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Importance of revisiting $(Vs)_{30}$ site class index, Sarpol-e-zahab Mw=7.3 earthquake

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ABSTRACT: On 12 Nov. 2017 an earthquake of Mw=7.3 struck Kermanshah province, Iran. The epicenter center was located at Lat. 34.77 and Long. 45.76, by the Iranian Seismological Center with focal depth of 18 km. The event was assigned to Mountain Front Fault (MFF) activity due to its focal mechanism. Sarpol-e-zahab was the most affected city by the earthquake in the region, thus the event was named as Sarpol-e-zahab earthquake. Level of damages and damage Geographical distribution emphasized the role of Geotechnical local site effects of the earthquake. The current study presents outcomes of post-earthquake ambient vibration analyses at Sarpol-e-zahab city, and interpretation of extracted Vs profiles of the subsurface ground layers. Furthermore, it highlights the coherence of $(Vs)_{30}$ site class index with fundamental frequency of the ground (F_0) that is calculated from HVSR analysis of ambient vibrations. Finally, it investigates effectiveness of $(Vs)_{30}$ on the local site effect assessments.

1 INTRODUCTION

On 12 Nov. 2017 at 21:48 IRST an odd earthquake with moment magnitude of Mw=7.3 struck Kermanshah province at west of Iran, next to Iraq border. The event was recognized at several cities in Iran and Iraq. Iranian Seismological Center (IRSC) announced the most accurate location of the epicenter as Lat. 34.77 of North and Long. 45.76 of East, and the focal depth was determined about 18 km (Tatar et al. 2018). The closest residential area was Ezgeleh about 10 km North-West of the epicenter with population of about 1500 persons. Also Tazeabad with population of about 15000 persons was about 35 km East of the epicenter, and Sarpol-e-zahab with population of about 56000 persons was 35 km South of the epicenter. Neither Ezgeleh nor Tazeabad were the most damaged cities by the earthquake. But Sarpol-e-zahab with the same epicentral distance as Tazeabad was the most affected city, so that the earthquake was named as Sarpol-e-zahab earthquake. Concentration of the earthquake damages toward South of the epicenter was assigned to forward directivity effects of rupture mechanism (Tatar et al. 2018). The event was attributed to a known fault zone named Mountain Front Fault (MFF) that extends almost North to South along the Iran-Iraq border with strike direction of North-West to South-East. The focal mechanism of the event was thrust with low dip angel of about 10 degrees and some slip component (Figure 1). The event had a main pre-shock of Mw=4.5, at 43 minutes earlier than the main-shock, which was a crucial warning for the people of regions close to the epicenter. Also it was followed by numerous after-shocks. The event has resulted in increase of seismicity of the region, which was assigned to activation of shallower faults with strike slip mechanism (Tatar & Yaminifard 2018).

Damage distribution at Sarpol-e-zahab revealed that the entire city was not affected at comparable levels, and damages to structures and buildings were proportional to the alluvium

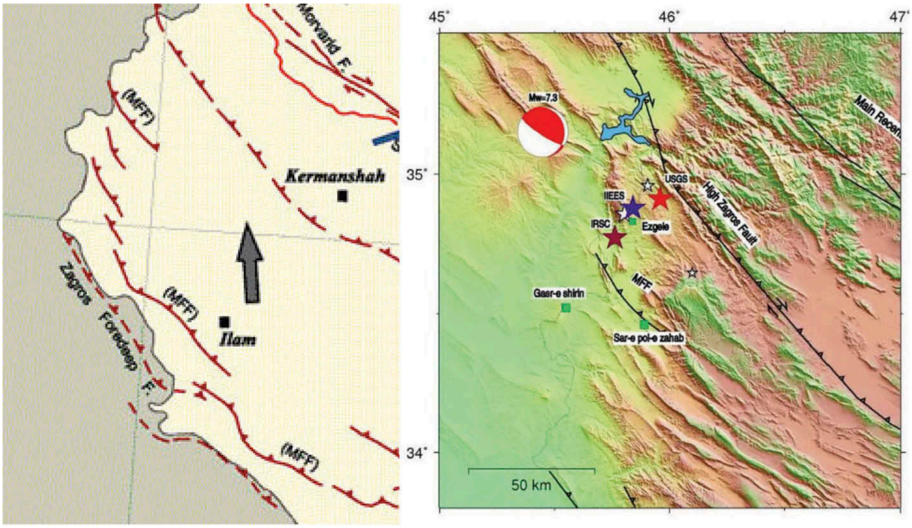

Figure 1. Fault map (left), Epicenter and focal mechanism (right) of the Sarpol-e-zahab earthquake (Tatar et al. 2018).

