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Seismicity and seismic hazard assessment for greater Tehran region using Gumbel first asymptotic distribution

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Abstract. Considering the history of severe earthquakes and the presence of active faults in the greater Tehran region, the possibility of a destructive earthquake occurring is high and seismic hazard analysis is crucial. Gumbel distributions are commonly-used statistical distributions in earthquake engineering and seismology. Their main advantage is their basis on the largest earthquake magnitudes selected from an equal-time predefined set. In this study, the first asymptotic distribution of extremes is used to estimate seismicity parameters and peak ground acceleration (PGA). By assuming a Poisson distribution for the earthquakes, after estimation of seismicity parameters, the mean return period and the probable maximum magnitude within a given time interval are obtained. A maximum probable magnitude of 7.0 has a mean return period of 100 years in this region. For a return period of 475 years, the PGA in the greater Tehran region is estimated to be 0.39g to 0.42g, depending on local site conditions. This value is greater than that of the Iranian Code for Seismic Design of Buildings, indicating that a revision of the code is necessary.

Keywords: seismic hazard analysis; Gumbel first asymptotic distribution; returns period; probable maximum magnitude; PGA

1. Introduction

Tehran, the capital and largest city in Iran, has a history of severe earthquakes. There are several active faults in the greater Tehran region, thus the possibility of a future destructive earthquake is high. Yazdani and Kowsari (2013) estimate that the probability of exceedance an earthquake with magnitude of 6.5 or higher over 50 years in this city is more than 70 percent. Such an earthquake imposes a serious threat to this metropolitan with a population of more than 12 million and one way to mitigate the ruinous impact of such event is to conduct a seismic hazard analysis. Seismic hazard analysis includes the quantitative estimation of ground motion intensity measure in a particular region over a given time. Peak ground acceleration (PGA) which is the simplest and best parameter to characterize earthquake hazard is commonly used as an intensity measure of ground motion in seismic hazard analysis by engineers and those concerned with the effects of earthquakes on society.

Assessment of this measure has been conducted by much research in Tehran up to know.

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Tavakoli and Ghafory-Ashtiany (1999) estimated the contour levels of the peak ground acceleration (PGA) map of Iran to be 0.15g to 0.48g for a return period of 475 years. They also estimated earthquake hazard parameters for 20 seismotectonic provinces. Ghodrati *et al*. (2003) calculated seismic hazard maps based on PGA over bedrock for spaced grid points in Tehran. Their results showed that the PGA ranges from 0.27g-0.46g and 0.33g-0.55g for a return period of 475 and 950 years, respectively. Zafarani *et al*. (2009) applied a stochastic finite fault model to derive the horizontal acceleration time series for greater Tehran. Peak horizontal accelerations from their earthquake scenarios exceeded 0.7g, with the highest value occurring northwest of the city. Nowroozi (2010) estimated the potential magnitude of active faults near Tehran and obtained the probability of earthquake ground accelerations at various epicentral distances from Tehran for a given set of exposure times.

Probabilistic modeling of earthquakes occurrence is one of the main tools in safety design which is compatible with current trends in earthquake engineering and the development of building codes. A probabilistic seismic hazard analysis (PSHA) takes into account the ground motions from the full range of earthquake magnitudes that can occur on each fault or source zone that can affect the site (Cornell 1968). This approach is able to quantify the annual probability of exceeding the ground-motion levels for the parameters of interest. In analyzing earthquake hazard, the return period and the maximum probable earthquake (MPE) are essential. The MPE is an earthquake derived using a seismic probability calculation for a recurrence within a selected number of years (Krinitzsky 2002).

One of the popular methods to assess the mentioned hazard parameters and to estimate seismicity for a specific region is the Gumbel asymptotic distribution. This approach takes into account only the largest magnitude from an equal-time predetermined set (Bayrak *et al*. 2008). According to Bath (1975, 1983), the main advantage of the method is that the process is dependent on the occurrence of large earthquakes, since the accuracy of historically-determined great shocks is higher than for small shocks. The Gumbel asymptotic distribution of extreme values has been employed by a number of researchers (Makropoulos and Burton 1984, 1985, Tsapanos and Burton 1991, Burton *et al*. 2003, Bayrak *et al*. 2008, Ozturk *et al*. 2008). Makropoulos and Burton (1984), Tsapanos and Burton (1991) concluded that the estimated parameters from Gumbel's theory are better-fitted to the tectonics of the regions than those obtained from Gutenberg-Richter law. This method was used to obtain peak ground acceleration by Makropoulos and Burton (1985) to analyze the seismic hazard for Greece. Burton *et al*. (2003) then updated it by increasing the length and quality of earthquake catalogue data for Greece. Also, Bayrak *et al*. (2008) used the Gumbel first asymptotic distribution for evaluation of the seismicity in 24 seismic regions in Turkey which the *b*-values calculated from G-R law reveal a better fit to the tectonic environment of the 24 seismic rather than Gumbel's first distribution.

In the current study, the Gumbel first asymptotic distribution is used for two reasons. In the first part of this study, the asymptotic distribution of extremes is used to obtain seismic parameters which subsequently, the mean return period and the probable maximum magnitude within a given time interval are estimated. In the second part, peak ground acceleration is estimated for the region and for different local site conditions using the Gumbel first asymptotic distribution.

2. Seismicity and data used

The Iranian Plateau lies in the Alpide belt and is one of the most seismically active areas in the

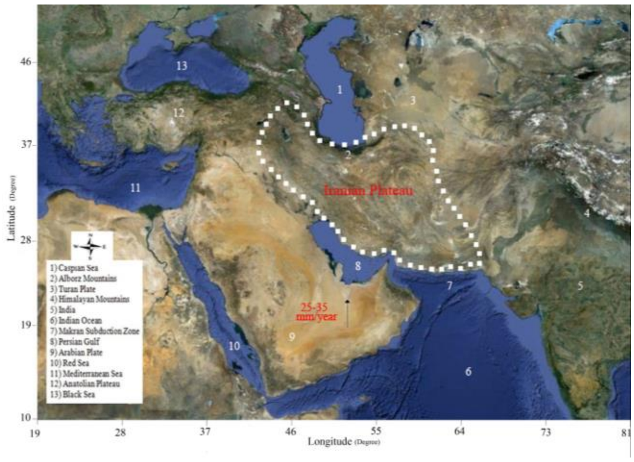

Fig. 1(a) Active tectonic features of Iran demonstrating convergence rate between Eurasian and Arabian plates (Original figure from Google map and edited by authors)

