Investigation of Site Response Analyses of the Ezgeleh - Sarpol-e Zahab Earthquake, Iran, in West of Sarpol-e Zahab Town

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ABSTRACT

In this paper, the site conditions of the western parts of Sarpol-e Zahab were studied for their impact on the seismic waves of the Ezgeleh - Sarpol-e Zahab earthquake, which occurred on November 12, 2017. The aforementioned earthquake resulted in widespread damage in the town, particularly in its south-west parts. Although the first assumptions focused on construction issues or design weaknesses related to the buildings, the site effects should not be underestimated. Site effects are widely recognized as an important factor of seismic risk. Subsurface geotechnical and geophysical data in four different sites in the town from the north to the south of the western parts have been obtained, and used to estimate the local site condition on earthquake ground motion in the area. The ground response analyses have been conducted considering the nonlinear behavior of the soil deposits using equivalent linear approach. From the results of this study, it was determined that the reason for the increase of destruction from North to the South parts of the region was the amplification of seismic waves.

Keywords:
Earthquake; Site Effects; Sarpol-e Zahab

1. Introduction

The geotechnical conditions, particularly of the near surface, are of paramount importance in a variety of amplitude and frequency content of earthquake records. Due to their direct influence on behavior of structures, it can be used to estimate damage distribution [1-2]. Understanding the geotechnical conditions of a site is needed for site response analysis, which can be used to examine how the ground surface shakes under a given seismic record at the bedrock, if the properties of the soil profile are known [3]. One-dimensional site response analysis has been used as one of the most popular approaches to qualify the influences of soil deposits in recent years [4-5]. In this method, it is assumed that not only soil, but bedrock is horizontally layered and the earthquake's shear waves propagate vertically [6].

1.1. Ezgeleh - Sarpol-e Zahab Earthquake

On November 12, 2017, the Ezgeleh - Sarpol-e Zahab Earthquake (Mw 7.3) occurred at depth of 18 kilometers in the West of Iran, 37 Kilometers from North-West of Sarpol-e Zahab town. The event continued for around 30 seconds and was felt in vast areas of Middle East. According to the active fault map of Iran [7], this earthquake can be considered as the result of the movement of Zagros Mountain Front Fault (MFF) in the Zahab region. The earthquake's location, according to different seismological centers, is shown in Figure (1). In addition, three pre-events occurred before the main event [8]. Although this area had experienced several earthquakes in recorded history such as mb 6.5 [9], no earthquake has been recorded with a magnitude above 7 in this area.

2. Damages in West of Sarpol-e Zahab

Many buildings were damaged in this earthquake

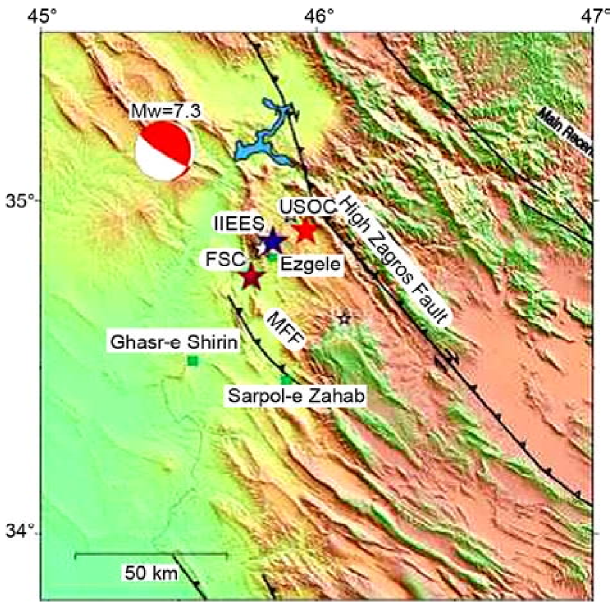


Figure 1. Location of the Ezgeleh - Sarpol-e Zahab earthquake [8].

to varying degrees including several cases of total collapse of major structures in initial hours and days after earthquake. Some photos of damaged structures known as "Maskan-e Mehr" in the West of Sarpol-e Zahab town that have been noticeable in the news are shown in Figure (2).

Based on site visit of Sarpol-e Zahab town by the first author of this paper a day after the earthquake and the preliminary report regarding geotechnical earthquake hazards [8], there were different damage situations (north to south) in western area of Sarpol-e Zahab town as shown in Figure (2) due to local site effects and next damage assessments published [10] to validate it (Figure 2). The purpose of this research would be to understand well enough the physics of site effects, and findings about how local geology significantly modifies strong ground motion and controls the irregular distribution of damage observed during this earthquake in this area. It should be mentioned that some collapsed structures in north (Figure 3) and in south due to the weakness of design and construction not related to site effects.

