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Investigation of forward directivity effects on design spectra of industrial complexes near Assaluyeh fault

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Abstract

Recorded ground motions in near-fault region have completely distinct nature from others that recorded in far field of the fault. Near source outcomes cause much of the seismic energy to appear in a single large and long period pulse at the beginning of the velocity record. Assaluyeh complex is located near the reverse Assaluyeh fault that is a segment of Mountain Front Fault. This complex contains facilities which have a wide range of structural periods. Effects of this vicinity on the seismic hazard of this region can be considered by using approaches which incorporate effects of near-fault in seismic hazard analysis. It can be achieved by using near source specific ground motion models in probabilistic seismic hazard analysis and using accelerograms which contain the pulse-like effects of forwarding directivity. The results indicate that the site-specific design spectra of this study fall at an upper level in comparison with the standard design spectra of Iranian Code of Practice for Seismic Resistant Design of Buildings (Standard No.2800) and the site-specific design spectrum of International Institute of Earthquake Engineering and Seismology (IIEES). It is worth noting that near-fault effects should be considered in probabilistic seismic hazard analysis and preparation of site-specific design spectra if the site is located near source region of a fault.

Keywords: *Forward directivity, Design Spectrum, Near fault*

1. Introduction

An earthquake is a shear dislocation that begins at a point on a fault and spreads at a velocity that is almost as large as the shear wave velocity. The propagation of fault rupture toward a site at very high velocity causes most of the seismic energy from the rupture to arrive in a single large long period the pulse of motion which occurs at the beginning of the record [1]. The near-fault zone is typically assumed to be restricted to within a distance of about 20 km from the ruptured fault [2]. Ground motion in a specific site is significantly affected by the faulting mechanism, rupture propagation toward the site and the fling step caused by tectonic dislocations. Depending on the first two factors, the near-fault zone can experience dynamic outcomes as "forward directivity," "backward directivity," or "neutral directivity." As a result of the third factor, ground motions near the surface rupture may involve a significant permanent static dislocations, which is referred to as "fling step" [3].

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One of the most important seismic structures at the foot of the fold belt of Assaluyeh is the blind Assaluyeh basement fault with 80 km lengths. This structure is part of the Mountain Front Fault (MFF), and evidence suggests that this reverse fault is the most active segment of the MFF near the site [4]. For the first time, this fault was identified by Berberian 1981 from a study on 10 damaging to devastating earthquakes [5]. In areas like the Zagros where seismicity has a diffuse pattern and active basement faults are covered by Phanerozoic sedimentary cover recognition of seismogenic faults is elusive. Berberian 1995 has identified a number of master blind thrusts and a number of strike-slip faults in the bedrock and surface that caused a number of earthquakes in the Zagros Folded-Thrust belt [6].

Somerville et al. 1997 used a large set of near-fault strong motion recordings to develop a quantitative model of rupture directivity effects. This model can be used to modify existing ground motion attenuation relations to incorporate directivity effects in ground motions used for seismic design [1]. Abrahamson 2000 proposed a similar approach to the near-field seismic hazard analysis by introducing modification factors to the Somerville 1997 approach. Hence, these approaches were called Somerville-Abrahamson model for the modification of near-fault hazard analysis [7]. Similar approaches have been proposed, including Tothong et al. 2007, and the study of Shahi and Baker 2011 [8, 9].

In this study, to take into account the effects of near-field on probabilistic seismic hazard analysis, Campbell & Bozorgnia 2003, Ambraseys & Douglas 2003, Campbell 1997 ground motion models are employed, which are specifically presented for near-fault as well as Chiou and Youngs 2006 ground motion model that is adapted to the near and far-field analysis. Seismic hazard analysis is carried out using the relationships presented in the Shahi and Baker 2011 approach [9-13]. In addition, having identified the other seismic sources by using Campbell & Bozorgnia 2008 Ghasemi et al. 2009 and Chiou & Youngs 2006 ground motion models, the five percent damped pseudo acceleration response spectra of probabilistic seismic hazard analysis(PSHA) in this region are prepared [13-15]. Chiou & Youngs 2006, and Campbell & Bozorgnia 2008 were developed as part of the PEER Next Generation Attenuation (NGA) project. The site-specific design spectrum was conducted by IIEES in the past, but near-fault effects have not been specifically considered in that research. Finally, in this study, by considering the calculated pseudo acceleration response spectra, accelerograms containing the pulse of near-fault are obtained from PEER. The analysis of soil properties is carried out and then site-specific design spectra are prepared.

2. Forward directivity in footwall of the Assaluyeh fault

In the areas where seismicity is related to exposed surface active faults, like central Iran, Alborz or some parts of the western United States, capable faults are easily recognized on the surface, in aerial photographs and in satellite imagery [6]. The Zagros seismic faults have been buried at depths of 8-12 km, and the resulting ruptures have never reached to the ground surface. As a result, none of the seismic parameters of active faults in the Zagros area cannot be directly measured [4]. Rupture directivity effects are largest in the region centered on the up-dip projection of the rupture surface. By definition of footwall and hanging wall, this region occupies more of the footwall than the hanging wall [16]. The minimum focal depth of earthquake in Zagros is 5 km and the maximum is 18 km. The thickness of the seismic layer is changing from about 8 km to 10 km in the central part of Iran to 18 km in the Persian Gulf and shield of Arabia [4]. Among the active reverse faults reported from modern and historical earthquakes are the Mountain Front Fault (MFF), the Dezful Embayment fault (DEF), and the Zagros Foredeep fault (ZFF). Re-appraisal of fault plane solutions for earthquakes along these reverse faults indicate that they dip 30–60 NE, suggesting they are inverted normal faults that originally developed during rifting of the Arabian continent [17]. Shahi and baker 2011 proposed a comprehensive framework to incorporate the effects of near-fault pulse- like ground motions in probabilistic seismic hazard analysis (PSHA) computations. The effects of pulse-like ground motion can be included in hazard analysis by using a modified ground-motion model that accounts for the amplification effect of directivity pulses on Sa values. Because directivity effects depend mainly on source-site geometry, the ground motion model accounting for pulses needs to be a function of source-site geometry along with magnitude and distance. Equation 1 shows how directivity effects can be accounted for in a PSHA calculation [9].