depth and local site amplification of the strong motion (Haghshenas et al. 2018). These evidences encouraged the authors to investigate local seismic site effects of the earthquake by means of rapid and dense microzonation of Sarpol-e-zahab. This paper compares fundamental frequency (F_0), with average of shear wave velocity of top 30 meters $(Vs)_{30}$, of the ground. The F_0 is obtained from horizontal to vertical spectral ratio (HVSR) analysis of the ambient vibrations, and $(Vs)_{30}$ is a widely used index for site effects in many seismic design codes of practice.

2 POST-EARTHQUAKE AMBIENT VIBRATIONS ANALYSIS

Ambient vibration analysis is one of the most applicable surveys in earthquake Geotechnical engineering. The survey is rather simple as well as time and cost effective in both application and analysis. The simplest ambient vibration or noise analysis method is simultaneously recording of three components of noise by a single seismometer. The analyses of the single station records was firstly introduced by Kanai & Tanaka (1961), Nogoshi & Igarashi (1971), and then was developed by Nakamura (1989). The analysis method is generally known as Nakamura technique and formally is called Horizontal to Vertical Spectral Ratio (HVSR) or simply H/V method. The method considers the peak frequency of the Fourier spectrum ratio of the average horizontal components to the vertical component as the fundamental frequency of the site. Although the analytical bases of HVSR method has been criticized (the review chapter by Lunedei & Malischewsky 2015), it is widely accepted and applied in determination of the site fundamental frequency (Molnar et al. 2018).

Ambient vibrations recordings at Sarpol-e-zahab was started on 15 Nov. 2017 and continued for next 6 months at monthly intervals. The investigation consists of 56 single station recordings with a three components broadband seismometer (30 Sec. to 50 Hz) of CME-4111 and a 24-bit digital data acquisition system at sampling frequency of 200 sample per seconds. Each recording was continued about an hour to be assure of adequate record length. The 56 stations were distributed over Sarpol-e-zahab district respect to damage concentration. Furthermore, ambient noise was recorded at four circular arrays of radius 30 to 40 meters with six (one at center and five on the perimeter) three components broadband seismometers of Guralp 6TD (10 Sec. to 50 Hz). Figure 2 presents locations of the single station and array recordings.

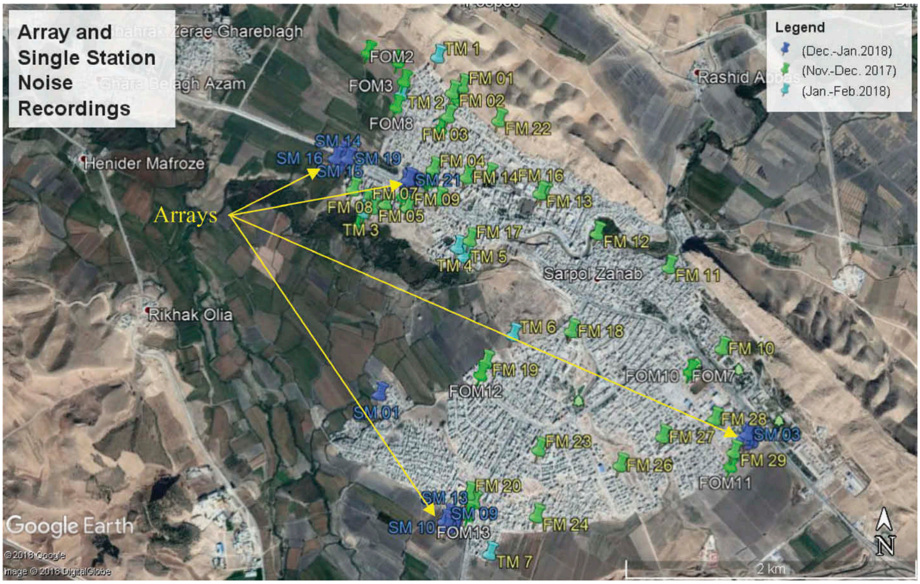

Figure 2. Location of single station and array measurements of ambient vibrations at Sarpol-e-zahab.