The south-western part of Sarpol-e Zahab was the most populous district of the town. Thus, the widespread damage in that area attracted more attention as mentioned. It was visibly observed that the damage pattern was worse while heading north-west to south-west, although there were some exceptions (Figure 3). The whole concept of this

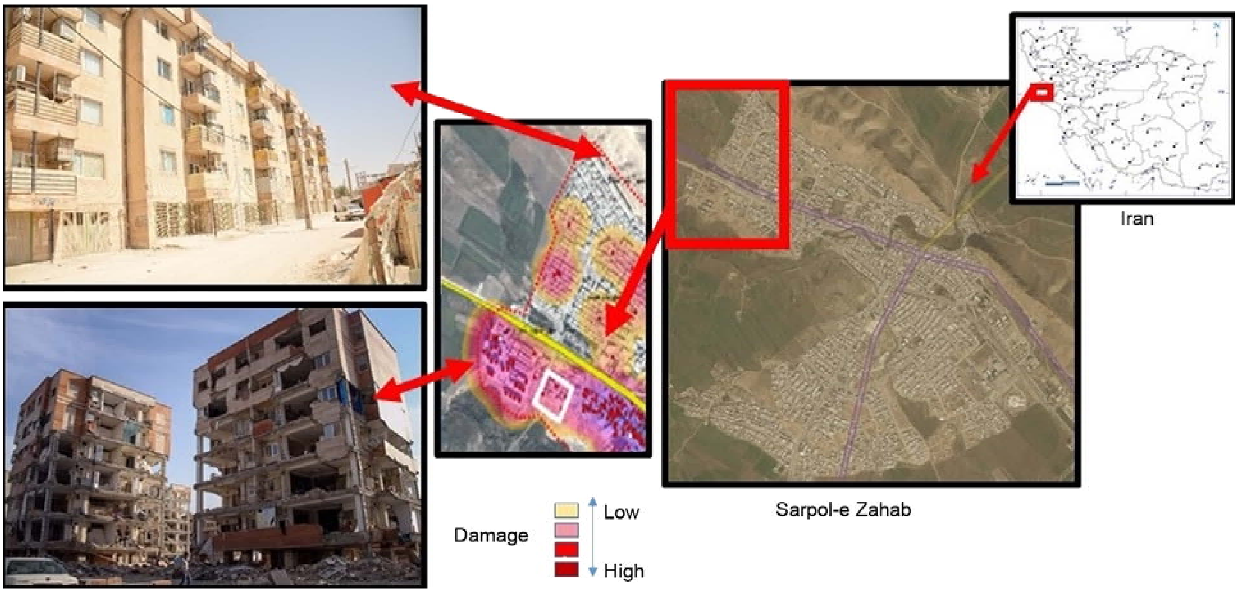
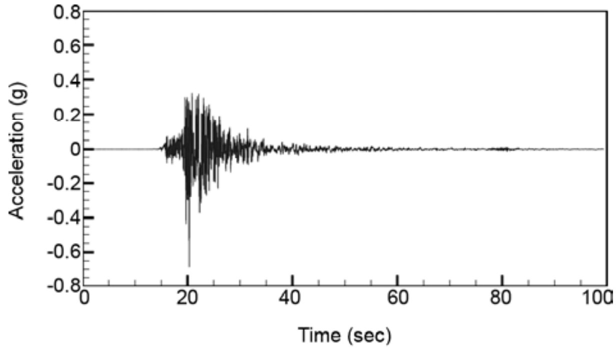
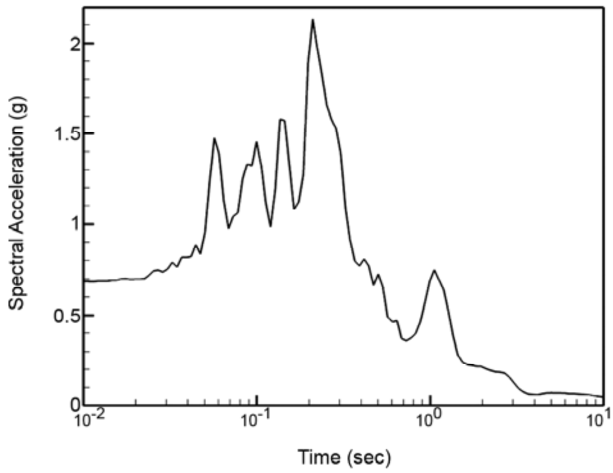


Figure 2. Study location and destructing trend in north and south of the study area in west of Sarpol-e Zahab town (damage assessment based on Unitar [10]).

Figure 3. A pancake collapse in northern part of the study area due to the weakness of design and construction.



(a) Time History Acceleration of Northern Component



(b) Spectral Acceleration of Northern Component

Figure 4. Ezgeleh - Sarpol-e Zahab earthquake [11].

trend is shown in Figure (2).

As explained before, the initial hypothesis was focused on the constructional defects in the South-Western buildings. However, it was noted that the site effects could have significant influence on the resultant damages. Thus, the main objective of this paper became a broader investigation into determining the factors contributing to the destruction in the West of Sarpol-e Zahab as explained in next parts.

