Investigating the role of source mechanism, surface topography, and attenuation on the observed PGA pattern in May 28, 2004, Mw 6.2 Baladeh earthquake (Iran)

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Abstract In this paper, we use seismic waveform simulation to investigate the influence of source mechanism complexity, surface topography, and quality factor on the observed peak ground motions in May 28, 2004, moment magnitude (Mw) 6.2 Baladeh earthquake. The observed peak ground acceleration (PGA) pattern in this event, which is the biggest earthquake to hit the Central Alborz Mountains of Iran in modern instrumental era, is irregular in some respects. First, the observed PGA contours are elongated toward north-west and, second, the maximum observed PGA value of 1049 cm/s² on the horizontal component of Hasan Keyf station 50 km away from the epicenter is quite high and irregular for an earthquake of this magnitude, at such long distance. In this study, we employ the spectral element method, implemented in SPECFEM3D software package to simulate the 3D wave propagation from several source models in the area. Our results suggest directivity effect is the main cause of the anomalous observations in this earthquake and could account for the elongation of PGA contours and also the anomalous maximum PGA value observed at Hasan Keyf strong motion station. We show that the surface topography has minor effect on the observed peak ground acceleration and the resulting PGA maps. Also by finding the bounds of seismic quality factor effect on the peak ground acceleration values, we show that this factor could not account for the elongation of iso-acceleration contours in the north-west direction.

Keywords Seismic wave simulation · Ground-motion prediction · Spectral element method · Baladeh earthquake

1 Introduction

The Mw 6.2 (NEIC) earthquake that hit the Central Alborz Mountains of northern Iran on May 28, 2004 is the largest and by far the best recorded earthquake in modern instrumental era in the region. The epicenter of Baladeh earthquake is located at 36.257° N, 51.565° E. at a depth of 27 km (Engdahl et al. 2006). This moderate sized earthquake caused widespread damage in its surrounding area and according to officials, had 37 casualties. It was felt strongly in the
capital Tehran at epicentral distance of 70 km and caused much panic in this metropolitan area with day time population of 12 million people. Baladeh earthquake is the best recorded earthquake in the Central Alborz region and in addition to local seismic networks, it is recorded by 168 strong motion stations. It provides a wealth of information and unique opportunity to study the active tectonics of the southern margin of the South Caspian Basin.

Gheitanchi (2005), using far-field data, studied the source mechanism of this event and found three subevents for this earthquake and a unilateral westward propagating rupture along the fault. Tatar et al. (2007) formed a picture of the co-seismic faulting in this earthquake and showed that Khazar Fault (Fig. 1) is responsible for this event. They also found the extent of the fault plane using the distribution of aftershocks recorded by a temporary seismic network.

Some observations on the recorded accelerograms make this earthquake interesting for further studies. The first observations is the anomalously high horizontal PGA at Hasan Keyf station (1049 cm/s²) at epicentral distance of 49 km which is higher than the observed values at closer stations. This value is too high for a moderate size earthquake, at such a long distance. At this distance range, the ground motion prediction equation of Zare et al. (1999) predicts a value of 116 cm/s² for horizontal PGA of an earthquake of this magnitude. Table 1 lists the maximum acceleration values recorded at different components of some of stations close to the epicenter of this event. We can see that station Hasan Keyf at epicentral distance of 49 km has recorded much higher values than station Karaj Dam at about the same epicentral distance (53 km). We should note that the Building and Housing Research Center (BHRC) which operates the strong motion network in Iran routinely checks the stations after anomalous recordings, so we could dismiss defective recording as the cause of this observation.

The second interesting aspect of this earthquake is the pattern observed in the peak ground acceleration map compiled from 168 recorded accelerograms (Fig. 2). This PGA map shows stretched contour lines toward west and north-west of the epicenter. Stations much farther from the epicenter in the north-west direction have recorded the same acceleration as stations closer to the epicenter in the east and south east of the epicenter. These observations were the main motivation for us to investigate the cause of these anomalous behaviors, through waveform simulations.

