

# A selected dataset of the Iranian strong motion records

H. Zafarani<sup>1</sup> · M. R. Soghrat<sup>1</sup>

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**Abstract** Iranian strong motion records as well as detailed conditions of their instrument sites and the characteristics of their causative seismic sources are compiled and processed. The dataset consists of 2286 three-component records from 461 Iranian earthquakes with at least two high-quality records having moment magnitude from 3.9 to 7.3. These records are about 20% of the Iranian database and are suitable for seismic hazard analysis and engineering applications. Perhaps for the first time in the literature, the distance to the surface projection of the fault is reported for a great number of records corresponding to earthquakes with  $M > 6.0$ . The raw accelerations are processed using the wavelet de-noising method. Having corrected and filtered these raw data, the pseudospectral accelerations are calculated for each of the three components of time series, separately. In addition to the ground motion parameters, a large and comprehensive list of metadata characterizing the recording conditions of each record is also developed. Moreover, careful revision of the characteristics of the earthquakes such as location, magnitude, style of faulting and fault rupture plane geometry, if available, is carried out using the best available information in a scientifically sound manner. Finally, we also focus on special ground motion records including records with peak ground acceleration (PGA)  $> 300 \text{ cm/s}^2$  and distances less than 30 km. These are “exceptional” records in the Iranian dataset and include less than 2% of the selected dataset.

**Keywords** Iran · Dataset · Strong ground motion · Seismic hazard

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✉ H. Zafarani  
h.zafarani@iiees.ac.ir

<sup>1</sup> International Institute of Earthquake Engineering and Seismology (IIEES), No. 26, Arghavan St., North Dibajee, Farmanieh, P.O. Box: 19395/3913, Tehran, Iran

## 1 Introduction

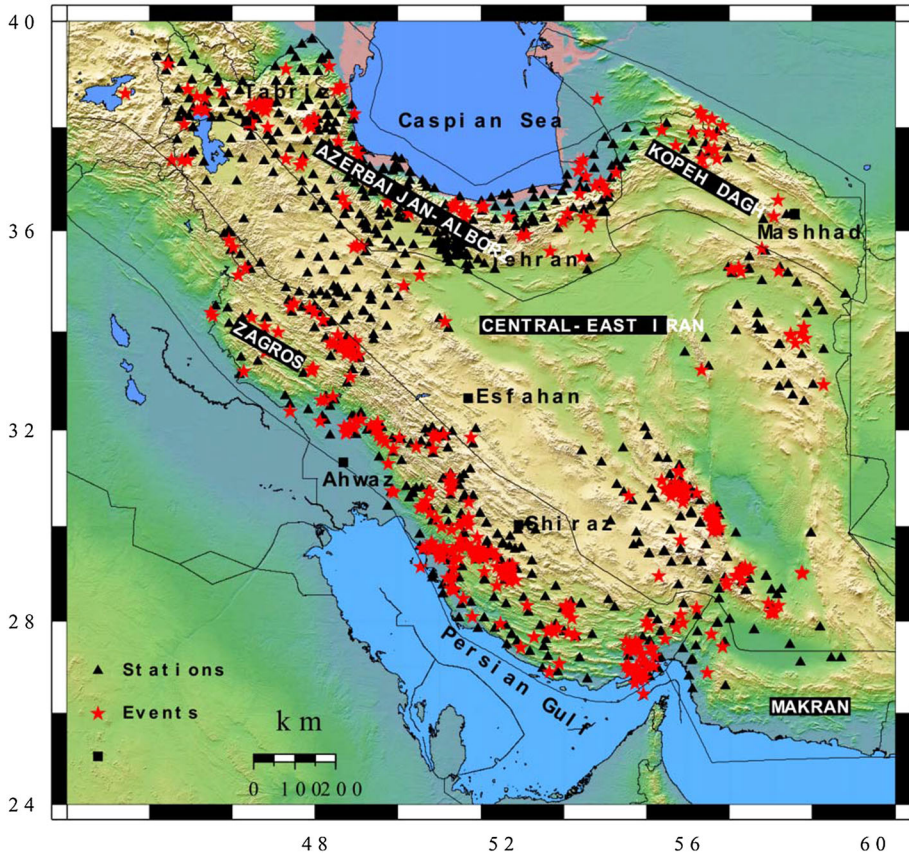
The Iranian plateau, located along the Alpine–Himalayan orogenic belt, is one of the tectonically active regions of shallow crustal earthquakes. This region has been experienced many large and destructive earthquakes such as Tabas (1978), Rudbar (1990), Bam (2003) and Varzaqan (2012) earthquakes. Therefore, the development of a strong ground motion dataset with appropriate quality and content would be an essential component/tool in local ground motion studies and for engineering practice. The first strong motion instruments (Kinematics SMA-1 analog recorders) were installed in 1973, 5 years after the devastating Mw 7.1, August 31, 1968, Dasht-e Bayaz earthquake. The instruments recorded their first main shock at Jahrom station during the Mw 5.2, February 24, 1973, earthquake. Since then, the number of strong motion stations has been gradually increased. Currently, the Iranian strong motion dataset includes more than 10,000 three-component time series, recorded at about 1100 permanent stations. The Iranian earthquake strong motion database is one of the most significant databases in the world, comparable to the Californian and Japanese strong motion databases.

In this study, about 3046 records of 738 earthquakes are selected from all records and events since 1975. These events were recorded by at least two stations, and their moment magnitude was greater than 3.9. By probing into the quality of the records and the metadata information, 2286 time series recorded on 743 stations from 461 earthquakes with a maximum moment magnitude of 7.3 (i.e., the 1978 Tabas earthquake) are finally selected for further studies. The epicenters of the selected earthquakes (461 events) in this study are illustrated in Fig. 1. The distribution of 743 stations, which have recorded 2286 acceleration time series in the selected dataset, is also shown in the same figure.

The proposed model of Mirzaei et al. (1998) is used to characterize the seismotectonic and seismicity features of Iran in this work. The model defines five distinct tectonic regions including Azerbaijan–Alborz, Kopeh Dagh, Zagros, Makran and Central–East Iran as shown in Fig. 1.

Figure 2 shows the growth of the both number of earthquakes and number of records versus time. Remarkable differences can be observed in the figure for the number of both earthquakes and records before and after 1994. In other words, since 1994, the number of records and earthquakes considerably increased because of rapid development of the number of digital strong motion stations. Specific seismic activity close to the stations or improvement in the operational status of the instruments could be considered as other causes of this growth. To elucidate the effect of such growth, it is worth mentioning that the 2004 Baladeh earthquake (Mw 6.2) in the Azerbaijan–Alborz region was recorded by about 145 stations, while the greater Rudbar earthquake in 1990 with Mw 7.3 was recorded only by 23 stations. In Fig. 2, the “All” stands for the initial dataset comprising 738 events and 3046 records, while “Selected” shows the final dataset including 461 earthquakes and 2286 time series accelerations. Most of the earthquakes occurred in six years (i.e., 1996, 1997, 1998, 2004, 2005 and 2006) with more than 40 events. Moreover, most of the recorded data belong to the years 1999, 2004, 2005 and 2012.

The aim of this paper is first to present the new catalog with comprehensive metadata for engineering and research practices. In order to underline the significance of the newly established dataset, it is worth mentioning that, for example, Kale et al. (2015), Saffari et al. (2012) and Ghasemi et al. (2009a) developed empirical ground motion prediction equations (GMPEs) for Iran using about 528, 351 and 893 records, respectively. The record



**Fig. 1** Location of the stations and epicenters of the earthquakes (461 events and 743 stations)

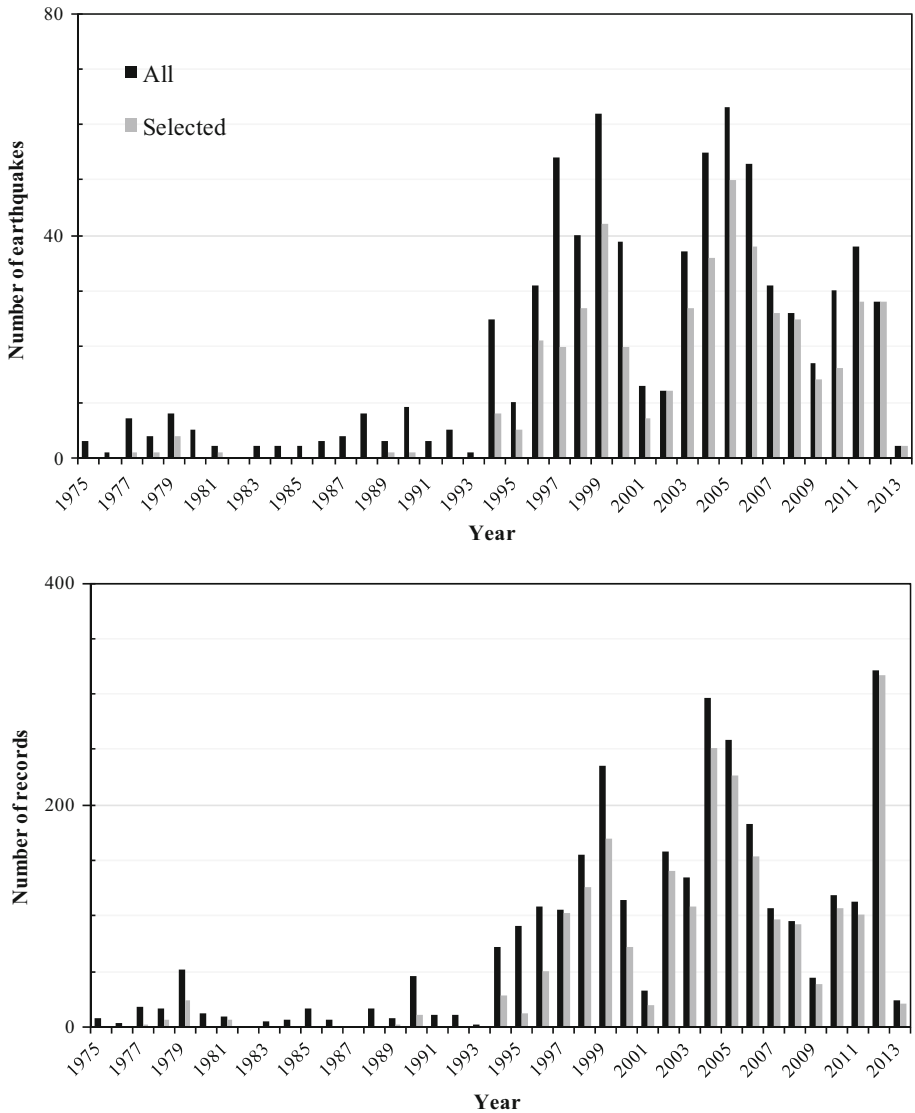
selection for development of new GMPEs for various strong motion parameters can be performed by using the provided catalog.