3. Methodology

Based on the existing geological and geotechnical data and geophysical data measurements conducted by IIEES, one-dimensional site response analysis was developed. Geologic deposits can amplify strong ground motions depending on the physical properties of the soil as well as their three-dimensional geometrical distribution. Detailed information for the region on the three-dimensional distribution of materials was not available to be incorporated into maps showing variations in ground response. Consequently, site effects were studied based on the variation of surface layers. The methodology of the site effect assessment throughout the study area adopted here consisted of the following steps:

- The strong motion of the November 12, 2017, Mw 7.3 main shock had been recorded by 98 stations of the Iran Strong Motion Network (ISMN) [11]. It was the Sarpol-e Zahab strong motion record that was the most important record of this earthquake, due to its highest acceleration value (0.69 g). In this paper, the northern component of the record had been chosen since it had the highest Peak Ground Acceleration (PGA). The northern component of this record and its spectral acceleration can be seen in Figure (4).
- In order to be well-informed on the site characteristics for different locations in the study scope, some geophysical investigations had been completed within days following the earthquake by IIEES (Figures 5 and 6). One of the tests conducted in a place where the main acceleration was recorded there (St.13). This is attributed to lack of any reliable data about the site characteristic at which the accelerogram was installed. Due to the geophysical investigations, some useful parameters, for example shear wave velocity within different layers, could be estimated. Although geophysical surveys do not illustrate the precise details of the different layers, they have a significant impact on recognizing an approximate estimation of the layer's depth [12]. In 2006, during construction in the region, some geotechnical tests had been done by the designers of buildings in the west of Sarpol-e Zahab. According to these

geotechnical tests, the soil type of the region was largely clay. Furthermore, during the authors' filed visit to the town, which was some months after the earthquake, once the locals had begun rebuilding their homes, the soil condition was assumed to be clay for this paper.

The variety of shear wave velocity, the unit weight of soil, and thickness of each layer estimated in stations are shown in Table (1). Furthermore, these characteristics are illustrated in the projected line of section A-B, in Figure (7).

❖ Deconvolution via frequency domain analysis is a useful method for applying the input motion at anywhere in the soil column. In such circumstances, the rock motion is then computed and provided to the user (DEEPSOIL manual). Since the time-history acceleration of Sarpol-e Zahab station had been recorded on top of the soil, a deconvolution scheme in site response analysis based on the geophysical investigation near the

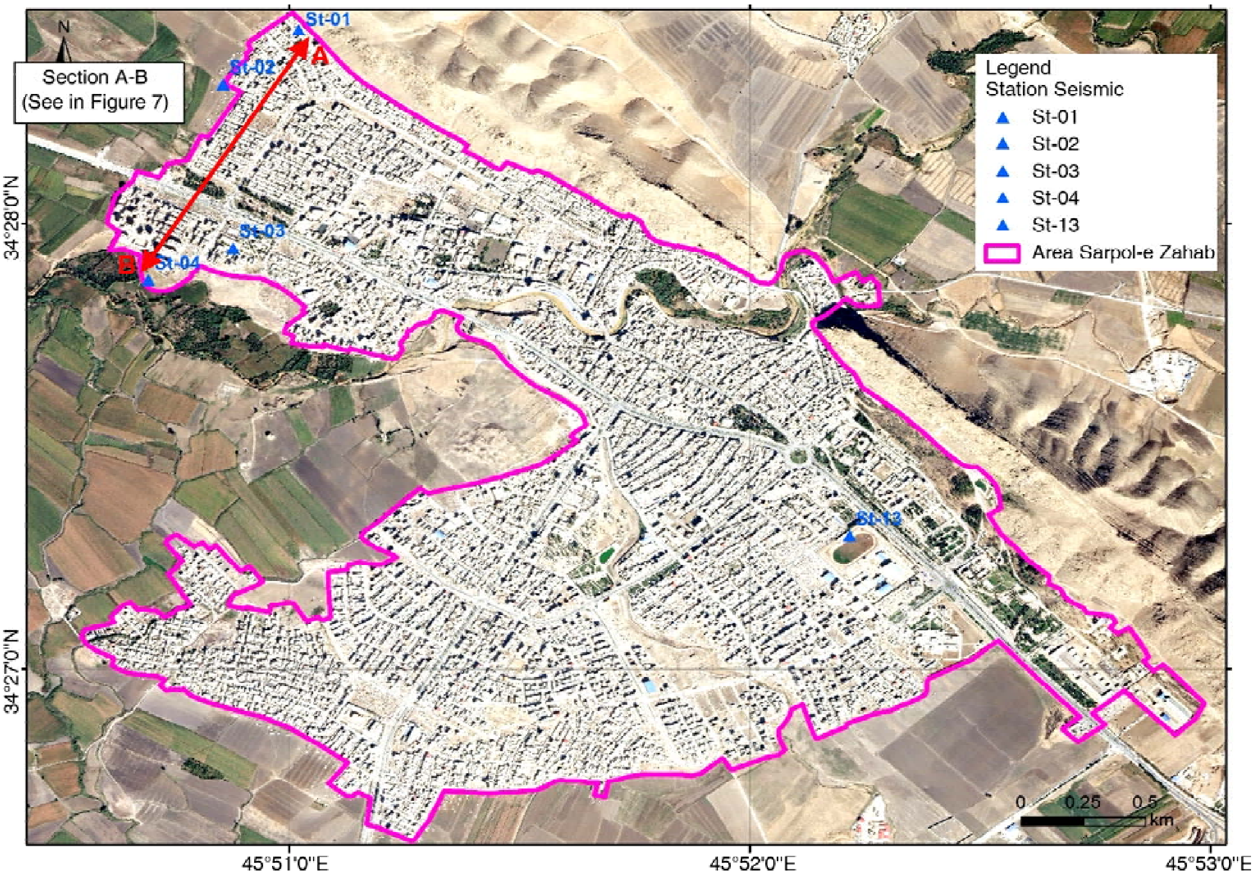


Figure 5. Location of geophysical investigations.

