Simulation of 2009, M_w=4 Tehran earthquake using a hybrid method of modal summation and finite difference.

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SUMMARY:
The Greater Tehran area is the most important city of Iran and hosts about 20% of the country population. Despite the presence of major faults and the occurrence of historical earthquakes, nowadays the seismicity is relatively quite low and this enhances the use of simulation methods for microzonation and seismic hazard assessment. To simulate the ground motion caused by the 2009, Mw 4 earthquake, occurred south-east of the city, a hybrid technique is used. It combines two methods: the analytical modal summation and the numerical finite difference, taking advantage of the merits of both. The modal summation is applied to simulate wave propagation from the source to the sedimentary basin and finite differences to propagate the incoming wavefield in the laterally heterogeneous part of the structural model that contains the sedimentary basin. Time and frequency domain parameters are simulated along 2 (E-W and SE-NW) profiles for various stations.

Keywords: Tehran, Hybrid Simulation, Strong Motion, Response Spectral Ratio.

1. INTRODUCRION

Tehran, the capital city of Iran, is located in a high seismic zone at the foot of the Alborz Mountains. The Alpine–Himalayan seismic belt is well known as one of the seismically active areas of the world. The Iranian plateau, located in this area, has experienced several major and destructive earthquakes in the recent past. The M_W =4.0 earthquake occurred at 10:53:57 (GMT) on October 17, 2009 in the southern part of Tehran. The earthquake has been (not strongly) felt in Tehran, which hosts about 20% of the country population, and caused great concern, since the urban area of Tehran is developed on the alluvial layers accumulated on the hard rocks of complex geological formations. The urban development has been rapidly progressing in Tehran without proper disaster prevention measures against the occurrence of very likely strong earthquakes. This is necessary to implement reliable preventive actions, for the effective reduction of seismic risk of this important city. Evaluating a preventive hazard scenario by scaling extended source to higher magnitude and depth of historical events is the future plan of this study.

2. THE 2009, MW=4, TEHRAN-REY EARTHQUAKE

The earthquake considered for simulation occurred at the south-eastern part of Tehran city and caused, in almost all parts of the city, intensity from IV to III, in the EMS98 scale, as evaluated by IIEES reconnaissance team (Farahani and Zare, 2011). It has been recorded by three seismography networks (Table 1): IGTU (Institute of Geophysics of Tehran University), TDMMO (Yaminifard, Tehran Disaster Mitigation and Management Organization) and IIEES (fig. 1). TDMMO location is used for the source location (Hamzehloo et al., 2009). The event also recorded by BHRC (Building and House Research Center of Iran). Figure 1 shows all stations of IGTU, IIEES, TDMMO and BHRC with three different location report of the earthquake. The source azimuthal Parameters are reported by Hamzehloo et al. (2009) and Farahani and Zare (2011). Mechanism of two reports are shown in fig 1.

The earthquake was recorded by a total of 18 accelerographs of the strong motion array operated by BHRC. Out of them, the six stations (Tab. 1) closer to the two profiles (red lines, fig. 2) have been selected as reference observed data set to be used in the comparison between simulated accelerograms and recorded ones. Presences of subsoil information, covering both southern and central parts of the city which include the highest density of population beside adjacent to the recording stations were the reasons for selecting profiles. The profiles extend in the E-W direction, with a length of 6 km, and in the SE-NW direction with a length of 10 km. All stations recorded the 3 components (N-S, E-W and vertical) of motion with a sampling of 0.05 sec. Coordinates of stations 2 and 3 are identical, but one is operating at the free surface, while the other is inside a 30 m deep hole (green small rectangle, fig. 2).

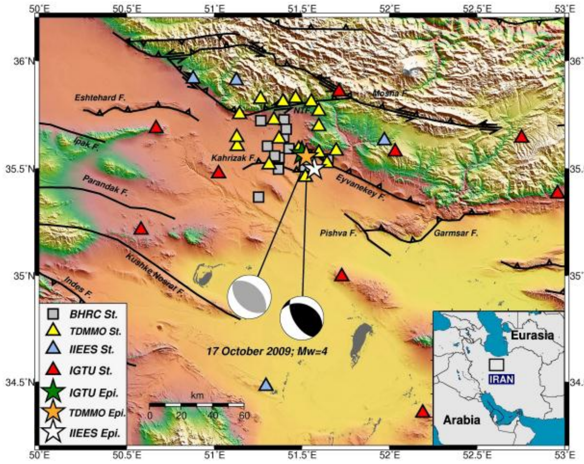

Figure 1. Distribution of IGTU, IIEES, TDMMO and BHRC Stations around the epicenter of the earthquake. Three different epicenters are shown by different color stars. The two reported focal mechanisms are shown.