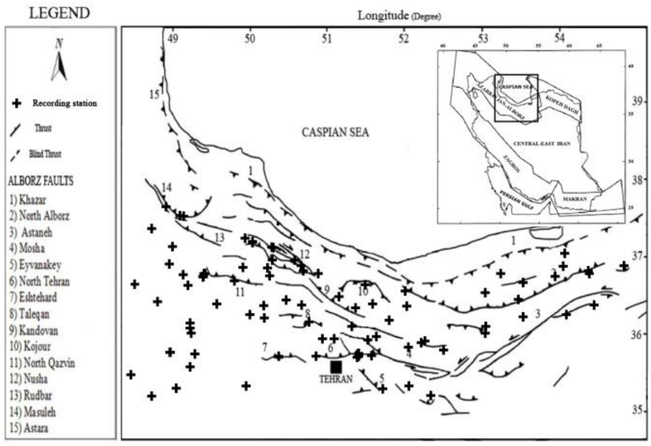

Fig. 1(b) Major active faults around greater Tehran region and seismotectonic provinces of Iran proposed by Mirzaei *et al*. (1997a)

world. Tsapanos and Burton (1991) rank Iran as 10^{th} out of 50 countries in seismic activity using the most probable earthquake magnitudes over 85 years. This plateau accommodates a 35 mm/yr convergence rate between the Eurasian and Arabian plates with strike-slip and reverse faults with relatively low slip rates across a zone of about 1000 km (Berberian and Yeats 2001) (Fig. 1(a)). One of the highly seismic regions is Alborz range in north-central and portions of northwest Iran. The pattern of seismicity for Alborz is discontinuous with large earthquakes. These mountains are under the influence of tectonic activity caused by the northward convergence of central Iran-Eurasia and the northwest motion of the southern Caspian basin (Ashtari 2007). Earthquakes in this region occur at all depths, with a median depth of 20 ± 8 km (Engdahl *et al*. 2006) and most occur in the eastern and central Alborz range. The Rudbar earthquake of June 20, 1990, with a magnitude of M_w=7.3, caused 40,000 deaths and was the most destructive earthquake of the 20^{th} century in the Alborz region.

Tehran is located near the foothills of the south-central Alborz range, a high seismic region, and is surrounded by active faults such as Mosha, North Tehran, Taleqan and etc. The Mosha, North Tehran and Taleqan faults are capable of producing moment magnitudes of 6.62-7.23 (Nowroozi 2010). Fig. 1(b) shows the Alborz region and its active faults. These regional active faults have produced a number of destructive earthquakes (M_s 7.2 in 743, M_s 7.1 in 855, M_s 7.7 in 958, M_s 7.2 in 1177, M_s 7.1 in 1830) (Ambraseys and Melville 1982, Berberian 1995, Berberian and Yeats 1999, 2001). These historical events indicate that the region may experience a major earthquake in the near future.

In seismic hazard analysis of a region it is assumed that occurred earthquakes are location and time independents. Therefore the occurrence time of an upcoming earthquake is independent from the last earthquake (Ghodrati *et al*. 2009) which means the data set should be distributed Poissonian. Recently some studies have been done in Iran which shows earthquake occurrence in Alborz is Poissonian (Yazdani and Kowsari 2011, Zafarani and Ghafoori 2013). In addition, Gardner and Knopoff (1974) showed after removing aftershocks from earthquake catalog, the main sequence list that remains is Poissonian. A suitable data sample appropriate for a seismicity study must be accurate, complete and homogenous. Earthquake catalog in Iran is based on different magnitude scales and is not homogenous so it is necessary to convert these magnitude scales in order to interpr*et al*l earthquakes with one scale using empirical relationships. However recently, Shahvar *et al*. (2013) presented a unified homogeneous earthquake catalog in moment magnitude (M_w) scale which is the most reliable and important scale in seismic hazard studies. Therefore in this study we used this catalog and there is no need using empirical relationships for converting different magnitude scales. Thus, the earthquakes of moment magnitude (M_w) > 4.0 within a 150 km radius of Tehran for 1930-2012 are also gathered and the final collective catalog was prepared by eliminating the aftershocks and foreshocks using Gardner and Knopof (1974) model from the data which are shown in Figs. 2(a) and (b).

On the other hand, the minimum magnitude of completeness of an earthquake catalog is prominent factor in seismic hazard and appropriate determination of it is necessary. This parameter is defined as the lowest magnitude above which all seismic events in a space-time volume are detected (Wiemer and Wyss 2000). Gholipoor *et al*. (2009) evaluate the completeness of Tehran's catalog which the results are shown in Table 1. The region considered in their study is the area in the radius of 150 km from the center of the greater Tehran (the same as this study). The results indicate that completeness for magnitude 4 and 4.5 is very short that we consider M_w=5 as a cut-off magnitude which is complete in the year 1930-2012.

In the second part of this study the PGA is estimated using Gumbel first asymptotic distribution. Previous studies such as Burton *et al*. (2003), Markopoulos and Burton (1985) used the attenuation relationships for estimating the PGA while in this paper we used the earthquake records. We believe that using actual records show seismicity and hazard of the region under study better than empirical attenuation relationships. To increase our dataset, we developed our area study to a radius of 300km around Tehran. Since for estimation of PGA we did not use attenuation relationship which depends truly to seismotectonic features of the region under study. This developing does not make any problem because as it has shown in Fig. 1(b) almost all of the used records are in Alborz region so the whole data used is really homogeneous.

