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LOCAL GEOLOGY EFFECTS ON STRONG GROUND MOTION DURING THE BAM EARTHQUAKE

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ABSTRACT

The influence of local geologic and soil conditions on the intensity of ground shaking is addressed in this study. The amplification of the ground motion due to local site effects resulted in severe damage to dwellings in the Bam area during the 2003 Bam Earthquake. A unique set of strong motion acceleration recordings was obtained at the Bam station. Although the highest peak ground acceleration recorded was the vertical component (nearly 1g), the longitudinal component (fault parallel motion) clearly had the largest maximum velocity as well as maximum ground displacement. Subsurface geotechnical and geophysical (down the hole) data in three different sites have been obtained and are used to estimate the local site condition on earthquake ground motion in the area. Seismic site response analyses have been conducted considering the properties of the soil deposits using both equivalent linear and nonlinear approaches. It is shown that thick alluvium deposits amplified the ground motion and resulted in significant damage in residential buildings in the earthquake stricken region. The response spectra of the motion showed strong amplification during propagation of waves from the base to the surface. The observed response spectra are shown to be above the NEHRP building code design requirements, especially at high frequencies.

Introduction

The powerful earthquake of December 26, 2003 almost destroyed the city of Bam. City of Bam is located in the southeastern part of Iran. The magnitude of the earthquake was Mw 6.6 (USGS), its epicenter was close to City of Bam in Kerman province, and the focal depth was estimated to be 8-10 km. The city had a population of around 150,000 prior to the earthquake. The earthquake destroyed almost 70 percent of the conjugated cities of Bam and Baravat and the historical castle of Arg-e-Bam. The earthquake left about 27,000 people dead and about 50,000 persons injured. The intensity of the earthquake has been estimated to be VIII on the modified Mercally scale and the causative compression fault had an N-S trend. The influence of local geologic and soil conditions on the intensity of ground shaking and earthquake damage has been recognized for many years. Local site conditions can profoundly influence all of the important characteristics of strong ground motion: amplitude; frequency content; and duration. The extent of their influence depends on the geometry and material properties of the subsurface materials, on site topography, and on the characteristics of the input motion. Previous earthquakes such as Kobe (1995),

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Northridge (1994), and Loma Prieta (1989) have depicted the role of local site condition in modifying and changing the characteristics of strong motions. Various levels of structural damage have been observed in the same general area depending upon the local site variations. Damage patterns in Mexico City after the 1985 Michoacan earthquake demonstrated conclusively the significant effects of local site conditions on the seismic response of the ground. In the 1989 Loma Prieta earthquake, major damage occurred on soft soil sites in the San Francisco – Oakland region where the spectral accelerations were amplified two to four times over adjacent rock sites and caused severe damage to foundations and structures. Thus, the understanding of local site effects on strong ground motion is of particular importance for the mitigation of earthquake disasters as well as future earthquake resistant design. The effect of local geology on earthquake ground motion in Bam earthquake is investigated in this study.

The earthquake forces can be determined using the equivalent static load method, or the dynamic analysis method. In the equivalent static load method, earthquake forces are estimated as lateral forces based on the dead load of the structure and the base shear coefficient. In dynamic analysis method, the seismic forces are evaluated using either response spectrum or time history analysis. For critical structures, irregular structures and some other types of structures, the dynamic method must be used. The dynamic analysis usually involves three phases: the first phase defines expected source of earthquake; the second phase evaluates the ground surface response (motion) taking into account local soil properties; and the third phase applies response spectra techniques (acceleration and velocity amplitudes due to earthquake) to the proposed structure to evaluate the earthquake forces. This study discusses the sources of earthquakes in Bam and their characteristics such as earthquake magnitude, predominant period, maximum acceleration and duration. In addition, it presents a case study for evaluating the ground surface response spectra using the finite element computer program QUAKE W.