Table 1. BHRC Station name and location which are used in this study.

BHRC Station Name	Station code used in this study	BHRC Record Number	Longitude (Deg)	Longitude (Deg)
Shahre Rey	St.1	4860	51.42	35.59
Haram Emam	St.2	4910	51.37	35.55
Haram Emam Borehole	St.3	4910B	51.37	35.55
Azad university	St.4	4867	51.34	35.55
Farhangsaraye Bahaman	St.5	4866	51.39	35.64
Park Shahr	St.6	4864	51.41	35.68

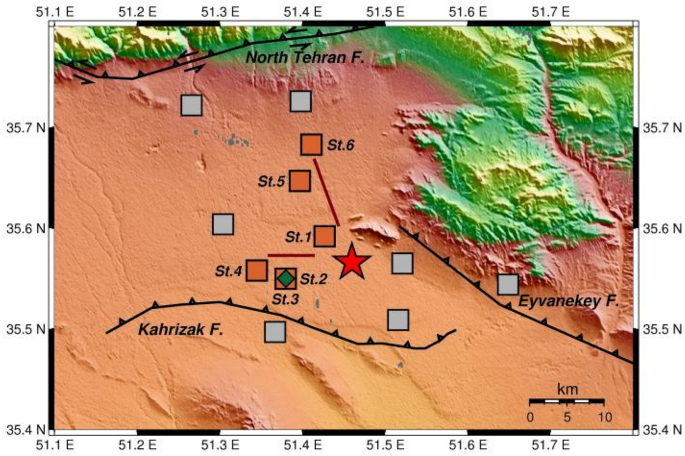

Figure 2. Selected stations (orange and green squares) from BHRC Network for comparison between synthetic and observed data. Red lines show the direction of the two profiles, in E-W and SE-NW direction, respectively, along which the synthetic waveforms have been generated.

3. SIMULATION METHOD

A hybrid method developed by Fäh et al. (1993a, b) is used in this paper that combines the modal summation (MS) technique, valid for laterally homogeneous anelastic media, with finite difference, which permits the modeling of wave propagation in complicated and rapidly varying velocity structures, as it is required when dealing with sedimentary basins, and optimizes the advantages of both methods. The method permits the accurate computation of the earthquake ground motion in two-dimensional (2D), laterally heterogeneous, anelastic media (Panza 1985; Panza and Suhadolc 1987; Florsch et al, 1991; Fäh et al. 1994; Panza et al. 2001). Wave propagation is treated by means of the analytical modal summation technique from the source to the close vicinity of the local, heterogeneous anelastic structure that we may want to model in detail. The laterally homogeneous anelastic structural model, which includes attenuation, velocity and density, represents the average crustal properties of the region and it is considered as the bedrock reference model. The wavefield generated by modal summation is then introduced in the grid that defines the heterogeneous area (for which the attenuation, velocity and density profiles must be specified) and it is propagated numerically according to the finite-differences scheme. With this approach, source, path, and site effects are all taken into account, and it is therefore possible to carry out a detailed study of the wavefield.

4. STRUCTURAL MODEL PARAMETERS

The reference (1D) layered model of the crust and upper mantle has been obtained from Rahimi (2010) and is shown in Table 2. The local models, where the FD scheme is applied are 2D models of attenuation, velocity and density as well (see Table 3 and Figure 3). The geometry of the two profiles in East-West and Southeast-Northwest directions has been retrieved from the literature (JICA 2000) and geological cross sections of GSI (Geology survey of Iran, www.gsi.ir). The parameters and physical properties for local 2D models are obtained from (Hamzehloo et al., 2007).

Table 2. Structural regional reference model of crust and upper mantle used in MS technique.