The Iran Strong Motion Network records earthquakes using the Kinemetrics SMA-1 that registers data in an analog format from 1974 to 1991. After the Rudbar earthquake, the Kinemetrics instruments have been progressively replaced by digital SSA-2 instruments (Bard *et al*. 1998). The Iranian Code of Practice for Seismic Resistant Design of Buildings (2005)

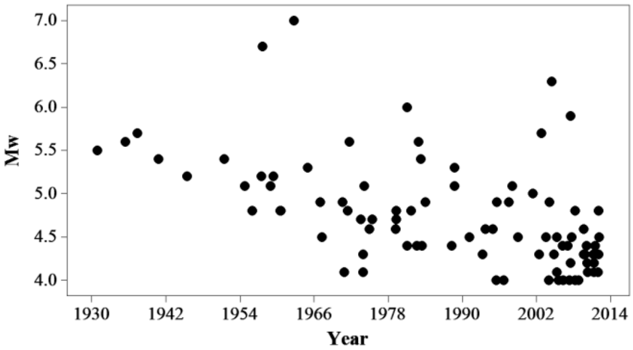

Fig. 2(a) Earthquakes of $M_w \geq 4.0$ in greater Tehran region after removal of foreshocks and aftershocks

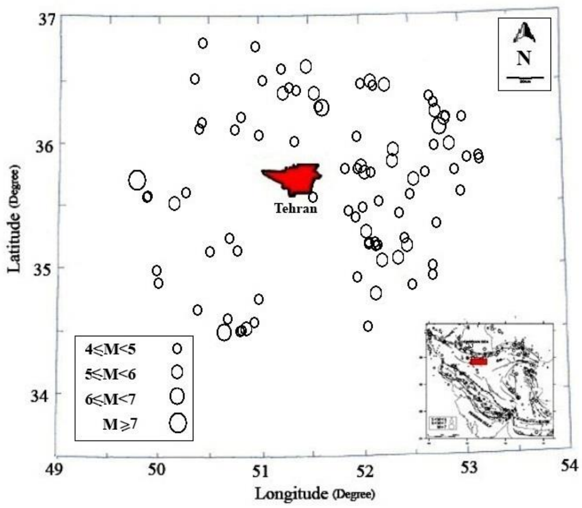

Fig. 2(b) Distribution of earthquake epicenters for greater Tehran region after 1930

Table 1 Proposed completeness periods for 0.5 magnitude bins within a 150 km radius of Tehran (Gholipoor *et al*. 2009)

Magnitude	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0
Year	1990	1965	1930	1930	1930	1600	855	Before 855	No events

categorizes soil types into four classes. The first two types, where shear wave velocity is ≥375 m/s, is known as "rock" and the two latter types, where shear wave velocity is ≤375 m/s, is known as "soil". In this study, all attempts were made to identify the type of soil on which a specific recording machine is located. If the soil type cannot be identified, site data from the Sinaeian (2006) study is employed. In addition, records having a PGA≤ 0.05g have been omitted because they have no practical significance in engineering. For correction of the records a Butterworth band-pass filter is applied. This type of filters is a good choice since it has a fairly sharp transition from pass band to stop band and it has a moderate group delay response (Bard *et al*. 1998). The frequency range over which the band-pass filter attenuates in the shape of a cosine curve was decided to be 0.2-20 Hz, on the basis of the characteristics of the analog and digital ISMN (Iranian

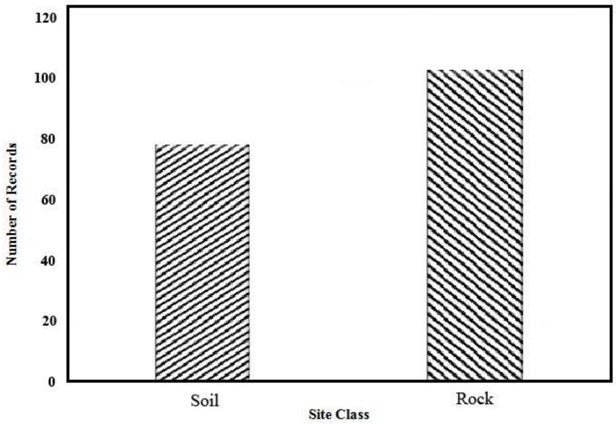

Fig. 3 Number of earthquake records versus site soil class

Strong Motion Network) instruments (Saffari *et al*. 2012). Finally, the final records contain 183 records in different local site conditions presented in Appendix 1 and Fig. 3.

3. Methodology

The Gumbel distribution which is also known as the extreme value distribution of type I is the widely applied statistical distribution for problems in engineering. Extreme value theory estimates the probability of events that are more extreme than any previously observed. This theory is formulated under the assumptions that the prevailing conditions must be almost the same in future and observed largest values are independent of each other (Ozturk *et al*. 2008). In this study, the Gumbel distribution of extremes is used to obtain seismicity parameters and peak ground acceleration which express in the following:

3.1 Seismicity parameters

The frequency distribution of earthquakes is the integral criteria for seismicity assessment. This is presented by Gutenberg and Richter (1944) in a logarithmic relationship:

$$\log(N) = a - bM \tag{1}$$

where N is the cumulative number of earthquakes, M is the earthquake magnitude and a and b are constants describing the seismicity of a region. The b value provides information about the occurrence of an event, the magnitude distribution and the average occurrence rate of earthquakes for a given region.

The whole process and part process are the methods used to process the distribution of earthquake magnitudes by time and in size. The whole process follows the Gutenberg and Richter distribution and uses all available data. The part process uses the well-known Gumbel theory of extreme values (Bayrak *et al*. 2008). Assume that earthquakes occur according to a Poisson process at occurrence rate α and the double-truncated Gutenberg-Richter distribution $F(x)$ of earthquake magnitude x. Yazdani and Kowsari (2011), Zafarani and Ghafoori (2013) showed the

Poisson model is adequate assumption for earthquake occurrence in Alborz. The double-truncated exponential distribution can be represented as (Kijko and Sellevoll 1989)

$$F(x) = P(X \leq x) = \left(\frac{A_1 - A(x)}{A_1 - A_2} \right), \qquad m_{\min} \leq x \leq m_{\max} \tag{2}$$

where A_1 = exp(-$\beta m_{\min}$), A_2 = exp(-$\beta m_{\max}$), $A(x)$ = exp(-βx), m is the magnitude and β is a parameter. Probability X (the largest magnitude within a period of t years) will be less than the number of specified magnitudes x (Kijko and Sellevoll 1989)

$$G(x|t) = P(X \leq x) = \exp(-\alpha t \left(\frac{A_2 - A(x)}{A_2 - A_{10}} \right)) \tag{3}$$