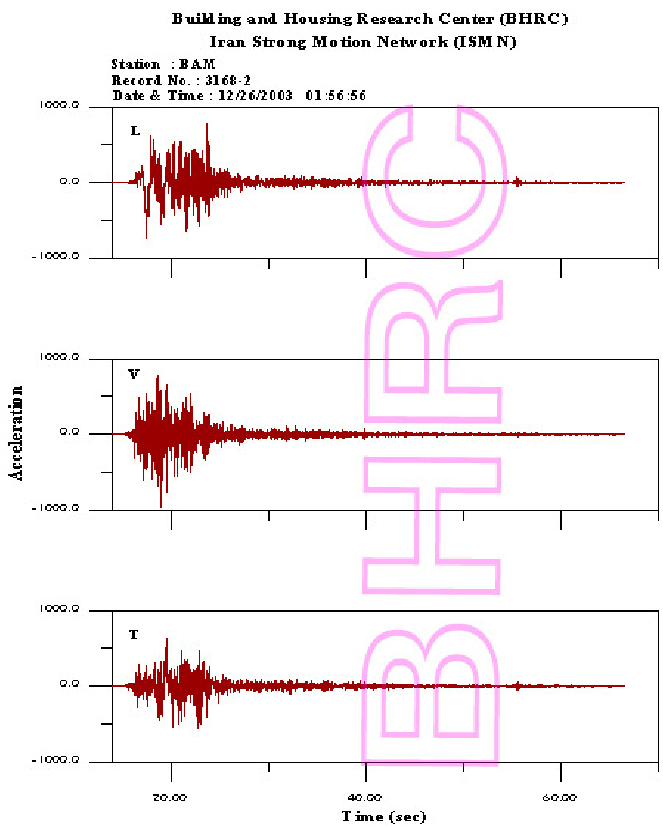


Figure 1. The acceleration time histories (Longitudinal, Vertical, and Transverse components) recorded in Bam.

Earthquake Ground Motion

The strong motions are recorded in 18 stations of the Iranian strong motion network (BHRC). The free field record obtained in Bam station (Fig. 1) shows the greatest PGA of 0.8g for the longitudinal component and 0.98g for the vertical component. The preliminary observations on the strong motion record obtained in the Bam station, as well as the observed damages in the region, suggest a vertical directivity effect caused by near-fault seismicity. This effect can be assigned to the Bam earthquake fault rupture. The Bam fault is a 50 km long right-lateral strike slip fault with north-south trend. It is the main tectonic feature in the area that overlaid the old quaternary sediments on younger sedimentary layers, east of Bam. As a result, the old quaternary sediments formed a hilly morphology that has been cut by some drainage systems at the area and made several deep channels prone to landslide. The thickness of the sediments having low to medium compaction is about 200 meters. The effects of deep erosion can be observed in these sediments.

The acceleration response spectra of horizontal and vertical motion at the BHRC site, presented in Fig. 2, show that the peak spectral acceleration of the V-component reached a value of 4.1g with a predominant period of 0.2 s. It is believed that this period reflects the characteristics of the source mechanism, whereas the period of a secondary spectral peak (0.8-1.5s) is most probably associated with the soil conditions at the site of accelerogram station (Zare, 2004). The observed response spectra are shown to be above the Iranian building code design requirements, especially at high frequencies.

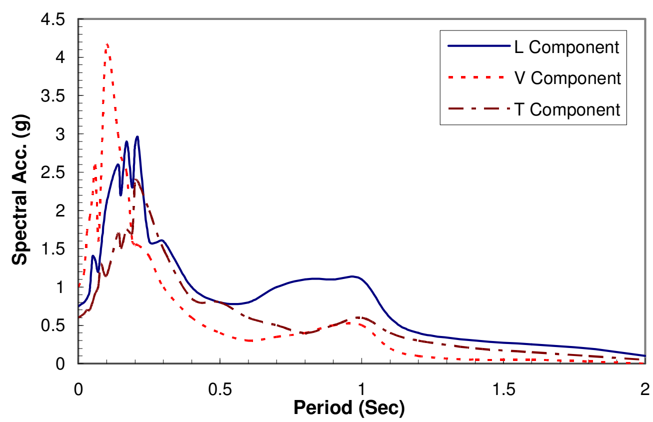


Figure 2. The acceleration response spectra (for 5% damping), at the accelerogram site.

