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Evaluation of 1-D Seismic Site Response Analysis and Design of Acceleration Spectra for Different Site Conditions

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ABSTRACT: Understanding how regional geology and soil conditions affect the intensity of ground shaking is one of the fundamental tasks of seismology and earthquake engineering. As a result, it is necessary to explore a wide range of features, including material, nonlinearity, and different non-linear models. In this study, five different earthquake models with peak accelerations ranging from 0.01 to 0.8g are used to examine the impact of the local site on design parameters. This study uses three different types of recorded ground motions, with maximum accelerations between 0.001 and 0.1g (type I), 0.1 and 0.3g (type II), and 0.3 and 0.8g. (type III). Downhole tests in four bore-holes in the Hormozgan province were used to assess wave shear velocity (Vs) for this purpose. To determine soil parameters, various tests such as sieve or hydrometer and atterberg limits were performed on samples. The results showed that a larger frequency band is caused by increased soil cohesiveness and that the frequency band's increase enhances the possibility of resonance. Based on the results, it is clear that the non-linear method provides a more comprehensive explanation of true non-linearity in soil behavior than equivalent-linear approaches. This study tends to support the idea that site analysis is essential for significant projects and that response analysis should be performed on each identified site.

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1- Introduction

Historical investigations of several earthquakes over the last 40 years have shown that local geology and soil characteristics may significantly affect the severity of ground movement and earthquake damage. Different features of strong ground motion can be significantly impacted by geotechnical conditions (e.g.amplitude, frequency, duration). Side effects should be taken into consideration while developing ground motion for seismic designs to prevent or lessen the severity of earthquake damage. Therefore, before constructing a structure, ground investigations are performed. The local site impact is influenced by factors such as soil deposit type, sublayer material quality, site topography, and input motion requirements. Therefore, evaluating local site impacts on major ground motion through site reaction assessments is a crucial starting step in the seismic evaluation of many geotechnical projects and soil-structure interaction problems. This may be accomplished by conducting site response assessments. Several authors have published lists of widely used computer programs for 1-D seismic site response evaluations [1-3]. DESRA2 was used by Yu et al. (1993) to investigate the differences between linear and non-linear soil reactions at various degrees of base excitation. For an unsaturated shallow soil deposit of 20 m in thickness, the results showed that soil non-linearity produces amplification and a shift in peak frequencies to lower values utilizing this direct non-linear method [4]. Aschheim and Black (1999) investigated the seismic response of degraded SDOF systems that had already suffered damage (e.g., damage caused by earlier earthquake ground movements to the design-level earthquake) under a set of 18 earthquake ground motions with various ground motion properties. Rodriguez-Marek et al. (2001) provided a method for the geotechnical characterization of sites that incorporates soil depth and stiffness, which indicated that soil depth is a significant component in site response [5]. For the Hyogo-ken-Nanbu and Nisqually earthquakes, Frankel et al. (2002) reported variable degrees of soil non-linearity, depending on the site conditions [6]. The influence of recurrent earthquake ground motions on the seismic response of non-linear SDOF systems was explored by Amadio et al. (2003). The findings revealed that the reaction of basic structures to repeated earthquakes is influenced by the period of vibration, the type of series, and the ductility of the system [7].

Due to the significant discrepancy in bedrock depth and soil stiffness, the site coefficients provided in the Korean seismic design code (taken from UBC and NEHRP requirements) overestimate the amplification factor in the mid-period range and underestimate it in the short-period range [8].

The effect of local soil conditions on ground motion parameters was investigated using the Equivalent-Linear Earthquake Response Analyses (EERA) model [9]. Cavallaro et al. (2008) used non-linear models GEODIN and linear

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models EERA to compare the ground response of the Tito Scalo site in Southern Italy [10]. Yang et al. (2011) used one-dimensional equivalent linear analysis to examine the effects of permafrost on ground motion characteristics. The findings revealed that the presence of permafrost could dramatically modify ground motion characteristics, implying that it may not be prudent to neglect permafrost impacts in civil structure seismic design [11]. By completing a one-dimensional equivalent-linear ground response analysis for some of the typical Mumbai soil sites, Phanikanth et al. (2011) investigated the role of local soil sites in changing ground response [12].

Goda (2012) investigated the non-linear response potential of the mainshock and aftershock sequences for Japanese earthquakes from the K-NET and KiK-net databases. Using probabilistic framework analysis, this study investigated the validity of artificially generated sequences based on generalized Omori's law.

The peak ductility demand ratio between mainshock–aftershock sequences and mainshock alone is affected by the amplitude of the mainshock [13]. Cadet et al. (2012) recommended using two correction factors, the depth correction factor, and the impedance contrast normalization factor, to normalize the site amplification factors for a standard outcropping rock site by current design codes [14].

A real-time prediction model of strong ground motions based on non-parametric wave type was suggested by Zahedi-Khameneh et al. (2013). It uses adaptive windowing technology to capture the main frequency of ground motions and a radial basis function (RBF) network to predict the next time step acceleration of earthquake records [15]. With the Park-Ang damage index, Zhai et al. (2013) investigated the damage spectra for main-shock–aftershock sequences. This research calculated the predicted damage spectra using observed and simulated seismic ground motions [16]. Nimtaj and Bagheripour (2013) investigated the seismic response of a layered soil deposit by rewriting the dynamic equation of motion in the frequency-time domain [17]. The impacts of soil non-linearity on the horizontal-to-vertical spectral ratio (HVSR) of recorded ground vibrations were demonstrated by Nagashima et al. (2014) [18]. Han et al. (2015) developed an approach for analyzing the seismic performance of non-ductile reinforced concrete buildings, with a focus on the interplay between aftershocks and various post-quake decisions [19].

In the centrifuge, Hashash et al. (2015) studied the reaction of a similar 26m-thick deposit of Nevada Sand to six horizontal seismic movements. The findings showed that by utilizing the medium-dense dry sand, 1-D seismic site response assessments may reliably compute soil response [20]. Stamati et al. (2016) investigated the influence of complex site factors and soil non-linearity on seismic ground motion in the city of Xanthi, North-Eastern Greece. Results showed that anticipated ground motion varied between 1D and 2D studies, indicating complicated site impacts [21]. Mianshui Rong et al. (2016) investigated the horizontal-to-vertical spectral ratio using strong ground-motion records from the mainshocks and aftershocks of the 2008 Wenchuan (Ms 8.0) and 2013 Lushan (Ms 7.0) earthquakes (HVSR) [22].

Roy et al. (2018) calculated shear-wave velocity (VS) based on seismic site response analysis and available VS - SPT correlations. In this regard, equivalent linear site response analysis has been performed and utilized strong-to-weak ground motion records. The site response analysis results show that amplification spectra of the generated VS profiles using all soil types and specific soil-type VS–N correlations show significant variations [23]. The effect of variability of soil profile properties on the weak and strong seismic responses was investigated by Gobbi et al. (2020). In this regard, a data set of 300 one-dimensional soil profiles was generated using a Monte Carlo method for employing the average shear wave velocity in the top 30 m of the soil profile Vs. According to the findings of various site response assessments, it is necessary to add complimentary site parameters to account for site impacts in the design response spectrum [24].

Roy et al. (2020) studied the influence of trapped soft and stiff soil layers on the equivalent linear ground seismic site response analysis (by the STRATA program). The numerical findings showed that the profile of the trapped soft soil layer (i.e., inversely stiff soil profile with soft layer) has a greater impact on the outcomes than the profile of the trapped stiff soil layer. For weak to moderate ground vibrations, increasing the depth of the trapped soft layer reduced peak amplification and peak frequency. For higher ground motion, only peak frequency was considerably reduced [25]. Effective input velocity and depth for deep and shallow sites for site response analysis were investigated by Bajaj and Anbazhagan(2022). The results show that a layer having $Vs \geq 1500$ (±150) m/s is suitable for capturing the surface amplification spectra for both deep and shallow deposits [26]. Chavan et al. (2022) evaluated site response analysis of liquefiable soil employing continuous wavelet transforms. It is revealed that the moment soil undergoes initial liquefaction, it causes a spike in the acceleration–time history. From the analysis, the frequency of the spikes is found to be greater than the predominant frequency of the acceleration time history recorded at the ground surface [27]. A fully coupled flow deformation model to characterize the nonlinear seismic site response of liquefiable marine sediments, considering the ocean wave environment studied by Zhao et al. (2022). The obtained results indicate that the ocean wave environment has a significant effect on the nonlinear seismic site response of liquefiable seabed at shallow depths [28]. Site-specific seismic ground response analysis for typical soil sites in central Khartoum, Sudan was investigated by Al-Ajamee et al. (2022). The site response analysis revealed that the peak ground acceleration was found to range from 1.7 to 2.5, and Fourier amplitude ratios were found to vary from 4.3 to 8.35 [29]. Despite various research performed about 1D or 2D site response analysis, the effect of geotechnical conditions (different geotechnical parameters) combined with earthquakes with different accelerations has been less attention to the case study in Iranian cities.

Table 1. Input ground motion.

Event	year	M_W	Station name	Recording identifier	*PGA* (g)	*Vs*	Group no.
Whittier Narrows	1987	6	"LA - Wonderland Ave"	RSN643_WHITTIER.A	0.0414	1222	1
Morgan Hill	1984	6.19	"Gilroy Array #1"	RSN455_MORGAN_G01230	0.0942	1428	1
Northridge	1994	6.69	"LA - Chalon Rd"	RSN989_NORTHR_CHL070	0.215	740	2
Kobe	1995	6.9	"Kobe University"	KOBE_KBU000	0.2758	1043	2
Loma Prieta	1989	6.93	"Los Gatos - Lexington Dam"	RSN3548_LOMAP_LEX000	0.442	1070	3
Tabas	1978	7.35	"Tabas"	TABAS_TAB-T1	0.854	766	3

This paper aims to evaluate the effect of geotechnical parameters on the ground motion factors at the surface of the ground. For reaching this purpose in different sites in Hormozgan province, four bore-holes have been drilled to a depth of 30 meters. Experimental and field laboratories have been conducted at different depths. Geophysical experiments (such as the downhole test) were performed for the determination of seismic parameters. Earthquakes in the present work have been selected in such a way that the record of earthquakes is on a bedrock (Vs >750 m/s) and have a magnitude between 6 and 8. Such stations where the shear wave velocity is more than 750 m/s are very low and limited.

Three types of earthquakes with a different range of earthquakes with accelerations between 0.01-0.8g are considered to access a better understanding effect of geotechnical conditions of sites on the ground motion parameters. However, even earthquakes with lower accelerations can cause significant damage due to the resonance phenomenon Seismic site response analysis is compared in the current study with the values of various regulations, which may greatly help engineers in producing more accurate and cost-effective designs.

2- Earthquake Ground Motion

One of the most significant instruments for the design of civil engineering constructions is ground motion. Ground motion parameters have long been used to define the characteristics of powerful ground motions, such as amplitude, frequency content, and duration. Ground motion is commonly characterized in terms of acceleration, which may be measured directly using a time history of ground motion, as well as other factors like velocity and displacement. The ground motion intensity at each frequency band is described by the greatest absolute acceleration, velocity, and displacement values. An accelerogram's highest horizontal acceleration (PGA) is a crucial component.

2- 1- Input motion

The PEER database was used to acquire the recorded ground motions. The recorded strong vibrations are used as outcrop strong motions on the hard rock or stiff soil (NEHRP site class A/B). Six earthquake motions with various parameters were employed in this work to span a wide range of amplitudes (e.g., arias intensities, peak ground accelerations, PGA), frequency contents (e.g., predominant periods, Tp), and durations. However, the primary goal of this work is to investigate peak ground accelerations, or PGAs, on the ground's surface. Three types of recorded ground motions are used in this study, with maximum accelerations ranging from 0.001 to 0.1g (type I), 0.1 to 0.3g (type II), and 0.3 to 0.8g (type III). The magnitude of the earthquake and the distance from the epicenter determine the peak ground acceleration in a given zone. As a result, earthquake magnitude has a significant impact on spectral amplification, and the acceleration amplification for earthquakes with a magnitude of 6<M<7 is greater than the amplification for earthquakes with a magnitude of 5<M<6, so the earthquake motions chosen are those with a magnitude of 6 to 8. Table 1 lists the features of the suite of achieved basic motions. Figs. 1 to 3 illustrate the acceleration time histories of motions observed at the outcrop during a distinct earthquake.