At this point, A_{10} = exp(-βm_0) and m_0 (the threshold magnitude) can be defined. From the definition of A_{10} and A_2, it follows that, where $m_{\max} \rightarrow \infty$, $A_2 \rightarrow 0$ and, where $m_0 = m_{\min} = 0$, $A_{10} = 1$ and t =1. Thus Eq. (3) becomes

$$G(x) = \exp(-\alpha(\exp(-\beta x))) \tag{4}$$

This is equivalent to the first Gumbel asymptote of extremes, where *G(M)* is the probability of all occurring earthquakes of magnitudes $<M$ in a specific unit of time. The logarithmic form of this is

$$\ln(-\ln(G(x))) = \ln \alpha - \beta M \tag{5}$$

This equation has the same form as the Gutenberg-Richter relationship. The parameters a and b of the Gutenberg-Richter distribution are related to α and β as (Bayrak *et al*. 2008)

$$a = \frac{\ln \alpha}{\ln 10} \qquad b = \frac{\ln \beta}{\ln 10} \tag{6}$$

If the parameters obtained from Eq. (6) are substituted into Eq. (5), the following is obtained

$$\log(-\ln(G(x))) = a - bx \tag{7}$$

To evaluate probability *G(x),* Gringorten's (1963) equation, which is the best for the double-truncated distribution, is applied

$$G(M_j) = \frac{j - 0.44}{n + 0.12} \tag{8}$$

Eq. (8) plots the point probability of the j^{th} observation where j is the rank, n is the number of observations and M_j is the extreme magnitude for n successive years ranked in order of increasing size (Bayrak *et al*. 2008). According to Burton (1979), this equation is the most suitable for the first asymptotic distribution of extremes. Since it is difficult to find annual extremes, especially in catalogs for the earlier years, the data set is divided into k-years extremes and the annual year extreme is calculated from the following relationship (Ozturk *et al*. 2008)

$$a_1 = a - \log k, \qquad k \geq 2 \tag{9}$$

The chi-square test is used to obtain k-years for the area under investigation. The data are divided into n bins (classes) and the test statistic is defined as (NIST/SEMATECH 2003)

$$\chi^2 = \sum_{i=1}^{n} (O_i - E_i)^2 \Big/ E_i \tag{10}$$

where O_i is the observed frequency and E_i is the expected frequency for the bins. The mean return period for events of magnitudes $\geq M$ is calculated by

$$T_m = \frac{10^{bM}}{10^{a_1}} \tag{11}$$

In addition, the maximum probable magnitude occurring in an area during time period t is

$$M_t = a_1 \big/ b + \log t \big/ b \tag{12}$$

3.2 Peak ground acceleration

Traditionally, engineers have focused on seismic acceleration related to force, which can be reliably measured (Reiter 1990). However, is important to accurately estimate the PGA in order to design earthquake resistant structures and retrofitted buildings in active seismic regions. The first Gumbel asymptotic distribution is

$$G(A) = \exp(-\exp(-x(A-y)) \tag{13}$$

where $G(A)$ is the probability of A as the annual extreme of peak ground acceleration (cm/s^2) and x and y (the characteristic modal extreme) are the parameters of this distribution. The value of PGA for the annual maximum with probability P is

$$A_P = y - \frac{(\ln(-\ln(P))}{x} \tag{14}$$

where P is replaced by $G(A)$ and $A_{P,T}$ is the peak ground acceleration (cm/s^2) in which P is not exceeded within T years (Makropoulos and Burton 1985)

$$A_{P,T} = y - \frac{\ln(-\ln(P))}{x} + \frac{\ln(T)}{x} \tag{15}$$

4. Conclusions

In the first part of this study, by using Gumbel's first asymptotic distribution, seismicity parameters and their standard deviations for the greater Tehran region are presented in Table 2. A suitable data sample should include all earthquakes over a given time period with magnitudes larger than a certain cut off value (Tsapanos and Papazachos 1998). The data comprises earthquakes with cut-off magnitudes of $M_w \geq 5$ in a 150 km radius around Tehran after 1930. The missing years in the catalogue refers to the years for which earthquake data are not available due to some reasons. Burton (1979) states that if the missing years are less than 25% of the total time span, the seismicity parameters can be accurately estimated. Furthermore, data before 1930 are incomplete and unusable for this study. After compilation of a dataset, the next task is to find the

Table 2 Seismicity parameters estimated using Gumbel first asymptotic

Method	a	σ_a	b	σ_b
Gumbel	4.3	0.2	0.9	0.04

Table 3 Maximum probable magnitude and standard deviations for given time period.

Year	Maximum probable earthquake	Standard deviation (σ_M)
5	5.55	0.02
10	5.90	0.03
25	6.33	0.06
75	6.86	0.08
100	7.00	0.09

years of extremes (k extremes in Eq. (9)). For the region under study, a chi square test is employed for datasets containing populations with specific distributions. The optimum chi square test obtained is k = 4 for the extreme years when the results are minimized.

The results are compared with those obtained from other methods to verify the approach and its performance for the region. Nowroozi and Ahmadi (1986) studied earthquake hazard in Iran based on seismotectonic provinces. Their results for seismicity parameters in Alborz province is 3.69 and 0.78 for a and b values, respectively. Mirzaei *et al*. (1997b) estimated the b-value in Alborz-Azarbayejan seismotectonic province and obtained 0.83 and 0.85 for hard and soft soil, respectively. Tavakoli and Ghafory-Ashtiany (1999) obtained b-values of 0.60 ± 0.04 for the Kijko and Sellevoll method and 0.52 ± 0.02 for the Gutenberg-Richter method in the Alborz region (province 15). Yazdani and Abdi (2011) using Gutenberg-Richter recurrence relationship estimate b-value as 0.55±0.04 for an area within a radius of 200 km of the greater Tehran region. The coefficients obtained in this study are higher than those of Tavakoli and Ghafory-Ashtiany (1999) and Yazdani and Abdi (2011). This may be because they considered threshold magnitude of 4.5 for their analysis and in general, estimation of seismicity parameters is so sensitive to threshold magnitude. The seismicity parameters estimated from this study is close to that obtained by Nowroozi and Ahmadi (1986), Mirzaei *et al*. (1997b).

The results indicate that the Gumbel method is suitable for Tehran; thus this method is proposed for regions with incomplete data sets. As mentioned, for this method, data for all earthquakes are not required; only those for extreme years are needed to calculate seismicity parameters.

After estimating a and b values, the hazard measures for this region could be calculated. Table 3 illustrates the probable maximum magnitude and the standard deviations, obtained for the given time span for the Tehran region. Also, the mean return period for given magnitude are shown in Fig. 4. The results indicate the return period of moderate and large earthquakes in this region are 10-100 years which is very dangerous for this high populated region. The peak ground acceleration is then estimated for the greater Tehran region for soil and rock site types (Table 4 and Fig. 5). The earthquake data recorded within a 300 km radius around Tehran with a PGA > 0.05g includes 79 soil site types and 104 rock site types. The Iranian Code of Practice for Seismic Resistant Design of Buildings (2005) designates that the probability of exceeding in 50 years is 10% for design and 99.5% for operational earthquakes. The code suggests a value of 0.35g for peak ground acceleration as the 475 year probabilistic design earthquake in the greater Tehran region.