In addition, the main features of the Iranian strong motion dataset are provided in this paper. To this end, careful revision of the characteristics of the earthquakes such as location, magnitude, style of faulting and fault rupture plane geometry, if available, are scientifically carried out for the first time using the best available information.

Finally, we concentrate on special ground motion records including records with peak ground acceleration  $PGA > 300 \text{ cm/s}^2$  and distances less than 30 km. These are designated as “exceptional” records in the Iranian dataset, because they include less than 2% of the selected dataset.

## 2 Earthquakes

The final dataset consists of 2286 records from 461 earthquakes. In the dataset, 27 events with the magnitude more than 6 exist as shown in Table 1. Some information including date and time of the events, epicenter of the earthquakes, focal depth, focal mechanism, unified moment magnitude are shown in the table (for accessing to the whole dataset,



**Fig. 2** Distribution of number of earthquakes and records versus years since 1975

please contact the corresponding author). In this table, the host seismotectonic regions according to the model proposed by Mirzaei et al. (1998) are also specified. In addition, the magnitude and location references are also shown in the same table. Among 27 earthquakes with  $M_w \geq 6$ , the most (12 events) occurred in Central Iran. The Zagros, Alborz–Azerbaijan and Kopeh Dagh regions lie in the next ranks with contribution of 7, 6 and 2 events, respectively. It is obvious that there is no earthquake with  $M_w \geq 6$  in the Makran region according to provided dataset. Regarding the earthquake location, the published coordinates of epicenter and focal depths determined by waveform modeling are used if they are available. For other earthquakes, where available, the results of Engdahl et al.

**Table 1** Earthquake with  $M_w \geq 6$  in the Iranian plateau

| No. | Zone <sup>a</sup> | Date       | Time     | Lat   | Lon   | $M_w$ | $H^b$ (km) | SoF <sup>c</sup> | M. ref. <sup>d</sup> | L. ref. <sup>d</sup> |
|-----|-------------------|------------|----------|-------|-------|-------|------------|------------------|----------------------|----------------------|
| 1   | Z                 | 03/21/1977 | 21:18:00 | 27.60 | 56.45 | 6.7   | 12.0       | RV               | GCMT                 | AMB98                |
| 2   | CI                | 09/16/1978 | 15:35:57 | 33.22 | 57.33 | 7.3   | 9.0        | RV               | Wea03                | Wea03                |
| 3   | CI                | 01/16/1979 | 9:50:00  | 33.91 | 59.48 | 6.5   | 11.0       | RV               | Bea93                | Bea93                |
| 4   | CI                | 11/14/1979 | 2:21:18  | 33.96 | 59.73 | 6.6   | 10.0       | SS               | Bea93                | Bea93                |
| 5   | CI                | 11/27/1979 | 17:10:33 | 34.08 | 59.79 | 7.1   | 8.0        | SS               | B93                  | B93                  |
| 6   | CI                | 07/28/1981 | 17:22:23 | 29.98 | 57.77 | 7     | 18.0       | SS               | Bea01                | Bea01                |
| 7   | AA                | 06/20/1990 | 21:00:11 | 36.96 | 49.33 | 7.3   | 12.0       | SS               | Cea94                | Cea94                |
| 8   | KD                | 02/04/1997 | 10:37:47 | 37.39 | 57.35 | 6.4   | 8.0        | SS               | J02                  | J02                  |
| 9   | AA                | 02/28/1997 | 12:57:45 | 38.10 | 47.79 | 6     | 9.0        | SS               | J02                  | J02                  |
| 10  | CI                | 05/10/1997 | 7:57:29  | 33.86 | 59.83 | 7.2   | 13.0       | SS               | Bea99                | Bea99                |
| 11  | CI                | 03/14/1998 | 19:40:27 | 30.08 | 57.59 | 6.6   | 5.0        | SS               | Bea01                | Bea01                |
| 12  | Z                 | 03/04/1999 | 5:38:26  | 28.26 | 57.21 | 6.2   | 28.0       | RV               | Tea04                | Tea04                |
| 13  | Z                 | 05/06/1999 | 23:00:53 | 29.54 | 51.93 | 6.1   | 7.0        | SS               | Mea02                | Mea02                |
| 14  | KD                | 12/06/2000 | 17:11:05 | 38.53 | 54.80 | 7     | 31.0       | RV               | GCMT                 | ENGD                 |
| 15  | CI                | 06/22/2002 | 2:58:20  | 35.67 | 48.93 | 6.4   | 10.0       | RV               | Wea05                | Wea05                |
| 16  | CI                | 12/26/2003 | 1:56:52  | 29.05 | 58.37 | 6.5   | 8.0        | SS               | Pea14                | Pea12                |
| 17  | A                 | 05/28/2004 | 12:38:44 | 36.28 | 51.58 | 6.3   | 17.0       | RV               | Tea07                | Tea07                |
| 18  | CI                | 02/22/2005 | 2:25:26  | 30.77 | 56.74 | 6.4   | 7.0        | RV               | Tea06                | Tea06                |
| 19  | Z                 | 02/28/2006 | 7:31:03  | 28.13 | 56.82 | 6     | 18.0       | RV               | GCMT                 | ENGD                 |
| 20  | Z                 | 03/31/2006 | 1:17:02  | 33.62 | 48.91 | 6.1   | 6.0        | SS               | Pea08                | Pea08                |
| 21  | Z                 | 09/10/2008 | 11:00:38 | 26.65 | 55.72 | 6.1   | 12.0       | RV               | GCMT                 | GCMT                 |
| 22  | CI                | 12/20/2010 | 18:41:59 | 28.33 | 59.19 | 6.5   | 5.0        | SS               | Wea13                | Wea13                |
| 23  | CI                | 01/27/2011 | 8:38:28  | 28.17 | 59.04 | 6.2   | 9.0        | SS               | Wea13                | Wea13                |
| 24  | AA                | 10/23/2011 | 10:41:21 | 38.64 | 43.40 | 7.1   | 12.0       | RV               | GCMT                 | GCMT                 |
| 25  | AA                | 08/11/2012 | 12:23:15 | 38.31 | 46.80 | 6.4   | 7.0        | SS               | Cea2014              | Cea2014              |
| 26  | AA                | 08/11/2012 | 12:34:34 | 38.39 | 46.81 | 6.4   | 19.2       | RV               | GCMT                 | IGTU                 |
| 27  | ZA                | 04/09/2013 | 11:52:50 | 28.47 | 51.57 | 6.3   | 11.0       | RV               | GCMT                 | IGTU                 |

<sup>a</sup> Z Zagros, CI Central Iran, AA Alborz–Azerbaijan, KD Kopeh Dagh

<sup>b</sup> D Focal depth of earthquakes in km

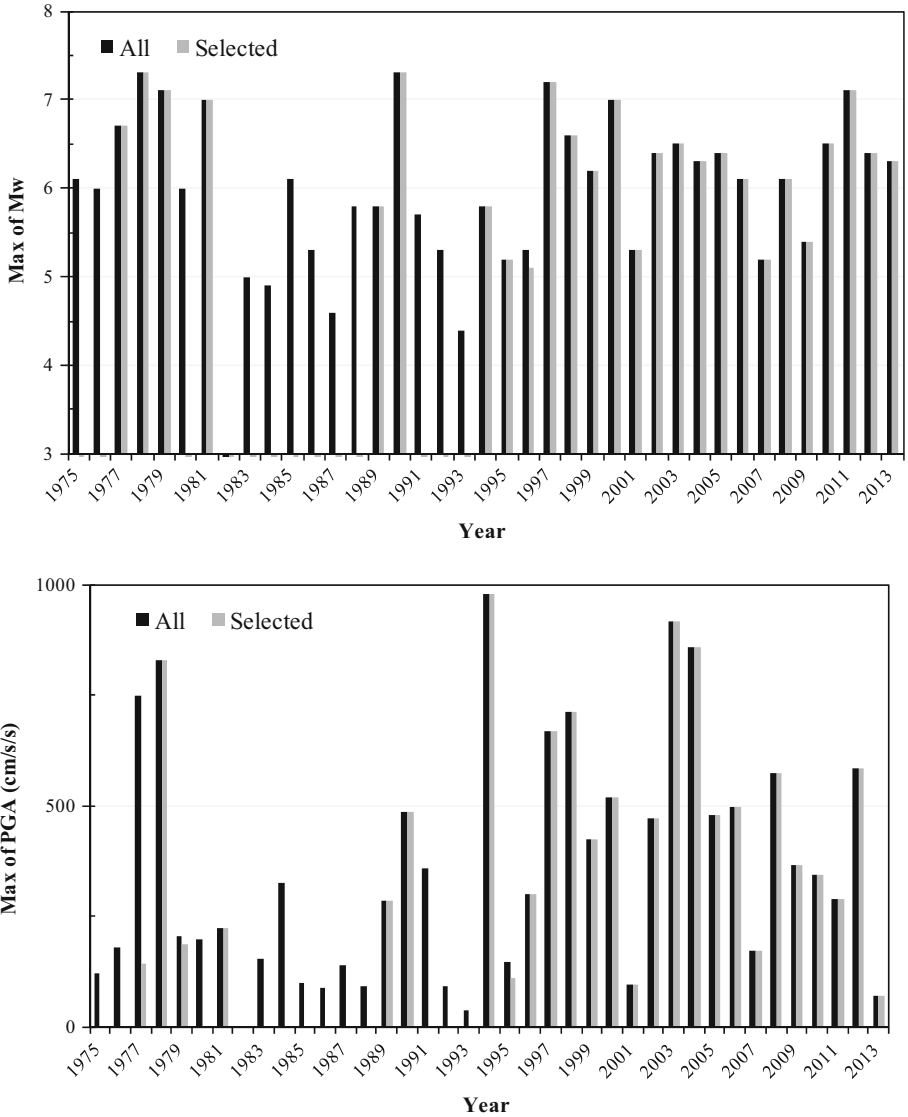
<sup>c</sup> SoF Style of faulting, RV reverse, SS strike-slip

<sup>d</sup> M. ref. and L. ref. The references of magnitude and location in the dataset; Ambraseys and Jackson (1998): AMB98, Baker et al. (1993): Bea93, Berberian et al. (1999): Bea99, Berberian et al. (2001): Bea01, Campos et al. (1994): Cea94, Engdahl et al. (2006): ENDG, Global Centroid Moment Tensor Catalog (<http://www.globalcmt.org>): GCMT, Jackson et al. (2002): J02, Maggi et al. (2002): Mea02, Peyret et al. (2008): P08, Poiata et al. (2012): Pea12, Poiata et al. (2012): Pea14, Talebian and Jackson (2004): TJ04, Talebian et al. (2006): Tea06, Tatar et al. (2007): Tea07, Walker et al. (2003): Wea03, Walker et al. (2005): Wea05, Walker et al. (2013): W13

(2006) which are based on an advanced technique for 1-D earthquake relocation are applied. These results are more precise than those reported by international or local agencies but less accurate than body waveform inversions (see Engdahl et al. (2006) for details). Finally, the coordinates reported by international or local agencies (with azimuth gap  $<160^\circ$ ) are used. It should be emphasized that reported depths for these moderate

events have large uncertainty; however, this is not a crucial issue taking into account that usually the epicentral distance is used in development of ground motion prediction equations.