Layer Thickness (km)	Density (g/cm^3)	$V_{P.}$ (km/s)	$V_{S.}$ (km/s)	$Q_{P.}$	$Q_{S.}$	Depth (km)	Layer
2	2.20	4.80	2.40	264	120	2	1
6	2.66	5.89	3.40	264	120	8	2
11	2.74	6.15	3.56	264	120	19	3
9	2.78	6.29	3.64	264	120	28	4
17	3.10	7.28	4.21	330	150	45	5
20	3.25	7.75	4.48	330	150	65	6
27	3.29	7.78	4.50	330	150	92	7

Table 3. Physical properties of the cross section along the local profiles

Layer Formation	Density (g/cm^3)	$V_{P.}$ (km/s)	$V_{S.}$ (km/s)	$Q_{P.}$	$Q_{S.}$	Layer
Silt and clay	1.7	0.5	0.25	88	40	1
Kahrizak formation (young alluvial Deposits)	1.8	0.8	0.5	88	40	2
Conglomerates with a few lenses of sandstone, siltstone and mudstone	1.9	1.1	0.6	88	40	3

5. RESULTS

The hybrid technique has been applied to generate synthetic signal along the two profiles shown in Figure 2. The six recording stations closer to the profiles have been selected for comparison and test of the reliability of synthetic data. For each station, earthquake ground motion acceleration, velocity and displacement have been generated as time domain parameters and response spectra and response spectral ratio between 2D and 1D signals are calculated as frequency domain parameters. For the finite difference computation along the E-W profile, a grid of 700 by 165 points, along the X and Z axis, respectively, has been used while for SE-NW profile the grid is 2600 (X) by 440 (Z) points. The grid step is 0.01 km for E-W profile and 0.004 km for SE-NW profile. The signals are computed with a cutoff frequency of 10.0 Hz and filtered down to frequencies less than 6 Hz. The waveforms are scaled to the desired magnitude in the frequency domain using the scaling law of Gusev (1983) as reported by Aki (1987). Figure 3 shows the synthetic signals for different distances along the E-W profile for Radial component (the other components are not shown because of page limitation) and Figures 5 gives the same information for SE-NW profile. The distance between the signals shown in the figure is 60 m for the E-W profile and 100 m for the SE-NW profile. Peak values of acceleration (cm/s2), velocity (cm/s) and displacement (cm) are shown, in the figures, close to the pertinent signal. Peak values of synthetic and observed data are given in Tables 4-5. The resulting time domain signals are used for local seismic microzoning, using as zoning criteria the "response spectra ratio" (RSR), i.e., the spectral amplification defined by: RSR= [Sa(2D) / Sa(1D)] where Sa(2D) is the response spectrum (at 5% of damping) for the signals calculated in the laterally varying structure, and Sa(1D) is the one calculated for signals at the top of the counterpart bedrock regional reference structure. Site amplification estimated in terms of response spectra ratios for the two profiles are shown in Figure 4 (E-W) and Figure 6 (SE-NW).

Synthetic and observed signals are shown in Figures 7-12, for the various stations and components. Response spectra of observed and synthetic signals are compared in Figures 13-14. Both reported mechanisms have been tested as input values without any data fitting. Hamzehloo et al. (2009) solution shows better agreement when average RMS error of response spectra for all six stations is calculated between simulated and observed data. The RMS corresponding to Hamzehloo et al. (2009) mechanism is 0.32 while for Farahani and Zare (2010) the value is 0.49.