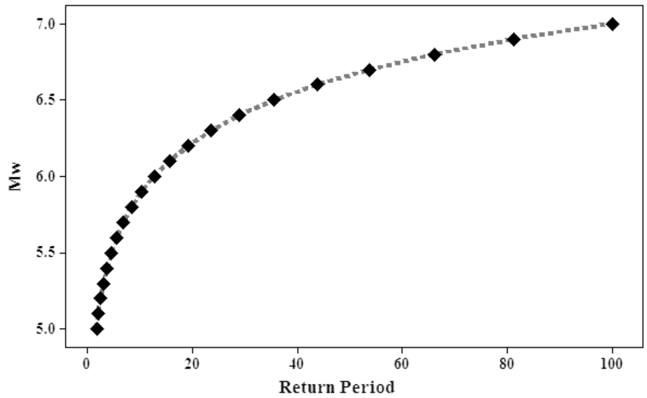

Fig. 4 Mean return period versus given moment magnitudes in greater Tehran region

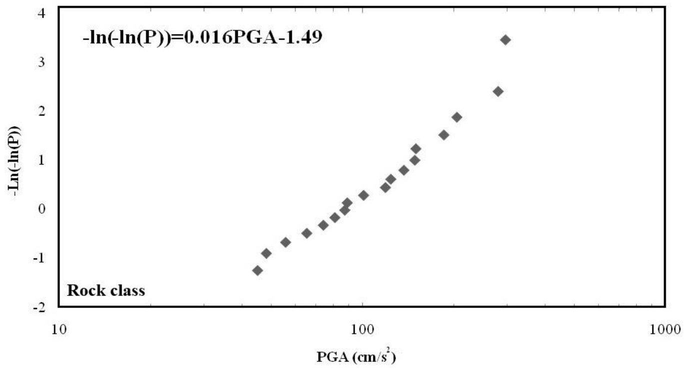

Fig. 5(a) Gumbel first asymptotic distribution for obtaining PGA in rock class

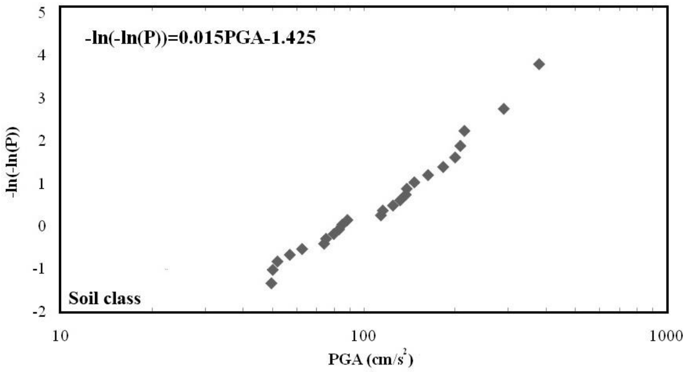

Fig. 5(b) Gumbel first asymptotic distribution for obtaining PGA in soil class

Table 4 Estimated peak ground acceleration for two levels over 50 years

Site class	PGA	
	Design Level	Operative Level
Soil	0.42 g	0.15 g
Rock	0.39 g	0.14 g

Ghodrati *et al*. (2003) assessed the seismic hazard map of the PGA over bedrock for spaced grid points in Tehran. In their study, the PGA was estimated for 0.27g to 0.46g for a return period of 475 years. Tavakoli and Ghafory-Ashtiany (1999) calculated that the maximum mean acceleration in Tehran should be about 0.45 g for a return period of 475 years and 0.3 g for a return period of 75 years. Yazdani and Abdi (2011) obtained PGA ranges of 0.33 g to 0.47 g for seven zones based on the stochastic finite fault model. In these studies, the PGA estimated over bedrock and the local site conditions are not included. In the present study, an exact PGA value is obtained using earthquake records for soil and rock site classes. This is an advantage, since other research that applied the Gumbel theory employed an attenuation relationship to estimate the approximate value for the PGA.

The results obtained in this research using the Gumbel first asymptotic distribution for estimation of seismicity parameters and the PGA are compatible with those obtained using other methods. The study reveals that the buildings metropolitan Tehran should be designed for more serious earthquakes than those currently accommodated by the current Iranian Design Code. The construction of most buildings in Tehran does not comply with engineering standards, especially in the central and southern parts of the city where the buildings have also been constructed using substandard materials. They will not be stable in even moderate earthquakes (JICA 2000); thus, an earthquake with a magnitude of M_w = 7.0 can be catastrophic. In addition, the Iranian Design Code uses PGA as the measure for designing structures, however, previous and current studies show that the PGA value is greater than that considered in the code. This indicates that the majority of Iranian seismic design codes for metropolitan Tehran metropolitan need to be revised.

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Symbols and notations

A: annual extreme value of peak ground acceleration (cm/s^2)
a: Gutenberg-Richter relationship parameter
a_1: Gutenberg-Richter relationship parameter for annual year extreme
$A_{P,T}$: peak ground acceleration (cm/s^2) where P is not exceeded within T years
A_p: annual maximum value of peak ground acceleration with probability P (cm/s^2)
b: Gutenberg-Richter relationship parameter
E_i: expected frequency for bins in chi-square test
$F(x)$: doubly truncated exponential distribution of earthquake magnitude
G(A): probability of **A** in Gumbel asymptotic distribution
$G(M_j)$: plotting point probability value of j^{th} observation
j: rank of observed value
k: years of extremes

M: earthquake magnitude (Mw)
m: earthquake magnitude (Mw)
M_j: extreme magnitudes during n successive years
M_t: maximum probable magnitude
N: cumulative number of earthquakes
n: number of observations
O_i: observed frequency for bins in chi-square test
P: probability of A in Gumbel asymptotic distribution
t: time period (years)
T: time period (years)
T_m: mean return period
x: Gumbel distribution parameter
y: Gumbel distribution parameter
α: mean rate of occurrence
β: doubly truncated exponential distribution parameter
χ^2: chi-square test to obtain year of extremes