In recent years, numerical simulations have been increasingly used to investigate the complicated nature of the seismic wave propagation (e.g., Olsen et al. 1995; Graves 1996; Olsen 2000; Komatitsch et al. 2004). In this study, we use the SPECFEM3D software package (Komatitsch et al. 2004) to simulate 3D seismic wave propagation, in order to investigate the role of directivity, surface topography, and the regional quality factor, on the observed strong motions in Baladeh earthquake. SPECFEM3D software package performs three-dimensional simulation of seismic wave propagation based on the spectral element method (SEM). SEM is a numerical method for solving partial differential equations and is based upon a weak formulation of the equations of motion (Komatitsch and Tromp 1999). It is similar to a high order finite-element method with high degree polynomial basis functions. Patera (1984) first used SEM in computational fluid dynamics and since then, it has gained interest for problems related to 2D and 3D seismic wave propagation. This method is likely the second most used numerical method to model seismic wave propagation in complex media, after the finite-difference method (Komatitsch and Erlebacher 2010). The main advantage of SEM over other numerical techniques is its ability to incorporate free-surface topography (e.g., Lee et al. 2008, 2009). The maximum resolved frequency in the simulations, depends on the mesh size and also the shear wave velocity in the region of interest, while the lower frequency of the simulations is not limited and very low frequencies can be modeled accurately. Komatitsch and Villette (1998) and Komatitsch and Tromp (1999) provide a detailed introduction to the SEM for 3D seismic wave propagation. The method has been recently applied in many areas of seismology (e.g., Komatitsch et al. 2002a, b, 2004; Tromp et al. 2008; Peter et al. 2011).

In general, three parameters affect the strong shaking resulting from an earthquake at a given point, i.e., the source mechanism, the propagation media, and the local site effects. One of the main components of the source mechanism which has strong effect on the shaking pattern is earthquake directivity. Earthquake directivity usually happens when a rupture propagates unilaterally along a fault, and as a result of constructive interference of seismic waves, higher amplitudes
and shorter source durations in the direction of rupture and lower amplitudes and longer source durations in the opposite direction, are observed. This effect focuses the seismic energy and causes stronger shaking and more damage in the direction of rupture propagation. The seismic quality factor is one of the main properties of the propagation media that alters the ground shaking amplitudes. It is the term that quantifies the effect of anelastic attenuation, on the seismic waves, as they propagate through the media. This factor is inversely proportional to energy loss and a higher value for quality factor would mean less energy loss and an increase of the observed amplitudes at an observation point. Non uniform quality factor in a region would cause a non uniform shaking pattern in that area. The topography effect is one of the main components of the local site effects. Surface topography usually increases the amplitude of seismic waves at the mountain tops and decreases them in the valleys (Hartzell et al. 1994). This effect could lead to observation of anomalously large amplitudes from earthquakes at stations located in mountainous areas.

In this study, we investigate the role of source directivity, the regional quality factor, and the surface topography, on the observed strong shaking in the region, from Baladeh earthquake. We perform several seismic waveform simulations and try to isolate

![Image](image.jpg)

**Fig. 1** The Central Alborz region. The red star shows the location of the Baladeh earthquake (Engdahl et al. 2006). The focal mechanism is from Global CMT catalog. The black solid lines show the major faults in the region.

<table>
<thead>
<tr>
<th>Station</th>
<th>Epicentral distance (km)</th>
<th>Horizontal PGA (cm/s²)</th>
<th>Vertical PGA (cm/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hasan Keyf</td>
<td>49</td>
<td>1049</td>
<td>415</td>
</tr>
<tr>
<td>Moulem Kelayeh</td>
<td>102</td>
<td>402</td>
<td>79</td>
</tr>
<tr>
<td>Poul</td>
<td>19</td>
<td>334</td>
<td>253</td>
</tr>
<tr>
<td>Karaj Dam</td>
<td>53</td>
<td>192</td>
<td>64</td>
</tr>
<tr>
<td>Gazanak</td>
<td>72</td>
<td>32</td>
<td>18</td>
</tr>
</tbody>
</table>

The location of stations are shown in Fig. 2.
and find the role of each of these parameters on the observations through simulations.