The maximum moment magnitude and the maximum PGA in each year are shown in Fig. 3. According to this figure, there is at least one earthquake with moment magnitude greater than 5 in each year after 1994 for the “Selected” dataset. Furthermore, the figure shows that at least 15 time series accelerations were recorded with  $PGA > 300 \text{ cm/s}^2$  since 1994 (about 20 years).



**Fig. 3** Distribution of maximum magnitude (*top*) and maximum recorded PGA (*bottom*) in each year since 1975

In the selected dataset, most of the earthquakes (243 events) happened in the Zagros region, but the greatest earthquakes occurred in Central Iran (four earthquakes with  $M_w \geq 7$ ).

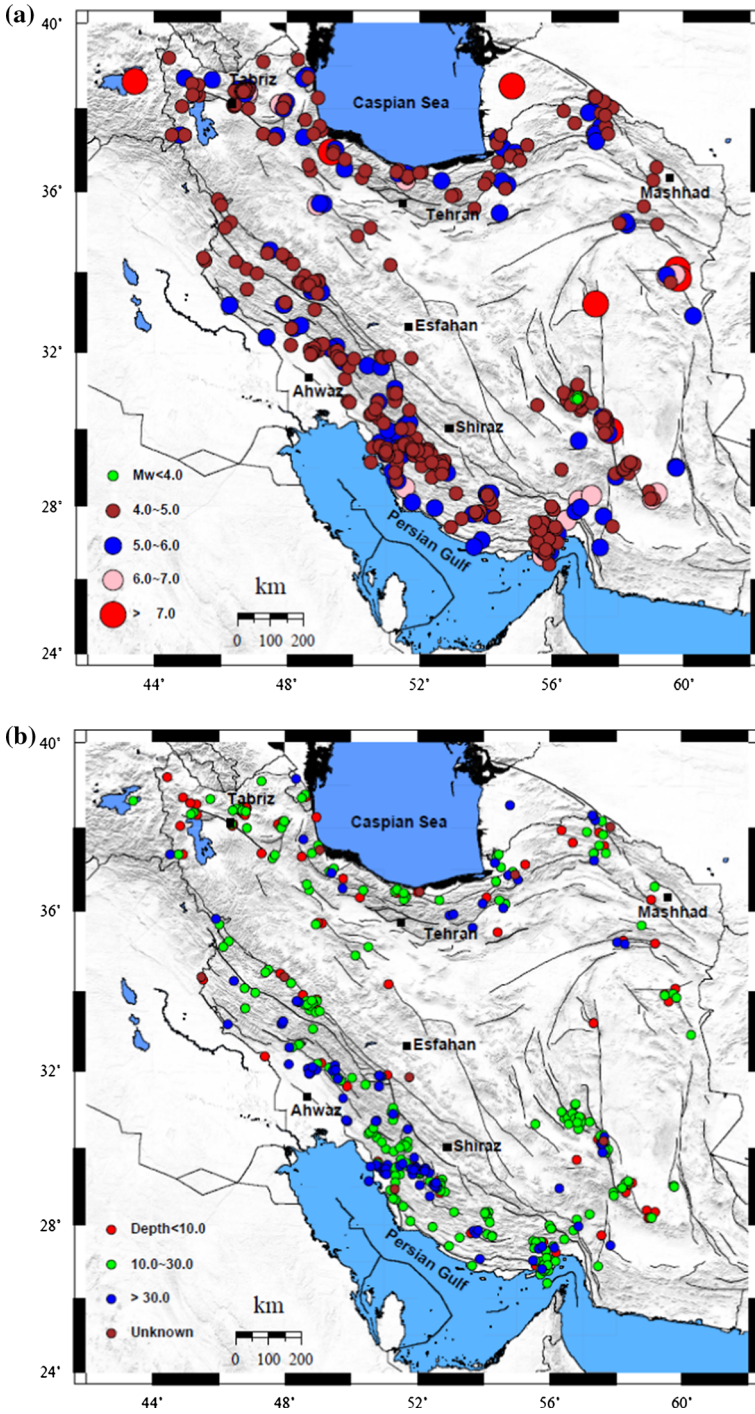
The geographic distributions of events in terms of magnitude, depth and style of faulting are shown in Fig. 4. The majority of the events in the dataset are shallow crustal earthquakes (depths less than 30 km). The earthquakes with focal depth exceeding 40 km occurred mostly in the Zagros region (42 of 52 events with depth more than 40 km occurred in the Zagros region). Figure 4c also shows that most of the events in the dataset correspond to earthquakes with strike-slip faulting (in contrast to normal faulting).

The moment magnitude is provided from international or local seismological agencies or from earthquake-specific literature studies in about 40% of the events (201 of 461 events) or 70% of the records (1623 of 2286 records). For the remaining events (260 of 461 events), we use the empirical magnitude conversion equations of Shahvar et al. (2013) to obtain the more homogenous magnitude information and increase the number of events associated with moment magnitude values. The calculated moment magnitudes are mainly (235 of 260 events) between 4 and 5. The converted moment magnitudes belong to small earthquakes that are originally reported with magnitude scales of Nuttli (MN), local (ML), body wave (mb) and surface wave (Ms). In the selected dataset, ML, mb, Ms and MN are available according to seismological agencies or from published article for about 16, 173, 208, 148 events, respectively. So, the Ms and Mw scales were originally reported in the dataset more than the other magnitude scales. Investigation on the distribution of the number of earthquakes and records versus moment magnitude shows the dominance of data for moderate-size events so that about 90% of earthquakes and 70% of accelerograms are related to the earthquakes with  $4 \leq M_w \leq 6$ . It is worth mentioning that only 5% of events (or 25% of records) correspond to greater events (i.e.,  $M_w \geq 6$ ).

It should be mentioned that the bulk of events in the dataset are shallow continental earthquakes with depths less than 30 km. About 75% of the events or 90% of the records are in this range of the aforementioned focal depth. The number of earthquakes with unknown focal depth is less than 1% in the selected dataset. Moreover, more than 85% of the events (and 85% of the records) have focal depth less than 40 km. The events with focal depth more than 40 km are mainly from the Zagros region.

In the selected database for most of the events (about 66% of the events and 40% of the records), there is no available information (NA) about their faulting mechanisms. The dominant faulting mechanisms are reverse (20% of the events and 36% of the records) and strike-slip faulting (12% of the events and 20% of the records). The minority of events and accelerograms are related to normal faulting mechanism (1% of the events and 1.75% of the records). The number of earthquakes and records in terms of faulting mechanisms for each tectonic region is shown in Table 2, separately.

Focal depths and faulting mechanisms are unknown for about 2 and 66% of the events (or 0.5 and 42% of the records). Most of the unknown faulting mechanisms are attributed to the events with small magnitude ( $M_w \leq 5$ ) due to lack of double-couple fault-plane solutions for these earthquakes. Great events were studied to determine the faulting mechanisms due to their importance, while the small events are rarely paid attention. In the provided dataset, most of the great earthquakes have focal depth less than 30 km in the selected dataset.



**Fig. 4** Geographic distribution of the events based on **a** magnitude, **b** depth and **c** style of faulting



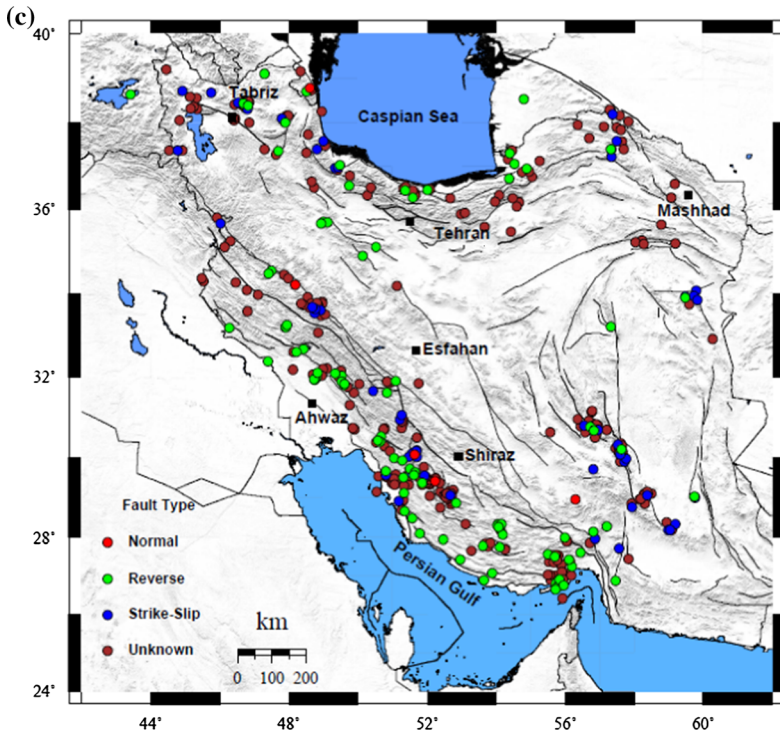


Fig. 4 continued

**Table 2** Number of earthquakes and records, EQ (rec), in terms of faulting mechanisms

| Region            | SS       | RV       | NM     | NA        | Sum       |
|-------------------|----------|----------|--------|-----------|-----------|
| Makran            | 1 (5)    | 1 (2)    | 0 (0)  | 1 (2)     | 3 (9)     |
| Zagros            | 20 (138) | 66 (305) | 3 (24) | 154 (391) | 243 (858) |
| Central Iran      | 18 (161) | 11 (140) | 1 (2)  | 62 (178)  | 92 (481)  |
| Kopeh Dagh        | 4 (15)   | 2 (14)   | 0 (0)  | 14 (38)   | 20 (67)   |
| Alborz–Azerbaijan | 10 (121) | 16 (365) | 1 (14) | 76 (371)  | 103 (871) |

*EQ/rec* Earthquake and record, *SS* strike-slip, *RV* reverse, *NM* normal, *NA* not available

### 3 Stations

The strong motion data were recorded by the Iranian strong motion network (ISMN) of the Building and Housing Research Center (BHRC). This network was equipped first with Kinematics SMA-1 analog strong motion accelerograph in the early years and then have been progressively replaced by SSA-2 digital instruments after the Mw 7.3, 1990 Rudbar earthquake. The SMA-1 instruments recorded important earthquakes such as Tabas (1978) and Golbaf (1981) events. Moreover, the digital strong motion digital accelerometer

(CMG-5TD), solid-state recorder (SSR1) and portable drum recorder (PS2) have been recently added to ISMN. The CMG-5TD accelerometer, installed recently, recorded some ground motions such as the earthquake on August 24, 2015, in Firozkuh, Tehran, with moment magnitude of 4.5. Since 1975, more than 1100 stations have been used to record more than 10,000 accelerograms in the Iranian plateau. Among the stations, the  $V_{s30}$  is measured only in 30% of them (About 350 of 1100 stations).