Appendix 1

Appendix 1. Characteristics of selected records

Earthquake Date Y-M-D	Earthquake Time H:M:S	Station code	Lon.	Lat.	Mw	Depth (Km)	H1	V	H2
1976-04-16	23:23:04	1033	54.40	36.80	4.9	5	60.15	33.07	83.11
1978-11-04	15:22:20	1098-3	48.91	37.67	6.3	34	56	28	58
1979-01-01	04:25:39	1099	50.03	37.20	4.0	33	53.89	19.14	57.76
1980-07-22	05:17:06	1150	50.03	37.20	5.5	37	68.10	62.61	114.3
1980-07-22	05:17:06	1151	50.3	37.13	5.5	37	94.83	95.55	108.8
1980-12-03	04:26:15	1185	50.3	37.13	5.3	44	121.10	43.18	72.10
1981-01-12	21:11:50	1184	50.88	36.80	0.0	10	51.98	13.04	30.59
1983-12-20	22:21:01	1218	50.88	36.80	4.9	26	49.54	39.10	84.92
1984-09-09	17:55:01	1236	49.22	35.58	4.6	50	88.33	112.0	00.00
1985-10-29	13:13:40	1260	54.06	36.89	6.1	13	42.59	23.26	48.18
1988-08-22	21:23:35	1325-1	52.34	35.21	5.3	18	102.9	56.73	53.90
1988-10-24	17:01:59	1327-1	52.34	35.21	5.0	34	92.93	44.14	101.0
1988-10-24	17:01:59	1328	52.06	35.33	5.0	34	36.22	26.11	73.77
1988-10-26	14:49:20	1327-3	52.34	35.21	4.7	6	55.73	31.79	48.25
1988-12-03	18:42:50	1332-4	52.34	35.21	4.4	10	80.43	50.74	137.85
1988-12-03	18:42:50	1332-5	52.34	35.21	4.4	10	68.43	41.61	53.55
1990-01-20	01:27:10	1373	53.06	36.11	5.9	25	98.49	36.57	104.08
1990-04-21	21:57:53	1374	53.05	36.55	4.5	29	142.69	60.28	142.57
1990-06-20	21:00:11	1361	51.32	36.11	7.3	18	72.11	39.73	101.65
1990-06-20	21:00:11	1407	51.39	35.71	7.3	18	53.24	28.33	60.41
1990-06-20	21:00:11	1408	51.39	35.71	7.3	18	53.9	30.79	51.28
1990-06-20	21:00:11	1353-1	50	36.26	7.3	18	204.59	99.04	136.24
1990-06-20	21:00:11	1354	49.22	36.09	7.3	18	129.61	76.25	215.29
1990-06-20	21:00:11	1355	50.30	37.13	7.3	18	93.90	85.43	81.12
1990-06-20	21:00:11	1357-1	50.03	37.21	7.3	18	112.09	86.93	187.94
1990-06-20	21:00:11	1359	50.88	36.80	7.3	18	132.57	35.02	87.54
1990-06-20	21:00:11	1364	48.50	36.66	7.3	18	132.49	55.12	60.20
1990-06-20	21:00:11	1372	50.37	35.72	7.3	18	70.59	45.96	76.92
1990-06-20	21:00:11	1355	50.30	37.13	7.3	18	93.90	85.43	81.12
1990-06-21	09:02:15	1362-8	48.95	36.92	5.7	15	75.07	43.56	148.03
1990-06-21	12:17:32	1362-9	48.95	36.92	5.0	10	37.93	25.70	66.76
1990-06-21	21:27:39	1362-10	48.95	36.92	5.2	10	36.26	32.95	65.01
1990-06-24	09:46:01	1360	49.39	36.76	5.3	10	414.65	199.93	406.80
1990-06-24	09:46:01	1362-12	48.95	36.92	5.3	10	37.31	14.18	50.31
1990-06-29	06:25:52	1368-1	49.40	36.80	4.5	46	97.15	89.25	123.44
1990-07-01	17:19:49	1393-4	48.95	36.92	4.6	54	58.15	81.19	46.88
1990-07-01	21:16:52	1368-5	49.40	36.80	4.8	45	90.44	28.03	57.61
1990-07-02	17:44:57	1368-8	49.40	36.80	4.5	10	66.51	21.73	49.45
1990-07-06	19:34:54	1377-1	49.39	36.76	5.3	51	177.15	115.18	205.31
1990-07-06	19:34:54	1393-7	48.95	36.92	5.5	34	54.15	24.85	47.81
1990-08-21	03:47:31	1377-2	49.39	36.76	4.9	10	104.17	30.37	76.34
1990-08-21	03:47:31	1381	49.39	36.75	4.9	10	39.82	30.51	73.56
1990-08-21	03:47:31	1382-7	49.40	36.80	4.9	10	203	93.24	101.66
1990-09-25	12:12:20	1382-9	49.40	36.80	4.8	40	20.91	9.19	49.68
1990-09-25	12:12:20	1397-3	49.39	36.76	4.8	40	50.33	29.75	103.01
1990-10-22	03:50:26	1382-11	49.40	36.80	4.8	58	67.49	32.52	58.56
1990-12-27	13:26:57	1395-1	49.40	36.80	4.7	10	44.77	65.90	102.98
1990-12-28	04:03:54	1395-5	49.40	36.80	5.1	10	101.07	46.29	62.22
1990-12-28	04:03:54	1397-8	49.39	36.76	5.1	10	59.73	18.70	58.77

