/ (last accessed May 2013).
*Column 9 gives the magnitude estimated by the attenuation relation of Total Effective Shaking (TES).
†*d*E is the distance between the SMC location and the epicenter.

The methodology of Convertito *et al.* (2009) is also used for filling the wide spaces between recording stations. This interpolation technique is based on a triangulation procedure to locally correct predicted data at the triangle barycenters where their vertices correspond to seismic stations. If network arrangement permits, the methodology of Convertito *et al.* (2009) could be selected as an option to estimate peak values. The PGA values are estimated at phantom stations that are chosen in the area not covered by the seismic network. The estimated peaks at phantom stations along with peaks recorded at operational seismic stations contribute to computation of fine evenly spaced grid points by applying a numerical interpolation process. A 2D spline interpolation is used to approximate values between the sample points. Because the interpolation is defined by fitting lower-order polynomials to the points on the surface in a piecewise fashion, it is necessary to create a kind of partitioning to go from a coarser mesh to a finer mesh. Delaunay triangulation in combination with spline interpolation is applied for estimating values in the fine and regular network. At the last step in computational process of generation of shakemap, the interpolated amplitudes are amplified to their original site conditions.

Urban and Very Dense Urban Shakemaps

Because most of the vulnerable lifelines are placed in urban zones, the uncertainty of estimating local shakemaps should be minimized by increasing the instrumental data and also by elimination of uncertainty sources such as GMPEs, earthquake location and magnitude estimation. In the case of very dense urban seismic networks, among the aforementioned steps in the procedure of computing regional shakemaps, only numerical interpolation is executed (Fig. 5). The same algorithm is used in many urban areas. In Bucharest where the seismic network is rather sparse (we call these networks urban), the site correction procedure is of great importance especially during small earthquakes (Bartlakowski *et al.*, 2006). Thus, for mapping ground motion based on the data recorded in such urban networks, site reduction and amplification process are applied in addition to the numerical interpolation (Fig. 5). The procedure of producing a shakemap has to be chosen based on seismic network coverage. Regarding regional networks that comprise some dense local networks and a number of outlying stations, a proper algorithm will be applied automatically by considering user-defined distance between virtual stations and employing urban procedure.

IMPLEMENTATION OF PEEQMAP IN TEHRAN

There is an increasing interest in acquisition of ground-shaking parameters in real time, not only for earthquake risk mitigation and emergency management, but also for the purpose of collecting required data for rapid determination of earthquake source parameters and engineering studies. In addition, recent technological advances have contributed to make the installation and operation of seismic monitoring systems more practical and economical and to permit an almost immediate analysis of the ground-motion parameters.

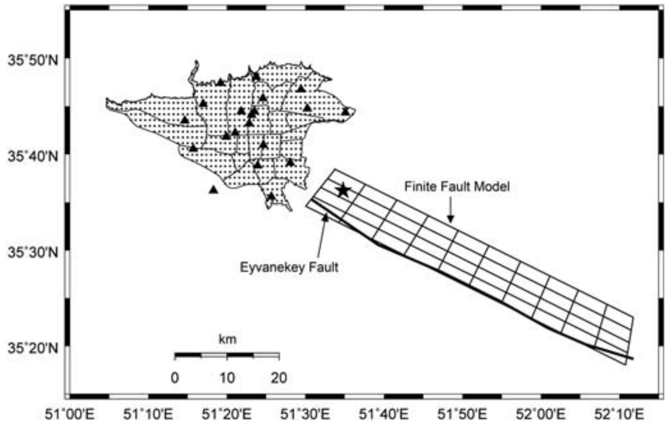
Generation of regional shakemaps requires GMPEs and data on surface geology. In addition, it needs suitable hardware equipments (i.e., seismic network and reliable communication), and finally software for estimation of ground-shaking parameters and plotting maps. Some efforts to fulfill the scientific requirements are performed recently in cooperation between ISMN and EQRC (Sadeghi-Bagherabadi, 2010; Babaei, 2011).