2 Tectonic and geological setting

The Alborz Mountains form the central part of mountains in northern Iran, which extend between the Talesh Mountains in the north-west and the Koppe Dagh Mountains in the north-east. The Central Alborz is an active orogenic belt roughly 600 km long and 100 km across (Fig. 1).

These mountains have an average elevation of nearly 3000 m and many of the highest points in Iran including Damavand volcano (the highest elevation in Iran with an altitude of 5678 m) are located inside them. The mean elevation in Alborz drops sharply from 3000 m in the inner belt to −28 m at the Caspian shoreline to the north. The topographic contrast is less pronounced to the south where the connection with the lowlands of the Central Iranian plateau is progressive.

The Alborz Mountains result from different tectonic events that occurred during two major orogenic cycles (Sengor et al. 1993). First, the end of Triassic period and collision of the Iranian micro plate with the Eurasia plate and, second, the post Neo-Tethys, intra-plate deformation related to the convergence of the Arabian and the Eurasian plates (Sengor et al. 1993; Zanchi et al. 2006). Seismological studies suggest that the range is being compressed and consequently uplifted against the relatively stable block underlying the southern Caspian Sea. This block, in turn, may represent a trapped remnant of Tethyan oceanic crust (Berberian 1983).

Many earthquakes of magnitude 6.0 and higher have occurred in the history of the Central Alborz region (Fig. 3). The historical earthquake of magnitude 7.6 that hit Taleghan region in 958 A.D.

![Fig. 2](image_url) The horizontal PGA map from the strong motion stations in the region. The color-map shows the horizontal PGA, interpolated in the Central Alborz region in unit of cm/s², overlaid on top of topography. The black triangles show the location of the strong motion stations. The red star shows the epicenter of the Baladeh earthquake. The white region is the location of capital Tehran.
is an example of destructive earthquakes in this region. The seismicity, structure, and evolution of this region are of particular interest because of the high seismic hazard they pose to the capital Tehran. With a population of over 12 million people, Tehran is located at the southern slopes of the Alborz Mountains.

Using global positioning system (GPS) data, Vernant et al. (2004) shows that the Central Alborz accommodates roughly 52 mm/year of shortening and 42 mm/year of left lateral strike-slip motion which is 25 % of the whole Arabian-Eurasian convergence in Iran. Structural and seismological data for the Alborz region show that the complex systems of strike-slip and thrust faults accommodate a fundamental part of this NNE-SSW oriented shortening. The oblique left-lateral motion across Alborz is partitioned into separate strike-slip and thrust faults almost parallel to the range (Jackson et al. 2002). Thrust faults in the Alborz Mountains are primarily dipping north in the southern side and dipping south in the northern side of the range.

The major faults in the Central Alborz Mountains include Khazar, North Alborz, Mosha, and Taleghan faults (Fig. 1) (Berberian 1976). The Mosha Fault is one of the main faults of southern part of the mountains. It is a left lateral strike-slip fault dipping toward north with the dip angle varying between 35 to 70° along its length. It extends from the edge of the mountains in the west to the eastern part

![Seismicity map of the Central Alborz region. The focal mechanisms are plotted based on the Harvard CMT catalog. The historical earthquakes are based on Ambraseys and Melville (1982) and the instrumental earthquakes are from the online bulletin of International Seismological Centre (ISC 2012)](image_url)
of the range in the east. The Taleghan Fault is a reverse fault with east-west trend dipping toward south with a length of about 70 km. This fault is the main candidate for the devastating historical earthquakes that happened at 958 A.D. (Ambraseys and Melville 1982) in Central Alborz Mountains. The North Alborz Fault is a steep, reverse fault with the cumulative displacement of more than 2 km resulting from the past earthquakes, along the fault (Berberian 1976). This fault has a total length of about 400 km and borders the northern part of Alborz Mountains in the south-west of Caspian Sea. Khazar Fault is a Quaternary reverse fault with length of 600 km (Berberian 1983) that lies between the northern flank of Alborz Mountains and the southern side of the South Caspian Basin. This fault is shown to be responsible for Baladeh earthquake (Tatar et al. 2007).