Fundamental frequency of the ground was calculated from the peak frequency of HVSR using Geopsy software (Geopsy 2016). Figure 3 presents the map of fundamental frequency of the ground at Sarpol-e-zahab district. It was observed that the ground frequency varies from as low as 1 Hz to higher values of more than 20 Hz. It is worth noting that damage concentration and magnification of buildings can be interpreted by the similarity and closeness of natural frequency of the building to fundamental frequency of the ground (Moosavi et al. 2018).

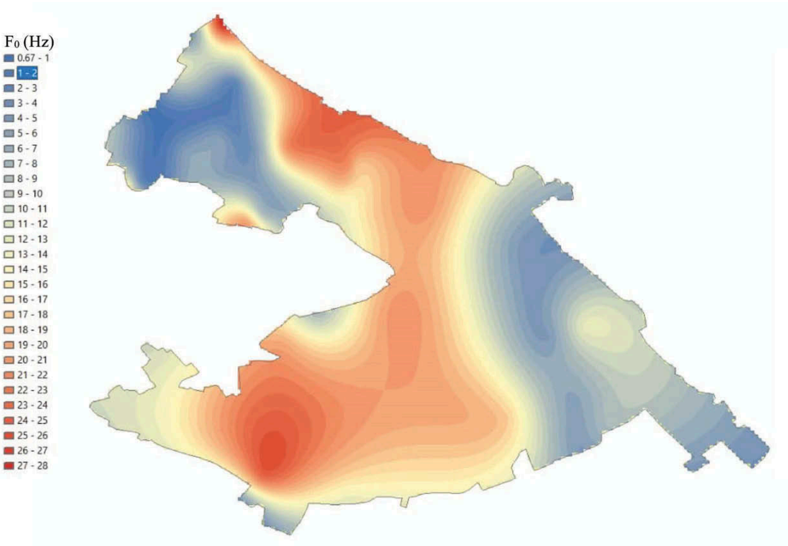

Figure 3. Fundamental frequency, F_0 .of the ground from HVSR analysis at Sarpol-e-zahab

3 BOREHOLE LOGS, V_S PROFILE, $(VS)_{30}$ & FUNDAMENTAL FREQUENCY

In order to find stratigraphy of surface layers, Geotechnical borehole logs were collected from clients. Figure 4 presents location of the three boreholes, which borehole Nos. 1, 2, and 3 were logged down to 10, 15, and 32 meters, respectively. It is worth noting that water table was observed only in borehole No.3 at depth of 14 meters. Table 1 presents the soil description of the boreholes and standard penetration test numbers, N_{SPT}. Borehole No.3, which extends down to 32 meters shows that depth of soil layers is more than 30 meters and engineering bed-rock cannot be reached in that region in top 32 meters.

In addition to fundamental frequency of the ground, ambient vibration records were used to obtain the ellipticity of Rayleigh waves using Time-Frequency Analysis of horizontal to vertical spectral ratio (HVTFA) (NERIES-JRA4-D4 2010). Furthermore, the ellipticity curve of Rayleigh waves were used jointly with peak frequency of HVSR to estimate shear wave velocity profile of the ground. The inversion of ellipticity curve of Rayleigh waves and peak frequency of HVSR were done using Geopsy software.

Figures 5 to 7 compare shear wave velocity Vs, average of top 30 meters shear wave velocity $(Vs)_{30}$, as well as corresponding fundamental frequency, (F_0), and amplitude of spectral ratio at fundamental frequency (A), of five sample stations.

Comparing $(Vs)_{30}$ of two stations of FM29 and FM19, reveals that both stations are on the similar ground class of Type-I according to Iranian Code of Practice for Seismic Resistant

Figure 4. Location of three Geotechnical borehole logs.

Table 1. Borehole logs and soil description.