Following establishment of TRRNet and collecting necessary seismological information, one of the peeqMap modules that is customized for producing urban shakemaps is implemented to portray the spatial distribution of PGA in Tehran. In the absence of a significant event, peeqMap presents the noise level every minute.

Apart from minute-by-minute maps, we have devised two mechanisms to detect events and generate shaking maps for specific earthquakes. The first one is applied on continuous data flow, and it is based on simultaneous exceedance of specified ground-motion amplitudes at five stations. A time window of about 20 s is required for a specific seismic signal to cross Tehran, which has to be traced to compute a reliable shakemap. However, because of instrument limitations, the shortest possible time window of one minute is adopted for the data flux stream to be stored. Because it is possible that an event starts in one time window and ends in the next one, each time window is considered with the previous and next ones for selecting the PGA values. The second method uses triggered waveforms for detecting significant events. In this mechanism if there are at least five triggered waveforms for which their start time is

Table 3
Site Correction Factors for NEHRP Classifications in Tehran

Site Class (NEHRP)	V_{S30} (m/s)	PGA (g)	Amplification Factor
A	2000	0.1	0.73
		0.2	0.80
		0.3	0.91
		4.0	1.04
B	815	0.1	1.00
		0.2	1.00
		0.3	1.00
		4.0	1.00
C	560	0.1	1.14
		0.2	1.10
		0.3	1.04
		4.0	0.98
D	280	0.1	1.45
		0.2	1.31
		0.3	1.11
		4.0	0.95



▲ **Figure 7.** Simulation points including filled triangles, 20 stations of TRRNet and black dots, 620 sites composed of 0.01° × 0.01° grid points located in the municipal districts of Tehran as well as epicenter of scenario earthquake and a schematic view of Eyvanekey finite-fault model.

within a one-minute time window, the shakemap will be generated by PGAs of these signals.

Surface geology is one of the contributing factors that affect strong ground motion, and its effects have been shown to play a key role in structural damage. A number of studies have been conducted to account for site conditions in Tehran (Center for Earthquake Studies of Tehran–Japan International Cooperation Agency [CEST–JICA], 2000; Shafiee and Azadi, 2007). To address the site corrections in Tehran, short-term correction factors have been calculated using the relation of Borcherdt (1994) and the map of V_{S30} presented by Shafiee and Azadi (2007; Fig. 2). We have selected the B site class in NEHRP site classification as a reference site (Building Seismic Safety Council [BSSC], 2001). The velocities assigned to the four sites are 2000, 815, 560, and 280 m/s for A, B, C, and D classes, respectively, and the correction factors are given in Table 3. The result of the numerical interpolation of PGA values is mapped in a 0.01° × 0.01° grid.

Table 4
Finite-Fault Geometry and Model Parameters for the M_w 7.1 Eyvanekey Fault Scenario Earthquake

Finite-fault geometry	
Fault length	80 km
Fault width	20 km
Strike	300°
Subfault length	8 km
Subfault width	5 km
Model parameters	
Shear-wave velocity	3.5 km/s
Rupture velocity (km/s)	0.8 × Shear-wave velocity
Crustal density	2.8 g/cm^3
Stress parameter	50 bar
Quality factor	$87f^{1.46}$
Geometrical spreading	R^{-1}(R < 70 km) $R^{+0.2}$(70 km ≤ R ≤ 150 km) $R^{-0.1}$(R > 150 km)
Windowing function	Saragoni–Hart
Slip distribution	Random