3 Data and method

The accelerograms we use to plot the PGA map are from the strong motion network of Iran, operated by BHRC. This institute has more than 1100 digital strong motion stations throughout the country. Baladeh earthquake is one of the best recorded earthquakes in this network and was recorded by 168 stations. The stations of this network are mostly equipped with SSA-2 and CMG-STD digital accelerometers. In Fig. 2, the triangles show the location of BHRC strong motion stations in the region.

We use the earth model developed by Abbasi et al. (2010), as the background 1D velocity model in the simulations (Table 2). In our model, the upper-mantle P-wave velocity is set to 8.1 km/s and the S-wave velocity is set to 4.5 km/s based on the Preliminary Reference Earth Model (PREM) (Dziewonski and Anderson 1981b), and the depth of Moho is set to 58 km (Abbasi et al. 2010). Throughout the entire model, density is defined based upon the PREM earth model. The quality factor (Q). Q(f) = 267(0.71) is based on the attenuation relationship found by Naghavi et al. (2012), for the Central Alborz region. The frequency band for Q-model used in the calculations is 0.03 to 2.0 Hz and the reference frequency for Q used in the code is 1 Hz. We incorporate the surface topography based on SRTM90 (Shuttle Radar Topography Mission) digital elevation model (Jarvis et al. 2008), which is freely available on the Internet. Since we did not include the soil layer in our model, the minimum shear wave velocity in the model is set to 3.1 km/s in accordance with the 1D velocity model used for simulations (see Table 2). Because the size of the meshes in the surface of our model (1000 m) is bigger than the spatial sampling of the SRTM90 elevation model (90 m), we did not need to use a more accurate digital elevation data.

For the point source simulation, we use the focal parameters reported by Global CMT catalog (Dziewonski et al. 1981a; Ekstrom et al. 2012). Since according to Tatar et al. (2007), Khazar fault is responsible for this earthquake, the nodal plane dipping SW is the fault plane with a strike of 119°, a dip of 24°, and a rake of 72°. In the extended fault simulations, we assume the fault plane to have length of 30 km and lie between depths of 14 to 28 km. We choose this depth range based on Tatar et al. (2007), who attribute the earthquake to Khazar fault with no surface rupture and find the extent of the coseismic fault plane. We choose the starting point of the rupture to lie at the focal point of the earthquake, at the south-east corner of the fault plane and assume the rupture to propagate radially to other points of the fault plane, in a mainly westward direction as suggested by Gheitanchi (2005). Figure 4 shows the extent of the fault plane used in this study. In the top panel, the black rectangle shows the surface projection of the fault plane and the bottom panel depicts the cross section of the fault plane.

In order to investigate the cause of anomalous strong motion observations at Baladeh earthquake, we simulate the wave propagation for a number of earthquake scenarios, using the SPECFEM3D software package (Komatitsch et al. 2004). In our simulations, we try to isolate the effect of different phenomena and evaluate their role in the observations, separately.

First, we investigate the role of directivity effect, by comparing the results of extended fault simulations with different rupture velocities. Since we do not have the details of slip distribution in this earthquake,

<table>
<thead>
<tr>
<th>Depth of layer top (km)</th>
<th>P-velocity (km/s)</th>
<th>S-velocity (km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>5.4</td>
<td>3.1</td>
</tr>
<tr>
<td>3.0</td>
<td>5.8</td>
<td>3.3</td>
</tr>
<tr>
<td>7.0</td>
<td>6.1</td>
<td>3.5</td>
</tr>
<tr>
<td>16.0</td>
<td>6.25</td>
<td>3.6</td>
</tr>
<tr>
<td>24.0</td>
<td>6.4</td>
<td>3.7</td>
</tr>
</tbody>
</table>
for the extended fault simulations, we use a simple slip distribution with the slip being uniform on the fault plane and assume the rupture to propagate radially from the hypocenter to other points on the fault plane. To compare the results of two simulations, we plot the map of their residuals (log(observed PGA)-log(simulated PGA)).