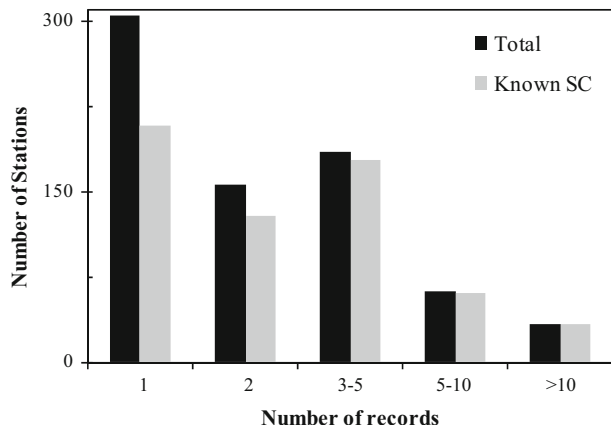
About 743 stations provide the accelerometric data in the selected dataset. The average shear-wave velocity between 0 and 30-meters depth ( $V_{s30}$ ) in more than 40% (306 of 743 stations) of these stations was measured and reported by the BHRC. The site classes for about 299 stations were determined either by geological surveys or by empirical methods (using H/V method). Ghasemi et al. (2009b) introduced an alternative empirical method to classify the sites based on the Spearman's rank correlation coefficient, which is compatible with the  $V_{s30}$ -based classification. In this study, we use the proposed method of Ghasemi et al. (2009b) for site classification where the  $V_{s30}$  is not available at recording stations. Therefore, we have no information about the soil categories for only 138 stations which most of those (127 stations) recorded one (in 96 stations) or two (in 31 stations) three-component time series. In other word, the site classes for about 18% of stations (138 of 743) cannot be recognized because they are either temporary stations or stations that recorded accelerograms less than 5 times.

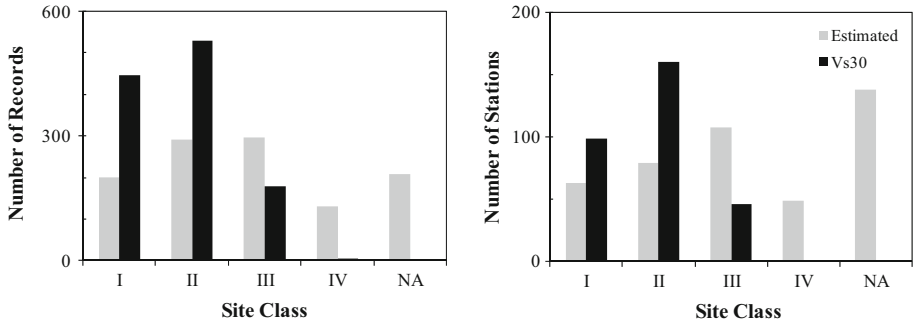
The site classification system based on the properties of the top 30 m ( $V_{s30}$ ) of the soil column is defined according to the Iranian code of practice for standard seismic resistant design of buildings, Standard No. 2800: I- $V_{s30} > 750$ , II- $375 < V_{s30} < 750$ , III- $175 < V_{s30} < 375$  and IV- $V_{s30} < 175$  m/s. Moreover, site classification evaluated according to the Eurocode 8 (EC8) is also reported in the provided dataset.

Many stations (305 of 743 stations) in the dataset recorded only one event. The distribution of number of stations versus number of records is shown in Fig. 5. The number of records in each station is important in some cases such as single-station sigma studies. In the figure, the stations with known site classes (either by  $V_{s30}$  or by empirical method) are distinguished from those with unknown site class.

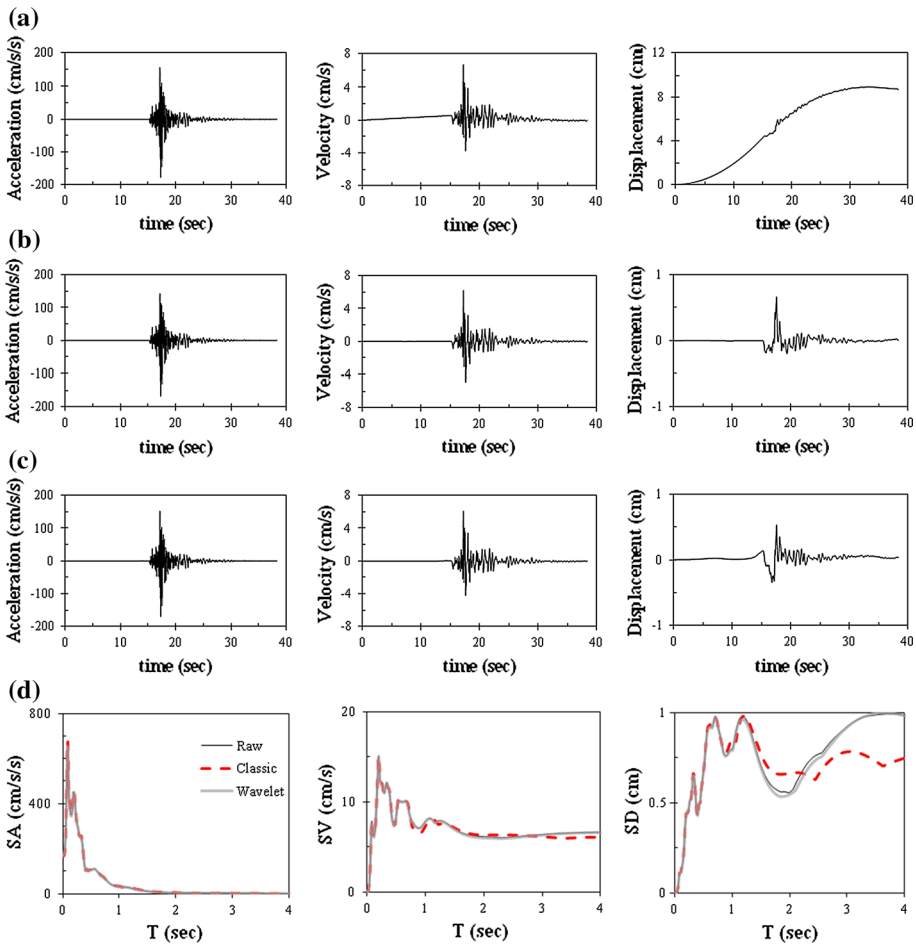
Figure 6 illustrates the histograms of records in terms of site class based on either measured  $V_{s30}$  or empirical method. The most of stations are placed in the categories of II, I and III based on the Iranian standard code (using the  $V_{s30}$  or empirical methods), respectively. Considering the  $V_{s30}$  criteria, the majority of the stations belong to site class

**Fig. 5** Histogram of number of stations versus number of records





**Fig. 6** Distribution of the number of recorded accelerations (*left column*) and number of stations (*right column*) for different site classes based on the Iranian code



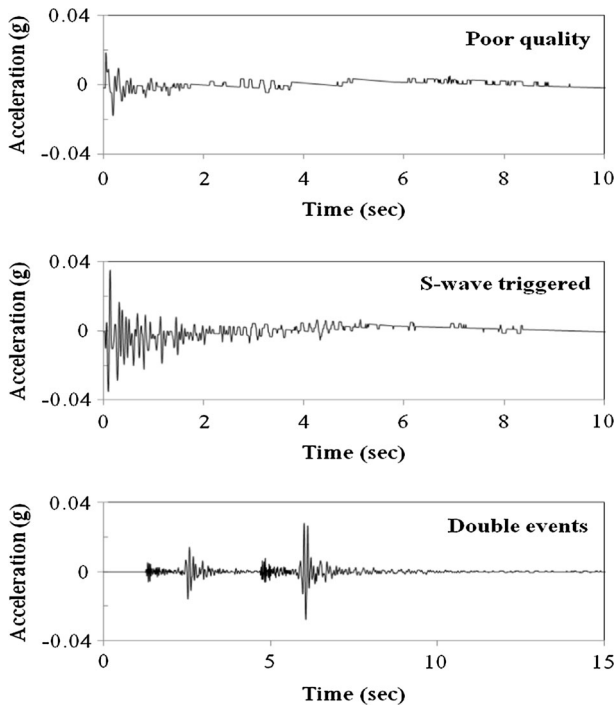
**Fig. 7** A sample record in raw format (a), processed by the classical (conventional) filtering method (b) and corrected by the wavelet de-noising approach (c) as well as comparison of spectral amplitudes (d)

II, while most of the stations lie in site class III provided that we use only the above-mentioned empirical method.