$$v_{S_a}(x) = \sum_{i=1}^{n_{sources}} v_i \iiint P^*(S_a > x|m,r,z).f_i(m,r,z)\,.\,dm.\,dr.\,dz \tag{1}$$

where z represents the source-to-site geometry information, $f_i(m,r,z)$ is probability density function of occurrence of such an earthquake (of magnitude m, distance r, geometric conditions z) on a particular fault i, vi represents rate of occurrence of earthquakes on the fault i, and $P^*(S_a > x|m,r,z)$ can give the rate of exceedance of Sa at the site. This equation can be practically evaluated by splitting $P^*(S_a > x|m,r,z)$ into two cases, depending on whether or not the pulse-like ground motion is observed. These two cases can then be combined to calculate the overall exceedance rate. Geometric parameters for calculating the probability of observing pulses are shown in Fig 1.

In this study probabilistic seismic hazard analysis (PSHA), by considering near-fault directivity effects of Assaluyeh fault is conducted by using Shahi and Baker 2011 approach. Furthermore, seismic hazard analysis of other identified seismic sources is carried out by using Baker 2008 approach [18]. In order to perform the seismic hazard analysis, a point in the central part of Assaluyeh site, which is located in the footwall of the Assaluyeh fault is assumed. According to available information and lack of accurate information about geometrical conditions of faults in this region, calculations of the source-to-site geometric conditions of the Assaluyeh fault are made on the assumption of distinct geometric conditions. In this regard, a hypothetical earthquake is assumed at the projection of the Assaluyeh fault on the ground surface, which is located in shortest distance from the selected point of analysis, in order to obtain the most critical conditions. The most rupture directivity effects are observed in the normal direction relative to the fault strike. Therefore, the angle α is assumed to be 90 for calculating the probability of observing the pulse. This angle is shown in Fig 1. As mentioned, from previous studies, the depth to the top of the rupture is 8-12 km, the dip of MFF is 30°-60° and the focal depth of the earthquake is changing from 5 to 18 km in Zagros. Therefore, it is assumed 8, 10 and 12 km depths to the top of the fault, 30°,45°,60° for fault dip and 10, 15, 20 Km for focal depth of earthquakes. The hypothetical geometric conditions include 24 distinct models are shown in Table 1. The available earthquake catalogs usually contain two types of information: macroseismic observations of major seismic events that occurred over a period of a few hundred years, and complete instrumental data for relatively short periods of time. A method that is generally used for the estimation of seismic activity parameters is Gutenberg-Richter which is not suitable for this type of data. Therefore, the Kijko & Sellevoll method is used to account for activity parameters [19].

By using Shahi & Baker proposed approach, which incorporates forward directivity effects in probabilistic seismic hazard analysis, the 5% damped pseudo spectral acceleration (PSA) for 10% probability of occurrence in 50 years is provided in this study for Assaluyeh fault. In this regard Campbell & Bozorgnia 2003, Ambraseys & Douglas 2003, Campbell 1997 and Chiou & Youngs 2006 near source ground motion models are used in probabilistic seismic hazard analysis.

For each one of 24 models, PSHA is carried out and an average value of PSA in each period of ground motion models is calculated by using MATLAB software. Pseudo spectral acceleration for each ground motion model is represented in Fig 2.

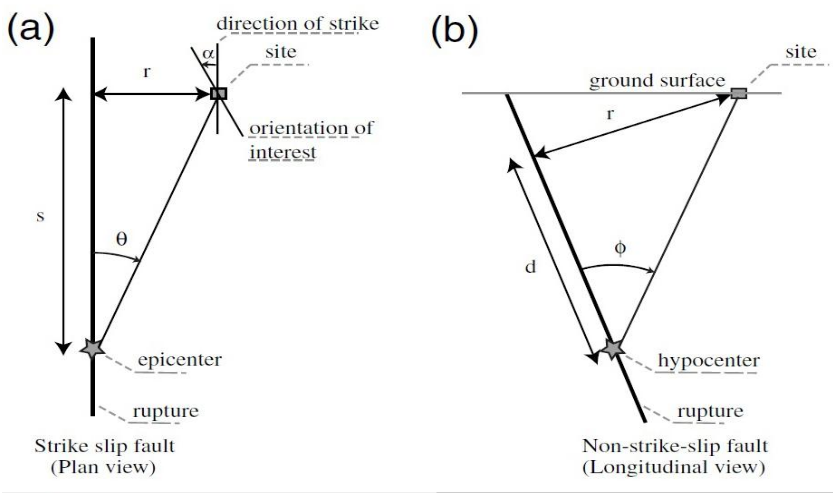

Fig 1. Plot explaining the parameters needed to fit the logistic regression for (a) strike-slip and (b) non-strike-slip faults[9].