3- Geotechnical characterization of the site

3- 1- Local geology of sites

The depth of the bore-hole was confined to the top of 30m as per the Iranian code requirement, and geotechnical drilling was undertaken at four different sites with differing geotechnical specifications to assess the subsurface layering characteristics (No. 2800, 2005). Boreholes are being drilled in Hormozan province, as well as Hajiabad and Qeshm. Hormozgan Province is one of Iran's 31 provinces, located in the south of the country, north of the Strait of Hormuz, in Iran's Region 2, which borders Oman and the United Arab Emirates. Bandar Abbas, the province capital, has a land area of 70,697 km2. Hormongan province's major cities are Qeshm and Hajiabad. Hormozgan province is unique in terms of geological setting and structural elements because of its geographical placement at the intersection of three structural-sedimentary zones: the Zagros, Makran, and Central Iran. As a result, Hormozgan province is separated into three geological zones: Zagros, Makran, and Iran. As can be seen in the seismotectonic map of the Hormozgan province zone (Fig. 4) and surrounding areas (only earthquakes with a magnitude greater than 4 are shown), the accuracy of earthquake epicenter position and magnitude increases not only due to the increased number of stations recording them but also due to the low error in reading the time at which a high magnitude earthquake occurs.

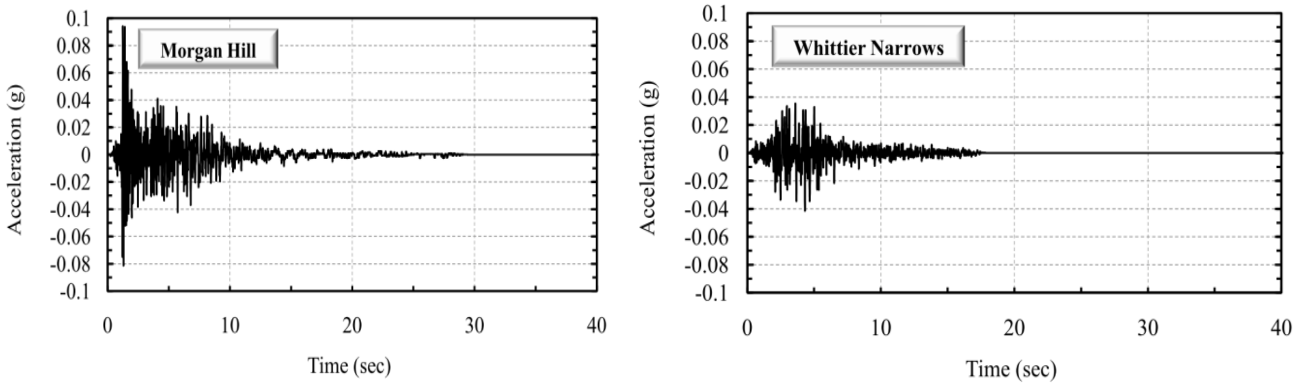

Fig. 1. Acceleration time-history for type I ground motion.

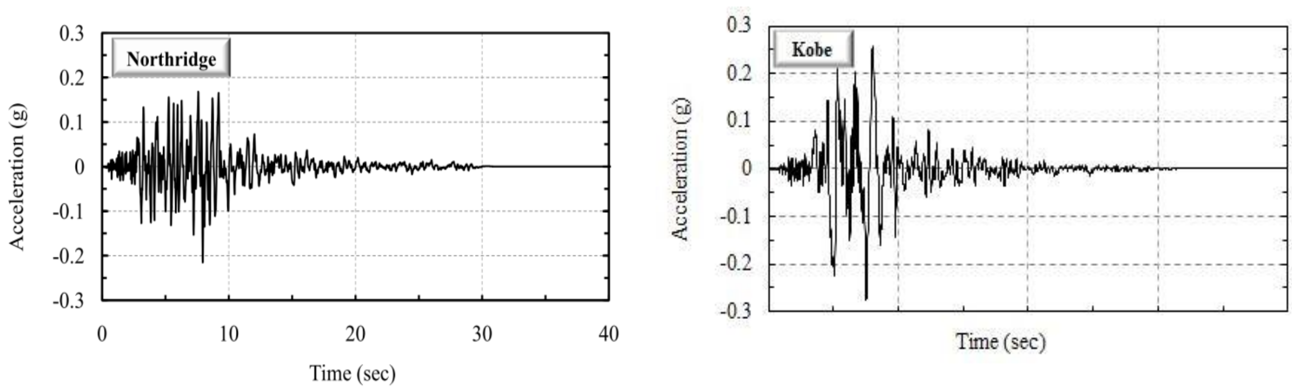

Fig. 2. Acceleration time-history for type Π ground motion.

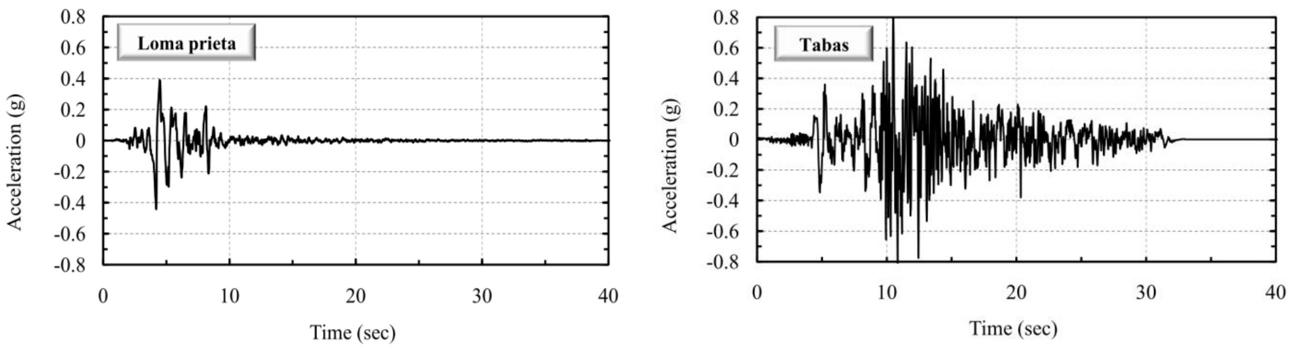

Fig. 3. Acceleration time-history for type III ground motion.

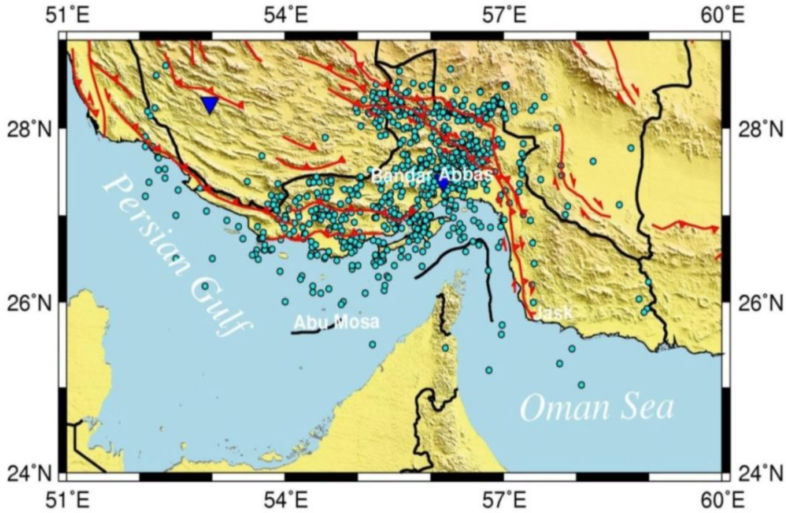

Fig. 4. Seismic zone map of Hormozgan province for earthquakes with magnitudes greater than 4 on the Richter scale.

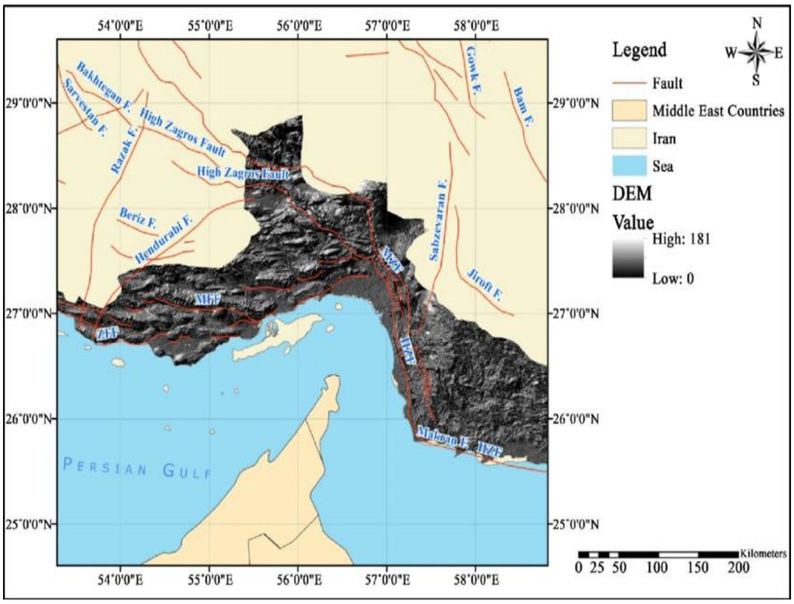

Fig. 5. The major faults map in Hormozgan.

In general, seismicity in the region correlates to the primary seismic structures that have influenced the path of Minab faults, the main Zagros thrust, and the eastern branch of the Dehshir-baft fault in the province's northern half. The epicenter of most earthquakes in the Hormozgan province zone is located at the Minab fault's collision point with the Main Zagros Thrust, while the epicenters of other earthquakes are located on the Qeshm and Bandar Lengeh faults. The main Zagros thrust fault, high Zagros fault (HZF), main Zagros reverse fault (MZRF), Qeshm fault, and Zagros Foredeep fault (ZFF) are all major faults in the region (Fig. 5).

Hajiabad is around 100 kilometers north of Bandar Abbas (the central city of Hormozgan Province).

Hajiabad's sediments are coarse-grain brown gravel (Fig. 6, BH 1, 2).