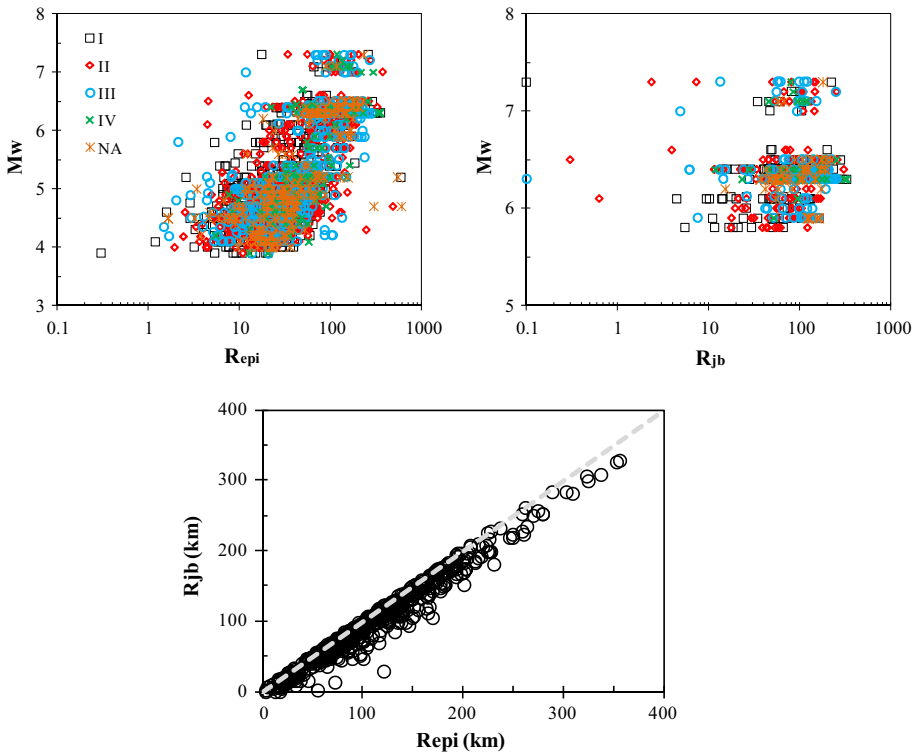
About 42% of the stations (or 50% of the records) have available  $V_{s30}$ , and about 40% of the stations (40% of the records) have known site class obtained from the empirical method. For the remaining sites (18% of the stations or 10% of the records), there are not enough data to estimate the corresponding site class. Consequently, most of the records (about 35%) are in site class II. Site classes I and III including 28% and 20% of the records, respectively, are in the next ranks. About 6% of the records belong to site class IV, and there are no available data to determine the site class for the remaining records.

## 4 Records

The acceleration time series are provided with sampling intervals of 0.005 s in raw (unprocessed) format by BHRC. Therefore, the uncorrected accelerograms recorded by a given station must be corrected for the instrument response, baseline shifts and high- and low-frequency noises (Boore et al. 2002; Boore and Bommer 2005). The methodology of baseline correction and the approach to filter out high- and low-frequency noises were studied by several authors (e.g., Boore et al. 2002; Boore and Bommer 2005; Kamai et al. 2014). For example, the proposed method of Boore et al. (2002) applies a quadratic function fitting to the velocity data and then removal of low and high frequencies by filtering. The important parts of the filtering procedure are the selection of filtering



**Fig. 8** Samples of records excluded due to the non-standard error such as poor quality (*top*), S-wave triggered (*middle*) and double events (*bottom*)

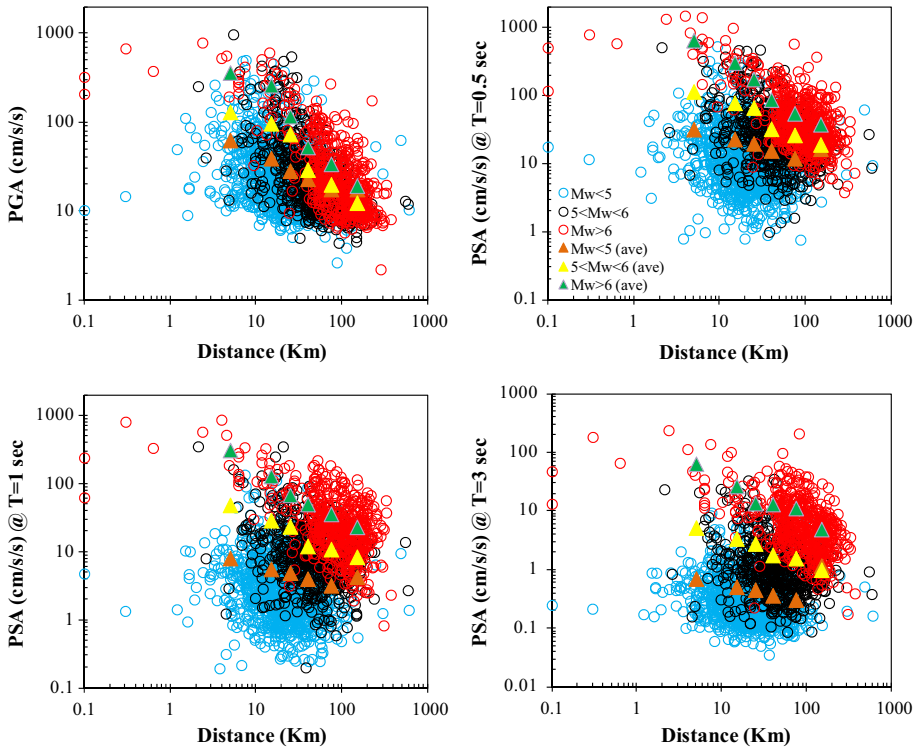


**Fig. 9** Distribution of Mw versus Rjb and Repl

technique, filter parameters and the usable range of corner frequencies after filtering. Usually, a technique based on the signal-to-noise ratio is employed to find out the corner frequencies. The technique is more suitable for records with long pre-event portions (Boore and Bommer 2005).

In this study, we use the multi-resolution wavelet analysis (Ansari et al. 2010, Chanerley and Alexander 2015) to remove undesirable noise from the recorded signals. It is shown that in this method, the noise can be attenuated in the whole frequency range of engineering interest. In addition, this method can detect and remove non-stationary noise in the time domain. Ansari et al. (2010) also showed that “the displacement response spectra of the wavelet de-noised records are more stable than conventional filtered ones and a large number of noisy records that are usually discarded from sets of records used for estimating the ground motions can be corrected using this new method.” Figure 7 shows a record from the dataset in raw and processed formats.

In the figure, a comparison between wavelet de-noising and conventional filtering methods is done. Estimation of corner frequencies based on signal-to-noise ratios is an essential step in the conventional or classical filtering method. Usually, a fourth-order causal Butterworth filter is used to reduce the noise in the accelerograms. The obtained PGA, PGV and PGD are about 166.74 (cm/s<sup>2</sup>), 6.24 (cm/s) and 0.66 (cm) in the conventional method, respectively. These parameters are about 169.98 (cm/s<sup>2</sup>), 6.13 (cm/s) and 0.54 (cm), respectively, when the wavelet de-noising method is used to process the



**Fig. 10** Distribution of spectral acceleration versus distance in different ranges of magnitude at  $T = 0, 0.5, 1$  and  $3$  s for average of horizontal components

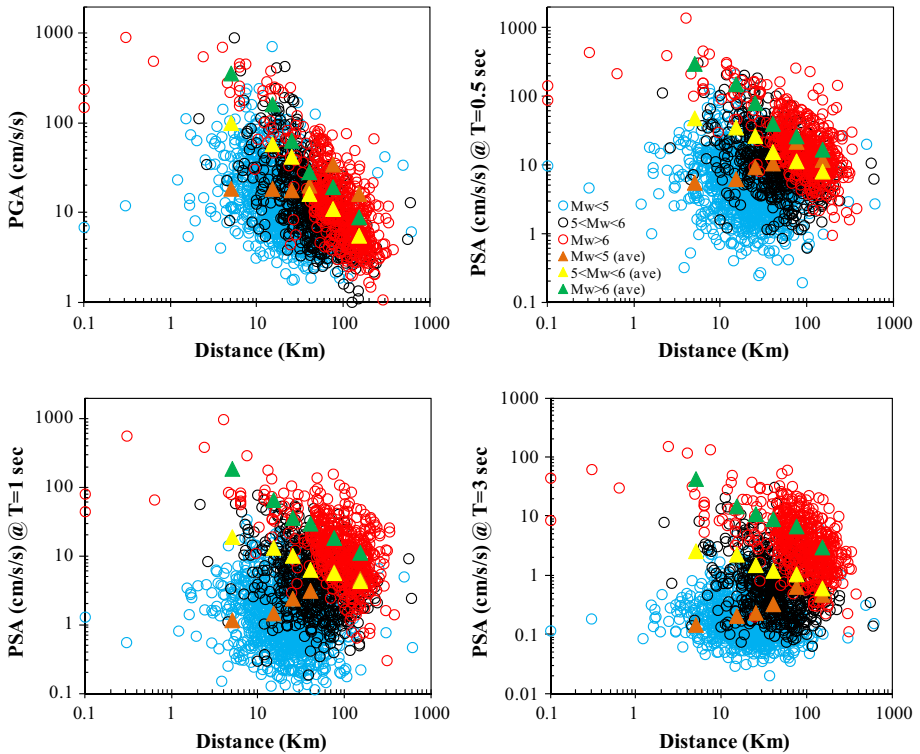
record. The spectral amplitudes are also shown in the figure for comparison with each other.

During the data processing, the records with the following features are eliminated from the dataset: data from instruments that triggered during the S-wave train; the records with only a single horizontal component; and the records obtained from the events with unknown or poor estimates of magnitude (which are attributed to the small events). Furthermore, the records with non-standard error (Douglas 2003) such as very high-frequency spikes and multi-event are excluded from the dataset (Akkar et al. 2010, Pacor and Luzi 2014). Three sample records, which are removed from the dataset, are shown in Fig. 8.

#### 4.1 Characteristics of records

The provided catalog consists of 2286 three-component accelerograms. More than 75% of the records are related to recent events (i.e., after year 2000). The distribution of moment magnitude ( $M_w$ ) versus distance is shown in Fig. 9.

It is obvious from the figure that there is scarcity of records for site class IV in the dataset. The introduced distance parameters in this study are epicentral distance ( $R_{epi}$ ) and closest horizontal distance to the surface projection of the fault plane ( $R_{jb}$ ).  $R_{jb}$  is computed by additional information about the ruptured fault geometry. Since there is not enough information on ruptured fault geometry and double-couple fault-plane solutions of



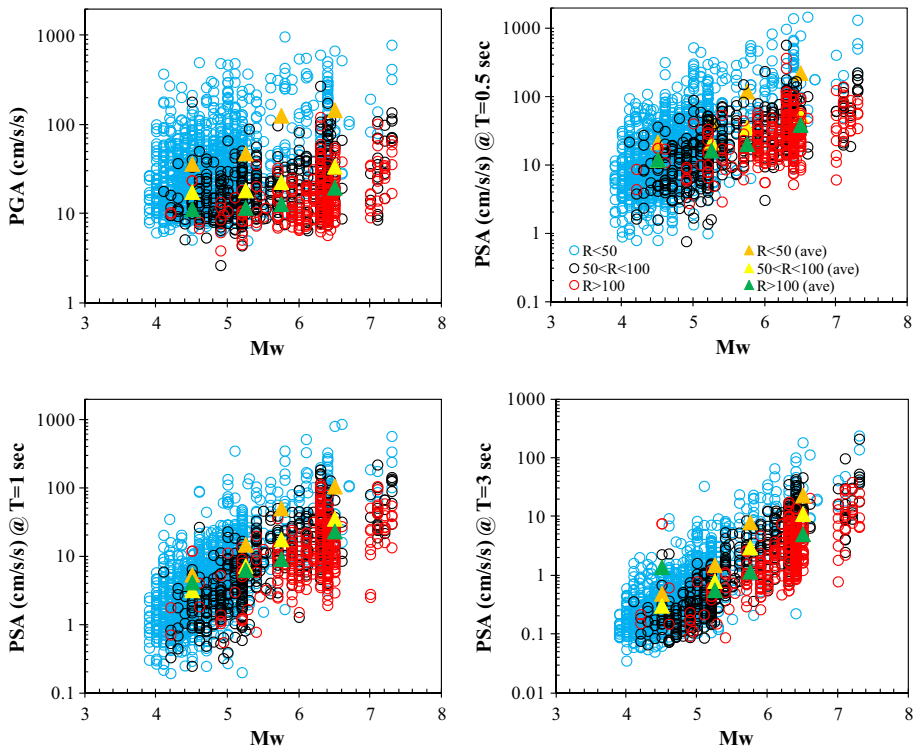
**Fig. 11** Distribution of spectral acceleration versus distance in different ranges of magnitude at  $T = 0, 0.5, 1$  and  $3$  s for vertical component

smaller magnitude events, Rjb is not available for the records with unknown ruptured fault geometry (which are about 70% of the records). For small earthquakes, Repi and Rjb are similar because of the small rupture planes of such earthquakes. Akkar et al. (2010) showed that the Rjb is almost smaller than Repi and the difference between Rjb and Repi can be noticeable for both  $Mw \geq 6$  and epicentral distances less than 40 km, which is observed in this study according to the figure.