Borehole No. 1			Borehole No. 2			Borehole No. 3		
Depth	USCS*	N_{SPT}	Depth	USCS	N_{SPT}	Depth	USCS	N_{SPT}
1-5.5 m	SC	17	1-7 m	CL	28	1-6 m	CL	45-50
5.5-10 m	CL	20	7-15 m	GC	50	6-11 m	GM	46
						11-32 m	CL	55-78

* Unified Soil Classification System

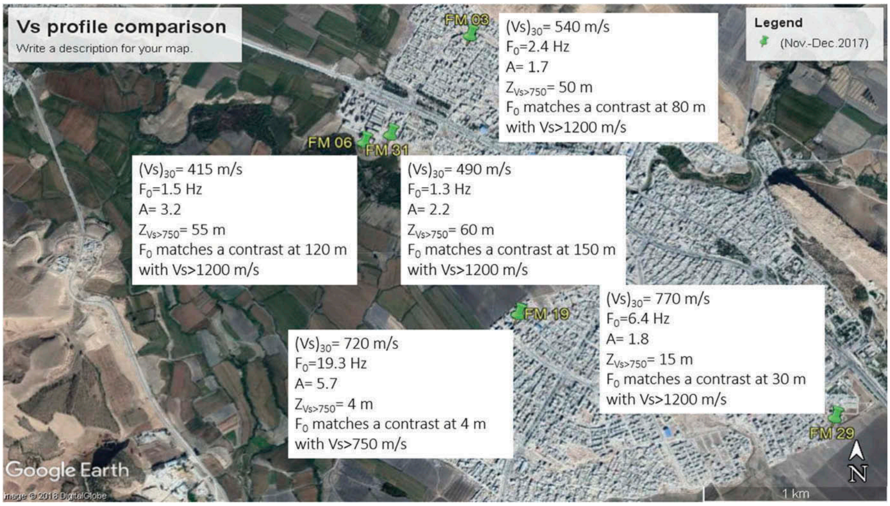

Figure 5. Location of five sample stations and comparison of shear wave velocity profiles.

Design of Buildings (IRCPSRDB 2014). However, the fundamental frequency of FM29 and FM19 are significantly different. The fundamental frequency of FM 29 corresponds to one or two story buildings, but the fundamental frequency of FM19 is not in the range of conventional buildings or structures. Additionally, the fundamental frequency of FM29 matches with an impedance contrast at about 30 meters depth, where the shear wave velocity exceeds 1200 m/s. While, the fundamental frequency of FM19 matches with a shallow impedance contrast at 4 meters depth. Thereby, while 30 meters is enough for FM29 to find the impedance contrast, it is too much for FM19.

Similarly, comparing $(Vs)_{30}$ of three stations of FM03, FM06, & FM31, shows that all the three stations are in the same category of ground, i.e. Type-II. However, the fundamental frequencies of FM06 and FM31 are close to each other and correspond to natural frequency of

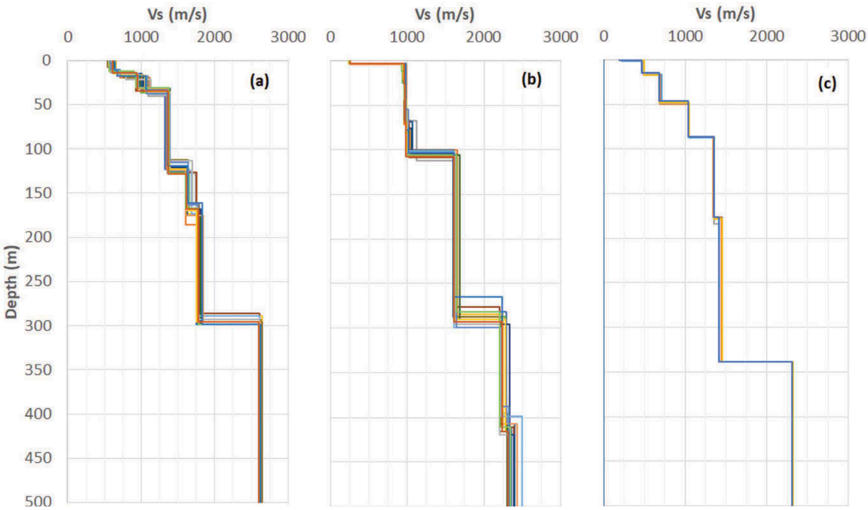

Figure 6. Shear wave velocity profiles a) FM29, b) FM19, and c) FM03.