COMPARISON OF TRRNET SHAKING MAP WITH A SIMULATED (M_w 7.1) SCENARIO EARTHQUAKE

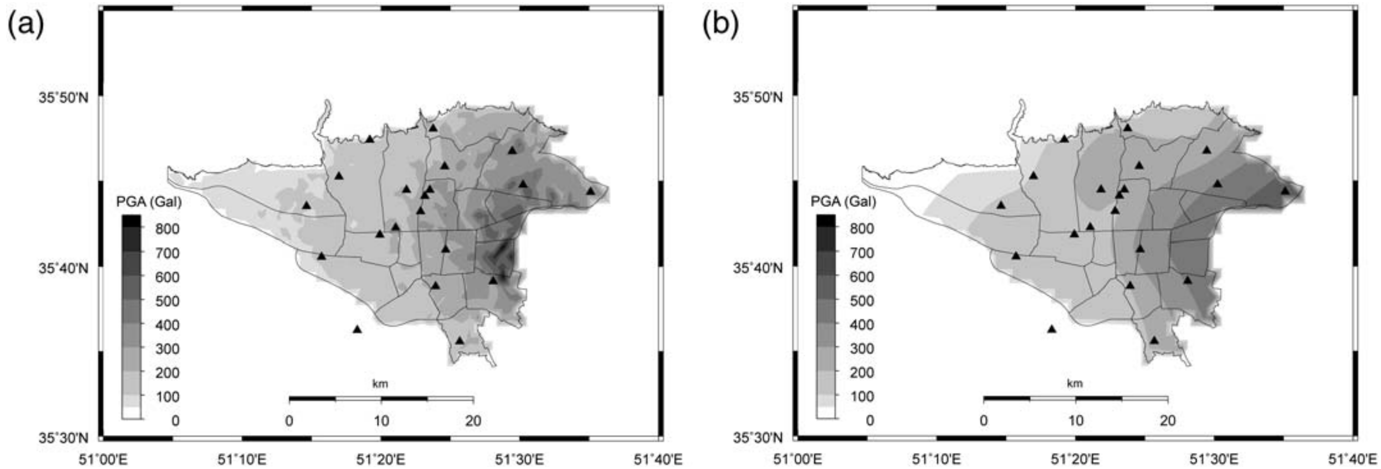
The occurrence of the earthquake of 17 October 2009 (M_w 4.0), southeast of Tehran, is evidence for the existence of active faults in the vicinity of the city. Taking the location and focal mechanism into consideration, the Eyvanekey fault could be the causative fault for this event (Sadeghi *et al.*, 2010).

Because during the instrumental period of seismology no significant earthquake has been reported for Tehran, we have developed a (M_w 7.1) scenario earthquake based on the empirical relation of Wells and Coppersmith (1994), as well as the seismic background of the Eyvanekey fault, which caused the large historical earthquake of 743 A.D. estimated at M_w 7.2 (Ambraseys and Melville, 1982).

The technique of stochastic finite-fault modeling based on dynamic corner frequency (Motazedian and Atkinson, 2005) has been used in order to simulate the PGA values at 640 sites, including 20 stations of TRRNet and 620 sites on a 0.01° regularly spaced grid covering the municipal districts of Tehran (Fig. 7). The epicenter of the scenario earthquake is at the same location with the epicenter of the 17 October 2009 (M_w 4.0) earthquake, close to Tehran. We have simulated the scenario earthquake using the region-specific key seismic parameters studied by Motazedian (2006) for earthquakes in northern Iran. Table 4 lists the finite-fault geometry and model parameters. The map shown in Figure 8a illustrates the distribution of simulated PGA values at the grid points spread over the municipal districts of Tehran (see Fig. 7). The map shown in Figure 8b is the shaking map generated by peeqMap for producing urban shakemaps using the simulated PGA values at TRRNet stations. The maximum, the mean, and standard deviation of simulated and estimated PGA values in municipal districts of the city are listed in Table 5. The table also includes the mean absolute percent difference (MAPD), which can quantitatively evaluate the difference between the estimated and simulated PGA values. Comparison between these maps shows that the current arrangement of TRRNet stations is able to discover the general trend of ground shaking. However, due to the coarse network of TRRNet stations, it could not detect some high values in the eastern part of the city.