Figure 9 illustrates the scarcity of data for magnitudes greater than 7 at distances less than 10 km (i.e., 4 of 2286 records) in the dataset. In addition, about 10% of the records (224 of 2286 records) have epicentral distances less than 10 km in entire magnitudes range, and the records are dominant in source-to-site distance between 15 and 30 km.

### 4.2 Ground motion parameters

The PGA and pseudospectral acceleration (PSA) at 34 periods between 0.01 and 4 s for the dataset are computed in this study. Distribution of spectral acceleration versus distance in different ranges of magnitude at  $T = 0, 0.5, 1$  and  $3$  s for horizontal (geometrical mean) and vertical components are plotted in Figs. 10 and 11. It is obvious that large earthquakes ( $Mw > 6$ ) are attenuated slower at greater distances. Also, the distribution of spectral acceleration versus magnitude in different ranges of distance at  $T = 0, 0.5, 1$  and  $3$  s for horizontal and vertical components are shown in Figs. 12 and 13. According to the figures,



**Fig. 12** Distribution of spectral acceleration versus moment magnitude in different range of distance at  $T = 0, 0.5, 1$  and  $3$  s for average of horizontal components

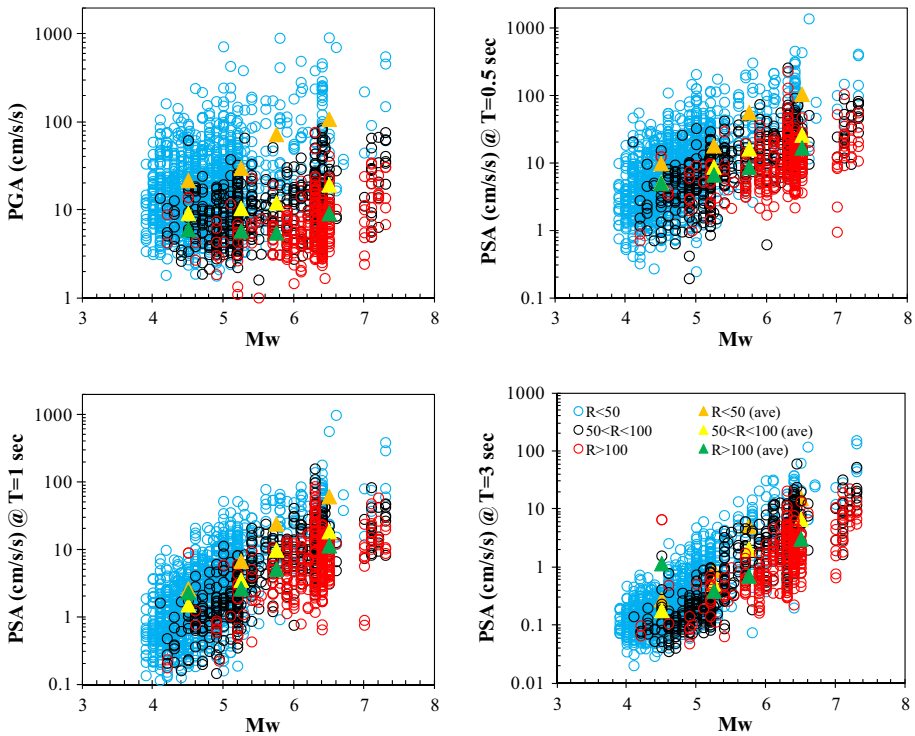
it can be found out that near distances have higher values of spectral acceleration; however, the difference between these values decreases in long periods.

Examination of these plots (Figs. 10, 11, 12, 13) shows some characteristics similar to those observed in the study of Boore et al. (2014). For example, the functional forms to develop GMPEs must consider “M-dependent geometrical spreading; anelastic attenuation effects; and strongly nonlinear (and period dependent) magnitude dependence of amplitude scaling at a fixed distance with a tendency toward saturation (no magnitude dependence) with increasing magnitude for short periods and close distances.”

The investigation of records in terms of PGA shows that about 80 and 90% of the records (1787 and 2076 of 2286 records) have PGA less than  $50 \text{ cm/s}^2$  for horizontal (geometrical mean GM) and vertical components, respectively. Furthermore, only 1.5% (35 of 2286 records) and 0.5% (13 of 2286 records) of records have PGA more than  $300 \text{ cm/s}^2$  in horizontal and vertical components, respectively, which all of them are related to records with distances less than 30 km.

The significant durations are also computed for horizontal and vertical components of the records. Significant duration is defined as the interval between the times at different specified values of Arias intensity. The starting point of the duration is when the Arias intensity is about 5% of total Arias intensity. The end point can be selected as where the Arias intensity is about 75 or 95% of the total Arias intensity (Boore and Thompson 2014). The estimation of the significant durations is schematically shown in Fig. 14. Distribution



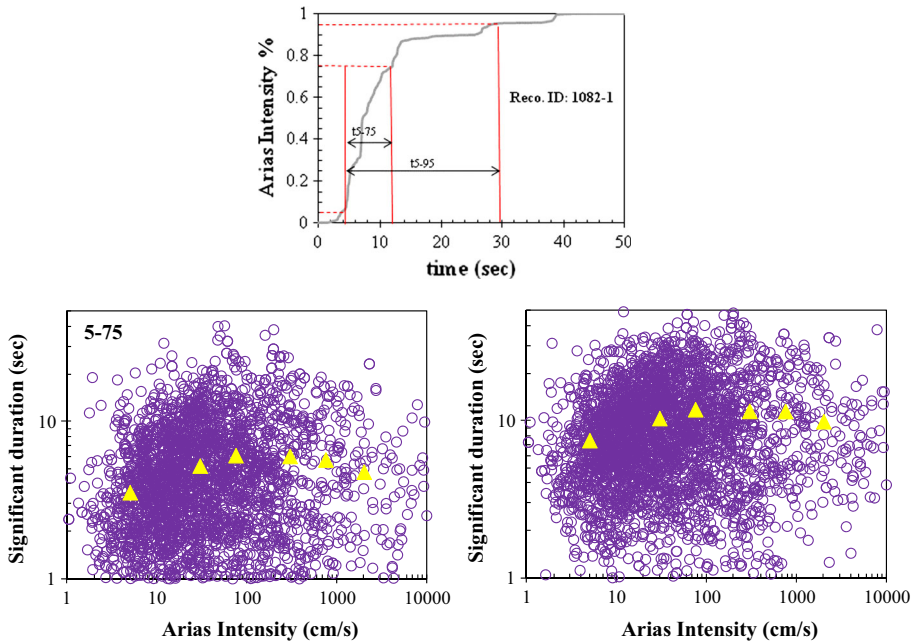


**Fig. 13** Distribution of spectral acceleration versus moment magnitude in different range of distance at  $T = 0, 0.5, 1$  and  $3$  s for vertical component

of significant durations ( $t_{5-75}$  and  $t_{5-95}$ ) with respect to Arias intensity is also plotted in the figure. As expected, the level of significant duration based on  $t_{5-95}$  is higher than another one (about two times).

Figure 15 shows that there is a good correlation between two definitions of significant durations. The number of records in different range of significant durations for horizontal (geometric mean) and vertical components is also depicted in the figure. Both definitions of significant durations in the figure are shown with “5–75” (or  $t_{5-75}$ ) and “5–95” ( $t_{5-95}$ ) labels. The first definition of significant duration (“5–75”) includes the energy from the body waves, whereas the second one (“5–95”) considers the full wave train. For horizontal component, about 44 and 26% of records (or 1003 and 592 of 286 records) have significant duration more than 10 s based on “5–95” and “5–75” definitions, respectively. The limitation of significant duration more than 10 s is important because it is a criterion for ground motion selection in time history analysis of structures according to some design codes (e.g., Iranian Code of Practice for Seismic Resistant Design of Buildings; Standard No. 2800).

In addition, we focus on special ground motion records including R records with  $PGA > 300 \text{ cm/s}^2$  and distances less than 30 km in this study. These are “exceptional” records in the Iranian dataset and they include about 2% of the selected dataset (or 48 of 2286 records). These records are listed in Table 3. About 48 and 30% of records (23 and 14 of 48 records) are attributed to events with reverse (RV) and strike-slip (SS) faulting mechanisms, respectively.