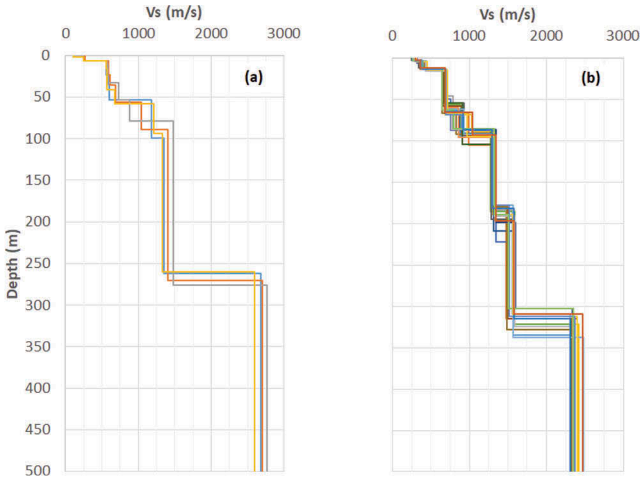

Figure 7. Shear wave velocity profiles a) FM06, and b) FM31.

buildings with five to seven stories. Although the three stations have the same ground class, the slight difference between fundamental frequencies of these sites can be interpreted due to their different depth of impedance contrast. The fundamental frequency of FM03 matches with an impedance contrast at depth of 80 meters, but that of FM06 and FM31 match with about two times deeper contrasts. Meanwhile, all impedance contrasts are attributed to exceedance of shear wave velocity than 1200 m/s. In these three cases, it is clear that 30 meters is too short to find the true impedance contrast that expresses the site effect characteristics of the ground.

In addition to above, all stations except for FM19 showed that shear wave velocity of 700 to 800 m/s that is known as engineering bedrock threshold, can be violated. Stiffer layers may act as engineering bedrock and may cause low frequency amplification of the ground motion with all overlaying hard soil/soft rock layers.

Figure 8-a compares the experimental HVSR with Fourier amplitude ratio of surface motion to the bedrock motion derived from linear elastic site response analysis for FM29 with top 35 meters of Vs profile of Figure 6-a. The fundamental frequency, F_0 from HVSR is estimated 6.4 Hz and the first natural frequency of the Vs profile from linear elastic response analysis is calculated 6.6 Hz. Figure 8-b presents the same analysis for FM31. Top 150 meters of the Vs profile of Figure 7-b is used for the linear elastic site response analysis. The fundamental frequency, F_0 from HVSR is estimated 1.3 Hz and the first natural frequency of the Vs profile from linear elastic response analysis is calculated 1.7 Hz.

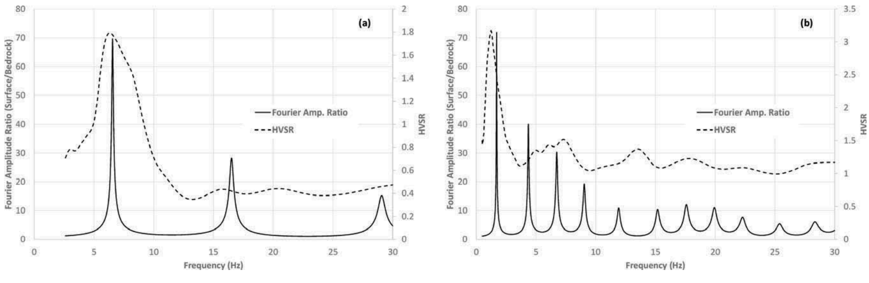

Figure 8. Fourier amplitude ratio and HVSR comparison at a) FM29, & b) FM31.

4 SITE EFFECTS AT STRONG MOTION RECORDS

This part of the paper presents observed site effects in recorded strong motions at two permanent accelerometric stations of Iran Strong Motion Network (ISMN) during the 12 Nov. 2017 Sarpol-e-zahab earthquake. Table 2 shows the strong motion characteristics of the main-shock recorded at Sarpol-e-zahab (SPZ), and Kermanshah (KRM1, KRM2) stations. Figure 9 present locations of these stations respect to the epicenter. The two stations at Kermanshah (KRM1 & KRM2) are about 3.6 km far from each other and about 132 km away from the epicenter and almost at the same Azimuth of about 292 degrees. Table 2 reveals that the recorded strong motions at KRM1 & KRM2 were highly attenuated respect to the one in SPZ in terms of PGA and sustained acceleration. However, the mean period of the motion was enlarged and the significant duration of the records are elongated. Furthermore, the comparison of the recorded PGA at KRM2 respect to KRM1 shows two time amplification that

Table 2. Strong motion characteristics recorded at ISMN stations.