CONCLUSIONS

In this paper, the algorithm used in peeqMap, the software for producing shaking maps for Iran, is presented. Using strong-motion records, peeqMap is able to determine the magnitude



▲ **Figure 8.** (a) Simulated PGA values for the M_w 7.1 scenario earthquake at the grid points shown in Figure 7. (b) TRRNet shaking map generated from the PGA values obtained from simulation of the scenario earthquake at the TRRNet stations.

of earthquakes in Iran relatively more accurately than those from the strong-motion centroid.

In addition, the implementation of the peeqMap in Tehran using the data acquired by TRRNet is discussed. A comparison between TRRNet shaking map for a scenario earthquake and the simulated distribution of PGA in Tehran shows good agreement. In general, the estimated PGA values over the city are close to the simulated values with MAPD less

Table 5
Maximum, Mean, and Standard Deviation (S.D.) of Simulated and Estimated PGA Values, As Well As Mean Absolute Percent Difference (MAPD) in Municipal Districts of Tehran

	Simulated PGA (gal)			Estimated PGA (gal)			
District Number	Maximum	Mean	S.D.	Maximum	Mean	S.D.	MAPD (%)
1	195.48	128.79	27.18	193.63	125.91	37.37	19
2	314.73	221.45	40.98	228.61	186.23	17.72	19
3	291.70	177.48	37.31	260.46	216.79	26.72	33
4	598.85	356.26	74.64	566.17	385.32	100.75	27
5	368.90	251.07	50.58	301.41	245.13	24.43	18
6	137.03	86.18	21.51	117.17	63.04	37.73	36
7	415.25	301.34	49.61	335.61	262.38	38.23	15
8	151.14	94.77	25.83	125.38	90.59	34.10	25
9	590.38	363.11	101.50	415.02	360.99	29.20	17
10	589.79	434.97	75.23	498.73	430.50	37.42	14
11	272.39	155.59	33.85	157.67	122.72	13.07	20
12	270.93	194.12	34.88	205.86	178.49	14.94	11
13	832.14	546.03	139.79	475.12	437.41	24.95	18
14	819.05	342.75	109.17	477.31	391.15	46.00	25
15	330.47	199.51	40.29	302.29	238.16	35.13	24
16	622.12	474.94	99.37	535.40	457.76	32.75	19
17	227.16	185.25	24.50	193.34	153.40	21.17	20
18	300.15	243.71	30.69	327.47	245.19	40.42	12
19	197.11	130.86	30.91	128.35	118.61	5.75	23
20	206.12	164.91	25.48	181.17	140.98	20.93	17
21	337.80	247.51	42.77	330.39	260.85	38.18	16
22	433.82	319.40	52.79	394.28	358.35	27.89	16

District numbers are marked in Figure 4.

than 20%. However, some eastern districts, near the epicenter, have larger MAPD values (up to 36%). We have used two procedures to generate event-specific shakemaps based on triggered waveforms and data flux streams, as well as every-minute PGA maps. Regarding site-effect corrections, although we have adopted a V_{S30} map of Shafiee and Azadi (2007), the map does not show enough detail, nor cover the entire city. Consequently, some further investigations into seismic site conditions should be conducted to derive more accurate estimated PGA values at the ground surface. The accuracy and reliability of the shakemap can be improved by increasing the density of station coverage. In this case, the current module of peeqMap, which is based on the urban algorithm, will be replaced by the very dense urban module to reduce the uncertainty caused by approximating site conditions.

By increasing the number of stations, the TRRNet shakemap is able to contribute to rapid response operations following disastrous earthquakes. The seismotectonic setting of Tehran province shows that rural and industrial districts face a significant seismic risk. Thus, we have planned to use the TRRNet in the near future as a part of a regional network that covers Tehran province to extend the shakemap's geographical coverage.