Figure 6. Geophysical investigations in the region.

Table 1. Characteristics of different stations.

Number of Station	Layers	Unit Weight (KN/m^3)	Thickness (m)	Shear Wave Velocity (m/sec)
1	Layer 1	18	3	450
	Layer 2	19	11	650
2	Layer 1	17	4	180
	Layer 2	18	2	450
	Layer 3	19	9	650
3	Layer 1	17	7	180
	Layer 2	18	9	450
4	Layer 1	17	3	180
	Layer 2	18	10	450

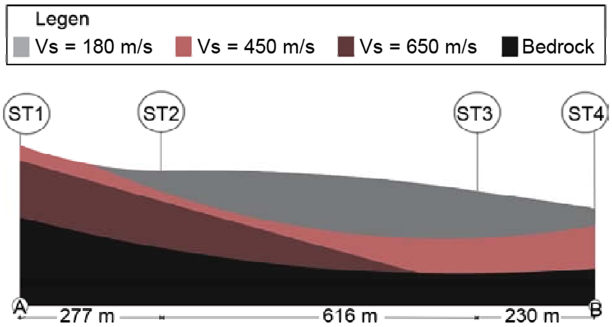


Figure 7. Characteristic of soil in section A-B in Figure (5).

main Sarpol-e Zahab station (St 13 in Figure 5), has been applied to provide a time-history record on the bedrock. The soil condition of this station is shown in Figure (8). In order to achieve this, the main recorded time-history, deconvolutioned considering nearest estimated profile assuming rigid and elastic half-space conditions. This was due to other reports from IIEES where researchers had recorded some shear wave velocities more than 1500 m/s in Sarpol-e Zahab and consequently, that estimated depth considered as the bedrock. In both cases, the strong ground motion parameters and the acceleration spectrum on the bedrock were analogous. According to the deconvolution analysis, the value of peak acceleration on rock was approximately 0.3 g.

- ❖ Considering time series that was obtained from deconvolution scheme as input motion for convolution scheme in site response analyses based on geophysical investigation data through the study area, and the estimation of strong ground motion characteristics, such as peak ground acceleration (PGA), on the free surface.

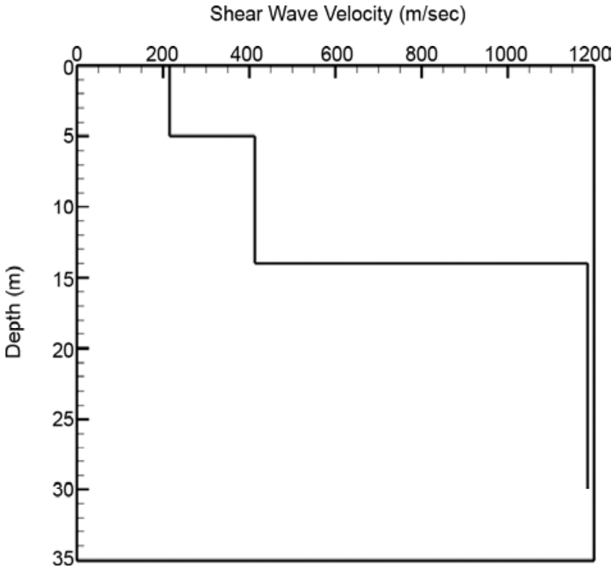


Figure 8. Soil condition near where the main accelerogram recorded.

Convolution analysis has been done in the four testing sites to explore the quantity of PGA in the neighborhood as well as their acceleration spectrums.

In the next section of the paper, one-dimensional site response analysis results of the representative profiles are presented.

4. Results

In this paper, the influence of the site effects on seismic response was examined by 1-D linear and equivalent linear analysis using DEEPSOIL [13]. The amplification of site was estimated using convolution analysis of the obtained record on bedrock. In this step, the bedrock was assumed as both rigid and elastic half-space. Additionally, Vucetic and Dorby [14] curve were used for estimating the shear modulus-strain and damping ratio-strain. This was because in such conditions, in the station near where the main accelerogram recorded, the obtained acceleration spectrum and PGA (0.69 g) were the same as the recorded acceleration spectrum and PGA by the installed accelerographs in the town. It would be reasonable if the time-history acceleration on bedrock is convolutioned considering all of the four stations to investigate the site effects during the studied earthquake. Four obtained PGA's after the convolution analysis of the stations are displayed in Table (2) for the equivalent linear and linear analysis respectively.

As shown in Table (3), the region had experienced a large amount of PGA especially in the southern parts of the town during the Ezgeleh - Sarpol-e Zahab Earthquake, which corresponds with the destruction. The obtained acceleration spectrums of these four sites on the ground are displayed in Figure (9).

The Figure (9) shows that there is an amplification during the period between 0.2 and 0.5 seconds in station 3, which means the effects can be seen on 2 to 5 stories structures as such buildings faced widespread damages in the vicinity of station 3.

Table 2. PGA obtained in stations.

Number of Station		Station 1	Station 2	Station 3	Station 4
PGA (g)	Upper Limit	0.57	0.80	0.79	0.79
	Lower Limit	0.38	0.52	0.62	0.50
	Mean	0.47	0.66	0.71	0.65

Table 3. The characteristics of earthquake and aftershocks in the region.