To investigate the role of surface topography on the observations, we compare the results of simulations with and without including surface topography in the meshes, using the extended source model with rupture velocity of 0.92 times the shear wave velocity. We finally compare the simulation results with and without including attenuation, to find the bounds of effect the seismic quality factor could have on the peak ground acceleration and investigate the role of regional quality factor on the observed PGA pattern.

In spectral element method, the first step is to create high-quality meshes for the model area. In this study, we use the internal mesh generation program of SPECFEM3D package (Meshfem3d) to generate the meshes. We choose the simulation area to be 35.6° N
to 37° N and from 50° E to 52.5° E, thus our model extent is about 250 x 180 km horizontally, and from 5.6 to −60.0 km (few kilometers below Moho) vertically. We choose the simulation area based on our computational limits and try to cover most of the north-central Alborz to reproduce the observed PGA map using synthetic seismograms.

We divide the fault plane to 3 x 3 km segments and since we do not have the details of slip distribution and asperities, we assume the slip distribution to be homogeneous on the fault plane, i.e., same value on all the fault segments. We further assume the rupture velocity to be constant for each earthquake scenario and set the source time function to a Gaussian with half duration of 0.3 s, for each of the fault segments.

In the simulations, we decompose the study area into 80 mesh slices (80 processors), for parallel computing. The average distance between the Gauss-Lobatto-Legendre integration points at the surface of the model is about 180 m. This is small enough to have the highest resolved frequency of approximately 2.0 Hz. The total number of spectral elements in the model is 1.8 million and the number of Gauss-Lobatto-Legendre integration points is 117.33 million, respectively. The total duration of the simulation is 60 s (6000 time steps with the time step of 0.01 s).

4 Simulation results

To investigate the directivity effect on the observed PGA pattern, we conduct a number of simulations with different source models. The aim of the first calculation is to show the deviation of observations from the results of a point source simulation with the source located at the epicenter of the Baladeh earthquake. Figure 5a, b shows the observed PGA map and the PGA map resulting from point source simulation, respectively. The observed PGA map (Fig. 5a), is a color map of the peak ground acceleration values of the norm of the three component records at seismic stations, interpolated in the model area and overlaid on top of topography. Figure 5b shows the PGA map resulting from the point source simulation. We plot this figure, using the PGA values of the synthetic accelerograms, at the locations of the observation points (BHRC stations, triangles in Fig. 5).

In Fig. 6, the residual map of the observed PGA values and the simulation results (log(absolute PGA)−log(simulated PGA)) is plotted. Fig. 6a, shows the residual map of the observed PGA values and the results of point source simulation. In the resulting color map, positive and negative values show amplification and de-amplification, respectively.

Next, by performing several extended fault simulations, we try to determine the role of source mechanism on the observed PGA pattern. Constructive interference of seismic waves along the fault is the cause of directivity and it becomes stronger as the rupture velocity becomes closer to the S-wave velocity (Lay and Wallace 1995). Several earthquake scenarios, with the rupture starting at the southeast of the fault plane and spreading toward north-west, with different rupture velocities, are simulated to inspect the role of directivity effect. We choose the fault plane for these earthquake scenarios to lie on the Khazar Fault and increase the rupture velocity from 0.70 to 0.98 times the shear wave velocity. Figure 5c, d shows the PGA maps resulting from the simulations with the rupture velocity of 0.70 and 0.92 times the shear wave velocity respectively. Figure 6b shows residual map of results of simulations with rupture velocities of 0.70 and 0.92 times the shear wave velocity and Fig. 6c shows the residual map of the observed PGA values and the simulation results with rupture velocity of 0.92 times the shear wave velocity.