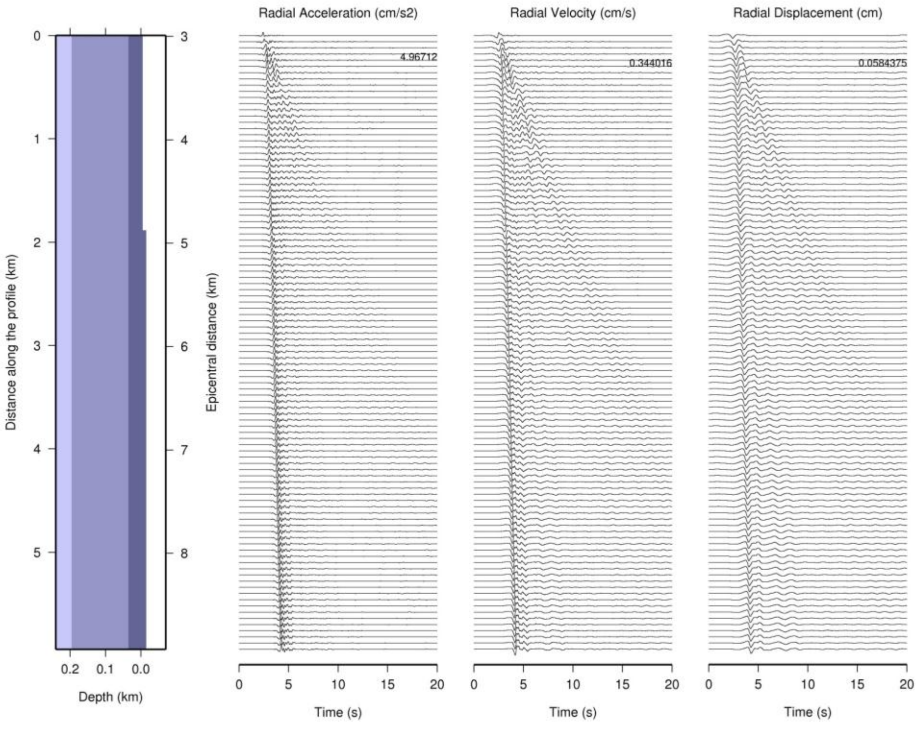

Fig. 3 Acceleration, velocity and displacement time series for the radial component of synthetic signals along the E-W profile. Two different layers (down to 0.2 km) are shown with different colors; topography (height) is increasing slightly from E to W. Distance between sites where signals are computed along the profile surface is 60 m.

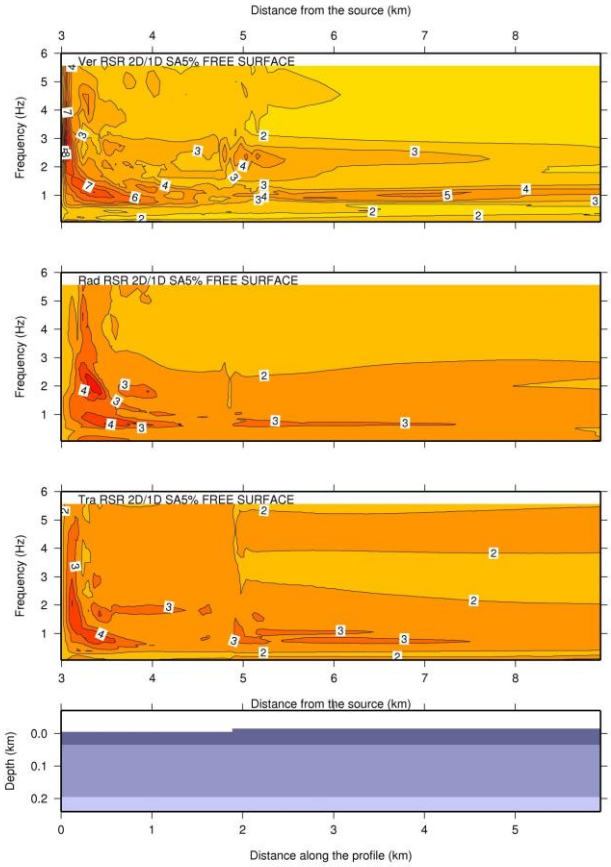

Fig. 4 Spectral ratios (damping 5%) for the vertical, radial and transverse components of synthetic signals along the entire E-W cross section.