No	Date	Lat.	Lon.	Depth	Mag.	Ref.
1	2017/11/12	34.877	45.841	18	7.3	IIEES
2	2017/12/11	35.069	45.76	15	5.3	IIEES
3	2018/01/11	33.727	45.683	17	5.3	IIEES
4	2018/01/11	33.838	45.766	15	5.1	IIEES
5	2018/01/11	33.741	45.669	15	5.1	IIEES
6	2018/01/11	33.663	45.686	18	5.2	IIEES
7	2018/04/01	34.427	45.827	15	5	IIEES
8	2018/07/22	34.625	46.293	6	5.6	IIEES
9	2018/08/25	34.62	46.212	15	6	IIEES
10	2018/11/25	34.334	45.724	18	6.4	IIEES
11	2018/11/25	34.301	45.644	17	5.1	IIEES
12	2018/11/26	34.335	45.726	15	5.2	IIEES
13	2019/01/06	34.158	45.669	16	5.9	IIEES
14	2019/04/01	33.69	45.62	10	5.4	IIEES
15	2019/05/11	34.82	45.71	16	5.4	IIEES

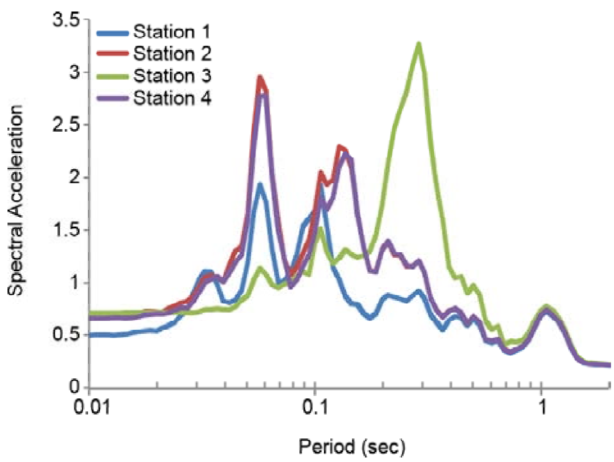


Figure 9. Calculated spectral accelerations.

5. Discussion

In Iranian seismic design code [15], seismic regions are divided by their potential risk into four categories; very low, low, high and very high probability. This particular area was deemed to be of high potential risk, but not predicted to be very intensive. The Sarpol-e Zahab earthquake was considered a special case to study because after the earthquake, the region converted to highly active from an unremarkable active seismic zone. More than 2500 aftershocks (m > 2.5) were recorded during a year after the earthquake and some were of high PGA; however, the first of all these questions arise that how was possible the highest acceleration value (0.69 g) in Sarpol-e Zahab accelerogram while the earthquake source had about 37 km distance to Sarpol-e Zahab town? Besides, is such a response spectrum of the earthquake possible to occur?

In this regard, it should be mentioned that many earthquakes in the past had different response spectrum compared to seismic codes as shown in Figure (10).

On the other hand, according to the results, the acceleration reached to the region was much higher than what was expected according to Iranian Seismic Code. In addition to this, it achieved its peak in southern part of the study area. This occurrence, however, was noted by Seed et al. [17], as can be seen in Figure (11) when the soil type is AB - "Stiff, very shallow soil over rock and/or weathered rock" - and peak rock acceleration (PRA) is around

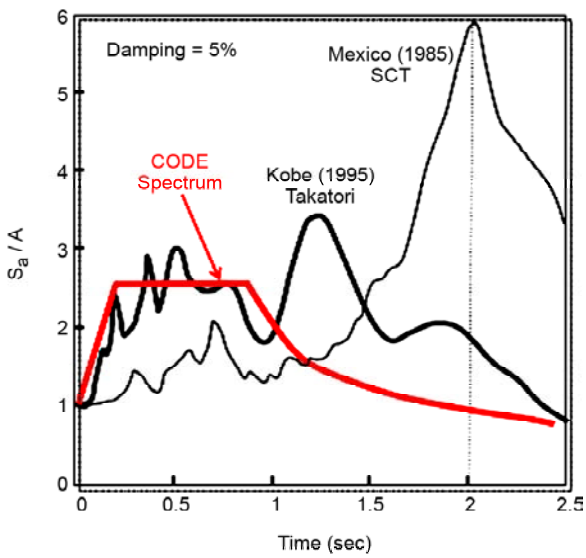


Figure 10. Spectral acceleration according to seismic code [16].