Qeshm Island is a small island on Iran's southern coast (Persian Gulf), directly across from the port cities of Bandar Abbas and Bandar Khamir. The island is 135 kilometers long and has a 300-square-kilometer (116-square-mile) free zone authority. The island is 40 kilometers broad at its widest point, which is towards the island's center (25 miles). Similarly, the island measures 9.4 kilometers wide at its narrowest point (5.8 miles). Qeshm city, on the island's easternmost

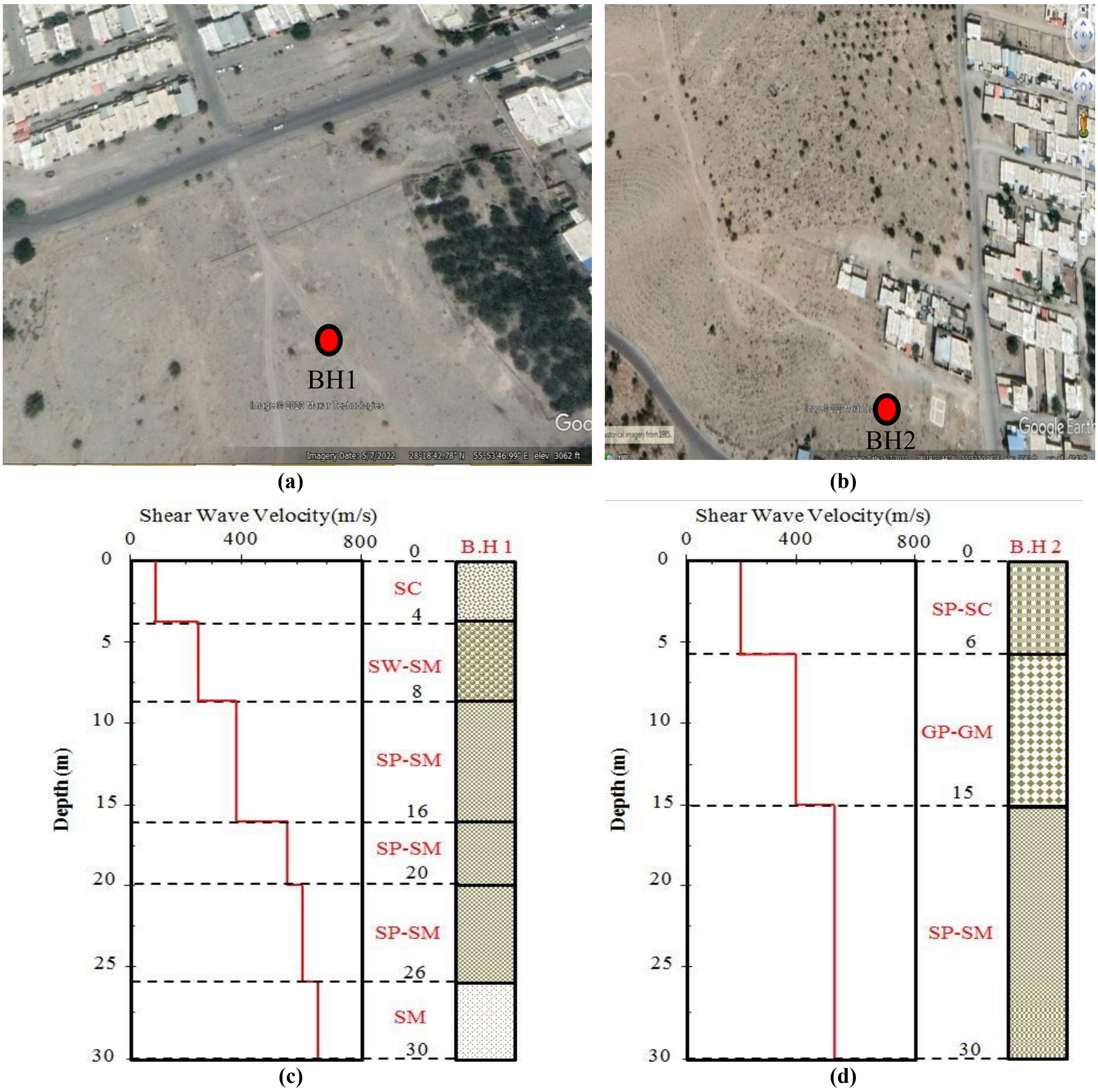

Fig. 6. Different specifications of site Type I: (a) Location of BH1, (b) Location of BH1, (c) various geotechnical parameters of BH1 (Depth=30m), and (d) various geotechnical parameters of BH2 (Depth=30m).

tip, is 22 kilometers (14 miles) from Bandar Abbas, but the island's closest point to the mainland is only two kilometers (1 mile). The island's most important geological formations strike east-west or northeast-southwest. There are profiles of several deposits ranging in age from the upper Precambrian to the quaternary at the island's surface.

According to the majority of geologists, this region has been active as a tectonic zone in the south part of the deformed forehead or convergent belt (Mesopotamia and Persian Gulf region), as well as the margins of the compression and collision plates of the Iranian continent, since the Late Tertiary. Sea terraces of the Tertiary Sediments of Qeshm Island are partially accompanied by Quaternary deposits, implying that they formed as a result of compressive tectonic processes associated with the Alpine orogeny. The terraces, which range in thickness from a few meters to ten meters, are constructed of corals, zoomorphic shells, and deposited marine villages in historic coastal locations. Fig. 7 depicts soil geotechnical factors in Qeshm (Fig. 7, BH 3,4). Different geotechnical parameters of sites are summarized in Table 2.

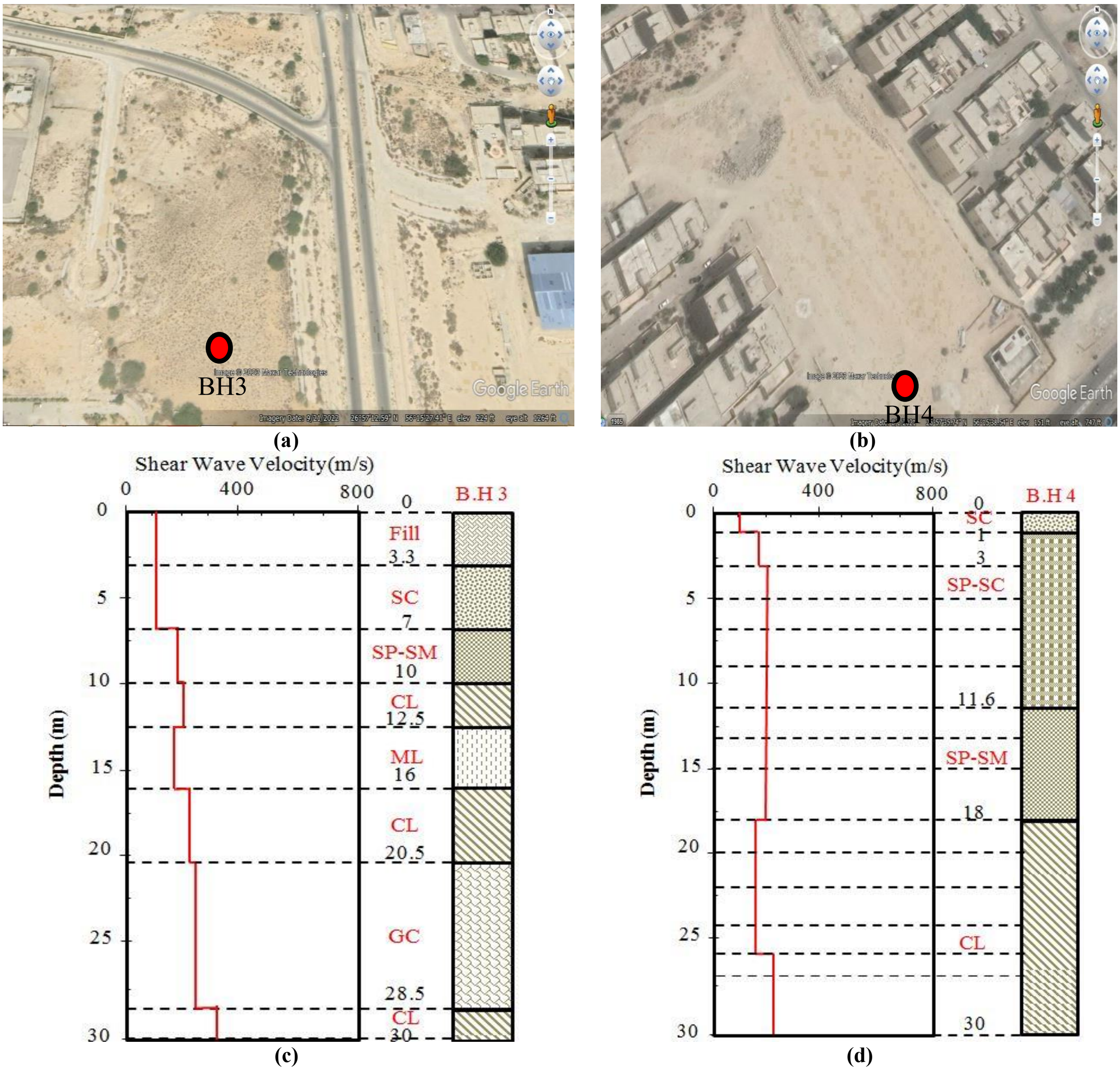

Fig. 7. Different specifications of site Type II: (a) Location of BH3, (b) Location of BH4, (c) various geotechnical parameters of BH3 (Depth=30m), and (d) various geotechnical parameters of BH4 (Depth=30m).

3- 2- Dynamic soil properties

Information on dynamic soil qualities that govern a site's response to seismic stimulation is required for site response analysis. Some of these parameters are shear wave velocity (VS), soil density, and shear modulus at low strain, G0, and G/G0 – and D– curves. In-situ measurements, such as the Standard Penetration Test (SPT), down-hole seismic survey, and complementing laboratory studies, were used to determine dynamic soil parameters. Shear wave velocity is assessed in this study. The soil profiles were modeled for site response evaluations based on in-situ geophysical tests using the spectral analysis of surface waves (SASW) approach (Figs. 6 and 7).

$$G = {V_S^2 \gamma_s}/{g} \qquad (1)$$

Where γs is soil unit weight.

The G/G0 –γ and D– γ curves are usually obtained through laboratory cyclic loading tests. However, such experimental data were not available for the soils studied in Hormozgan province. Therefore, degradation curves (G/G0 – γ and D– γ) have been allocated based on soils type and their index properties and the empirical relations e.g., Idriss (1990), Vucetic and Dobry (1991), Seed et al. (1996), and Darendeli (2001). These relations allow the determination of G/G0– γ and D– γ curves in terms of the plasticity index, PI, and the mean effective normal stress,σ´0, of a soil element. The main sets of curves are shown in Figs. 8 and 9.

Table 2. Geotechnical Characterization of different Sites.

	Boreholes	Depth(m)	Thickness of layer (m)	Description	γ_d (kN/m^3)	*SPT*	*W* (%)	V_s (m/s)
Site type I	BH1	0-4	4.0	SC	17.00	15	6.0	102
		4-8	4.0	SW-SM	18.30	31	9.5	246
		8-16	8.0	SP-SM	18.80	50	8.3	373
		16-20	4.0	SP-SM	21.10	50	7.1	561
		20-26	6.0	SP-SM	18.10	50	8.3	618
		26-30	4.0	SM	20.00	50	8.8	678
	BH2	0-6	6.0	SP-SC	18.80	-	-	205
		6-15	9.0	GP-GM	20.00	-	-	370
		15-30	15.0	SP-SM	21.50	-	-	560
Site typeII	BH3	0-3.3	AVE3	Fill	18.5	-	-	108.5
		3.3-7	AVE4	SC	17.75	11	-	195
		7-10	3	SP-SM	17.35	13	-	190
		10-12.5	2.5	CL	18	22	-	260
		12.5-16	3.5	ML	17.81	15	-	240
		16-20.5	4.5	CL	18.66	17	-	270
		20.5-28.5	8	GC	20.1	50	-	280
		28.5-30	AVE1	CL	19.8	29	-	315
	BH4	0-1	1	SC	18.25	-	-	186.4
		1-11.6	10.6	SP-SC	19.50	-	-	210
		11.6-18	6.4	SP-SM	16.5	-	-	180
		18-30	12	CL	19.50	-	-	245

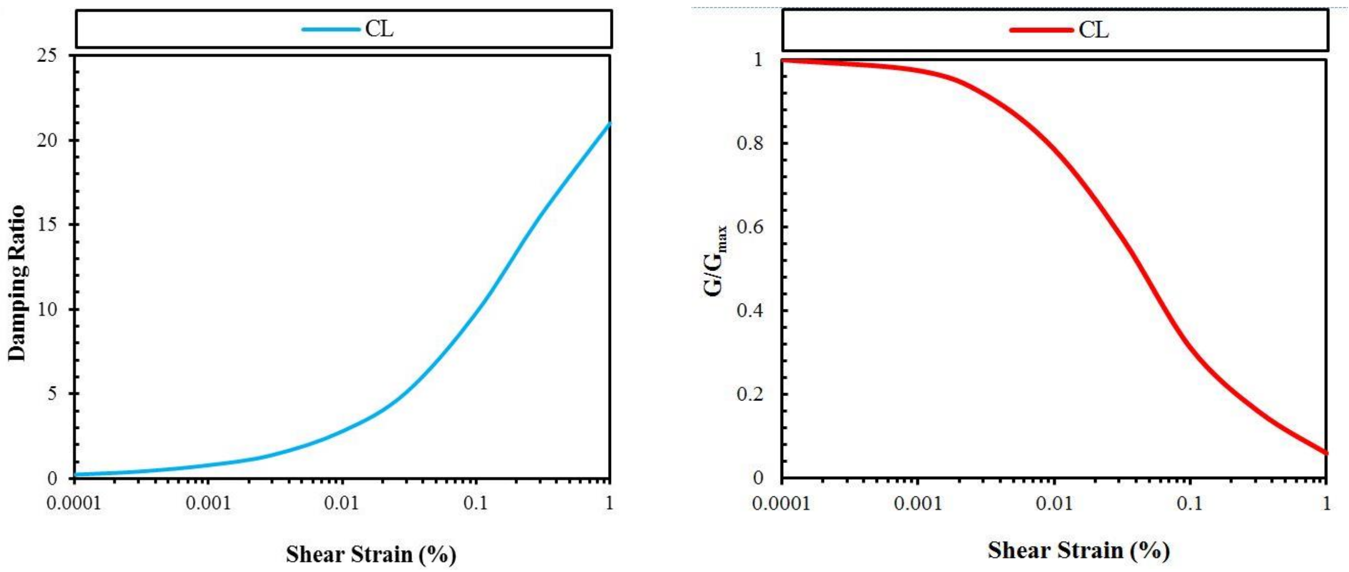

Fig. 8. Modulus reduction and damping curves for cohesive materials.