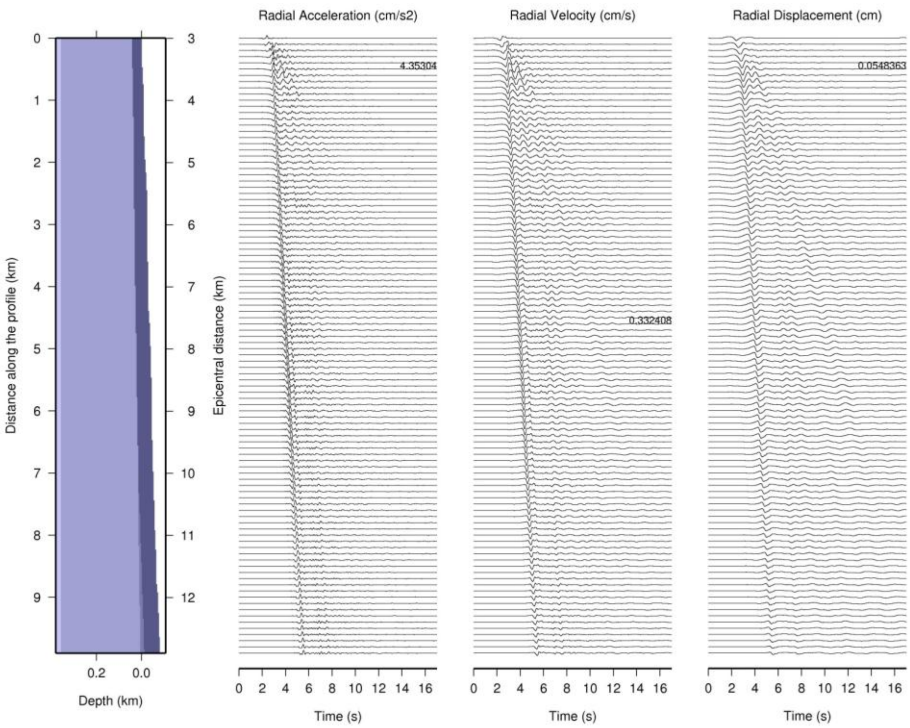

Fig. 5 The same as in Figure 3 for the radial component of synthetic signals for the SE-NW Profile. Three different layers are shown with different colors; topography (height) is increasing from S-E to N-W. Distance between sites where signals are computed along the profile surface is 100 m.

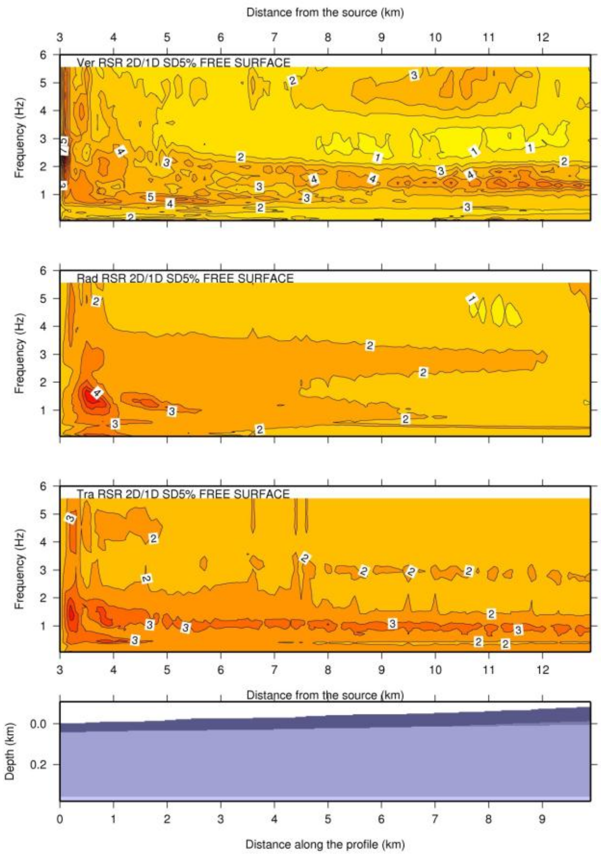

Fig. 6 Spectral ratios (Damping 5%) for the Vertical, Radial and Transverse components of synthetic signals along the entire cross section of SE-NW profile.

Table 4. Comparison of observed and synthetic waveforms: Peak Ground Acceleration (PGA). Station names inside parenthesis have taken from the BHRC standards.