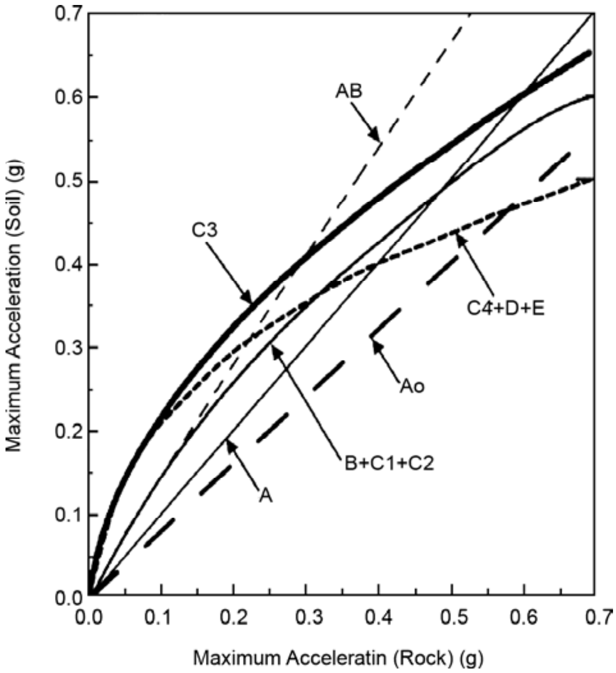


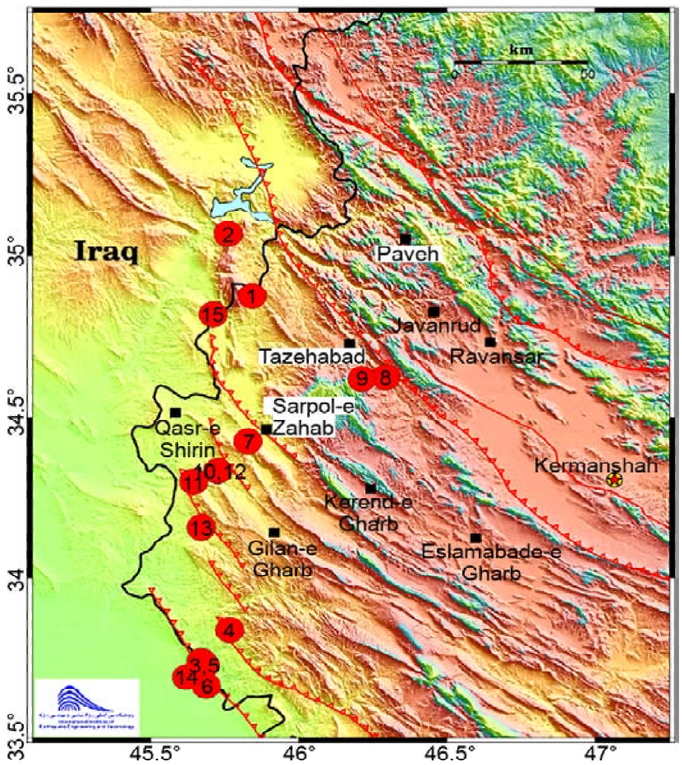
Figure 11. The relationship between PGA and PRA based on the site condition [17].

0.3 g to 0.5 g, maximum acceleration on soil can reach to approximately 0.4 g to 0.7 g.

Therefore, as the deconvolution scheme was also noted, site condition could be the main reason of this high PGA recorded in Sarpol-e Zahab.

The other reason related to it, can be satisfied by consideration of some more important earthquakes and aftershocks characteristics in this region as illustrated in Table (3) were of high PGA in Sarpol-e Zahab station. The locations of the main earthquake and aftershocks, recorded PGA of the main earthquake and some of the aftershocks in Sarpol-e Zahab town (including the occurrences in 2018, on the 1st of April (Mw 5) and 25th of November (Mw 6.4)), and the time-history of one of the mentioned aftershocks are shown in Figure (12).

Besides, in the second phase of the analysis, in order to examine the certainty of work and influence of soil layers on amplifications, 30 different strong

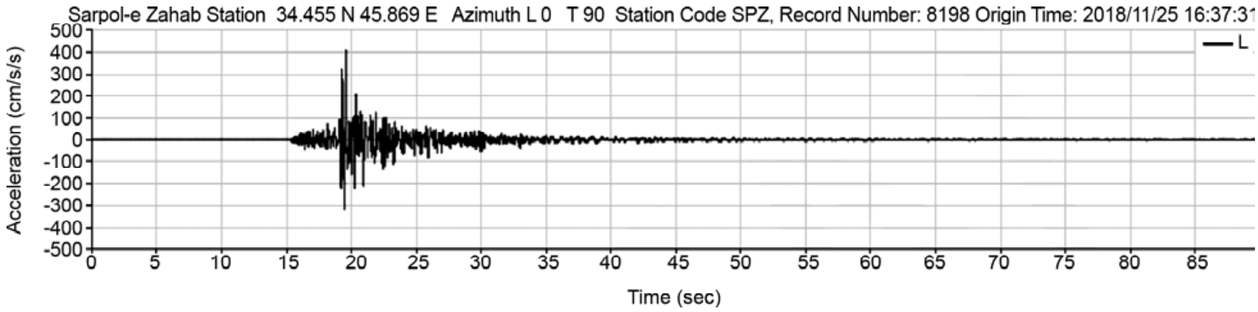


(a) Some earthquakes and aftershocks locations around Sarpol-e Zahab based on IIEES report [18].

Component / Date	Site to Source Distance (Km)	L (cm/s/s)	V (cm/s/s)	T (cm/s/s)
2017/11/12	38.6	684	385	553
2018/04/01	13	428	250	406
2018/11/25	23	410	156	345

(b) The PGA of the two aftershock components were recorded in Sarpol-e Zahab Station.

Figure 12. Some earthquakes and aftershocks locations around Sarpol-e Zahab.