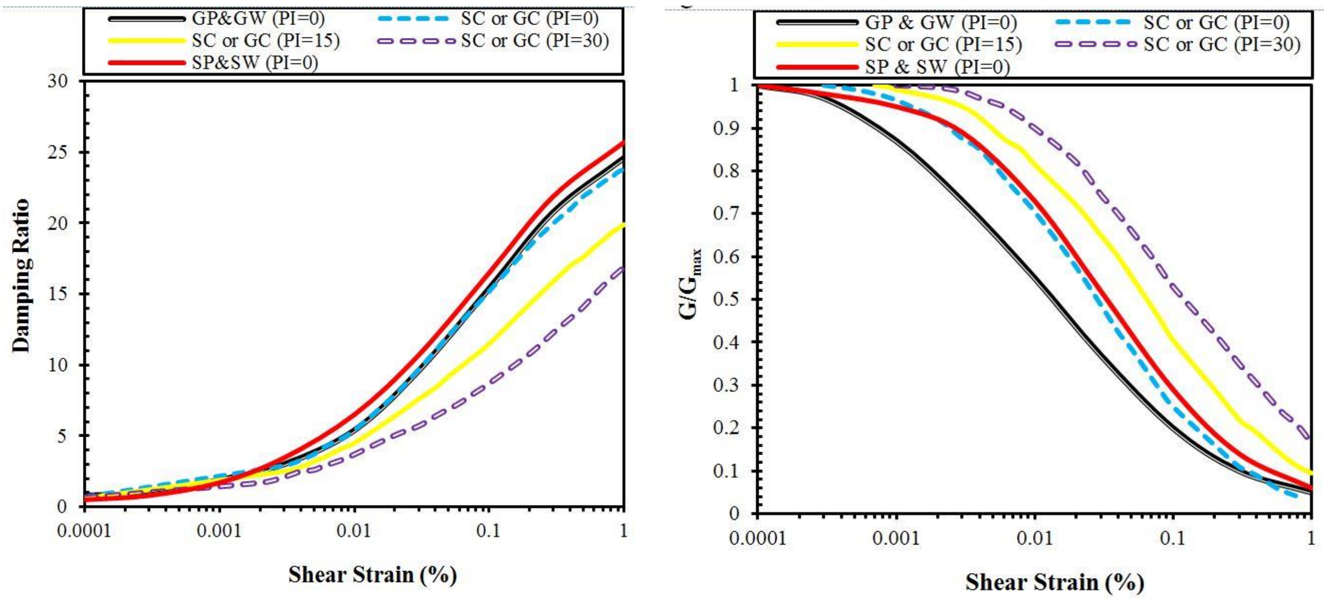

Fig. 9. Modulus reduction and damping curves for granular materials.

3- 3- Site response analysis methods

Ground vibrations on soil sites were found to be usually bigger than those on surrounding rock outcrops during previous earthquakes (e.g., Seed and Idriss, 1968). The three programs are investigating the behavior of soil layers and different constitutive models under various earthquake effects. a) EERA b) NERA c) DEEP SOIL.

SHAKE was one of the earliest computer programs to simulate soil site responses (Schnabel et al., 1972). SHAKE posits that cyclic soil behavior can be replicated using an analogous linear model based on Kanai (1951), Roesset and Whitman (1969), and Tsai and Housner (1970). (e.g., Idriss and Seed, 1968; Seed and Idriss, 1970; Kramer, 1996; Sugito, 1995; Idriss and Sun, 1992).EERA, a computer program developed in 1998, was based on the same core concepts as SHAKE (Bardet et al., 1998). Equivalent linear Earthquake Response Analysis (EERA) is an acronym for Equivalent Linear Earthquake Response Analysis.EERA uses FORTRAN 90 and the spreadsheet tool Excel to apply the well-known ideas of equivalent linear seismic site response analysis. In 2001, the same implementation techniques used for EERA were adapted to NERA, a non-linear site response analysis tool based on Iwan (1967) and Mroz's material model (1967). NERA (Nonlinear Earthquake Response Analysis) is a program that uses FORTRAN 90 and the spreadsheet tool Excel. Joyner and Chen (1975), Prevost (1989), and Lee and Finn (1990) all employed concepts comparable to those in NERA (1978). Deep soil software (Hashash et al., 2008) has recently been developed to perform one-dimensional site response evaluations in the frequency (linear and equivalent linear) and temporal (linear and non-linear) domains.

3- 3- 1- Equivalent Linear Site Response

The effect of the nonlinearity of soils has been reported extensively. Hardin and Drnevitch (1970), Seed and Idriss (1970), Seed et al. (1986), Sun et al. (1988), Vucetic and Dobry (1991), Kramer (1996), Bardet et al. (2000), and Kramer (2000), and Darendeli (2001) reported a decrease of the amplification factors and sometimes a decrease of resonant frequencies at peak accelerations due to non-linearity. The equivalent-linear method is commonly used in earthquake engineering for modeling wave transmission in layered sites and dynamic soil-structure interaction. This method employs linear properties for each element that remain constant throughout the history of shaking and are estimated from the mean level of dynamic motion, and this method consists of modifying the Kelvin-Voigt model to account for some types of soil non-linearity.

3- 3- 2- Non-linear Site Response

The seismic ground response is significantly affected by the non-linear behavior of the soil profile. Therefore, it is most important to properly model the soil non-linearity in the dynamic analysis of local site effects during earthquake excitations (Kramer 1996).

As illustrated in Fig. 10, Iwan (1967) and Mroz (1967) proposed a model of non-linear stress-strain curves using a series of n mechanical elements, having different stiffness ki and sliding resistance RI. Hereafter, their model is referred to as the IM model. The sliders have increasing resistance (i.e., R1 < R2 <… <Rn).

$$\frac{d\,\tau}{d\,\gamma} = \mathrm{H} \quad (2)$$

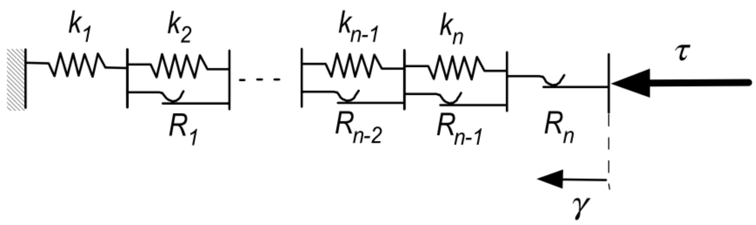

Fig. 10. Schematic representation of the stress-strain model used by Iwan (1967) and Mroz (1967).

Where the tangential modulus H is:

$$H=\begin{cases} H_1 = k_1 & if\ 0 \le \tau \le R_1 \\ H_2 = (k_1^{-1} + k_2^{-1})^{-1} & if\ R_1 \le \tau \le R_2 \\ . & \\ . & \\ H_{n-1} = (k_1^{-1} + k_2^{-1} + \dots + k_{n-1}^{-1})^{-1} & if\ R_{n-2} \le \tau \le R_{n-1} \\ H_n = (k_1^{-1} + k_2^{-1} + \dots + k_{n-1}^{-1} + k_n^{-1})^{-1} & f\ R_{n-1} \le \tau \le R_n \\ 0 & if\ \tau = R_n \end{cases} \tag{3}$$

3- 3- 3- Hyperbolic / Pressure-Dependent Hyperbolic (MKZ)

DEEP SOIL incorporates the pressure-dependent hyperbolic model. The modified hyperbolic model, developed by (Matasovic, 1993), is based on the hyperbolic model by (Konder and Zelasko, 1963), but adds two additional parameters Beta (β) and s that adjust the shape of the backbone curve:

$$\tau = \frac{G_0 \gamma}{1 + \beta \left(\frac{\gamma}{\gamma_r}\right)^s} \tag{4}$$

Where G0 = initial shear modulus, τ = shear strength, γ = shear strain. Beta, s, and γr are model parameters. There is no coupling between the confining pressure and shear stress.

DEEP SOIL extends the model to allow coupling by making γr confining pressure-dependent as follows (Hashash and Park, 2001)

$$\gamma_r = \text{Reference Strain} \left(\frac{\sigma_v^{'}}{Reference\ stress}\right)^b \tag{5}$$

Where $\sigma_v^{'}$ is the effective vertical stress. Reference Stress is the effective vertical stress at which γr =Ref. stress. This model is termed the pressure-dependent hyperbolic model.

The pressure-dependent modified hyperbolic model is almost linear at small strains and results in zero hysteretic dampings at small strains. Small strain damping has to be added separately to simulate actual soil behavior, which exhibits damping even at very small strains (Hashash and Park, 2001). The small strain damping is defined as

$$\xi = \text{Small Strain Damping Ratio} \left(\frac{1}{\sigma_v^{'}}\right)^d \tag{6}$$

The d parameter can be set to zero in case a pressure-independent small strain damping is desired.

In summary, the parameters to be defined in addition to the layer properties are:

Reference Strain
Stress-strain curve parameter, Beta (β)
Stress-strain curve parameter, s
Pressure dependent (reference strain) parameter, b
Reference Stress
Pressure dependent (damping curve) parameter, d

3- 4- Validation of the numerical model

The Treasure Island site is one of the few sites that features a nearby rock outcrop that allows for a direct comparison of motion at the rock outcrop and the soil surface. The Loma Prieta earthquake, recorded at the Treasure Island site, was used as the control motion for this work's numerical ground response analysis. The five percent damped reaction spectrum for the rock crop motion recorded during the Loma Prieta earthquake derived utilizing site response analysis of the Treasure Island site is shown in Fig. 11, together with the empirically observed response spectrum for the same event. The computed response spectrum matches the spectrum of the recorded motion on Treasure Island quite well.