Station	**Radial Comp. PGA (cm/s^2)**		**Transverse Comp. PGA (cm/s^2)**		**Vertical Comp. PGA (cm/s^2)**	
	Obs.	**Syn.**	**Obs.**	**Syn.**	**Obs.**	**Syn.**
St.1 (Shahre Rey)	3.36	3.62	2.95	2.62	2.59	2.78
St.2 (Haram Emam)	4.20	4.33	2.42	3.10	1.08	1.70
St.3 (Haram Emam Borehole)	2.38	1.73	0.62	1.19	0.19	0.85
St.4 (Azad University)	3.52	4.50	3.39	3.17	1.25	1.70
St.5 (Farhangsaraye Bahman)	2.83	2.22	3.69	3.23	1.93	1.45
St.6 (Park Shahr)	1.34	2.00	2.83	2.22	0.78	0.74

Table 5. Comparison of observed and synthetic waveforms: Peak Ground Velocity (PGV). Station names inside parenthesis have taken from the BHRC standards.

Station	**Radial Comp. PGV (cm/s)**		**Transverse Comp. PGV (cm/s)**		**Vertical Comp. PGV (cm/s)**	
	Obs.	**Syn.**	**Obs.**	**Syn.**	**Obs.**	**Syn.**
St.1 (Shahre Rey)	0.13	0.32	0.11	0.20	0.09	0.23
St.2 (Haram Emam)	0.16	0.31	0.11	0.22	0.03	0.10
St.3 (Haram Emam Borehole)	0.09	0.11	0.02	0.06	0.01	0.04
St.4 (Azad University)	0.13	0.30	0.15	0.22	0.05	0.11
St.5 (Farhangsaraye Bahman)	0.13	0.25	0.15	0.20	0.07	0.08
St.6 (Park Shahr)	0.05	0.10	0.13	0.14	0.03	0.04

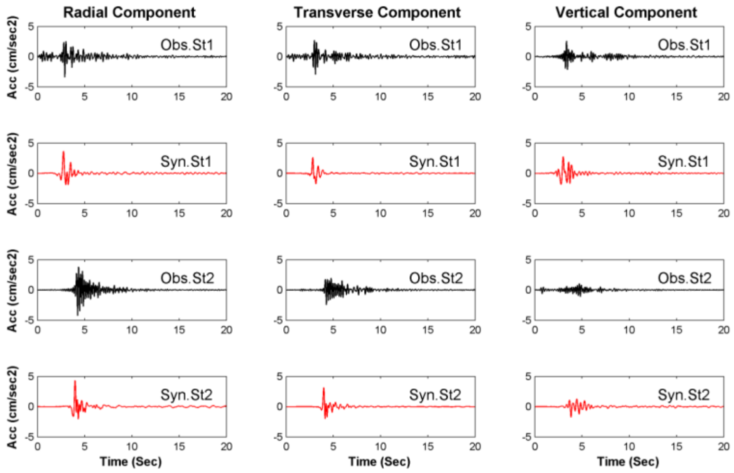

Fig. 7 Observed (black) and synthetic (red) waveforms of acceleration (cm/s^2) for stations 1-2.

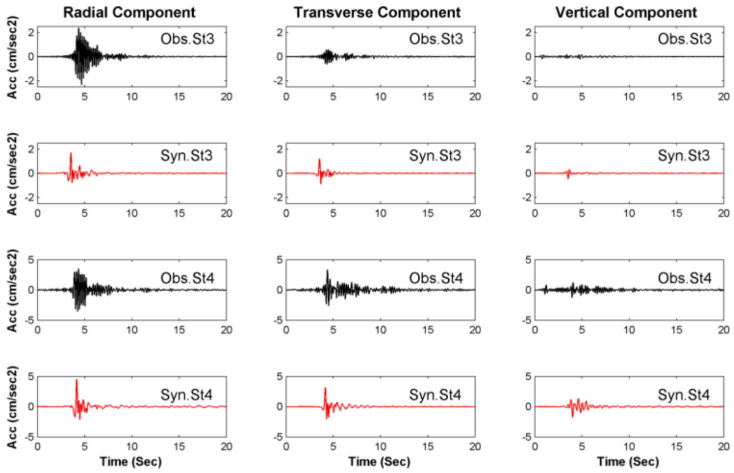

Fig. 8 Observed (black) and synthetic (red) waveforms of acceleration (cm/s^2) for stations 3-4.