Table 1. Probability of pulse occurrence

Model number	depth to the top of rupture(Km)	Focal depth of earthquake(Km)	Fault dip	r_{jb}(km)	r(m)	d(m)	Φ	α	P(pulse)	P(pulse at α|pulse)	P(pulse at α)
1	8	10	30	3	8544.0	4000	27.12	90	0.21	0.53	0.11
2	8	10	45	3	8544.0	2820	18.43	90	0.25	0.53	0.14
3	8	10	60	3	8544.0	2310	7.44	90	0.33	0.53	0.18
4	8	15	30	3	8544.0	14000	14.76	90	0.43	0.53	0.23
5	8	15	45	3	8544.0	9899	11.31	90	0.40	0.53	0.22
6	8	15	60	3	8544.0	8083	4.85	90	0.43	0.53	0.23
7	8	20	30	3	8544.0	24000	10.06	90	0.62	0.53	0.33
8	8	20	45	3	8544.0	16970	8.13	90	0.54	0.53	0.29
9	8	20	60	3	8544.0	13856	3.6	90	0.53	0.53	0.28
10	10	10	30	3	10440.3	0	223.3	90	0.0002	0.53	0.0001
11	10	10	45	3	10440.3	0	208.3	90	0.0003	0.53	0.0002
12	10	10	60	3	10440.3	0	193.3	90	0.0005	0.53	0.0003
13	10	15	30	3	10440.3	10000	22.14	90	0.30	0.53	0.16
14	10	15	45	3	10440.3	7072	16.93	90	0.30	0.53	0.16
15	10	15	60	3	10440.3	5773	8.57	90	0.34	0.53	0.18
16	10	20	30	3	10440.3	20000	14.54	90	0.50	0.53	0.27
17	10	20	45	3	10440.3	14142	11.98	90	0.43	0.53	0.23
18	10	20	60	3	10440.3	11547	6.31	90	0.44	0.53	0.24
19	12	15	30	3	12369.3	6000	31.35	90	0.17	0.53	0.09
20	12	15	45	3	12369.3	4243	23.20	90	0.20	0.53	0.11
21	12	15	60	3	12369.3	3464	12.49	90	0.26	0.53	0.14
22	12	20	30	3	12369.3	16000	19.88	90	0.37	0.53	0.2
23	12	20	45	3	12369.3	11314	16.19	90	0.33	0.53	0.18
24	12	20	60	3	12369.3	9238	9.15	90	0.36	0.53	0.19

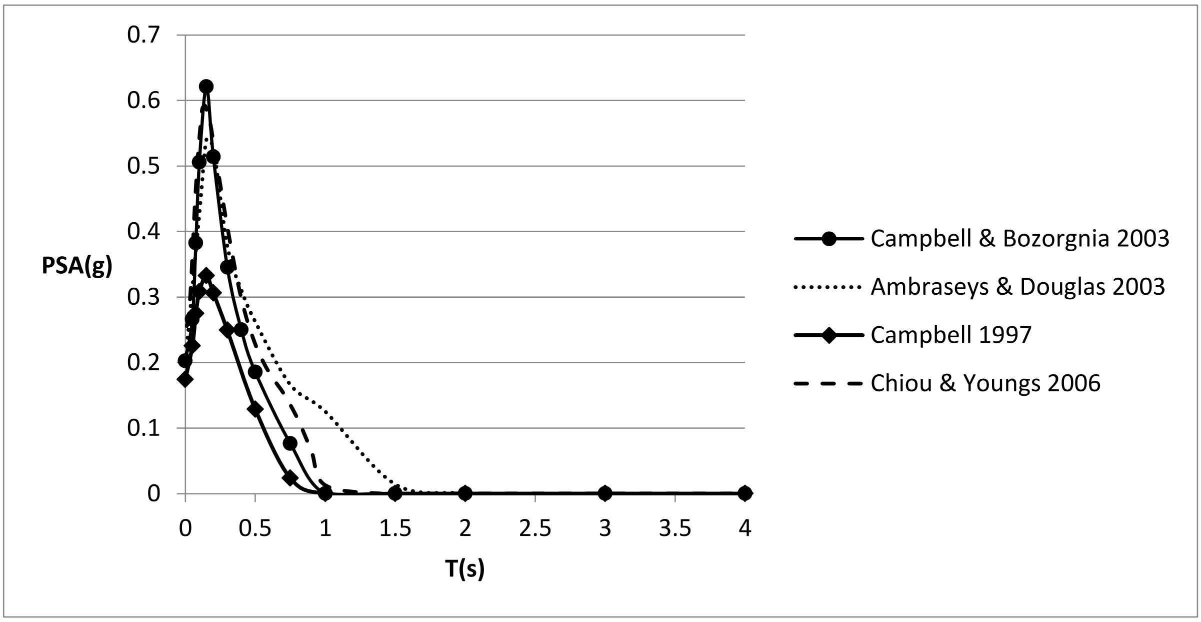

Fig 2. 5% Damped pseudo spectral acceleration for 10% probability of occurrence in 50 years

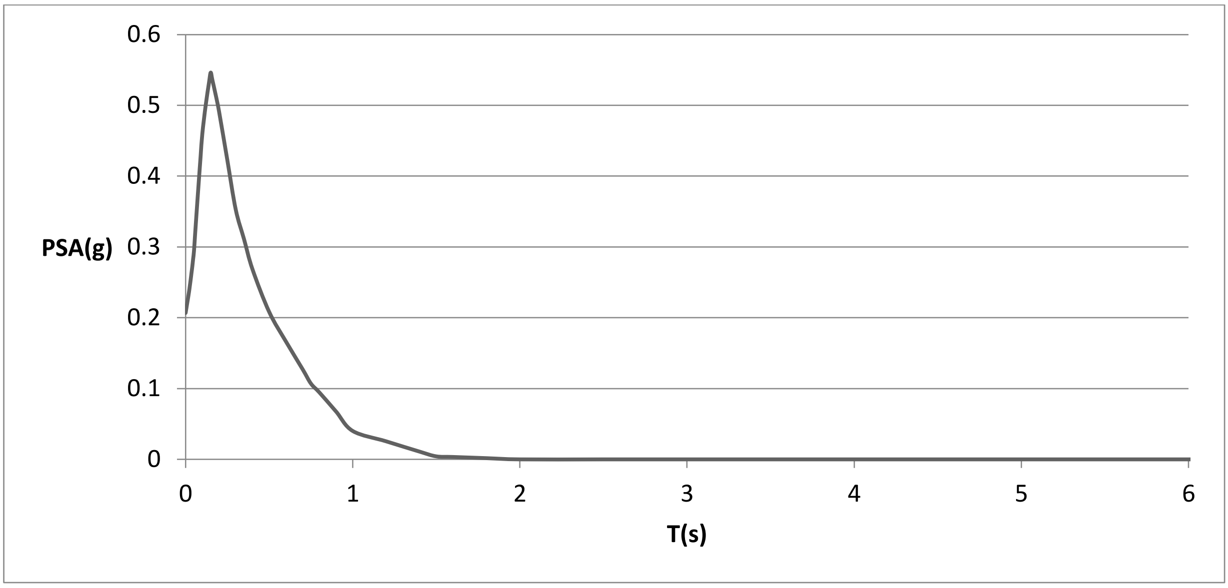

Fig 3. 5% Damped pseudo spectral acceleration for 10% probability of occurrence in 50 years for Assaluyeh fault from near source seismic hazard analysis