Station	Dist. (km)	Comp.	PGA (Gal)	Sust. Acc. (Gal)	Mean Period (Sec.)	Sig. Duration (Sec.)
SPZ	36	N	686	366	0.39	10.8
		E	563	517	0.32	9.8
		Z	325	298	0.28	10.5
KRM1	133	N	58.3	43.6	1.03	27.5
		E	36.6	33.2	0.98	37.4
		Z	24.6	19.6	1.5	42.7
KRM2	131	N	111.2	54	1.2	37.8
		E	68.2	48.4	1.2	41
		Z	35.2	32.8	1.03	36.4

Dist.: epicentral distance, Comp.: directional component, PGA: peak ground acceleration, Sust. Acc.: sustained acceleration, Sig. Duration: significant duration

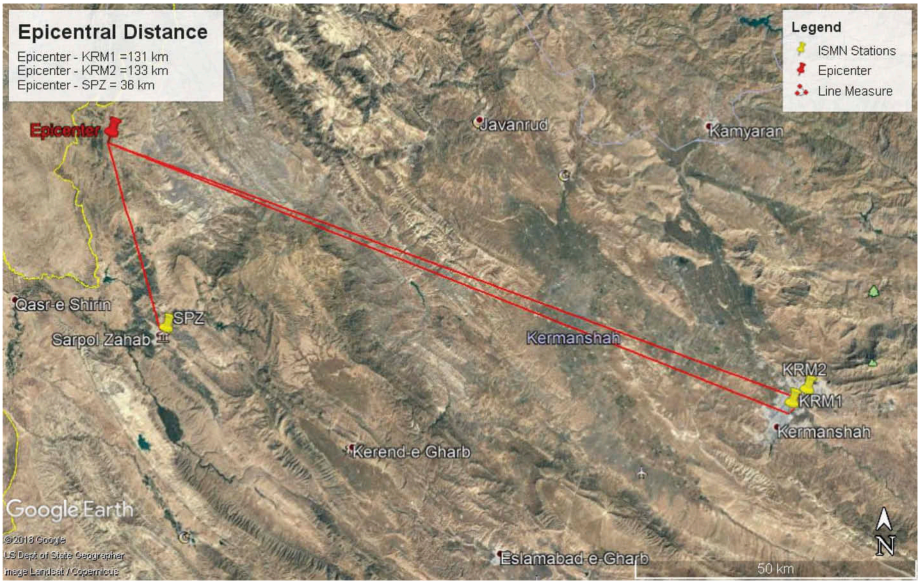

Figure 9. Location of the ISMN accelerometric stations at Sarpol-e-zahab and Kermanshah vs epicenter.

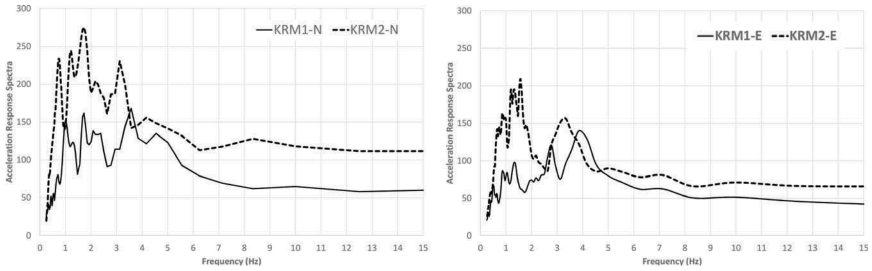

Figure 10. Acceleration response spectra of N (left), E (right) components of KRM1 & KRM2 stations.

presents site related contributions because both stations are at the same Azimuth and distance to the epicenter.

Figure 10 presents the acceleration response spectra of 5% damping for KRM1 and KRM2. It is clear from Figure 10 that the response spectra of both North and East components of the recorded strong motion at KRM2 is greater than KRM1. It is more evident at frequencies lower than about 4 Hz that is also important for tall buildings. Figure 11-a shows HVSR of the ambient vibrations recorded by the CME-4111 broadband seismometer next to KRM1 and KRM2. It shows the fundamental frequency of KRM1 is about 4 Hz and HVSR has a clear and reliable peak at this frequency. However, HVSR of KRM2 presents two peak frequencies one at about 3.5 Hz and a lower fundamental frequency of 0.9 Hz. Inversion of the ellipticity curve of Rayleigh waves at these two stations resulted into shear wave velocity profiles of the ground at KRM1 and KRM2 (Figure 11-b).