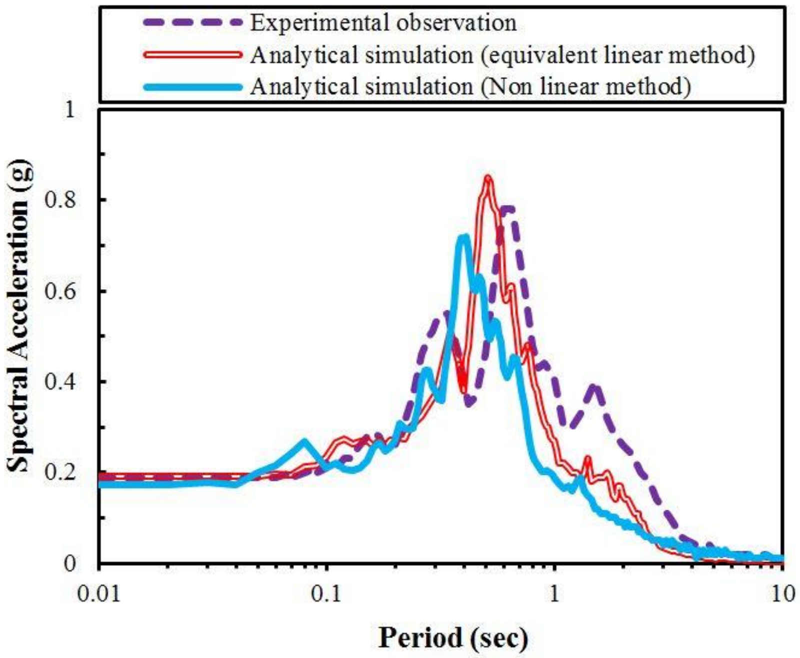

Fig. 11. Comparison of observed and numerically obtained 5% damped acceleration response spectra at Treasure Island, for the Loma Prieta earthquake.

4- Result and Discussion

A set of equivalent linear (EQL) and non-linear (NL) site response analyses using the four sites with different geotechnical specifications was carried out to evaluate the site response influence on ground motion parameters. The difference between NL and EQL analyses is compared to the information at the surface. To analyze the site effect for different geotechnical and seismic conditions, the ground response has been analyzed in this paper using two different sites and three different earthquake types and even employing equivalent linear and non-linear methods. In this regard, selecting the earthquakes to study is based on maximum horizontal acceleration as follows:

Type I: an earthquake with a PGA less than 0.1g

Type П: an earthquake with a PGA between 0.1-0.3g

Type Ш: an earthquake with a PGA of more than 0.3g

4- 1- Spectral acceleration Computed For 30 m Depth Models

In this part of the paper, a comparison between three types of earthquake response spectra at surface level for 5% damping was carried out with two methods equivalent linear (EQL) and three different non-linear methods (NL).

4- 2- Spectral Acceleration Response for Earth Quake Type I

Two earthquakes of Whittier Narrows and Morgan Hill having acceleration less than 0.1g were used to investigate the site effect on the acceleration response spectrum. The studied sites are selected in two different types of granular soil (I and II) and a mixture of granular aggregate and cohesive materials (III and IV).

At site I, the minimum results are related to the NERA method (the peak value is 0. 46g). The highest values are related to two methods of equivalent linear with messing and MKZ with non-missing with peaks of about 0.7g. The equivalent linear method provides values greater than the NERA method. Different methods of EERA, equivalent linear with messing, MKZ with messing, and MKZ with non-missing provide 20, 52, 30, and 50% higher values compared NERA method. The fact that the formulation and background ideas used in the dynamic analysis of these methodologies are not identical to one another is the primary factor that contributes to these disparities. The equivalent-linear method is dependent on the thin-layered theory, whereas the fully nonlinear approach is founded on the spring-concentrated mass method. Furthermore, the fully nonlinear approach takes into account the dynamic behavior of the soil in a manner that is more realistic than the other method. There is, however, a consistent pattern to the form of the spectra across all of the situations.

The equivalent linear with messing method has the acceleration response spectrum with greater periods, which means an increase in the frequency band in this method (Fig. 12).

The highest and lowest values of peak acceleration in site II are related to EERA and NERA methods. These are more than 50, 24, 30, and 52%, respectively. At Site II, NERA provides very different results compared to the other methods. The response spectrum in the NERA method is shifted to periods of 0.01 to 0.1 sec, whereas the periods in other methods ranged from 0.1 to 1 sec.

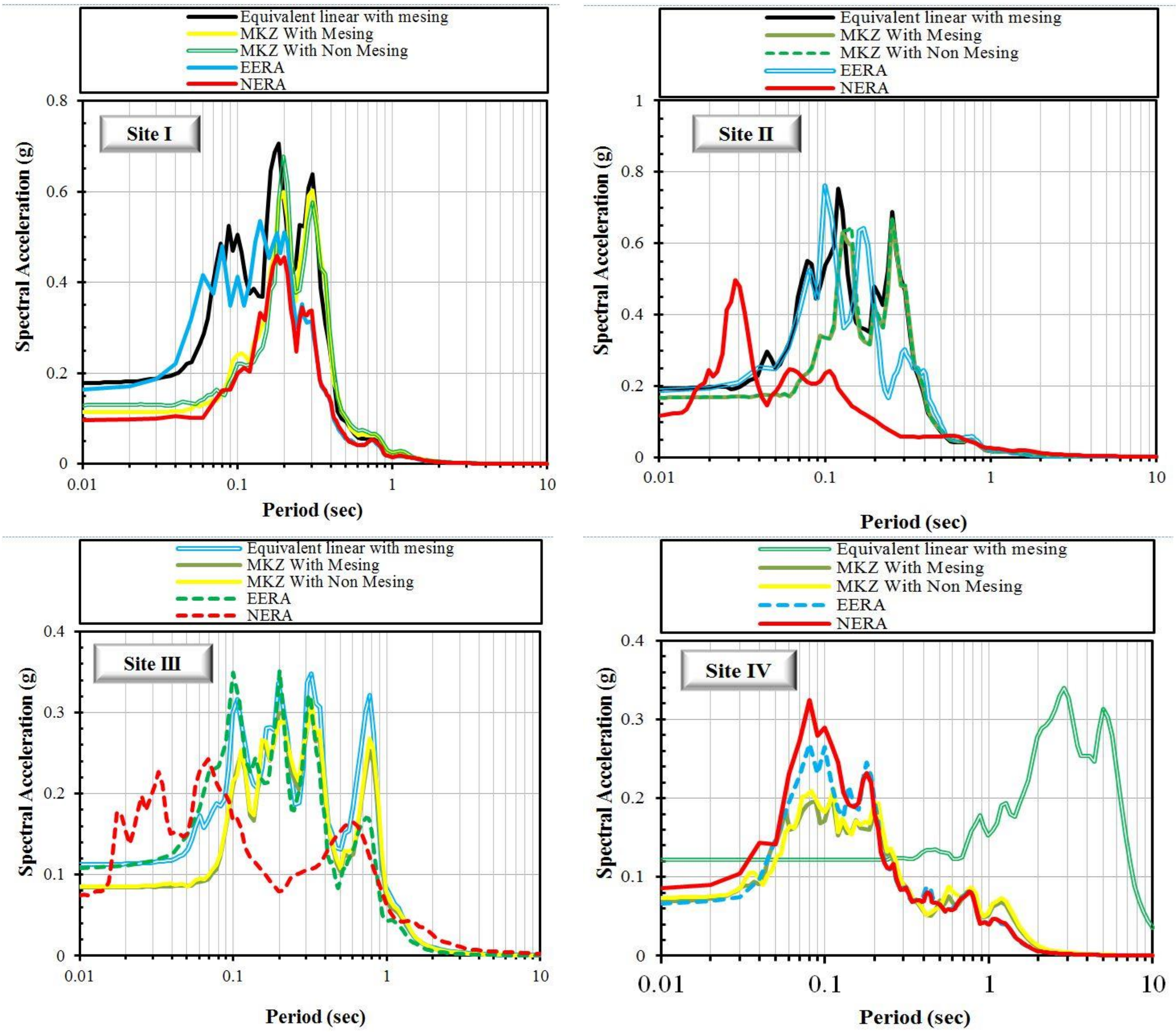

Fig. 12. Spectral acceleration for Whittier Narrows earthquake and different sites.

Sites III and IV, which are composed of a mixture of granular and cohesive materials, result in a lower acceleration response spectrum than coarse sites (I and Π).

At site III, the lowest values of results relating to the NERA, and other methods give the values very close to each other with a difference of less than 2% on average.

The highest results values are attributed to NERA and EERA methods at site IV, but these methods present the same shapes compared to others the NERA method has a 50% value on average compared to other methods). Of course, the equivalent linear with the messing method provides very different results than the others, and the periods are transmitted to the time ranging from 1 to 10 sec (Fig. 12).

The peak acceleration at sites III and IV is lower than 50% compared to values at sites I and II. But the frequency band increased more than 50% at sites III and IV compared to sites I and II.

The present study, like others before it, demonstrates that the maximum acceleration and spectrum ratios estimated via equivalent linear analysis are bigger than the observed records.

In sites I and II, regarding densely layered soil and greater shear wave velocities, the motion of the applied earthquake amplified compared to sites III and IV. The applied motion was deamplified by the soft and loose layers with lower values of shear wave velocities (sites III and IV). In sites

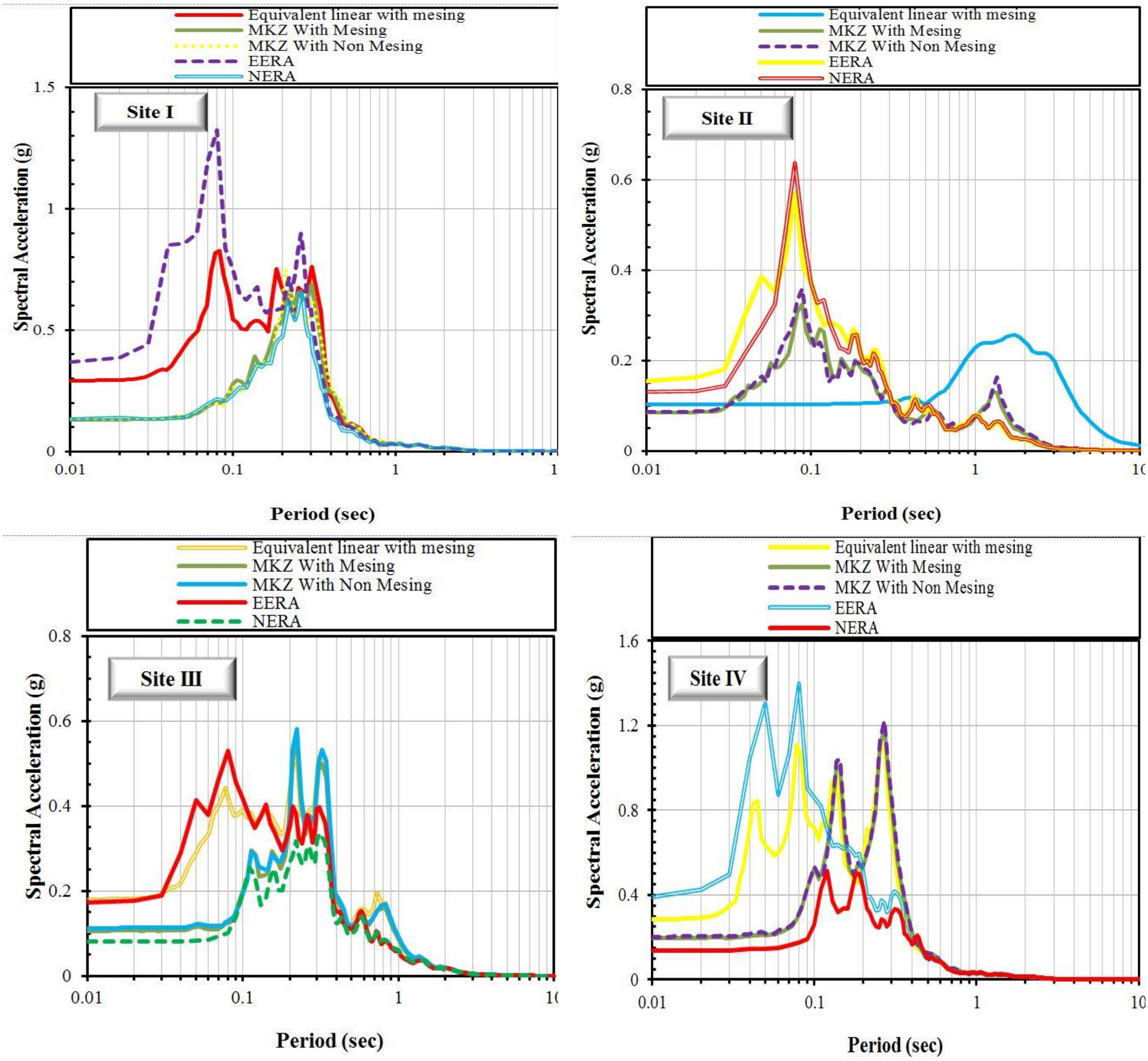

Fig. 13. Spectral acceleration for Morgan Hill earthquake and different sites.