Appendix 1 Continued

1990-12-28	04:03:54	1398-3	49.39	36.75	5.1	10	19.82	27.79	53.87
1991-05-29	15:15:18	1414	53.06	36.11	4.4	33	44.99	29.20	94.82
1991-09-08	17:01:26	1420-2	49.40	36.80	4.5	15	90.97	17.11	66.97
1991-11-28	17:19:58	1418	49.39	36.75	5.6	15	93.43	62.34	138.43
1991-11-28	17:19:58	1419-1	49.39	36.75	5.6	15	444.70	136.37	335.2
1991-11-28	17:19:58	1420-4	49.40	36.80	5.6	15	280.50	138.28	00.00
1991-11-28	17:19:58	1418	49.39	36.75	5.6	15	93.43	62.34	138.43
1991-12-01	11:18:24	1420-5	49.40	36.80	3.8	10	60.34	21.34	106.19
1991-12-04	06:02:49	1417-2	48.95	36.92	4.4	33	58.89	19.92	31.50
1991-12-04	06:02:49	1420-6	49.40	36.80	4.4	33	135.25	54.22	87.22
1992-11-29	00:00:00	1450	49.40	36.80	4.0	10	55.70	16.84	35.63
1993-08-19	10:04:28	1474	52.06	35.33	4.6	18	62.59	14.39	37.03
1994-11-21	18:55:16	1643	52.05	35.84	4.6	33	74.25	40.31	54.97
1995-01-06	06:57:56	1549-4	49.79	36.70			65.91	49.72	59.22
1995-04-26	11:46:12	1535-2	49.41	36.80	4.9	33	100.81	88.08	94.92
1995-04-26	11:46:12	1547-2	49.39	36.75	4.9	33	66.04	24.81	16.73
1995-06-03	20:08:33	1620-1	53.04	36.02	4.0	33	115.65	49.01	70.10
1995-06-26	21:12:55	1626	51.15	36.50	4.9	33	66.29	41.60	41.9
1995-07-28	20:44:27	1620-2	53.05	36.02	4.0	33	66.45	25.12	39.46
1996-07-27	11:52:58	1629-4	48.72	37.38	3.8	33	54.30	32.17	31.16
1996-08-08	02:09:39	1636-3	49.41	36.80	4.0	33	72.83	48.03	87.33
1996-08-08	02:09:39	1666-2	49.39	36.75	4.0	33	76.12	27.55	26.29
1996-08-25	14:17:08	1798	53.05	36.11	4.0	33	34.69	12.78	50.97
1996-08-25	14:17:08	1783-1	53.05	36.02	4.0	33	47.16	28.19	79.63
1996-10-14	12:17:40	2138	54.06	36.89			30.11	27.40	54.01
1997-06-07	20:29:48	1791	50.47	36.45	4.9	33	185.62	83.88	139.29
1997-06-07	20:29:48	1806-2	50.67	36.39	4.9	33	71.05	17.32	42.81
1997-11-03	07:21:50	1859-3	54.46	36.39	5.1	33	73.88	158.60	92.19
1997-11-03	11:43:21	1859-6	54.46	36.39	4.0	33	114.20	282.33	147.25
1998-01-02	02:49:20	2279-2	49.39	36.76	4.0	10	50.14	31.93	41.06
1998-01-30	19:44:35	2136-1	50.25	36.77	4.0	33	30.26	54.13	49.66
1998-02-28	00:39:12	1956	48.95	36.92	4.8	52	53.03	19.57	21.57
1998-07-30	13:15:48	2076	49.18	37.54	4.4	33	44.28	31.50	60.62
1998-10-09	21:11:07	2052-3	48.99	37.15			73.44	25.83	70.03
1998-12-03	13:13:33	2096-1	50.76	36.17	4.5	46	148.80	33.72	116.15
1998-12-03	21:07:15	2096-2	50.76	36.17	4.5	46	64.65	17.29	66.13
1998-12-19	04:54:00	2454-1	50.88	36.80	4.3	10	26.91	41.92	48.09
1999-03-26	12:06:52	1785	52.22	35.90	3.9	15	47.59	44.29	39.93
1999-11-19	04:40:24	2345	54.06	36.89	5.4	32	63.73	23.94	60.85
1999-11-19	04:40:24	2299	54.08	37.06	5.4	32	43.44	16.26	57.60
1999-11-19	04:40:24	2345	54.06	36.89	5.4	32	63.73	23.94	60.85
2000-04-02	16:55:52	2674-4	49.79	36.70		33	70.56	45.15	84.32
2001-08-04	07:32:55	2664-6	52.22	35.90			76.48	45.11	43.53
2002-01-05	14:43:42	2653	49.09	37.55	4.4	15	84.56	41.33	53.89
2002-02-14	20:06:23	2676-3	49.41	36.80	4.4	45	76.04	61.94	75.85
2002-04-08	18:30:58	2696	52.03	36.37	5.1	46	102.48	115.84	104.65
2002-04-19	13:46:49	2723-1	49.90	36.88	5.2	33	52.70	21.49	40.84
2002-04-19	13:46:49	2976-1	50.23	36.87	5.2	33	52.42	26.57	56.59
2002-04-19	13:46:49	2705-2	49.79	36.70	5.2	33	144.84	166.80	136.63
2002-04-19	13:46:49	2787-1	49.57	36.40	5.2	33	56.56	41.94	61.065
2002-06-22	02:58:20	2748-1	49.28	35.75	6.4	10	119.65	50.99	130.36
2002-06-22	02:58:20	2754-1	48.72	35.20	6.4	10	87.49	70.91	166.18
2002-06-22	02:58:20	2756-1	49.03	35.39	6.4	10	183.53	134.59	200.57
2002-06-22	02:58:20	2763	49.22	36.15	6.4	10	39.43	28.91	74.29
2002-06-22	02:58:20	2778	48.06	35.46	6.4	10	51.83	23.38	85.09