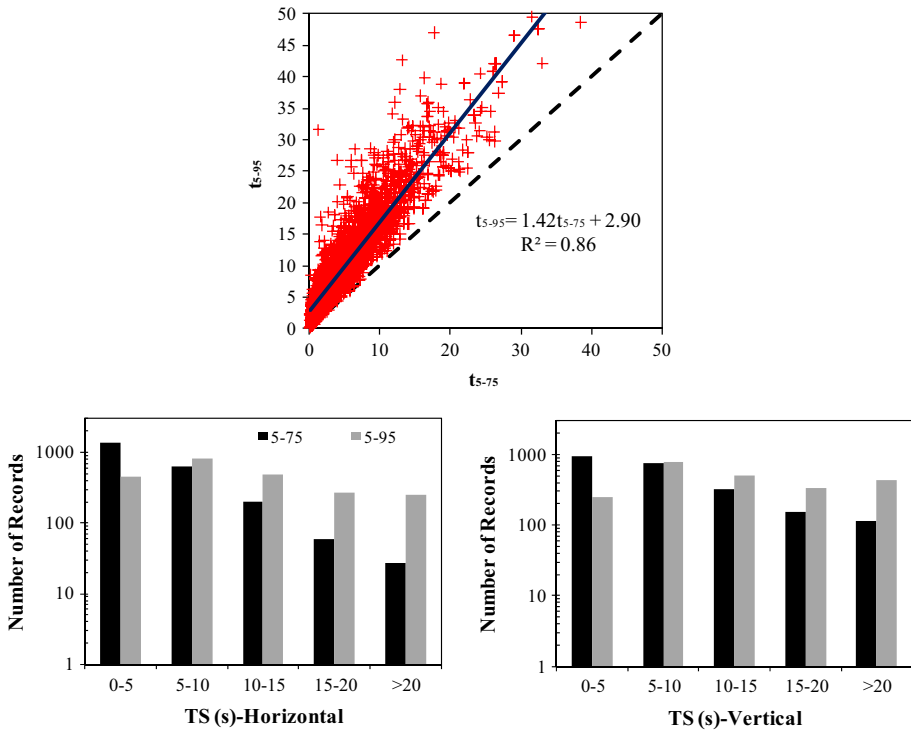
**Fig. 14** Definition of significant durations (*top*) and distribution of significant duration and Arias intensity based on  $t_{5-75}$  (*left*) and  $t_{5-95}$  (*right*)

Some characteristics of the exceptional records are shown in Fig. 16. According to this figure, about 67% of records (32 of 48 records) are caused by events with focal depth of less than 10 km. Furthermore, the spectral acceleration in the same figure shows that the value of acceleration spectrum for vertical components seems to be larger than horizontal components in short periods.

The vertical to horizontal spectral ratio as a function of period is also plotted in the same figure, which shows that the vertical component can be greater than the horizontal one in the period near 0.05 s. It is also obvious that these ratios can be greater than 2/3 in short periods (less than 0.1 s) where this coefficient is traditionally used to convert the horizontal spectrum to the vertical one. The importance of recorded accelerograms in near distances for vertical component was investigated by Button et al. (2002), Kunnath et al. (2008), Bommer et al. (2011) and Gülerce and Abrahamson (2011).

## 5 Development of the dataset

About 611 records with specific characteristics related to earthquakes with  $M_w \geq 6$  according to Table 1 are listed in Table A1 (“ESM Appendix A1”). The listed features are station name, station coordinate,  $V_{s30}$ , site class (based on the Iranian standard and EC8), Re<sub>pi</sub>, R<sub>jb</sub>, record ID, significant durations and PGA. In addition, their spectral amplitudes for horizontal (geometric mean) and vertical components at periods of 0.05, 0.1, 0.2, 0.3, 0.5, 1, 2, 3 and 4 s are tabulated in Table A2 (“ESM Appendix A2”). To access the characteristics of complete dataset, please contact the corresponding author. For example, to estimate the  $Z_{1.0}$  (the depth at which the shear-wave velocity is equal to 1 km/s), the models proposed by Jahanandish et al. (2016) have been used.



**Fig. 15** Correlation between different definition of significant durations; TS1 ( $t_{s-75}$ ) and TS2 ( $t_{s-95}$ ) (*top*) and distribution of number of records in terms of significant duration for horizontal and vertical components (*bottom*)

It is believed that this dataset can be a reference for ground motion studies such as development of GMPEs. It is noted that some studies have been done for simulation of ground motion (for example, Soghrat et al. 2012 and Zafarani and Soghrat 2012) or estimation of site amplification and earthquake parameters (such as Hassani et al. 2011, Zafarani et al. 2012 and Zafarani and Hassani 2013) in different regions of Iran using different databases. For example, as shown in Table 4 the datasets used to develop GMPEs for Iranian plateau were different in recent years. The NGA-2 database (NGA\_West2\_Flatfile) contains only about 40 records including a few ones from the Tabas (1978), Manjil (1990) and Bam (2003) earthquakes. In addition, about 396 records from 44 earthquakes are included in the RESORCE dataset, while in the current study a significant effort is made to compile, evaluate and extend the metadata on earthquake sources, travel paths and local site conditions of about 2286 strong motion records.

## 6 Conclusion

An important attempt was made to assemble and characterize the Iranian strong motion data in a single dataset. The data were recorded by the ISMN of the BHRC. About 1100 stations were used to record more than 10,000 accelerograms since 1975. Among these records, we collected the earthquakes with at least 2 records. As a result, 3046 records of 738 events were selected from the whole records and earthquakes. After omitting the

**Table 3** List of “exceptional” records in this study

| No. | Date       | Code    | Station                    | SC <sup>a</sup> | V <sub>s30</sub> | R <sup>b</sup> | PGA_H <sup>d</sup> | PGA_V | D <sup>c</sup> | Mw  | SoF |
|-----|------------|---------|----------------------------|-----------------|------------------|----------------|--------------------|-------|----------------|-----|-----|
| 1   | 09/16/1978 | 1082/01 | Deyhock <sup>a</sup>       | 1               | 826              | 0              | 357.5              | 151.2 | 9              | 7.3 | RV  |
| 2   | 09/16/1978 | 1084/01 | Tabas <sup>a</sup>         | 2               | 645              | 2              | 827.3              | 558.3 | 9              | 7.3 | RV  |
| 3   | 06/20/1990 | 1362/01 | Ab-bar <sup>a</sup>        | 2               | 691              | 7              | 485.3              | 461.9 | 12             | 7.3 | SS  |
| 4   | 06/20/1994 | 1490/02 | Maymand <sup>a</sup>       | 1               | 501              | 12             | 465.4              | 158.9 | 9              | 5.8 | SS  |
| 5   | 06/20/1994 | 1502/09 | Zanjiran                   | 1               | 936              | 5              | 979.6              | 908.0 | 9              | 5.8 | SS  |
| 6   | 06/02/1996 | 1638/01 | Talgerd                    |                 |                  | 3              | 300.2              | 92.9  | 39             | 5   |     |
| 7   | 02/28/1997 | 1833/02 | Kariq                      | 2               | 589              | 26             | 556.5              | 184.6 | 9              | 6   | SS  |
| 8   | 08/24/1997 | 1814    | Maymand <sup>a</sup>       | 2               | 501              | 7              | 667.4              | 172.8 | 2              | 4.9 |     |
| 9   | 03/14/1998 | 1913/01 | Sirch <sup>a</sup>         | 2               |                  | 4              | 639.2              | 712.2 | 5              | 6.6 | SS  |
| 10  | 11/13/1998 | 2049/01 | Khonj                      | 3               | 308              | 24             | 383.4              | 193.7 | 7              | 5.4 | RV  |
| 11  | 05/06/1999 | 2131/02 | Balaadeh                   | 1               | 1380             | 18             | 386.0              | 243.3 | 7              | 6.1 | SS  |
| 12  | 11/26/1999 | 2276/02 | Ali Abad                   | 2               | 562              | 6              | 423.4              | 388.3 | 10             | 5.3 | RV  |
| 13  | 07/03/2000 | 2324/02 | Boldaji                    |                 |                  | 21             | 518.4              | 87.3  | 56             | 4.1 |     |
| 14  | 06/22/2002 | 2749/01 | Avaj                       | 1               | 814              | 16             | 469.7              | 255.8 | 10             | 6.4 | RV  |
| 15  | 09/25/2002 | 2877/01 | Masjed<br>Soleyman<br>Dam2 | 1               |                  | 15             | 334.1              | 141.3 | 24             | 5.6 | RV  |
| 16  | 07/10/2003 | 3040/01 | HajiAbad                   | 2               |                  | 26             | 353.8              | 176.3 | 10             | 5.7 | RV  |
| 17  | 12/15/2003 | 3149/05 | Doobaran                   |                 |                  | 21             | 725.8              | 434.1 | 15             | 5.1 | RV  |
| 18  | 12/23/2003 | 3151/07 | Doobaran                   |                 |                  | 15             | 571.9              | 725.4 | 23             | 5   | RV  |
| 19  | 12/26/2003 | 3168/02 | Bam                        | 2               |                  | 0              | 759.1              | 917.6 | 8              | 6.5 | SS  |
| 20  | 03/02/2004 | 3239/01 | Abad                       | 2               | 482              | 16             | 402.5              | 246.3 | 15             | 5.1 | SS  |
| 21  | 05/28/2004 | 3333    | Hasan Keyf                 | 3               | 339              | 14             | 858.6              | 386.7 | 17             | 6.3 | RV  |
| 22  | 02/22/2005 | 3671/01 | Zarand                     | 3               | 226              | 13             | 302.5              | 293.3 | 7              | 6.4 | RV  |
| 23  | 02/22/2005 | 3697/01 | Shirinrood Dam             | 1               | 824              | 14             | 479.5              | 244.0 | 7              | 6.4 | RV  |
| 24  | 11/27/2005 | 3915/01 | Suza                       | 1               | 1334             | 11             | 313.1              | 115.6 | 9              | 5.9 | RV  |
| 25  | 03/30/2006 | 4027/05 | Chalan Choolan             | 2               | 428              | 21             | 311.5              | 194.9 | 10             | 5.1 | SS  |
| 26  | 03/31/2006 | 4027/08 | Chalan Choolan             | 2               | 428              | 1              | 413.8              | 496.5 | 6              | 6.1 | SS  |
| 27  | 03/31/2006 | 4035/03 | Tooshk-e-Ab-e-<br>Sard     | 1               | 891              | 20             | 366.9              | 221.5 | 6              | 6.1 | SS  |
| 28  | 06/28/2006 | 4147/13 | Tomban                     | 1               | 778              | 17             | 497.8              | 419.6 | 11             | 5.8 | RV  |
| 29  | 09/10/2008 | 4686/03 | Tomban                     | 1               | 778              | 5              | 574.9              | 285.4 | 12             | 6.1 | RV  |
| 30  | 10/24/2008 | 4714/01 | Abad                       | 2               | 482              | 16             | 443.0              | 155.9 | 10             | 4.8 |     |
| 31  | 07/22/2009 | 4882/03 | Tomban                     | 1               |                  | 7              | 363.4              | 182.1 | 9              | 5.4 |     |
| 32  | 07/20/2010 | 4994/01 | Eshkanan                   | 1               | 1066             | 21             | 342.3              | 97.0  | 12             | 5.8 | RV  |
| 33  | 09/27/2010 | 5062    | Ghaemiyeh                  | 2               | 617              | 30             | 326.8              | 99.0  | 17             | 5.9 | RV  |
| 34  | 08/11/2012 | 5579-1  | Varzaqan                   | 2               | 475              | 12             | 412.8              | 233.1 | 7              | 6.4 | SS  |
| 35  | 08/11/2012 | 5588-1  | Satarkhan Dam<br>3         | 3               |                  | 6              | 370.6              | 466.1 | 7              | 6.4 | SS  |
| 36  | 08/11/2012 | 5520-4  | Ahar                       | 2               |                  | 14             | 410.0              | 192.5 | 19             | 6.4 | RV  |
| 37  | 08/11/2012 | 5579-4  | Varzaqan                   | 2               | 475              | 12             | 517.6              | 206.2 | 19             | 6.4 | RV  |
| 38  | 08/11/2012 | 5587-5  | Satarkhan Dam<br>2         | 3               |                  | 6              | 323.6              | 262.2 | 19             | 6.4 | RV  |
| 39  | 08/11/2012 | 5588-6  | Satarkhan Dam<br>3         | 3               |                  | 6              | 338.7              | 427.4 | 19             | 6.4 | RV  |
| 40  | 08/14/2012 | 5589/07 | Varzaqan                   | 2               | 475              | 15             | 368.5              | 88.6  | 7              | 5   |     |
| 41  | 08/14/2012 | 5597/43 | Chai Kendy                 | 2               |                  | 17             | 348.5              | 100.0 | 7              | 5   |     |
| 42  | 08/14/2012 | 5611/02 | Mehtarloo                  | 2               |                  | 9              | 335.8              | 74.5  | 7              | 5   |     |