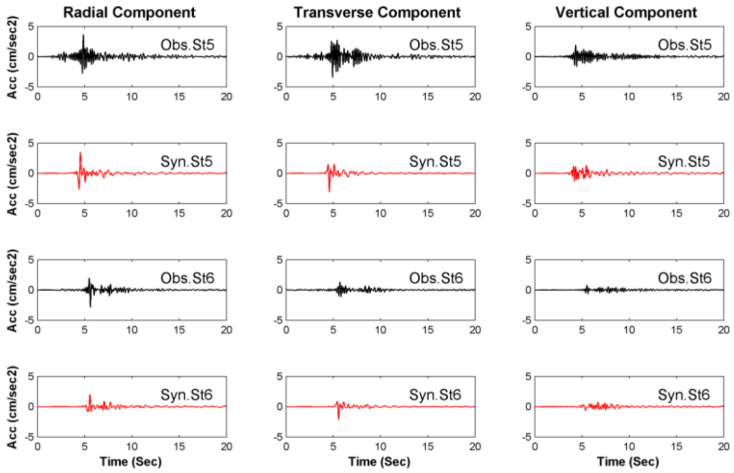

Fig. 9 Observed (black) and synthetic (red) waveforms of acceleration (cm/s^2) for stations 5-6.

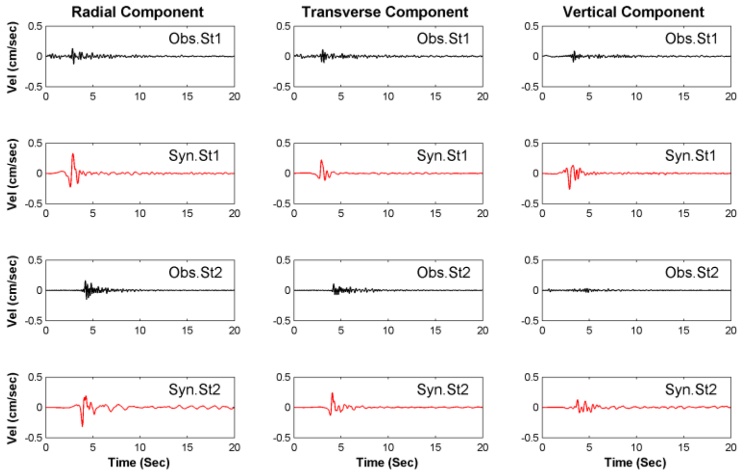

Fig. 10 Observed (black) and synthetic (red) waveforms of velocity (cm/s) for stations 1-2.

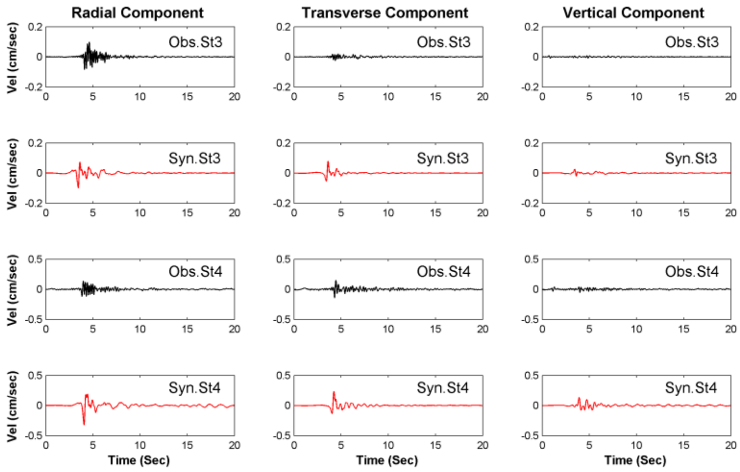

Fig. 11 Observed (black) and synthetic (red) waveforms of velocity (cm/s) for stations 3-4.