(c) Time history acceleration of 25th November aftershock (Mw 6.4) in Sarpol-e Zahab Station.

Figure 12. Continue.

Table 4. 30 earthquake records for using in the analysis.

No.	Earthquake Name	Mechanism*	Magnitude	Distance	PGA (g)	Number of Point
1	Abaraq, Iran, 2003/12/26, 05:26	SS	6.5	43	0.107	11777
2	Abaraq, Iran, 2003/12/26, 05:26	SS	6.5	43	0.136	11777
3	Abbar, Iran,1990/06/20	RV/SS	7.3	43	0.58	10702
4	Abbar, Iran, 1990/06/20	RV/SS	7.3	43	0.49	9198
5	Avaj, Iran, 2002/06/22, 02:58	RV	6.5	25	0.38	3500
6	Avaj, Iran, 2002/06/22, 02:58	RV	6.5	25	0.44	3500
7	Cape Mendocino, 1992/04/25,18:06	RN	7.1	8.5	1.04	1500
8	Cape Mendocino, 1992/04/25,18:06	RN	7.1	8.5	1.5	1500
9	Chi-Chi, TCU046 Taiwan, 1999/09/20	RN	7.6	14.34	0.116	17000
10	Duzce, 1060 Lamont, Turkey, 1999/11/12	SS	7.1	30.2	0.053	4400
11	Izmit, Gebze, 1999/08/17, 00:01	SS	7.6	47	0.135	4763
12	Izmit, Gebze, 1999/08/17, 00:01	SS	7.6	47	0.24	4763
13	Izmit, Meteoroloji, 1999/08/17, 00:01	SS	7.6	9	0.14	10535
14	Izmit, Meteoroloji, 1999/08/17, 00:01	SS	7.6	9	0.22	10535
15	Kocaeli, Turkey, 1999/08/17	SS	7.4	17	0.137	5600
16	Kocaeli, Turkey, 1999/08/17	SS	7.4	17	0.244	5600
17	Loma Prieta, 47379Gilroy, 1989/10/18, 00.05	RO	6.9	11.2	0.411	5990
18	Loma Prieta, 47379Gilroy, 1989/10/18, 00.05	RO	6.9	11.2	0.473	5990
19	Loma Prieta, 1032Hollister, 1989/10/18, 00.05	RO	6.9	42.8	0.036	5925
20	Loma Prieta, 1032Hollister, 1989/10/18, 00.05	RO	6.9	42.8	0.06	5925
21	Northridge, 127Lake Hunghes, 1994/01/17, 12:31	RN	6.7	26.8	0.165	2000
22	Northridge, 127Lake Hunghes, 1994/01/17, 12:31	RN	6.7	26.8	0.217	2000
23	Northridge, 90019San Gabriel, 1994/01/17 12:31	RN	6.7	41.7	0.141	3500
24	Northridge, 90019San Gabriel, 1994/01/17, 12:31	RN	6.7	41.7	0.256	3500
25	Pool (Baledeh Nour), Iran, 2004/05/28	RV	6.3	17	0.15	15965
26	Pool (Baledeh Nour), Iran, 2004/05/28	RV	6.3	17	0.3	15965
27	San Fernando, 127 Lake Hughes, 1971/02/09, 14:00	RN	6.6	23.5	0.088	3470
28	San Fernando, 127 Lake Hughes, 1971/02/09, 14:00	RN	6.6	23.5	0.134	3470
29	South Iceland, Minni-Nupur, 2000/06/17, 15:40	SS	6.5	13	0.12	6701
30	Tabas, Iran 09/16/78	Reverse	7.4	17	0.328	1192

*Mechanism: - SS = Strike Slip - RV = Reverse - RO = Reverse Oblique - RN = Reverse Normal

ground motions that had happened around the world have been selected to convolution in the four stations. Table (4) illustrates these earthquakes. Again, as the results show, the influences of such earthquakes and their high PGAs on top of soils in the four considered stations is similar to results of Seed et al. [17] (Figure 13). It seems that further study on the impact of soil types on the amplification in Sarpol-e Zahab would be of importance. The South-Western part of the town, which was more populated, became more important to study particularly with the widespread collapses of structures seen during the field investigation. Afterwards, the mean spectral acceleration and plus minus standard deviation of all of them in each station were computed separately in Figure (12), in each station for those 30 records. Again, a similarity in the period range of amplification are obvious between Figure (9) and Figure (14), and it should be mentioned that the results can be reliable for interruption regarding much more damage of structures in south-western part of Sarpol-e Zahab town around station 3.