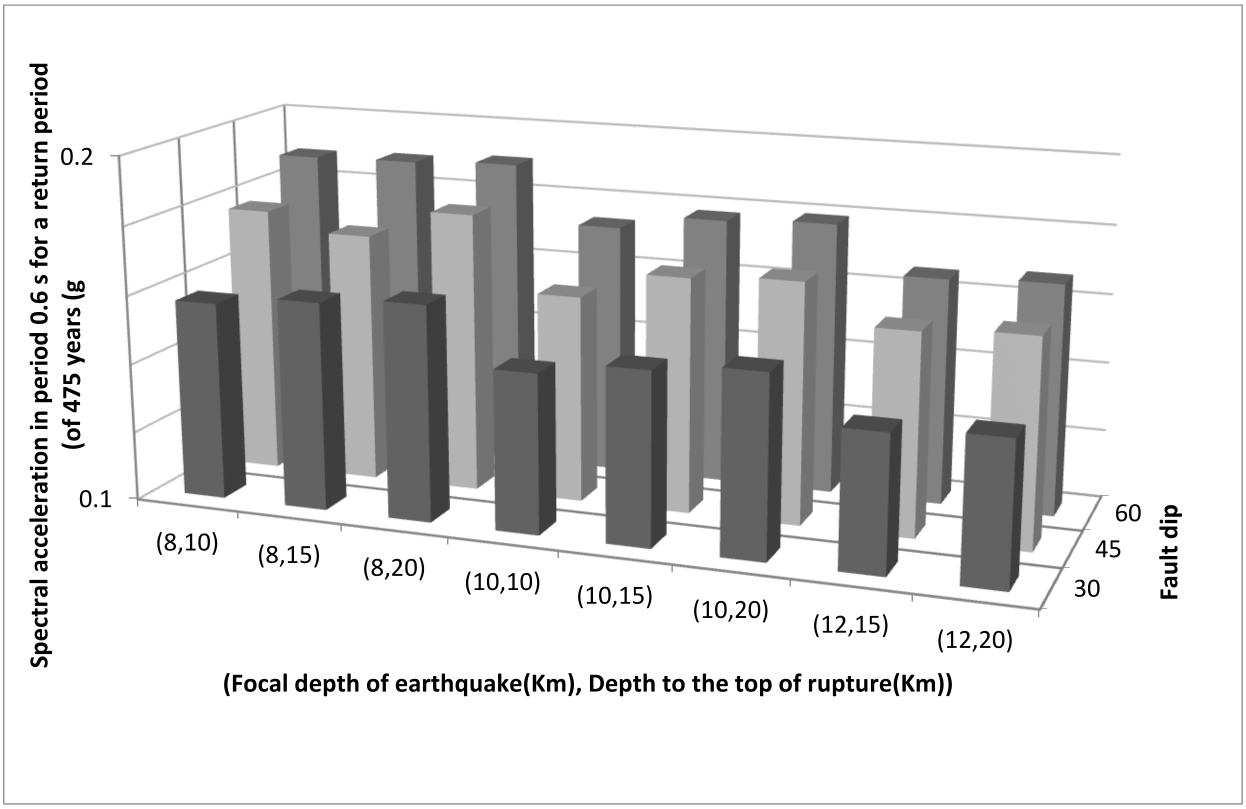

Fig 4. Deaggregation of spectral acceleration at period equal to 0.6 s for association of focal depth of earthquake, depth to the top of rupture and fault dip

5% damped pseudo acceleration response spectra of Assaluyeh fault from near source seismic hazard analysis is achieved by considering the impact coefficients of 0.35, 0.3, 0.15 and 0.2 for Campell & Bozorgnia, Ambraseys & Douglas, Campbell and Chiou & Youngs respectively. This is shown in Fig 3.

Disaggregation of pseudo spectral acceleration at a period equal to 0.6 s with a different source to site geometries is shown in Fig 4.

As seen in Fig4 the greatest value of spectral acceleration for different geometric conditions belongs to 8 Km to top of fault rupture, focal depth of 10 Km and fault dip of 60.

3. Probabilistic seismic hazard analysis of assaluyeh site

Probabilistic seismic hazard analysis of Assaluyeh site for the other seismic sources is carried out by using Baker 2008 proposed approach. In this regard, earthquakes with a magnitude greater than four which their focal distance to the selected point is less than 150 km are considered in this study. Three segments of Mountain Front Fault (MFF) are considered as line sources as well as 11 identified area sources. Two ground motion models of NGA, including Campbell & Bozorgnia 2008 and Chiou & Youngs 2006 are employed as well as Ghasemi et al. 2009, which is compatible with seismic conditions in Iran.

As is shown in Fig 5, pseudo acceleration response spectra of probabilistic seismic hazard analysis from the other identified seismic sources are provided by considering impact coefficients of 0.4, 0.4 and 0.2 for Campbell & Bozorgnia 2008, Chiou & Youngs 2006 and Ghasemi et al. 2009 ground motion models respectively.

Final 5% damped pseudo acceleration response spectra of PSHA for 10% probability of occurrence in 50 years containing near and far-field analysis (Assaluyeh fault in addition to their sources) which is achieved by summation of obtained results is represented in Fig 6.

As seen in Fig 6, peak ground acceleration (PGA) in this study is equal to 0.54g while this value is 0.3g and 0.42g for relative high- risk zone of 2800 standard and site-specific study of IIEES respectively [20,21].