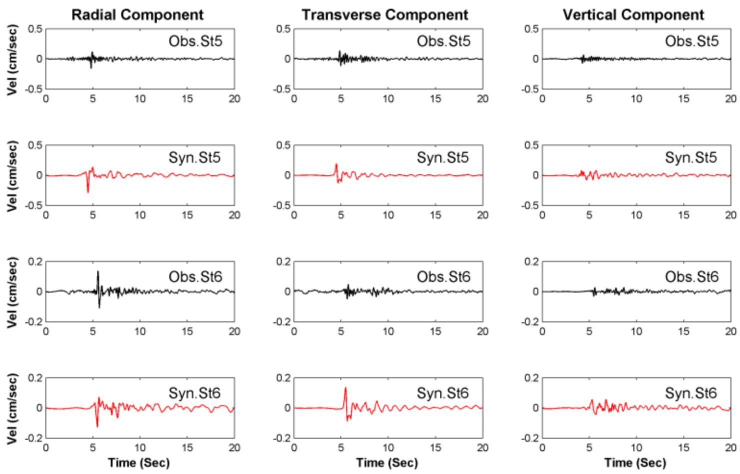

Fig. 12 Observed (black) and synthetic (red) waveforms of velocity (cm/s) for stations 5-6.

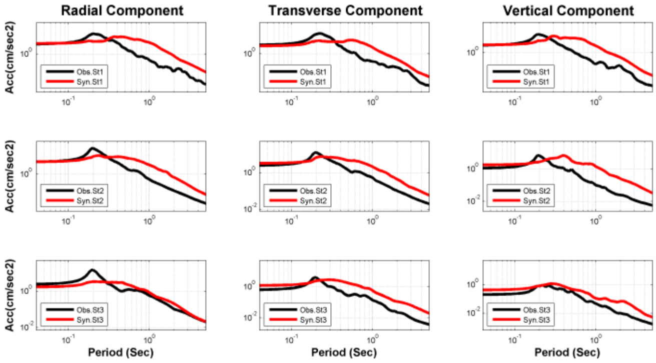

Fig. 13 Observed (black) and synthetic (red) response spectra (5% damping) for stations 1-3.

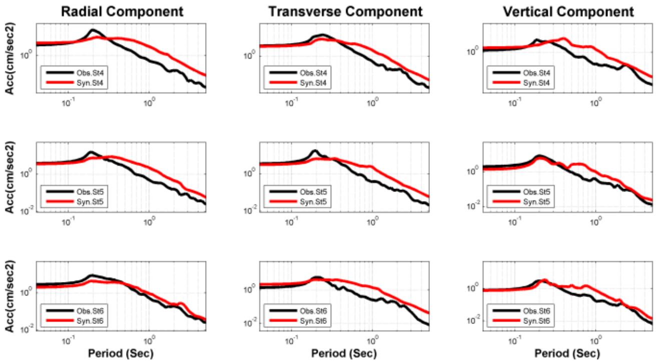

Fig. 14 Observed (black) and synthetic (red) response spectra (5% damping) for stations 4-6.

7. DISCUSSION

Ground motion simulation of 2009, Mw=4 Earthquake southeastern of Tehran metropolitan has been performed taking simultaneously into account the source, path and site effects. The comparison between observed and synthetized signals shows good agreement on account of the fact that no data fitting is made, but only literature data are used as input. In the time domain, a quite good agreement is seen between observed and simulated PGA, PGV (Tabs. 4-5). The observed differences can be easily related to the ambiguity and uncertainties of some basic information (local structure geometry, mechanical and attenuation parameters). Results show that in spite of the absence of some localized information about lateral variations of attenuation and velocity parameters for subsurface layers, the known values of the structural parameters have allowed us to capture most of the interesting features of the ground motion. The estimation of local site effect in term of response spectra ratios (figs. 4 and 6), in spite of the very simple geometry of the subsurface layers, shows the relevant effect the Quaternary sediments. The amplification level reaches 6 in some areas, well in agreement with the results obtained by Haghshenas (2005) and Hamzehloo (2007). Lots of simulation methods only provide limited band of low or high frequency parts of signal. The broad-band (0.1-5.4 Hz) synthetic signals, that take into account source characteristics, path and local (geological and geotechnical) conditions, have been produced at a very low cost/benefit ratio.

8. CONCLUSION

Regarding the physics of earthquake beside the effect of earth nature on the waveforms propagated from the source enable us to construct signals which are reliable data for area with no remarkable instrumental events we need for building codes and other structures. A database of synthetic accelerograms represents a scientifically and economically valid tool for seismic microzonation. The calculated accelerograms, with broad-band frequency content, can in fact be used for the determination of any parameter of engineering interest (in relevant frequency band used here) that describes the ground motion and the site response for different geological settings.

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