In Fig. 7 the root mean square (RMS) of the relative difference between the observed PGA-map and the map resulting from extended source simulations, with several rupture velocities, is drawn versus the ratio of the rupture velocity to the shear wave velocity. The relative difference is quantified as the peak acceleration obtained from observations, minus the simulation results, divided by their average and multiplied by 100, to find the percentage.

Figure 8 shows the vertical component of the observed and synthetic acceleration time histories for three different simulations at the location of Hasan Keyf station. In this figure from top to bottom, the waveforms represent the observation, the synthetic seismogram with rupture velocity of 0.92 times the shear wave velocity, the synthetic seismogram with rupture velocity of 0.70 times the shear wave velocity, and the synthetic seismogram from point source.
Fig. 5 Comparison of observed PGA map and results of point source and extended source simulations with different rupture velocities. 

**a** Observed PGA map compiled from strong motion observations in the model area. 
**b** Resulting PGA-map from point source simulation with focal mechanism parameters from simulation. All the seismograms in this figure are band-pass filtered between 0.1 and 1.0 Hz. Figure 9 shows the vertical component of the observed and synthetic seismograms, for the extended fault simulation with rupture velocity of 0.92 times the shear wave velocity, for stations listed in Table 1. The amplitudes in this figure are normalized and do not represent the true amplitudes observed.

Figure 10 shows the residuals of simulation results with and without including the surface topography in the model. In this figure, the residuals of PGA values computed at the locations of BHRC stations are plotted on the map.

One might suggest higher values for quality factor in the west and lower values in the east of the Alborz Mountains could explain the elongation of iso-acceleration contours in the west and their shortening in the east. To find the upper bound of attenuation effect on the observed amplitudes in the north-west direction, we perform two simulations, one with and
the other without attenuation. Figure 11 shows the residual of the results of these two simulations.

5 Discussion

We have investigated the role of source mechanism, surface topography, and seismic quality factor on the PGA pattern observed in Baladeh earthquake by performing several simulations using spectral element method. Comparison of the observed PGA map (Fig. 5a) with the results of point source simulation (Fig. 5b) shows the ground shaking observed in this event is very different from the results of a point source simulation with the source, located at the hypocenter of the Baladeh earthquake. As shown in Fig. 5b, point source simulation predicts the maximum PGA at the closest station and also a shaking pattern almost symmetrical around the epicenter of the earthquake, which are both different from the observations.
from Baladeh earthquake. According to Fig. 6a, the amplitudes recorded at points in the north-west of earthquake epicenter, shown by red star, have much higher amplitudes relative to the simulation results. Also the points at the epicenter and the east of epicenter show lower amplitudes than the results of point source simulation.

By performing several extended fault simulations with the fault plane located on the Khazar Fault, we find the role of source mechanism on the observed PGA pattern. In the earthquake scenario with rupture velocity of 0.70 times the shear wave velocity shown in Fig. 5c, we observe elongation of iso-acceleration contours toward north-west to some extent, relative to the results of point source simulation. Since the fault direction is also NW-SE, one could relate this change to the orientation of the fault plane, but it could also be the result of the uni-directional rupture. To determine the effect of changing the rupture velocity, we perform several extended fault simulations, increasing the rupture velocity at each step. Studies in the field of fracture mechanics for a planar fault show that the shear rupture accelerates quickly to a higher bound velocity. This higher bound velocity is either the Rayleigh wave velocity (92 % of shear wave velocity), for ruptures in which direction of slip is parallel to rupture propagation, or the shear wave velocity, for ruptures with direction of slip perpendicular to the rupture propagation direction (Freund 1990). For our simulations, we assume the rupture velocity to be in the range of 0.70 to 0.98 times the shear wave velocity. Since the sense of slip is not known in this event, we assume the upper bound to be the shear wave velocity.