III and IV the nonlinear approach with consideration of the nonlinearity of soil predicted more accurate results.

At all sites (except site П), the two equivalent linear methods (EERA and equivalent linear with messing) result in a higher acceleration response spectrum.

The EERA method at the site I predicted higher values compared to other methods (the difference between EERA and equivalent linear with messing is more than 66% and other methods have almost the same results and are on average 90% less than the EERA method). The frequency band for three methods of MKZ with messing, MKZ with non-missing, and NERA ranged between 0.1-1 sec, but EERA and equivalent linear with messing are transmitted to lower levels (0.02-0.6 sec).

At site II, NERA and EERA predict greater values (with a difference of 12%). Two methods of MKZ with messing, and MKZ with non-missing have the same values. It should be mentioned that the frequency band has intensified in this method, which increases the possibility of the resonance effect. The equivalent linear messing method estimates very different values with period ranges of 1 to 10 sec.

At site III, the NERA and EERA methods continued to provide the highest values (the difference in values is 27%). The frequency band at sites III and IV is between 0.02-1 sec.

Response spectrum values at site III are higher than at site IV, but the possibility of resonance occurrence at site III is more than the site IV (Fig. 13).

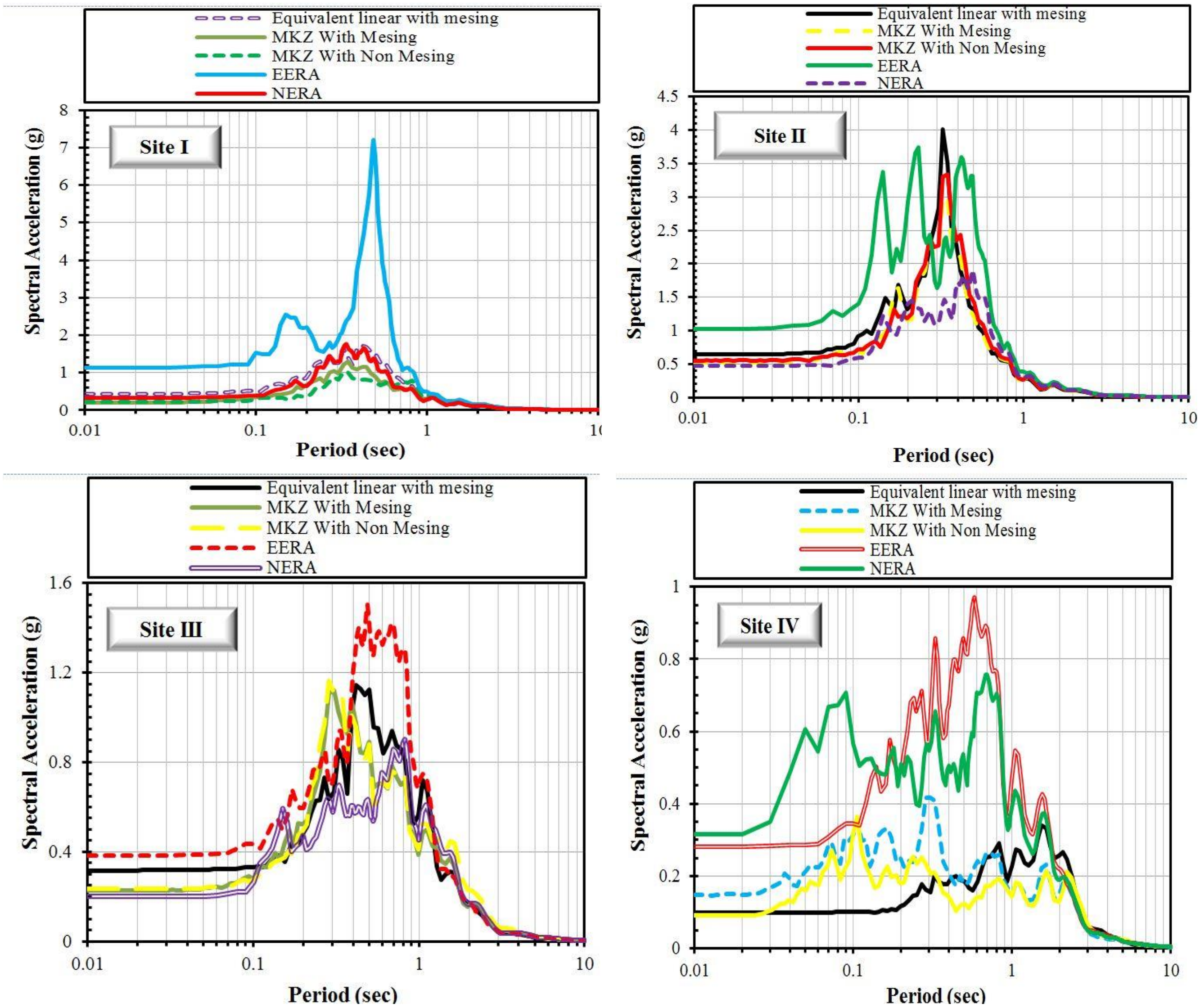

Fig. 14. Spectral acceleration for Northridge earthquake and different sites.

Although the Morgan Hill earthquake has a higher Peak Ground Acceleration (PGA) and a wider acceleration response spectrum than the Whittier Narrows earthquake (nearly twice), the Whittier Narrows earthquake's spectra are rougher at all sites, increasing the risk of resonance.

4- 3- Spectral Acceleration Response for Earth Quake Type Π

EERA method for the site I, considering the Northridge earthquake, estimates greater values than the other methods, and this site has similar performance to other methods. The difference between EERA and other methods is more than 300%, and with an evaluation of this method for the Northridge earthquake and site I revealed that this method has not provided the desired results and is because of the linear nature of the equivalent linear analysis. The NERA and equivalent linear with messing have the same diagram and the difference between values of peak acceleration is about 5%.

Values of various methods of equivalent linear with messing, MKZ with messing, MKZ with non-missing, and EERA, compared to NERA.

At site II, the acceleration response spectrum values for non-linear models are increased compared to site I, and the two linear equivalent models result in the most significant values (the values of acceleration response spectrum for EERA and linear equivalent with messing are 3.66 and 4g). Of course, EERA has more ripples than the equivalent linear with messing method. The minimum value was related to NERA (1.86g), and the two methods of MKZ led to very similar results (3.3 and 3.2g) (Fig. 14).

At site III, results have been reported for non-linear methods revealing that the peak spectrum acceleration has the lowest value among different methods and is nearly equal to 0.9g. However, at site IV, both EERA and NERA approaches give very different results. These two methods have more

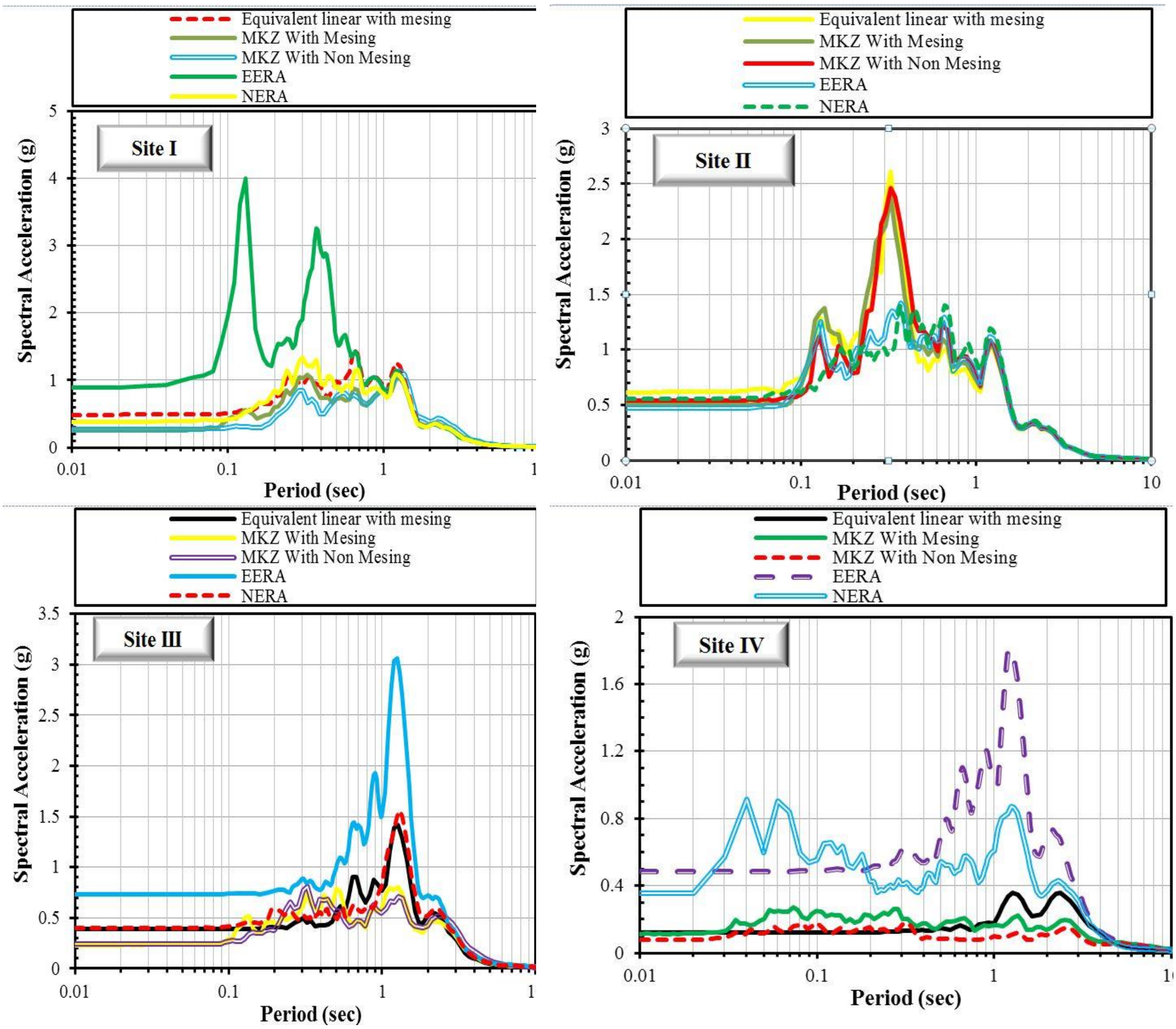

Fig. 15. Spectral acceleration for Kobe earthquake and different sites.

ripples so the possibility of resonance occurrence increases while using these two methods. The frequency band at sites III and IV increased compared to sites I and II (0.09-5 sec).

Fig. 15 shows the acceleration response spectrum for the Kobe earthquake and four different sites. At all sites except site III, the equivalent linear earthquake response analysis (EERA) provides higher values than the other models (on average more than 128%). This is because the linear nature of the equivalent linear method only uses a single stiffness and damping value throughout the full ground motion. Higher peak values result from overestimated stiffness and underestimated damping for shear strain greater than the effective shear strain. The EERA is frequently utilized in literature studies although it cannot accurately depict the non-linear behavior of soils under seismic stress because of its simplicity of usage. The equivalent linear with messing approach results in values closer to other non-linear models at sites I and II (the difference is lower than 10%).

The non-linear earthquake response analysis (NERA) leads to higher values than the other non-linear methods and includes more periods (at site I). The MKZ models and hyperbolic methods indicate the results are very close to each other at site I. Site II includes a greater acceleration response spectrum than the site I. The two MKZ models and equivalent linear with messing approach present very similar values. However, the two equivalent linear earthquake response analyses (EERA) and non-linear equivalent response analyses (NERA) estimate smaller and different values than the other methods. MKZ and equivalent linear with messing approaches include more periods at intervals of 0.1 to 3 sec.