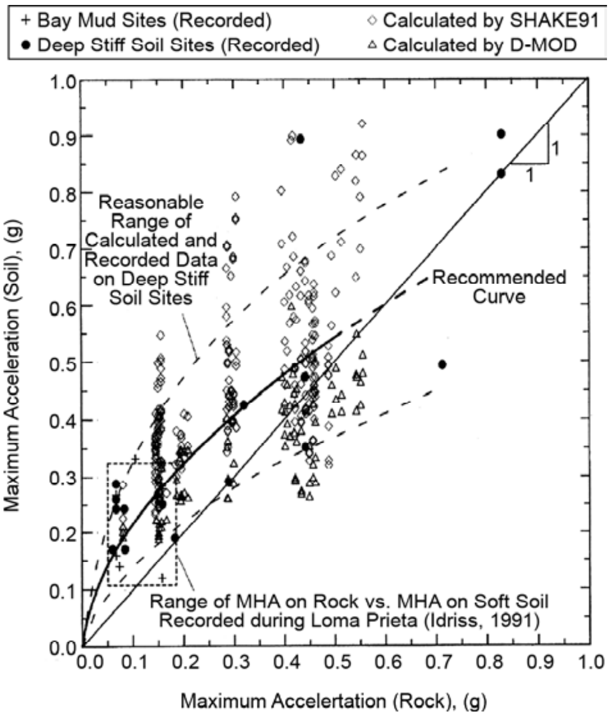


Figure 13. Relationship for a_{max} or $a_{max,\ rock}$ for deep stiff soil sites based on available empirical data from the Loma Prieta and Northridge Earthquakes and calculations using both equivalent linear and fully nonlinear site response methods (from Seed et al [17] based on Chang et al. [19]).

6. Conclusion

In this paper, efforts had been undertaken to evaluate the response of the site during the Ezgeleh - Sarpol-e Zahab Earthquake, which occurred on November 12, 2017. For this study, some geophysical investigations were made to identify the characteristics of the beneath layers. Firstly, the main recorded time-history in the town of Sarpol-e Zahab had been deconvolutioned, considering the characteristics of soil layer estimated in that vicinity. Therefore, the PRA of the region could be available and PGA could be calculated by convolution of the time-history record on bedrock in every favorite site. Since the destruction trend was meaningful, in authors' point of view, four different geophysical

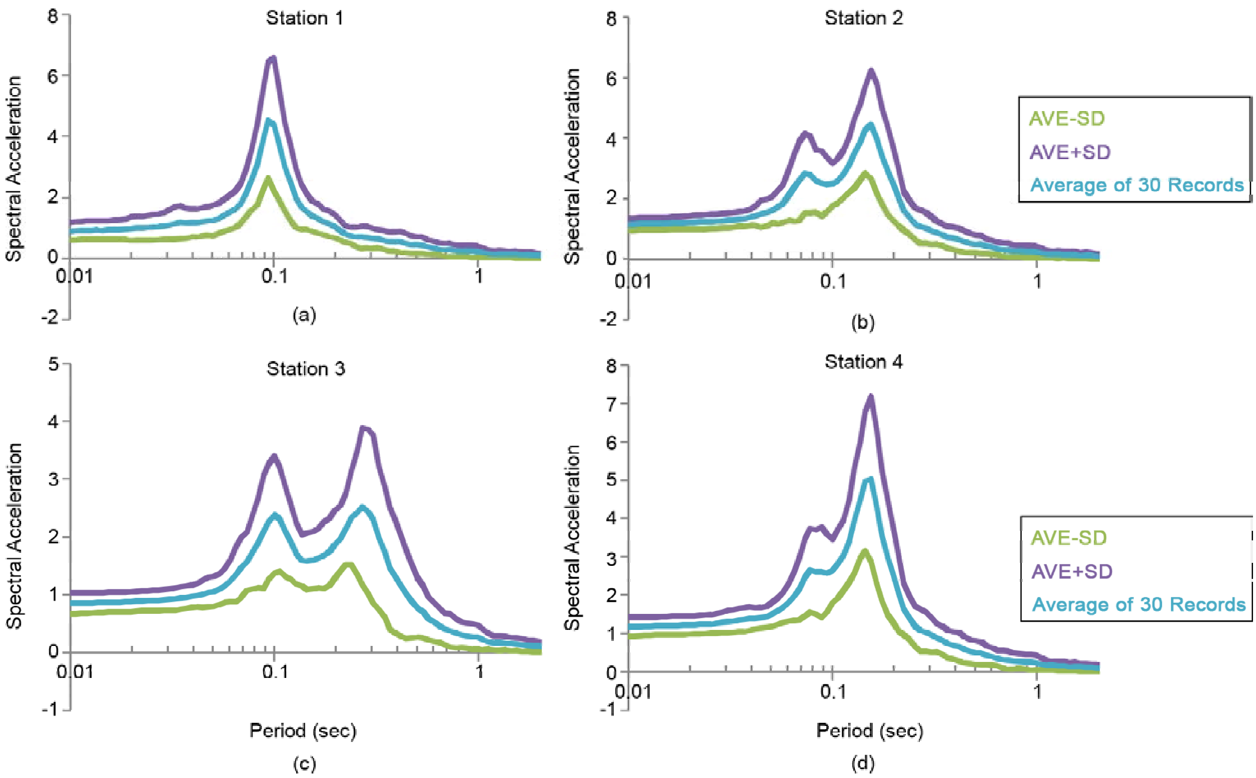


Figure 14. Spectral accelerations in the stations in comparison to 30 near field records.

investigations had been done on Western border of the town. Then, the bedrock's time-history record convolutioned due to these four stations. According to results, an increasing value of PGA occurred in that part of the town, which reached 0.71 g in the Southern parts of the town and 0.47 g in the Northern parts. According to the results, both PGA and periodic range in spectral acceleration are different in station 3, where the most extensive damages were observed, from other stations. In addition, 30 famous near field records over the world were used to compare spectral accelerations obtained in the current study.

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