Figure 7 shows the RMS of the relative difference between the observed PGA map and the PGA-map derived from the synthetics versus the ratio of the rupture velocity to the shear wave velocity. As we can see in this figure, a minimum exists at the location of rupture velocity of 0.92 times the shear wave velocity. This means until this rupture velocity, the further we increase the velocity, the difference between the observations and the simulation results decreases, and if we further increase the rupture velocity, the difference increases. This suggests the maximum correlation between the simulations and the observations is at the simulation with this rupture velocity. The method we use does not have the resolution to determine the exact value for the rupture velocity but here we merely mean to show the trend in increasing the correlation between the simulation results and the observations, as the rupture velocity increases to about 90 % of the shear wave velocity. This velocity is in general agreement with average rupture velocities (range of 0.7 to 0.9 times the shear wave velocity).

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Fig. 7 RMS of the relative difference versus rupture velocity. The vertical axis is the RMS of the relative difference between the observed PGA-map and the results of extended source simulations with different rupture velocities. The horizontal axis is the ratio of the rupture velocity to the shear wave velocity.
found in different near source and teleseismic studies (Aki 1968; Bouchon 1978; Olson and Apsel 1982; Hartzell and Heaton 1986; Beroza 1991; Wald et al. 1996).

Comparison of the PGA-maps derived from the synthetics with rupture velocity of 0.70 and 0.92 times the shear wave velocity (Fig. 5c, d) shows that with increasing the rupture velocity, the maximum peak ground acceleration point moves to the location of Hasan Keyf seismic station, in agreement with the observations. The residual map of these two simulations (Fig. 6b) shows that as a result of increasing the rupture velocity, the ground shaking is amplified in the north-west direction and de-amplified in the south-east direction. These figures show that the change in rupture velocity makes a big difference in the resulting PGA map.

Comparison of observation versus synthetics for different rupture scenarios at Hasan Keyf station (Fig. 8) shows a more acceptable match between the observed seismogram and the synthetic seismogram, simulated with extended source and rupture velocity of 0.92 times the shear wave velocity. The synthetics from point source simulation and the simulation with rupture velocity of 0.70 times the shear wave velocity show less similarity with the observations. Looking at the waveforms of stations listed in Table 1 (Fig. 9), we observe that stations in the west of the epicenter show waveforms with higher amplitude and shorter duration of shaking. In other directions, we observe lower amplitude and longer duration which could further imply existence of directivity effect in this event.

Although the details of slip distribution and rupture propagation are not included in the simulations and only a simple slip distribution with uniform slip on the fault plane is used and also the rupture is assumed to be very simple, our simulations capture the main properties of the observed pattern in the PGA map. The residual of the results of extended fault simulation with rupture velocity of 0.92 times the shear wave velocity and the observations (Fig. 6c) shows minimal difference between simulations and the observations. In this figure, we can see that the results of this simulation reproduces what happened in the observed data in a satisfactory manner.

The fact that our simulation results could capture the main anomalous behaviors observed in Baladeh

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**Fig. 8** Observation versus synthetics at station Hasan Keyf. a The observed seismogram. b The synthetic seismogram with rupture velocity of 0.92 times the shear wave velocity. c The synthetic seismogram with rupture velocity of 0.70 times the shear wave velocity. d The point source simulation. The vertical axis shows the ground acceleration in units of cm/s². All the seismograms are band-pass filtered between 0.1 to 1.0 Hz.
earthquake further proves the findings of Gheitanchi (2005) that rupture is unilateral and propagates westward, and Tatar et al. (2007) that Khazar fault is responsible for this event. Our results predict the location of the maximum peak ground acceleration and reproduces the shaking pattern in the region to a good extent. We conclude that the directivity effect has played a big role in this earthquake, since in a simulation with unilateral rupture, increasing the rupture velocity (stronger directivity effect) results in a PGA pattern similar to the observations and our simulations capture the main anomalous behaviors observed in this earthquake. This is consistent with the observation of PGA distributions amplified in the direction of rupture propagation, in many past earthquakes with strong directivity effect. Landers (1992), Northridge (1994), and Kobe (1995) earthquakes are examples of such events.