Appendix 1 Continued

2002-06-22	02:58:20	2781	48.45	35.48	6.4	10	179.76	92.54	128.06
2002-06-22	02:58:20	2769-2	49.23	36.02	6.4	10	55.67	42.32	77.59
2002-06-22	02:58:20	2824	49.95	35.33	6.4	10	36.89	20.93	47.12
2002-06-22	06:45:33	2748-3	49.28	35.75	5.1	10	54.32	20.96	72.67
2002-06-26	18:58:52	2764-2	48.96	35.77	4.5	33	55.56	23.88	27.83
2002-06-22	02:58:20	2781	48.45	35.48	6.4	10	179.76	92.54	128.06
2002-06-28	19:27:30	2904	54.09	36.26	4.2	33	53.03	18.34	36.42
2002-07-03	19:24:51	2816	48.96	35.77	4.3	10	52.54	23.12	41.98
2002-07-10	20:26:10	2827-1	48.96	35.77	4.1	33	146.0	30.8	87.85
2002-07-10	22:57:52	2827-4	48.96	35.77	4.1	33	81.13	60.55	133.20
2002-07-25	13:29:58	2841-5	48.96	35.77	4.2	10	56.67	88.87	150.28
2002-08-01	22:41:55	2982	49.39	36.75			68.86	29.33	28.48
2002-10-12	01:22:38	2910-1	52.22	35.90	4.1	28	143.40	137.37	98.46
2002-10-15	13:59:31	2910-3	52.22	35.90	4.4	10	25.24	14.28	18.72
2002-11-07	16:43:26	2917	49.22	35.58	5.4	33	59.39	17.15	39.95
2003-03-09	22:50:23	2970	51.58	35.73	4.8	14	55.91	12.63	29.87
2003-04-07	20:52:53	3096-4	48.96	35.77		33	63.90	37.57	65.41
2004-05-28	12:38:46	3317	50.93	35.95	6.3	17	97.39	25.43	91.12
2004-05-28	12:38:46	3321	50.85	35.72	6.3	17	52.10	28.27	42.14
2004-05-28	12:38:46	3330-1	51.59	36.40	6.3	17	290.42	253.47	167.34
2004-05-28	12:38:46	3368-1	51.49	36.65	6.3	17	73.28	38.13	106.73
2004-05-28	12:38:46	3369-1	52.01	36.57	6.3	17	50.15	19.42	60.35
2004-05-28	12:38:46	3373	50.28	37.14	6.3	17	48.53	22.79	52.63
2004-05-28	12:38:46	3378	49.79	36.70	6.3	17	57.06	26.17	59.99
2004-05-28	12:38:46	3446	49.94	37.26	6.3	17	47.09	14.73	58.18
2004-05-28	12:38:46	3297	51.41	35.76	6.3	17	57.53	28.36	54.40
2004-05-28	12:38:46	3298	51.41	35.76	6.3	17	46.22	24.73	40.57
2004-05-28	12:38:46	3299	51.41	35.72	6.3	17	58.59	55.45	61.26
2004-05-28	12:38:46	3317	50.93	35.95	6.3	17	97.39	25.43	91.12
2004-05-28	12:38:46	3318	50.76	36.17	6.3	17	96.44	63.21	121.09
2004-05-28	12:38:46	3325	51.53	35.93	6.3	17	36.62	31.43	59.15
2004-05-28	12:38:46	3326	51.63	35.98	6.3	17	65.09	42.09	72.95
2004-05-28	12:38:46	3355	50.57	36.97	6.3	17	93.16	38.20	143.31
2004-05-28	12:38:46	3364-1	51.09	35.95	6.3	17	189.28	63.94	37.21
2004-05-28	12:38:46	3367	50.47	36.45	6.3	17	296.68	78.64	271.96
2004-05-28	12:38:46	3378	49.79	36.70	6.3	17	57.06	26.17	59.99
2004-05-28	12:38:46	3376	49.90	36.88	6.3	17	108.17	53.33	100.80
2004-05-28	12:38:46	3420	50.66	36.90	6.3	17	77.59	22.39	49.26
2004-05-28	12:38:46	3427	49.39	36.75	6.3	17	82.89	23.19	49.77
2004-05-28	12:38:46	3430	50.69	36.83	6.3	17	129.78	46.41	68.67
2004-05-28	12:38:46	3436	50.28	36.97	6.3	17	55.86	26.29	38.10
2004-05-28	12:38:46	3442	50.23	36.87	6.3	17	134.27	84.31	125.51
2004-05-28	12:38:46	3444	50.18	36.38	6.3	17	43.41	29.74	59.87
2004-05-28	13:07:00	3330-4	51.59	36.40	6.3	17	58.26	16.58	57.81
2004-05-29	04:12:35	3330-11	51.59	36.40	4.3	10	65.57	14.04	41.46
2004-05-29	09:23:47	3330-12	51.59	36.40	5.2	10	83.39	36.96	81.41
2004-05-29	09:23:47	3432-1	51.80	36.19	5.2	10	42.68	20.58	110.78
2004-05-30	19:26:59	3381-4	51.59	36.40	4.6	10	57.19	18.14	39.45
2004-06-14	22:25:08	3493	49.79	36.70	4.5	10	68.39	43.2	49.92
2004-07-23	12:22:00	3736-1	49.39	36.75	4.1	45	70.70	15.29	14.41
2004-10-07	21:46:18	3545	54.38	36.83	5.6	34	104.14	47.00	63.83
2004-10-07	21:46:18	3552	53.25	36.80	5.6	34	33.04	15.47	48.19
2004-10-07	21:46:18	3543	53.54	36.68	5.6	34	46.75	41.16	52.27
2004-10-07	21:46:18	3559	53.48	36.46	5.6	34	51.80	19.11	40.09
2004-10-07	21:46:18	3542	54.85	36.90	5.6	34	61.72	35.44	53.81

Appendix 1 Continued

2004-10-07	21:46:18	3543	53.54	36.68	5.6	34	46.75	41.16	52.27
2004-10-07	21:46:18	3545	54.38	36.83	5.6	34	104.14	47.00	63.83
2004-10-07	21:46:18	3546	54.08	37.06	5.6	34	92.14	29.03	86.82
2004-10-07	21:46:18	3557-2	53.95	36.76	5.6	34	62.11	44.74	67.30
2004-11-19	09:32:25	3735-3	49.41	36.80	4.1	12	52.38	33.25	61.83
2005-01-10	18:47:30	3607	54.08	37.06	5.4	31	94.29	21.93	57.24
2005-01-10	18:47:30	3623	54.38	36.83	5.4	31	60.78	31.31	43.99
2005-04-14	08:44:13	3924	49.41	36.80	4.2	14	81.38	55.25	136.97
2006-02-22	23:19:26	3995	50.18	36.22	4.4	12	81	38	64
2006-06-28	14:11:11	4169-3	48.96	35.77	4.3	13	53	31	65
2006-11-05	20:06:40	4476-1	49.09	37.55	4.8	14	35	37	66
2006-12-26	21:57:02	4374	51.72	35.30	4.4	14	40	30	59
2007-06-04	08:04:17	4511	51.36	36.35	4.2	3	57	23	33
2007-09-29	21:52:18	4487	48.72	37.38	4.1	4	118	43	125
2007-10-18	20:48:39	4490	52.51	35.80	4.1	6	124	78	124
2007-11-01	15:21:49	4514	52.27	35.92	4.4	14	74	34	32
2007-12-12	02:52:45	4531	53.54	36.23	4.1	14	33	20	52
2008-05-27	06:18:08	4602	48.79	36.43	5.4	23	59	28	51
2008-05-27	06:18:08	4604	48.95	36.92	5.4	23	57	29	89
2008-05-27	06:18:08	4600	49.13	36.78	5.4	23	34	16	55
2008-05-27	06:18:08	4605	48.5	36.66	5.4	23	51	21	35
2008-05-27	06:18:08	4607	49.19	36.64	5.4	23	91	32	52
2008-09-13	19:24:13	4699	49.79	36.70	4.4	7	74	109	125
2009-08-14	22:05:03	4830-2	52.03	36.37	4.6	6	119	37	76

H_1, H_2 and V: Horizontal 1, Horizontal 2 and Vertical components of peak ground acceleration in cm/s^2