Contribution ratio is calculated from dividing PSA value of near source analysis into total PSA value in each period that is shown in Fig 7. Significant contribution of PSHA results in most periods belongs to the near source PSHA of the Assaluyeh fault. This high influence of the Assaluyeh fault in PSHA results is due to considered near source ground motion models, assumed geometric conditions, and calculated probability of pulse occurrence.

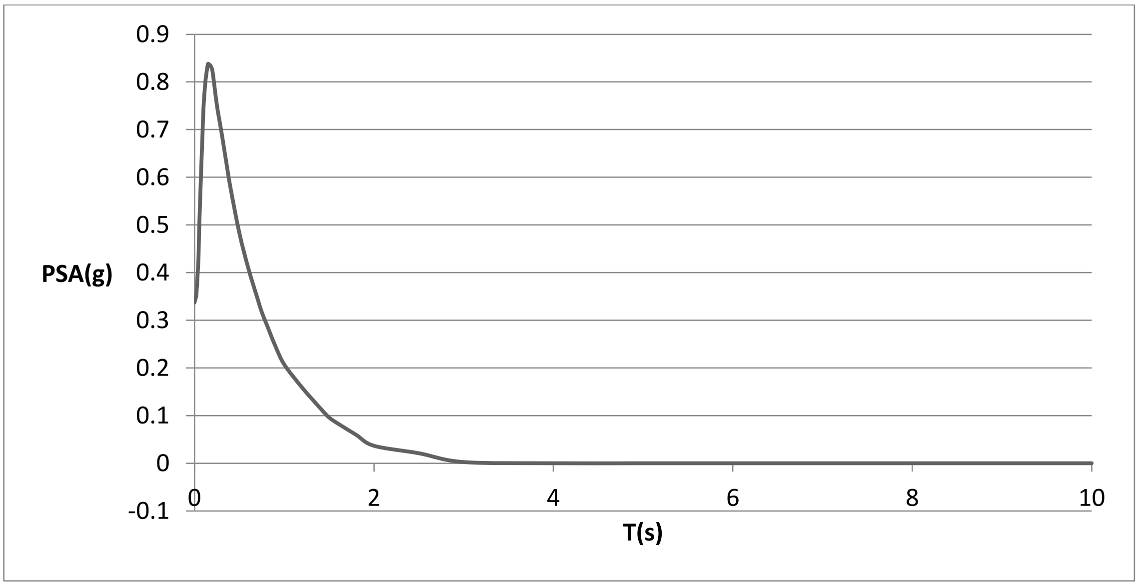

Fig 5. 5% Damped pseudo spectral acceleration for 10% probability of occurrence in 50 years for the other identified seismic sources

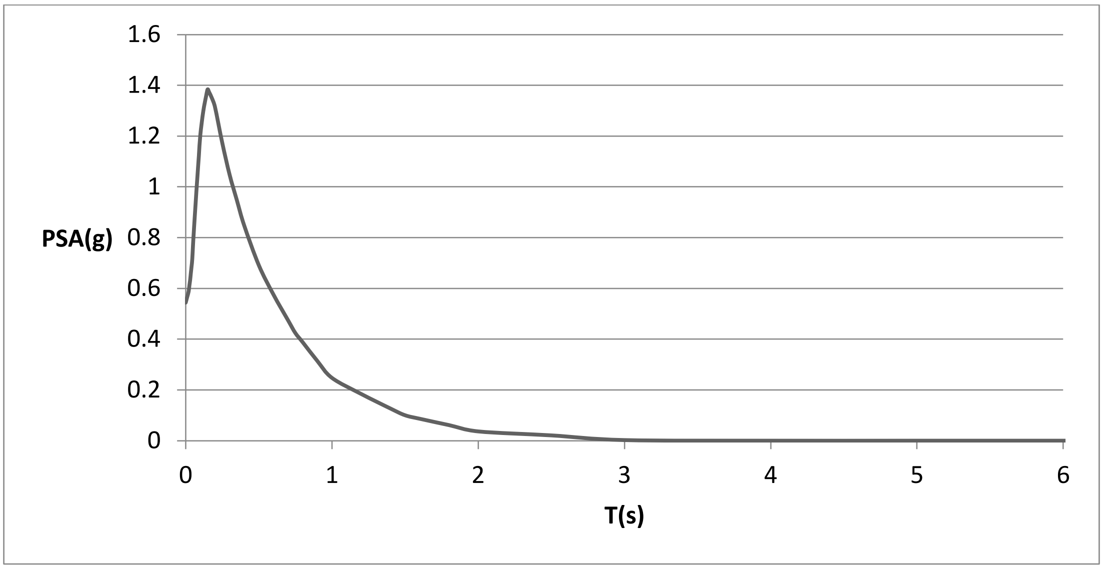

Fig 6. 5% Damped pseudo spectral acceleration for 10% probability of occurrence in 50 years for Assaluyeh site