For the Kobe earthquake, site I composing the layered granular materials results in a smaller acceleration response spectrum and frequency band than site II, which is composed of granular materials with high thickness.

At sites III and IV, which are composed of granular and cohesive materials (Fig. 7), the different acceleration response spectra are predicted for both sites. At site III, the two MKZ models give the response spectra very close to each other, with a difference of less than 2%. Of course, these methods include a range of higher periods.

Non-linear earthquake response analysis (NERA) and equivalent linear earthquake response analysis with messing provide the acceleration response spectrum very close to each other with a difference of less than 5%, but the NERA approach includes more frequency bands.

At site IV, both NERA and EERA approaches estimate higher acceleration response spectra than the other models. Of course, the NERA predicts lower values relative to the EERA, and this difference is almost 20% on average. It should be noted that the NERA approach contains a rougher spectrum. MKZ with messing method leads to higher values than the MKZ with with-non messing (Fig. 15).

The site I indicate a higher acceleration response spectrum for the Northridge earthquake than the Kobe earthquake, whereas the Kobe earthquake has higher horizontal acceleration than the Northridge earthquake. The frequency range is higher for the Kobe earthquake.

A greater response spectrum is predicted at Site Π in the Kobe earthquake, but site II has been more critical for the Northridge earthquake. Despite the greater response spectrum for the Kobe earthquake at sites III and IV, the probability of destruction and damage is higher for the Northridge earthquake because the Northridge earthquake contains a wide frequency band for both sites.

4- 4- Spectral Acceleration Response for Earth Quake Type III

Loma preita and Tabas earthquakes are two significant earthquakes in history, having large failures with an acceleration of 0.44g and 0.87g. This study attempts to use them and analyze their effects on different sites. The EERA method gives greater and different values than the other methods (at sites I and II the EERA method provided many irrational analyses and for other sites predicted results closer to other methods). However, the EERA method for the Loma Prieta earthquake in the granular sites (I and Π) predicted various results, but other methods have similar results (the difference for sites I and II on overage are 5 and 12%). At sites I and II, the smallest values are related to MKZ with-non messing model and NERA, respectively.

The cohesive soils (III and IV) have caused the earthquake to be decreased and provided a lower acceleration response spectrum relative to both granular sites (more than 70%). However, these two sites have caused rougher spectra. It should be mentioned that the NERA indicates a higher response spectrum and frequency bands rather than the other models at site IV (Fig. 16). It seems that sites III and IV are more critical despite having smaller response spectra.

Fig. 17 shows the acceleration response spectra for 4 sites using 5 different approaches in the Tabas earthquake. At the granular site, EERA methods predict substantial and unimaginable values (the acceleration response spectra are about 25g).

Among the non-linear methods at site I, NERA and MZK with-non messing have the highest and lowest values, respectively (the difference between the maximum and minimum values is about 100%). The frequency band for different methods at site I is 0.2-2 sec. At site II the equivalent linear with messing and NERA predicted maximum and minimum values of acceleration response spectra, respectively (5 and 3.2g). Site II includes periods ranging from 0.1 to 1 sec, whereas the periods at the site I are transmitted to higher values.

Sites with cohesive soils (III and IV) contain smaller response spectra (more than 150%), but these acceleration response spectra are very rough and have various ripples, and these sites have a higher frequency band (between 0.07 and 8 sec). It seems that these two sites are more critical than the two other sites due to lower values of response spectra, as the possibility of resonance occurrence increases with increasing frequency band (Fig. 17).

4- 5- Comparison of computed spectral acceleration with different codes

The impacts of local soil conditions on design ground motions are incorporated into seismic provisions of building codes by categorizing the extensive range of conceivable soil conditions into several groups and giving a foundation factor, or response spectra, to each category. This is because ground response analyses are used to develop design response spectra. The response spectra from this study were compared to the response spectra from the 1997 National Earthquake Hazards Reduction Program (NEHRP) regulations, UBC code, and Iranian code (Standard 2800, 2005). In this study, the soil profile in four regions was classified as site class C, D, and type 3,4 in the 2800 code, UBC, and NEHRP.

Fig. 18 represents the acceleration response spectra of the earthquake type I (PGA under 0.1) based on the nonlinear method, compared to the different standards. NEHRP code C, D almost covers all earthquakes and sites. However, site II for the Morgan Hill earthquake with low periods indicates values higher than NEHRP and UBC Standards of both codes C and D. Standard No. 2800, for both types III and IV, recommends higher values than the acceleration response spectrum of the desired earthquakes (more than 180%). For the studied sites in this paper and earthquakes with a maximum horizontal acceleration of less than 0.1g, NEHRP, and UBC Standards will provide critical design. Standard No. 2800 leads to safety in design and over design.

Two NEHRP and UBC codes C, D for earthquakes type Π (the maximum horizontal acceleration ranging from 0.1 to 0.4), provide values less than the response spectrum of the earthquakes presented in this research. Site II for Northridge and Kobe earthquakes with low periods has caused the values

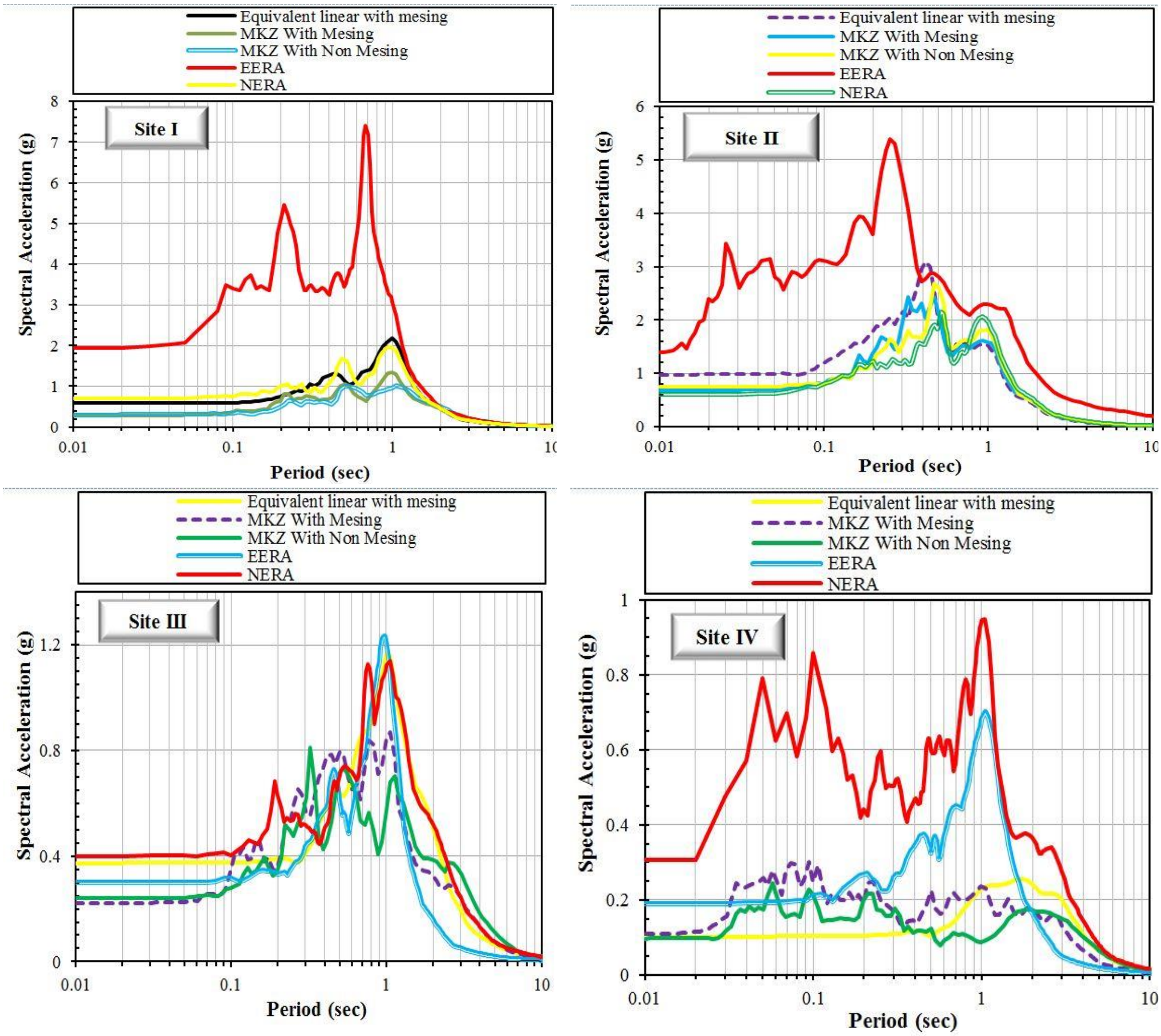

Fig. 16. Spectral acceleration for Loma Prieta earthquake and different sites.

to exceed the NEHRP and UBC Standards (more than twice).

It seems that designing following these two standards and for the same earthquakes, Northridge and Kobe at site II increase the possibility of damage occurrence. Of course, Standard No. 2800 well covers site II and Northridge and Kobe earthquakes (Fig. 19).

The acceleration response spectrum at sites I and Π for the earthquake of Northridge with a low period (ranging from 0.1 to 1 sec) is also higher than the values of NEHRP and UBC standards and is much less than the values recommended by Standard No. 2800. Designing based on Standard No. 2800 leads to safety in seismic design. Therefore, designing based on both NEHRP and UBC Standards in the study regions I, II, and III of this research increase the induced damages.

Fig. 20 shows the acceleration response spectrum of the earthquakes type III (PGA more than 0.4g) compared to the different Standards. The spectral values predicted for most sites of the Tabas and Loma Prieta earthquakes are more significant than the values of NEHRP and UBC Standards. Standard No. 2800 does not include the Tabas earthquake for site II. Thus, based on the obtained results of this study, it seems that the site analysis is of great importance for the major projects and arteries, and using the predicted values in the available standards is more desirable for the initial analysis.