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REFERENCES

Amini-Hosseini, K., M. Hosseini, M. K. Jafari, and S. Hosseinioon (2009). Recognition of vulnerable urban fabrics in earthquake zones: A case study of the Tehran metropolitan area, *J. Seismol. Earthq. Eng.* **10,** no. 4, 175–187.

Ambraseys, N. N., and C. P. Melville (1982). A History of Persian Earthquakes, in *Cambridge Earth Science Series*, Cambridge University Press, Cambridge, New York.

Ashtari-Jafari, M. (2010). Statistical prediction of the next great earthquake around Tehran, Iran, *J. Geodyn.* **49,** no. 1, 14–18.

Babaei, P. (2011). Rapid estimation of earthquake magnitude using strong ground motion in Iran, *M.S. Thesis*, Ferdowsi University of Mashhad, Earthquake Research Center (in Persian).

Babaei, P., H. Sadeghi, B. Rahimi, and A. Sadeghi-Bagherabadi (2010). Rapid magnitude estimation for moderate to large earthquakes using strong motion records in the Iranian plateau, *AGU Fall Meeting*, San Francisco, California, U.S.A.

Bartlakowski, J., F. Wenzel, M. Radulian, J. R. R. Ritter, and W. Wirth (2006). Urban shakemap methodology for Bucharest, *Geophys. Res. Lett.* **33,** no. L14310, doi: 10.1029/2006GL026283.

Borcherdt, R. D. (1994). Estimates of site-dependent response spectra for design (methodology and justification), *Earthq. Spectra* **10,** 617–654.

Building Seismic Safety Council (BSSC) (2001). *National Earthquake Hazard Reduction Program (NEHRP). Part 1: Recommended provision for seismic regulations for new buildings and other structure*, 2000 edition (FEMA 368), prepared by the Building Seismic Safety Council for the Federal Emergency Management Agency, Washington, D.C.

Center for Earthquake Studies of Tehran–Japan International Cooperation Agency (CEST–JICA) (2000). *The Study on Seismic Microzoning of the Greater Tehran Area in Islamic Republic of Iran*, Pacific Consultants International and OYO Corporation.

Convertito, V., R. De Matteis, L. Cantore, A. Zollo, G. Iannaccone, and M. Caccavale (2009). Rapid estimation of ground-shaking maps for seismic emergency management in the Campania Region of southern Italy, *Nat. Hazards* **52,** 97–115, doi: 10.1007/s11069-009-9359-2.

Cua, G., P. Kaestli, M. Fischer, D. Faeh, S. Wiemer, and D. Giardini (2008). Calibrating shakemaps in Switzerland, in *NERIES Third Annual Meeting*, Utrecht, Netherlands.

Hamzehloo, H., F. Sinaeian, M. Mahood, H. Mirzaei Alavijeh, and E. Farzanegan (2009). Determination of causative fault parameters for the 17 October 2009 Ray–Tehran earthquake, using near field SH-wave data, *J. Seismol. Earthq. Eng.* **11,** no. 3, 121–131.

Hessami, K., F. Jamali, and H. Tabassi (2003). *Major Active Faults of Iran*, scale 1:2,500,000, International Institute of Earthquake Engineering and Seismology, Tehran.

Kaka, S. I., and G. M. Atkinson (2006). Implementation of ShakeMap in Ontario: Challenges of detection and location in a sparse network, *Seismol. Res. Lett.* **77,** 780–792.

Kanamori, H. (1993). Locating earthquakes with amplitude: Application to real-time seismology, *Bull. Seismol. Soc. Am.* **83,** 264–268.

Masson, F., J. Chéry, D. Hatzfeld, J. Martinod, P. Vernant, F. Tavakoli, and M. Ghafory-Ashtiani (2005). Seismic versus aseismic deformation in Iran inferred from earthquakes and geodetic data, *Geophys. J. Int.* **160,** 217–226.