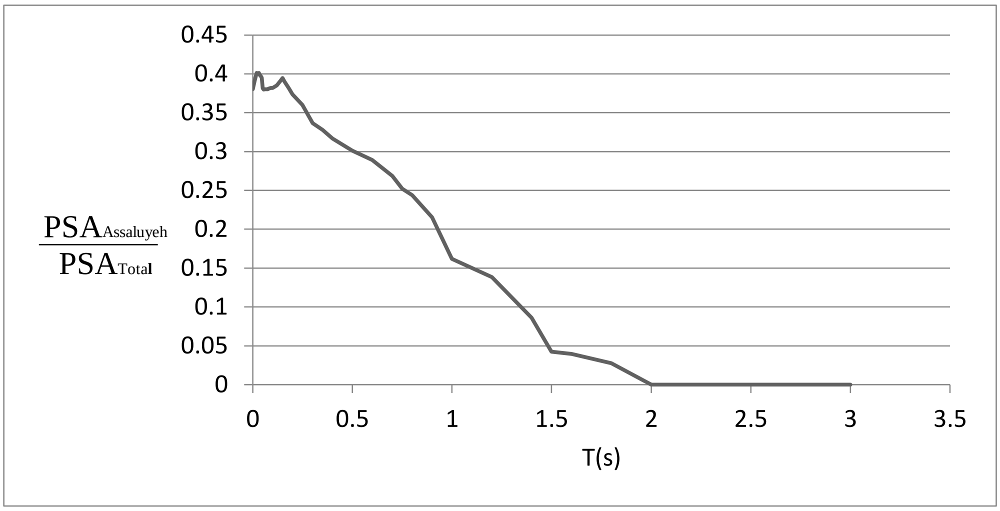

Fig 7. Contribution ratio of PSA

4. Site-specific design spectra

Earthquake records are needed to provide the site-specific design spectra. The selection of records should be based on compliance with the site conditions, including the expected intensity measures (IM) of PSHA, fault mechanism, soil condition, pulse occurrence, etc. In this regard, the Pacific Earthquake Engineering Research Center (PEER) supplies earthquake records by considering defined conditions by users.

In this study, an analysis was conducted on seismic bedrock, therefore, acceleration time histories must have been recorded on bedrock. Pseudo spectral acceleration of this study was uploaded on PEER database. This website proposed accelerograms with confirmed forward directivity pulse.

Nine acceleration time histories including seven fault normal and two fault parallel components are used to provide the site-specific design spectra. Scaling of accelerograms is conducted in two methods which in the first method, the accelerogram values are scaled to the calculated PGA and in the second method, are scaled to the pseudo spectral acceleration values at periods ranging from 0.01 to 10 seconds. Selected recordss and calculated scale factors are shown in Table 2.

Table 2. Selected accelerograms and calculated scale factors

Event	Year	Station	Direction	Scale factor	
				PGA	0/01-10
Loma Prieta	1989	Gilroy Array #1	FN	1.3217	1.019
Loma Prieta	1989	Gilroy - Gavilan Coll/	FN	1.9234	1.2479
Chi-Chi- Taiwan	1999	TCU102	FN	1.9291	1.4839
Chi-Chi- Taiwan	1999	TCU102	FP	3.3778	1.4839
Northridge-01	1994	Pacoima Dam (downstr)	FN	1.1363	1.2484
Northridge-01	1994	Pacoima Dam (upper left)	FN	0.4122	0.3878
Cape Mendocino	1992	Petrolia	FN	0.9212	0.6627
Cape Mendocino	1992	Petrolia	FP	0.8999	0.6627
San Fernando	1971	Pacoima Dam (upper left abut)	FN	0.3951	0.4501

Variety of soil properties in the wide area of Assaluyeh Complex is high, but the results of conducted experiments by IIEES show that most area of this site is covered by coarse-grained sediments, which this type is very dense soil [20]. Analysis of soil properties has been carried out using geophysical test data from one of the boreholes excavated in the region. A borehole drilling experiment with downward wave propagation was conducted to calculate dynamic soil parameters [22]. An environment with a shear wave velocity of over 750 m/s has been introduced in 2800 seismic standard as the seismic bedrock [21]. The 1997 edition of UBC code defines bedrock as an environment which has a shear wave velocity of over 760 m/s [23]. Seismic bedrock, in this study, is considered as an environment with a shear wave velocity of more than 760 m/s.

Analysis of soil properties is performed by using Shake 2000 software which is a computer program for analysis of geotechnical earthquake engineering problems [24]. The general profile of the soil layers in the borehole is described in Table 3.

The site- specific response spectrum of each accelerogram on the ground surface is calculated by considering soil properties data by Shake 2000.

As mentioned previously two methods were used to scale accelerograms. The site- specific design spectra in two methods, including scale to PGA and scale to pseudo spectral acceleration values at periods ranging from 0.01 to 10 s are represented in Fig 8 and Fig 9.

Table 3. Profile of the soil layers [21]

Depth(m)	V_s(m/s)	G(Gpa)	γ(kN/m3)
0-1	175	0.05	16.01633
1-2	275	0.15	19.45785
2-3	350	0.25	20.02041
3-4	425	0.4	21.72457
4-5	525	0.55	19.57551
5-6	550	0.6	19.45785
6-7	525	0.55	19.57551
7-8	600	0.7	19.075
8-9	650	0.8	18.57515
9-10	675	0.95	20.45432
10-11	685	0.95	19.86147
11-12	700	1	20.02041
12-13	700	0.95	19.01939
13-14	700	0.97	19.4198
14-15	700	1.03	20.62102
15-16	725	1.05	19.59667
16-17	725	1.1	20.52985
17-18	715	1.01	19.38109
18-19	775	1.17	19.10959
19-20	750	1.1	19.184
20-21	760	1.15	19.53168