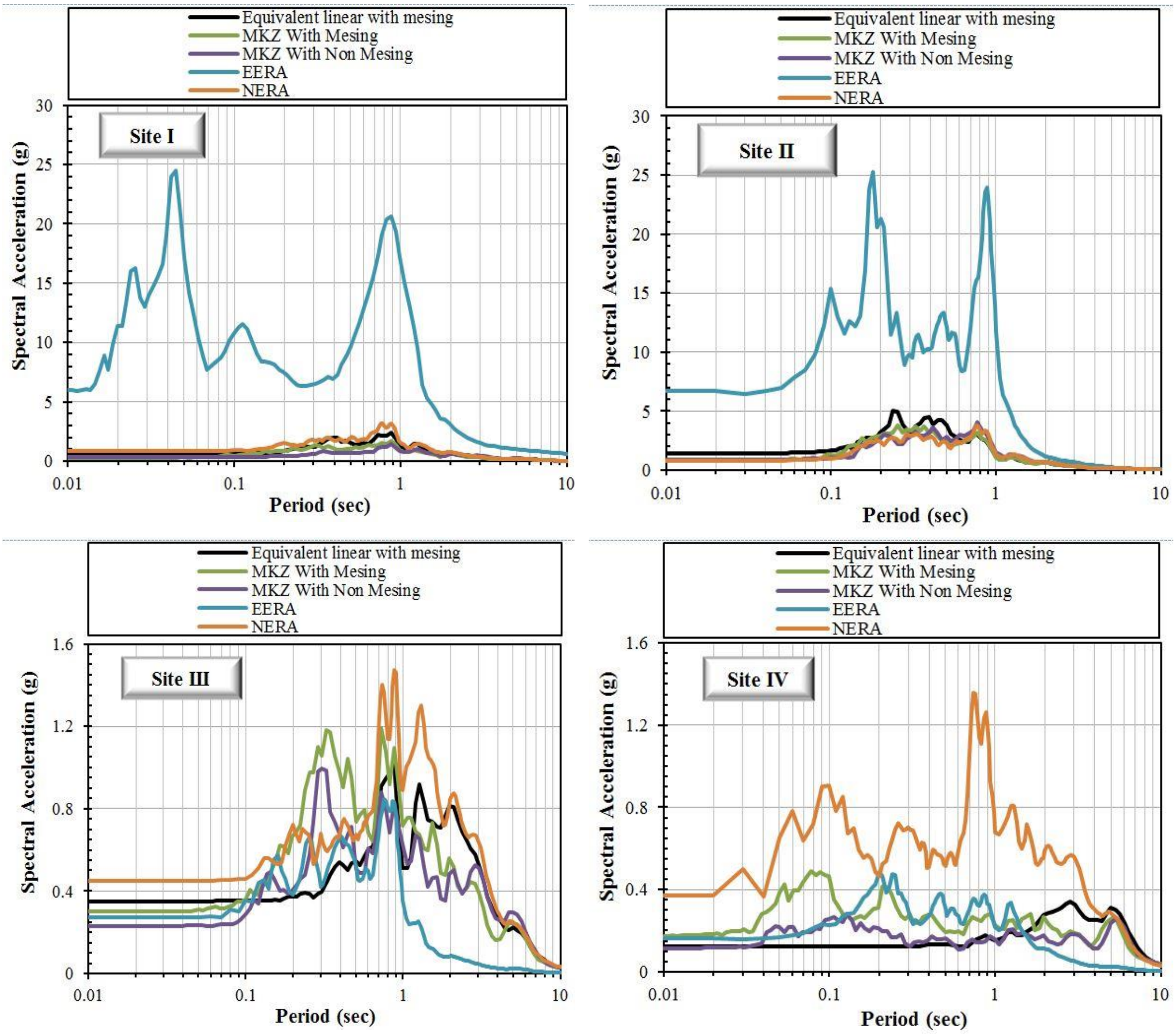

Fig. 17. Spectral acceleration for Tabas earthquake and different sites.

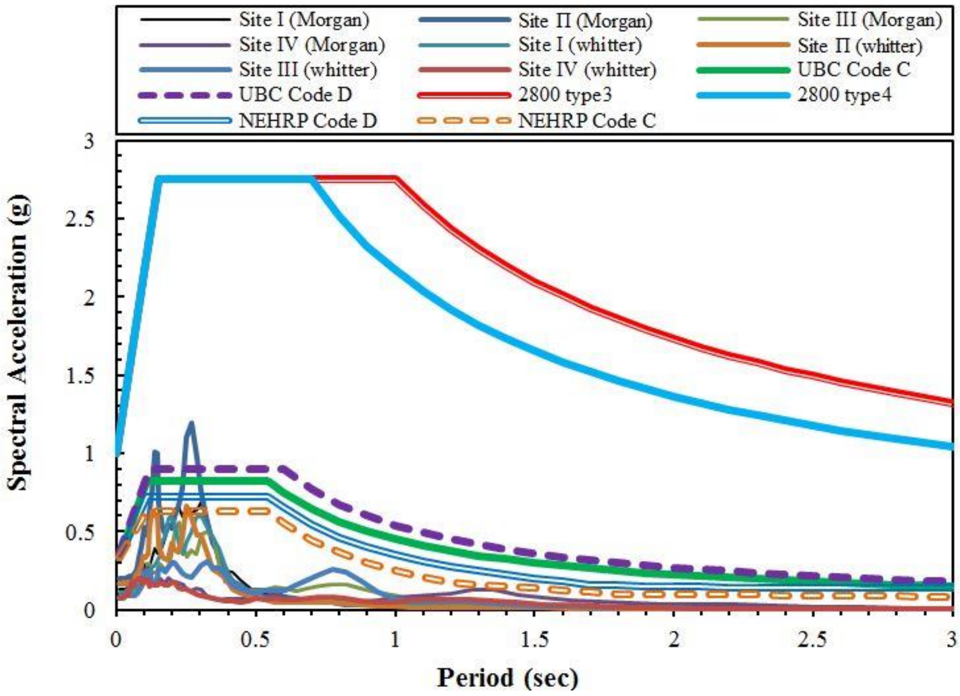

Fig. 18. Comparison of surface elastic acceleration response spectra with different codes for earthquake type I.

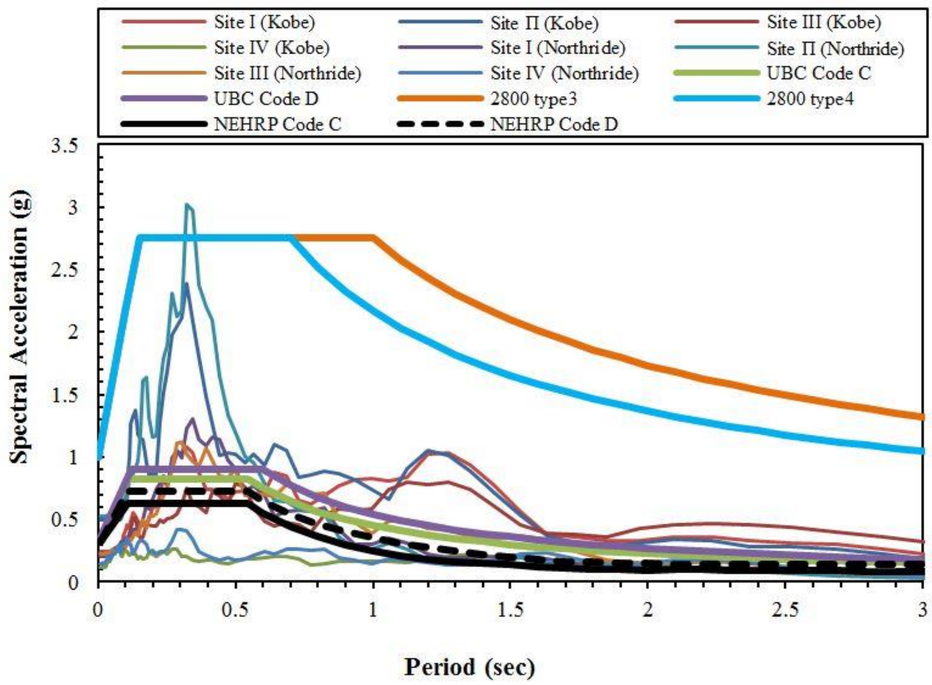

Fig. 19. Comparison of surface elastic acceleration response spectra with different codes for earthquake type Π.

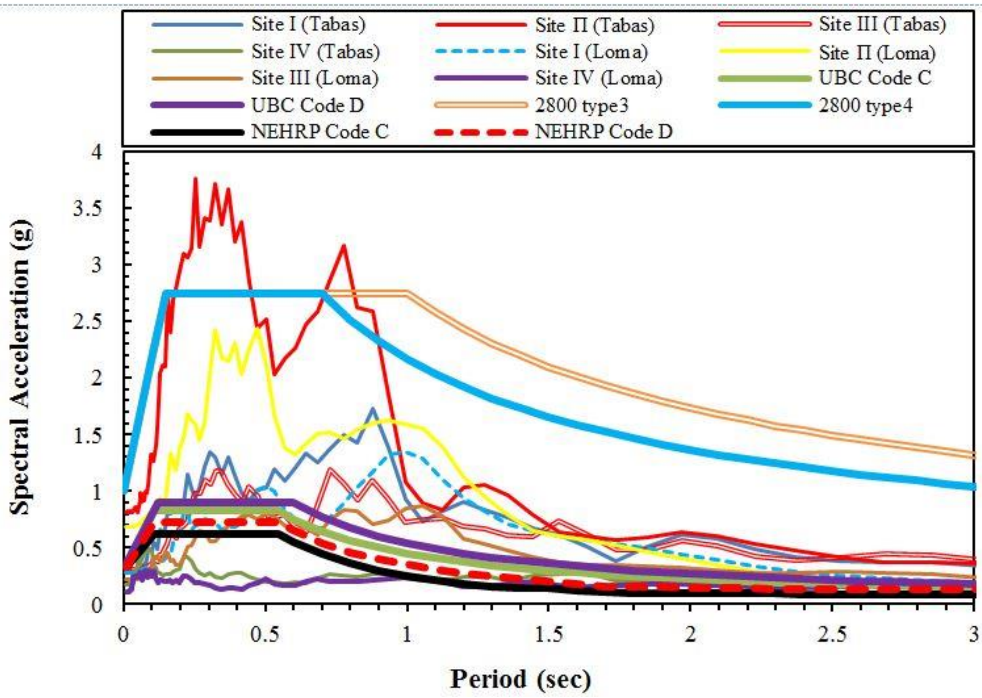

Fig. 19. Comparison of surface elastic acceleration response spectra with different codes for earthquake type II.

5- Conclusion

This study aimed to perform a one-dimensional equivalent linear and non-linear site response analysis. Specifically, the influence of geotechnical parameters combined with earthquakes with different accelerations on the ground motion factors at the ground's surface. For reaching this purpose, four sites were selected and drilled bore-hole to a depth of 30m. The laboratory and field tests are performed for the determination of soil characteristics in various sites. The geophysical test (downhole test) for each site is conducted to access shear-wave velocity (Vs). One-dimensional site response is performed for different sites and earthquakes (the criterion for selecting earthquakes was based on their location on a bedrock). The major conclusions can be listed as follows:

1. For earthquakes with PGA less than 0.1g (type I), the peak spectral acceleration response compared to PGA of earthquakes for granular and cohesive sites increased on average by more than 650 and 350%, respectively. In sites I and II, regarding densely layered soil and greater shear wave velocities the motion of the applied earthquake amplified, and in sites III and IV with the soft and loose layers caused deamplified. Of course, it should be noted that the frequency band has increased in sites III and IV.

2- For earthquakes with a PGA of 0.1-0.4g, Nonlinear methods include more detailed analyzes. The fact that the formulation and background ideas used in the dynamic analysis of these methodologies are not identical to one another is the primary factor that contributes to these disparities. Granular sites have increased spectral acceleration by an average of more than 580% relative to earthquake PGA. In adhesive sites, the percentage increase in acceleration has decreased (200%), but the frequency band has increased significantly (for granular sites 0.1-1 sec, but in cohesive sites is between 0.06-6 sec).

3- EERA method hasn't true and exact predictions for type III earthquakes. The peak spectral acceleration response compared to the PGA of earthquakes for granular and cohesive sites increased on average by more than 200% and 30%, respectively. This is because the linear nature of the equivalent linear method only uses a single stiffness and damping value throughout the full ground motion. Higher peak values result from overestimated stiffness and underestimated damping for shear strain greater than the effective shear strain. The EERA is frequently utilized in literature studies although it cannot accurately depict the non-linear behavior of soils under seismic stress because of its simplicity of usage.

4- Sites with cohesive materials (III and IV) contain smaller response spectra, but these spectra are very rough and have a higher frequency band. For earthquakes between 0.1 and 0.4g, the spectral acceleration has increased more than 3 times compared to the PGA, and for earthquakes with a magnitude greater than 0.4g, the acceleration has increased more than 1.3 times. The high-thickness fine-grained site (type IV) contains the highest frequency band. Increasing the frequency band may increase the likelihood of resonance and cause more damage to the structures. Consequently, analyses show that sites with dense cohesive grains require more attention.

5. Three seismic provisions of building codes offer logical response spectra of acceleration for earthquake type I, however for the other two types of earthquakes, these provisions do not provide accurate predictions. Therefore, it appears that site analysis is crucial for big projects and infrastructure, as evidenced by the findings of this study. Response analysis must be conducted on each of the identified sites.

6. Ground response assessments are carried out using both nonlinear and equivalent linear approaches, with quite distinct formulations and underlying assumptions. As a result, it is reasonable to anticipate that their outcomes may differ in certain ways. For the nonlinear technique, a trustworthy constitutive or stress-strain model is needed. Tests in the field or the lab are necessary to estimate the behavior of the nonlinear model. The dynamic behavior of the stress history cannot be included by the equivalent linear technique.

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