To investigate the influence of surface topography on the observed PGA pattern, we isolate and find
Fig. 11 The residual map of the PGA values from results of simulations with and without including the attenuation. Both simulations are extended fault simulations with rupture velocity of 0.92 times the shear wave velocity.

its role on the simulations and the resulting PGA pattern. The residual of the simulated PGA values, computed using the synthetic seismograms simulated at the location of BHRC stations, shows that the role of topography effect is minimal on the observed PGA map. Actually, if we take the topography into account, it reduces the difference of the simulations with observations in the northwest of the map (Fig. 6c) to some extent, but the topography effect could in general be dismissed as the main cause of the observed PGA pattern in this earthquake. The topography effect is highly dependent on frequency content of the incoming waves (Geli et al. 1988; Bouchon and Barker 1996). It should be noted that in this study, all simulations are up to 2.0 Hz and in this frequency band, we did not observe strong topography effect at the location of the seismic stations in the region. With better computational resources, it is possible to perform the simulations at higher frequencies and a different pattern for the topography effect might be observed.

To check if having a higher value for quality factor in the west of Alborz Mountains could result in the elongation of contours toward north-west direction, we perform two simulations one with quality factor value from a regional Q study (Naghavi et al. 2012) and the other with no attenuation. With the adopted uniform Q-model in this study, reproducing the complex pattern of observed PGA values is not expected and by performing this simulation, we do not mean to reproduce the observed PGA pattern. We merely mean to show the higher bound of effect the quality factor could have on the ground motions at this distance range. The residual of the results of the two simulations (Fig. 11) shows that attenuation has minor effect on the observed amplitudes. As we can see in this figure, as the distance with the epicenter increases, the effect of attenuation also increases. However, the highest value for this effect is about 0.4 in the residual map, and this value is much lower than the total observed residual in the northwest direction. Since we perform the simulation for the extreme of having no attenuation, even if the quality factor in the west of the Alborz Mountains was higher than the value we used in this study, the resulting amplitudes would be still lower than the simulation values with no attenuation.

By performing this experiment, we find the bounds of effect of seismic quality factor in the region, on the observed amplitudes in the north-west direction. Since we observe small changes between simulations with and without attenuation, we conclude that although a non uniform Q model could have some effect on elongation of contours in one direction, it is not the main factor and has minor effect on the observations in this earthquake. A higher value of quality factor relative to the one we used in our simulations could reduce the residuals observed at Fig. 6c to some extent, especially in the north-west portion of the map and reduce the misfit of simulations with the observations.

Since the properties of near surface soil layers and details of near surface velocity profile are not known
and are not included in the simulations, we are not able to find the local site amplification due to sub
surface low velocity layers in the stations and particularly the probable basin effect in station Hasan Keyf.
In future works, the amplification from low velocity layers should be considered, to better understand the
nature of shaking in the area and specially in Hasan Keyf station as an anomalous point in the observed
shaking pattern.

6 Conclusions

In this study, by performing seismic waveform simulations for different earthquake scenarios, using SEM
method, we have shown that the directivity effect has the strongest role on the anomalies observed in the

The result of our simulation using an extended source model on the Khazar Fault, with the rupture starting at the focal point in the south-east of the fault plane and propagating toward north-west, with a rupture velocity of 0.92 times the shear wave velocity, successfully predicts both the observation of maximum PGA at Hasan Keyf station (the location of highest observed amplitude) and also the elongation of the iso-acceleration contours toward north-west of the epicenter.

Although the details of rupture propagation and slip distribution are not included in the simulations, the results of our simulations using a simple model for both a good extent capture the main properties of the pattern observed in the PGA map and show that with increasing the rupture velocity, the residual of the observations and the simulation results decrease.

Our simulations also show that topography has minor effect on the observed amplitudes and the observed PGA pattern.

By comparing the results of simulations with and without attenuation, we observe that attenuation has
minor effect compared to other effects, and we conclude that a higher value of Q in the north-west could
not explain the high amplitude values observed in the north-west of the epicenter.

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All of the plots were made using the Generic Mapping Tools (GMT) version 4.2.1 (Wessel and Smith 1998).

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