**Table 3** continued

| No. | Date       | Code    | Station            | SC <sup>a</sup> | V <sub>s30</sub> | R <sup>b</sup> | PGA_H <sup>d</sup> | PGA_V | D <sup>c</sup> | Mw  | SoF |
|-----|------------|---------|--------------------|-----------------|------------------|----------------|--------------------|-------|----------------|-----|-----|
| 43  | 08/14/2012 | 5637/04 | Satarkhan Dam<br>2 | 3               |                  | 11             | 321.0              | 246.2 | 7              | 5   |     |
| 44  | 08/15/2012 | 5589/08 | Varzaqan           | 2               | 475              | 8              | 368.5              | 88.6  | 4              | 5   | RV  |
| 45  | 08/15/2012 | 5597/79 | Chai Kendy         | 2               |                  | 7              | 393.2              | 153.4 | 4              | 5   | RV  |
| 46  | 09/05/2012 | 5631/19 | Chai Kendy         | 2               |                  | 9              | 404.4              | 163.0 | 7              | 4.2 |     |
| 47  | 09/27/2012 | 5631/53 | Chai Kendy         | 2               |                  | 8              | 582.5              | 243.2 | 4              | 4.6 |     |
| 48  | 11/07/2012 | 5674/05 | Varzaqan           | 2               | 475              | 12             | 318.7              | 176.3 | 10             | 5.6 | SS  |

<sup>a</sup> SC Site class based on the Iranian code

<sup>b</sup> R Epicentral or Joyner–Boore distance

<sup>c</sup> D Depth of earthquake

<sup>d</sup> PGA\_H The maximum PGA between latitude and longitude directions (not geometric mean)

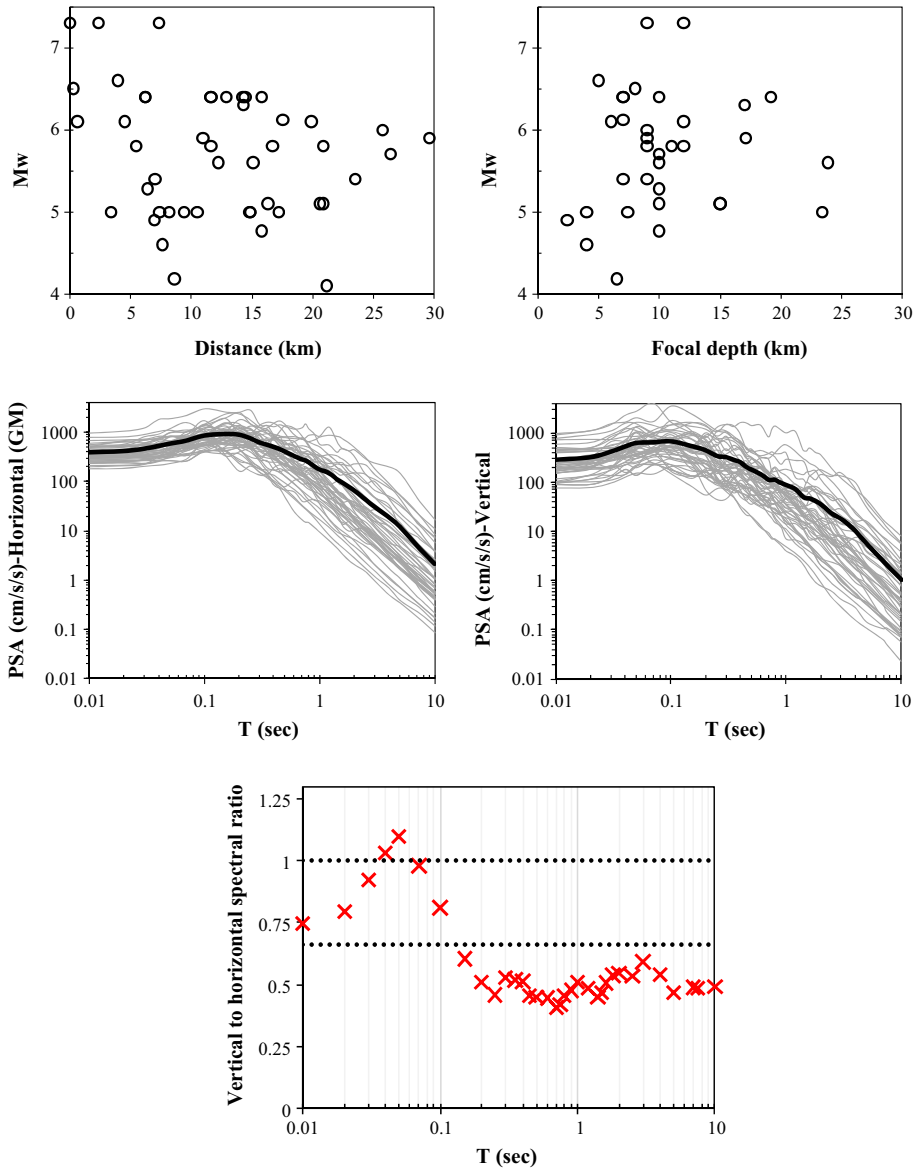
records with poor quality and unspecified some important metadata (same as magnitude), the dataset was reduced to 2286 records and 461 events. It is noticeable that the raw (unprocessed) accelerograms were uniformly processed in the entire dataset using the wavelet de-noising procedure of Ansari et al. (2010).

The earthquake magnitude (in moment magnitude scale) ranges between 3.9 and 7.3. Moment magnitude was not available for all events, especially for most of the small earthquakes. Therefore, other magnitude scales (such as M<sub>S</sub>, m<sub>b</sub> and M<sub>N</sub>) were converted to Mw scale using the best available correlations to obtain a unified seismic catalog. In addition, the entire databank included the epicentral distance information while R<sub>jb</sub> was computed only for about 30% of the records due to the lack of information on ruptured fault geometry and double-couple fault-plane solutions mainly for smaller magnitude events. About 743 stations recorded 2286 accelerograms in the selected dataset. The V<sub>s30</sub> of 306 of these stations was measured and reported by the BHRC. The site classes for about 299 stations were estimated either by geological surveys or by empirical methods. Therefore, there was no information about the soil categories for the remaining 138 stations.

Generally, the collected dataset included reliable information about the earthquake source parameters (from international or local seismological agencies and from earthquake-specific literature studies) and site features of strong motion stations (by average S-wave velocity to the depth of 30 m (V<sub>s30</sub>) or by means of empirical methods).

This detailed information provides a comprehensive catalog which includes different source-to-site distance metrics for each record (R<sub>epi</sub> and R<sub>jb</sub>), faulting mechanisms of the events and unified magnitude scales and other important parameters. The dataset can be considered as a major source for seismic risk and hazard studies for Iran and other seismically active environments in the Middle East and Mediterranean regions.

In the dataset, we emphasized on the “exceptional” ground motions that are simply characterized as records with PGA higher than 300 cm/s<sup>2</sup> and distance from the source less than 30 km. A list of 48 records was selected that shows the strongest shaking recorded in Iran since 1975. As expected, the greatest amplitudes may be due to site amplifications, and it is observed that most of the records (24 of 48 records) belong to class II. The comparison of these peak values with each other shows that some of the records come from small magnitude events (Mw ≤ 5) similar to the “exceptional” dataset introduced by



**Fig. 16** Some features of “exceptional” records

Pacor et al. (2011). The geometric mean of horizontal components is frequently used as a measure of ground motion. It is important to know that the recorded ground motions in the standard directions (i.e., NS and EW) can be significantly different from that on other horizontal directions (Pacor et al. 2011; Watson-Lamprey and Boore 2007). In “exceptional” records, it was found out that the maximum value of PGA from both horizontal directions can be up to 2 times the geometric mean of peak ground acceleration. The study

**Table 4** Different datasets in various studies

| Project/model | Provided by                  | Year | No. of event | No. of records | Mw range          | Distance type  | Max of distance |
|---------------|------------------------------|------|--------------|----------------|-------------------|----------------|-----------------|
| Present study | Zafarani and Soghrat (2012)  | –    | 461          | 2286           | Mw 3.9–7.3        | Repi, Rjb      | 400             |
| RESORCE       | Akkar et al. (2014)          | 2014 | 44           | 396            | Mw 4.56–7.42      | Repi           | 375             |
| Kea15         | Kale et al. (2015)           | 2015 | –            | 528            | Mw 4.2–7.3        | Rjb            | 200             |
| Sea12         | Saffari et al. (2012)        | 2012 | 78           | 351            | Mw 5–7.3          | Rup and Rhypo  | 135             |
| HM12          | Hamzehloo and Mahood (2012)  | 2012 | 109          | 258            | Mw 5–7.4          | Rjb            | 100             |
| Ghea10        | Ghodrati-Amiri et al. (2009) | 2010 | 189          | 416            | Ms and mb 3.2–7.7 | Rhypo          | 400             |
| Ghea09        | Ghasemi et al. (2009a)       | 2009 | 200          | 893            | Mw 5–7.4          | Rrup and Rhypo | 100             |

of strongest amplitude would be important in seismic hazard analysis because of constraining the upper bounds for ground motion predictions.

In conclusion, the effort made by the authors is somehow comparable to the preparation of the other databases such as the NGA (Power et al. 2008) and RESORCE (Akkar et al. 2014) databases. We do believe that the information presented in the paper could be very useful for anyone interested in using the Iranian strong motion database.

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