The shear wave velocity profile at KRM1 revealed that $(Vs)_{30}$ is about 412 ± 35 m/s. Similar calculations at KRM2 revealed $(Vs)_{30}$ is about 428 ± 28 m/s. This means that both ground profiles are classified as Type-II and adequately similar in terms of $(Vs)_{30}$. The shear wave velocity profile of KRM2 shows that an impedance contrast at about depth of 30 meters corresponds to the peak frequency at 3.5 Hz, but there exists another impedance contrast at depth of about 210 meters that matches with the lower fundamental frequency of 0.9 Hz. However, the shear wave velocity profile of KRM1 approves an impedance contrast at depth of about 30 meters that matches with the fundamental frequency of about 4 Hz, but no other impedance contrast is observed in the shear wave velocity profile down to depth of 500 meters. These records express how deeper impedance contrasts can effectively change the resultant ground motion at surface and consequently the response spectra. This also presents, if only $(Vs)_{30}$ is considered as the site class index, the corresponding design spectrum can be unable to capture the actual site amplification characteristics. Meanwhile, HVSR analysis of strong motion recorded at KRM1 shows peak frequency at 3.7 Hz that is close to 4 Hz from ambient noise analysis. The same analysis at KRM2 shows peak frequency at 0.7 Hz, which is again close to 0.9 Hz of ambient noise analysis. The insignificant frequency shift (0.2 to 0.3

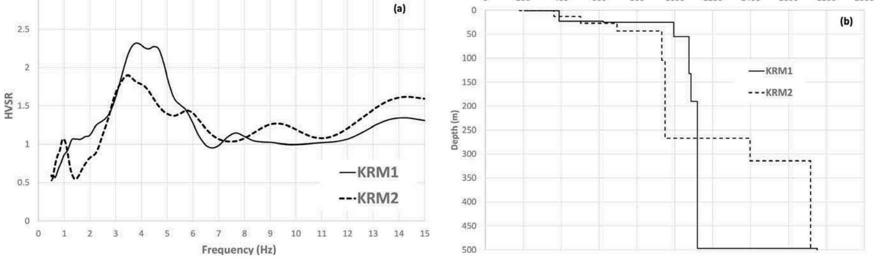

Figure 11. a) HVSR of ambient vibrations, & b) Vs profile at KRM1 & KRM2 stations.

Hz to lower frequencies) confirms that the nonlinearity of soil layers can be interpreted as secondary factor for the response variation at two stations.

5 CONCLUSIONS

On November 12th 2017 a massive earthquake was occurred with moment magnitude of Mw=7.3 in west of Iran close to Iraq border. The earthquake was named as Sarpol-e-zahab earthquake because Sarpol-e-zahab County was the most damaged residential area with about 35 km South East of the epicenter. The level of damage distribution in the city was assigned to the seismic site effects. The current paper presents the results of part of the ambient vibrations analyses were carried out after the earthquake, which deals with the effectiveness of $(Vs)_{30}$ as site classification index used in many seismic codes of practice as well as Iran's. The following conclusions are outlined.

1. The fundamental frequency of the ground could not be interpreted by $(Vs)_{30}$ of the shear wave velocity profile at most of the stations.
2. Top 30 meters of the ground was mostly found not to be enough to find the impedance contrast that the site amplification is attributed. There are situations that the 30 meters is too much and the impedance contrast occurs at shallower depth.
3. Comparisons showed that significantly different fundamental frequencies can be captured in sites with similar $(Vs)_{30}$. It is verifying that impedance contrast depth is important on the site amplification frequency.
4. Investigation of the strong motion records at two accelerometric stations in Kermanshah provided a clear example, which $(Vs)_{30}$ is unable to interpret amplification of recorded PGA and response spectra. However, HVSR analyses of the ambient vibrations and corresponding deep shear wave velocity profiles of two sites were capable of interpreting the recorded strong motion differences.
5. All the mentioned evidences support the importance of revisiting a single $(Vs)_{30}$ site classification index with a combination of Vs, fundamental frequency, and impedance contrast depth.

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