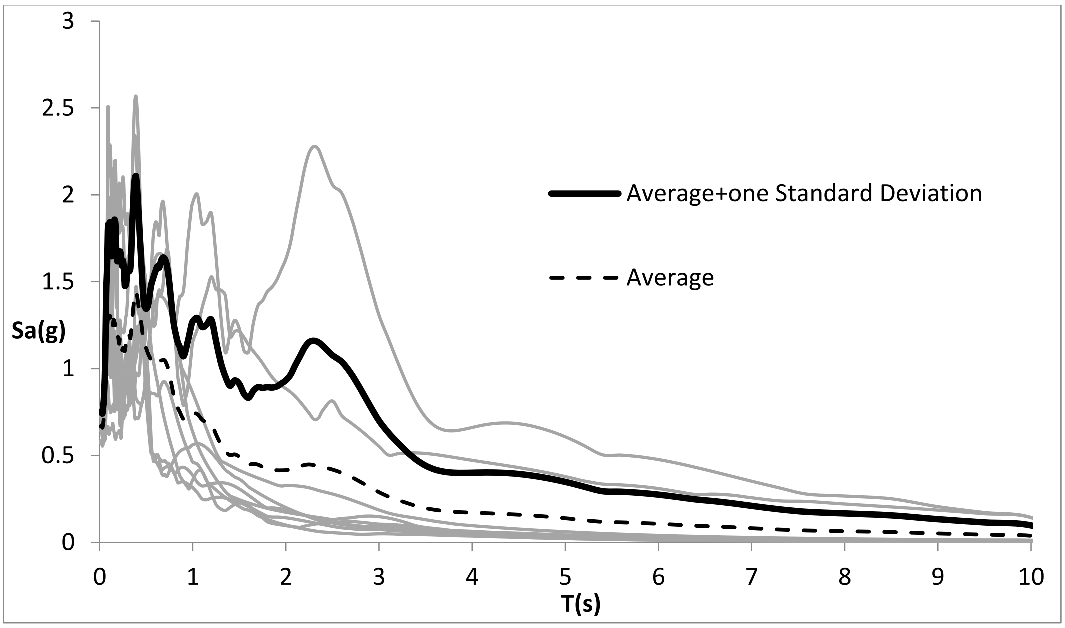

Fig 8. The site- specific mean and mean plus one standard deviation spectra of accelerograms which are scaled to the calculated PGA

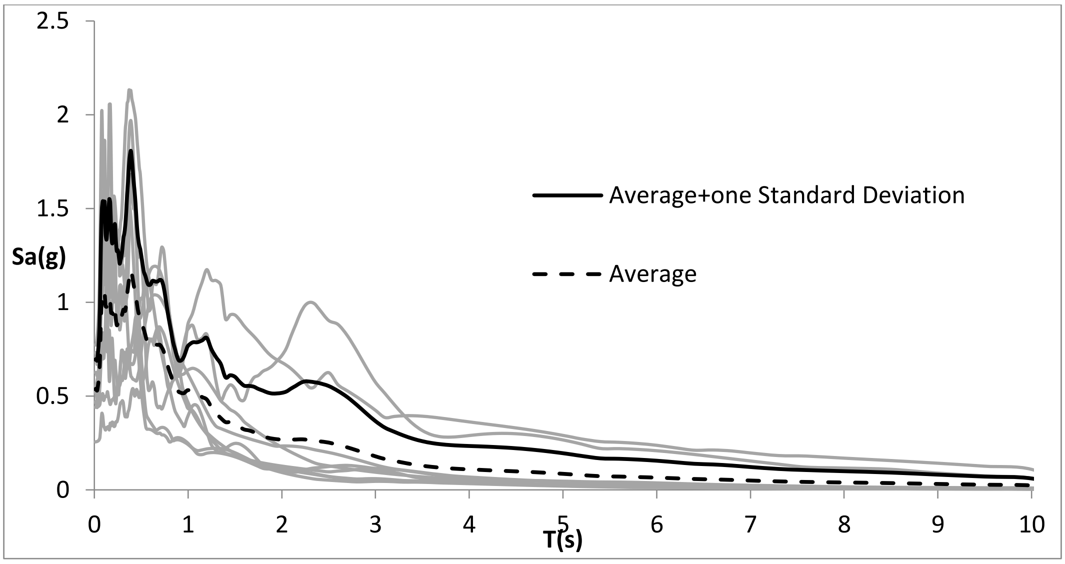

Fig 9. The site-specific mean and mean plus one standard deviation spectra of accelerograms which are scaled to pseudo spectral acceleration values at periods ranging from 0.01 to 10 s

Comparison of the site-specific design spectra of this study with the standard design spectrum of Iran's 2800 standard for soil type II and the relative high-risk zone is represented in Fig 10. Also, the comparison with the site-specific design spectrum of IIEES is represented in Fig 11.

Results show that the site-specific design spectra of this study fall at an upper level than the standard design spectra of 2800 and the site-specific design spectrum of IIEES.

As seen in Fig 11 site-specific design spectrum of this study, which is scaled to pseudo spectral acceleration values at periods ranging from 0.01 to 10 s, has a relatively acceptable coincidence with IIEES's spectrum at periods up to 0.35s. At higher periods, the spectrum of this study falls at an upper level.