Michelini, A., L. Faenza, V. Lauciani, and L. Malagnini (2008). ShakeMap implementation in Italy, *Seismol. Res. Lett.* **79,** no. 5, 688–697.

Moratto, L., G. Costa, and P. Suhadolc (2009). Real-time generation of ShakeMaps in the southeastern Alps, *Bull. Seismol. Soc. Am.* **99,** no. 4, 2489–2501.

Motazedian, D. (2006). Region-specific key seismic parameters for earthquakes in northern Iran, *Bull. Seismol. Soc. Am.* **96b,** 1386–1395.

Motazedian, D., and G. M. Atkinson (2005). Stochastic finite-fault modeling based on a dynamic corner frequency, *Bull. Seismol. Soc. Am.* **95,** 995–1010.

Sadeghi, H., A. Sadeghi-Bagherabadi, F. Sinaeian, H. Mirzaei Alavigeh, and E. Farzanegan (2010). Source parameters of the Tehran October 17, 2009, Earthquake, in *14th Geophysics Conference of Iran*, Tehran, Iran, 11–13 May 2010 (in Persian).

Sadeghi-Bagherabadi, A. (2010). Design of a post earthquake emergency management mapping mechanism, *M.S. Thesis*, Ferdowsi University of Mashhad, Earthquake Research Center (in Persian).

Sadeghi-Bagherabadi, A., H. Sadeghi, S. K. Hosseini, and P. Babaei (2010). peeqMap: A software for producing emergency earthquake maps, *AGU Fall Meeting*, San Francisco, California, U.S.A.

Sadeghi-Bagherabadi, A., H. Sadeghi, S. K. Hosseini, P. Babaei, and F. Sinaeian (2011). A software for generation of shaking map: Fundamental tool for estimating damage and rapid response following an earthquake, in *Sixth International Conference on Seismology and Earthquake Engineering*, Tehran, Iran, 16–18 May 2011.

Shafiee, A., and A. Azadi (2007). Shear-wave velocity characteristics of geological units throughout Tehran city, Iran, *J. Asian Earth Sci.* **29,** 105–115.

Vasheghani-Farahani, J., and M. Zare (2011). The southeastern earthquake of 17 October 2009 ($M_w = 4.0$), *Seismol. Res. Lett.* **82,** no. 3, 404–412.

Wald, D. J., V. Quitoriano, T. H. Heaton, H. Kanamori, C. W. Scrivner, and C. B. Worden (1999). "Trinet ShakeMaps": Rapid generation of instrumental ground motion and intensity maps for earthquakes in southern California, *Earthq. Spectra* **15,** 537–556.

Wald, D. J., C. B. Worden, V. Quitoriano, and K. L. Pankow (2006). ShakeMap® manual, technical manual, user's guide, and software guide, available at http://pubs.usgs.gov/tm/2005/12A01/pdf/508TM12-A1.pdf (last accessed May 2013), 156 pp.

Wells, D. L., and K. J. Coppersmith (1994). New empirical relationships among magnitude, rupture length, rupture width, rupture area and surface displacement, *Bull. Seismol. Soc. Am.* **84,** 974–1002.

Wiemer, S. B., G. B. Cua, P. Kästli, J. Clinton, D. Faeh, S. Maraini, and D. Giardini (2007). ShakeMaps at the Swiss Seismological Service: Current status, innovations, and outlook, *AGU Fall Meeting*, San Francisco, California, U.S.A.

Worden, C. B., D. J. Wald, T. I. Allen, K. Lin, D. Garcia, and G. Cua (2010). A revised ground-motion and intensity interpolation scheme for ShakeMap, *Bull. Seismol. Soc. Am.* **100,** no. 4, 3083–3096.

Wu, Y. M., and T. L. Teng (2004). Near real-time magnitude determination for large crustal earthquakes, *Tectonophysics* **390,** 205–216.

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