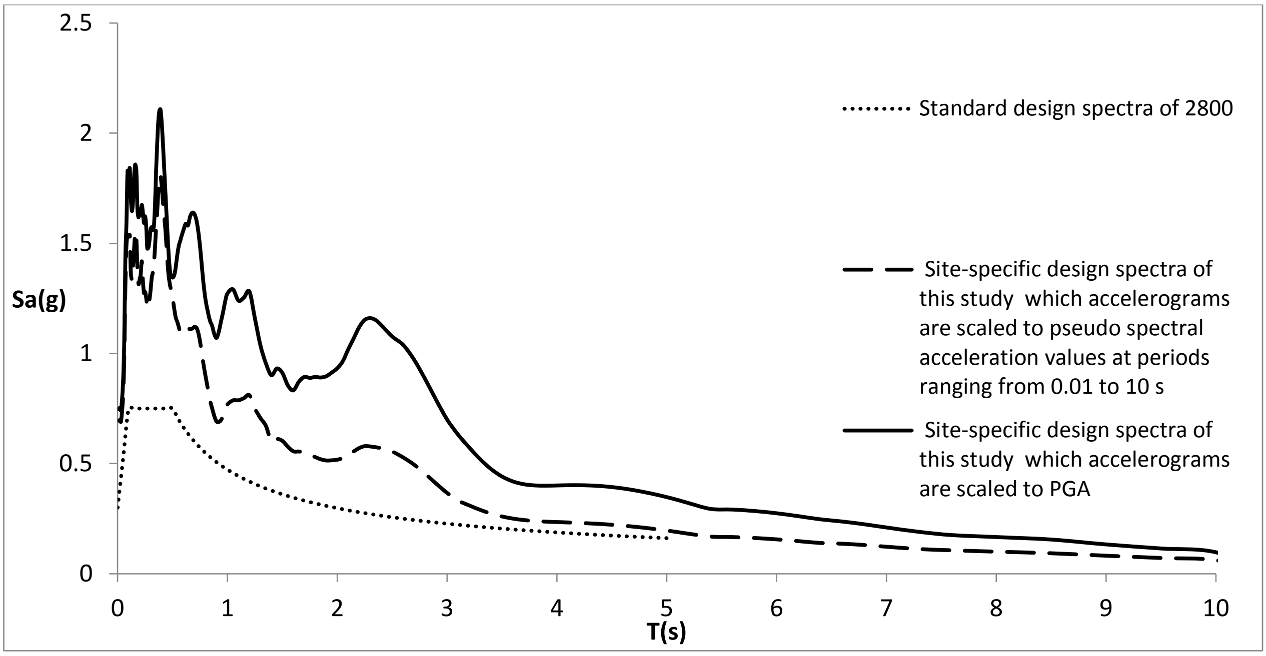

Fig 10. Site-specific design spectra of this study in comparison with the standard design spectrum of Iran's 2800 standard

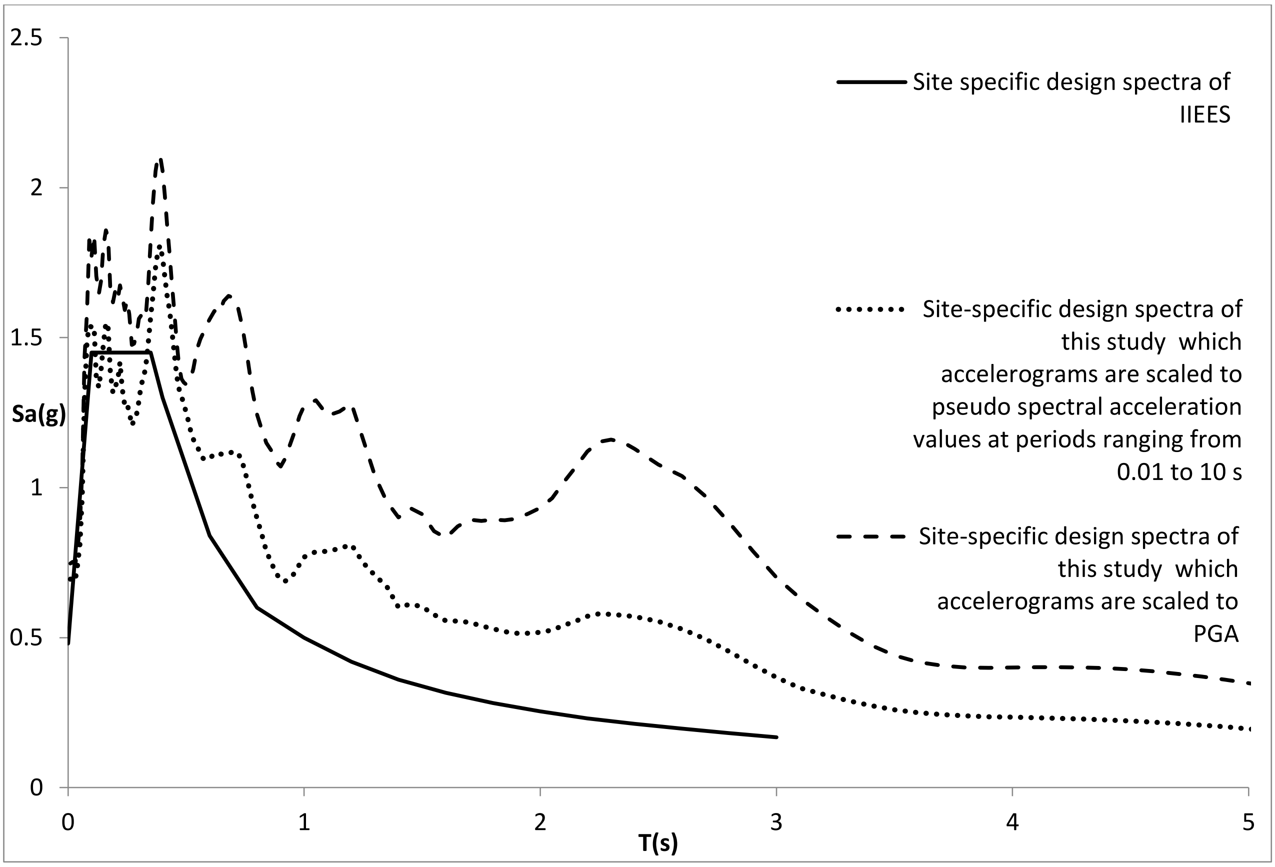

Fig 11. Site-specific design spectra of this study in comparison with the site-specific design spectrum of IIEES

5. Conclusions

In this study, probabilistic seismic hazard analysis by considering near source effects is performed. In this regard, a number of ground motion models are used to provide the 5% damped pseudo acceleration response spectra for 10% probability of occurrence in 50 years containing near and far-field analysis (Assaluyeh fault in addition to the other sources).

Results show that the calculated PGA of Assaluyeh is greater than 2800 standard and IIEES's values. PGA in this study is equal to 0.54g while this value is 0.3g and 0.42g for the relative high-risk zone of 2800 standard and site-specific study of IIEES respectively.

Also in this study two types of site-specific design spectra based on scaling earthquake records to PGA and scaling to pseudo spectral acceleration values at periods ranging from 0.01 to 10 s are prepared. Scaling to PGA is a more common method but scaling to pseudo spectral acceleration values at periods ranging from 0.01 to 10 s generally has better coincidence with pseudo spectral acceleration of PSHA.

Both site-specific design spectra of this study fall at an upper level than the standard design spectra of Iran’s 2800 standard.

The spectra in which accelerograms are scaled to PGA falls at an upper level than IIEES’s site-specific design spectra. This ascendency is more for period values greater than 0.5 s. The spectra in which accelerograms are scaled to pseudo spectral acceleration values at periods ranging from 0.01 to 10s has a relatively good coincidence with site-specific design spectra of IIEES at periods up to 0.35 s, but at greater periods falls at an upper level.

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