Soil Properties

A representative soil profile of this region and the measured values of Standard Penetration Test blow count (N_{SPT}), based on borings at the Bam station are shown in Table 1. This table shows that the soil layers are stiff/dense sand, silts and gravels characterized by high values of N_{SPT}. It should be noted that the water table was not encountered up to the explored depth of 30 m in this site. The thickness of the alluvium at the Bam station is believed to be greater than 60 m. The shear wave velocity, V_s, of the subsurface layers, measured from down-hole tests are shown in Fig. 3. The value of V_s varied between 100-670m/sec and increased with depth as shown in Fig. 3.

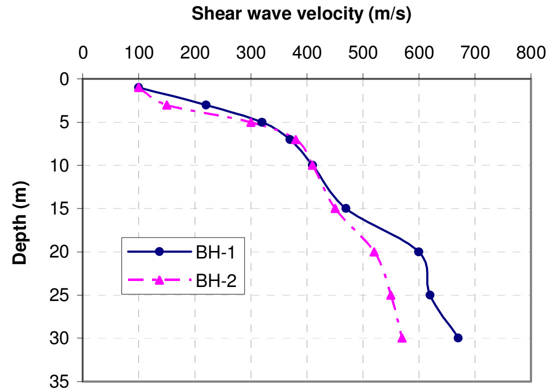


Fig. 3: Shear wave velocity profile in Bam area obtained from down-hole measurements

Local Geology Effects

The earthquake intensity is influenced by its magnitude and energy, site characteristics and features of wave propagation. In near fields, the influence of lithology on earthquake intensity is low. The variation of natural periods in high acceleration motion is not affected by lithological characteristics of the site, but depends on the rate of ground motion (Ishihara et al. 1992). Hence, the period of the ground response is affected by the predominant period of the strong motion. This phenomenon was clearly observed in the Manjil earthquake, 1999.

Due to the combination of large magnitude (Mw = 6.6), and being situated on the epicenter of the earthquake, City of Bam was subjected to a strong motion. In addition, the local site effects, and the thickness of sediments, were significant in many locations. In the location shown in Fig. 4, a thick alluvial deposit has amplified the earthquake ground motion and consequently increased the damage in north Bam. The residential buildings on the thick alluvial suffered more damage compared to similar nearby buildings founded on shallow sediments (Rayhani and El Naggar, 2005).

Table 1. Soil characteristics in the study area.

Borehole	Depth(m)	Description	W(%)	γ_d(gr/cm^3)	SPT	LL	PL	PI	V_s(m/s)
BH1	0.0-4.0	SC	6.0	1.68	15	19.8	13.7	6.1	105
	4.0-8.0	SW-SM	9.5	1.81	31	-	-	-	243
	8.0-16	SP-SM	8.3	1.86	50	-	-	-	370
	16-20	SP-SM	7.1	2.12	50	-	-	-	560
	20-26	SP-SM	8.3	1.86	50	-	-	-	612
	26-30	SM	8.8	2.03	50	-	-	-	670
BH2	0.0-1.0	SC	6.3	1.80	43	17.0	12.8	4.2	105
	1.0-10.0	SP-SM	5.7	1.92	50	-	-	-	295
	10.0-20	SM	5.3	2.08	50	-	-	-	435
	20-24	SP-SC	5.0	1.80	50	15.5	12.4	3.1	560
	24-30	GP-GM	6.0	1.84	50	-	-	-	560

Figure 4. Damage intensity variation of similar buildings on different site conditions in north Bam.

Site Response Analysis

In order to study the effects of local geology on the ground seismic response at the City of Bam 1-D numerical model of the ground profile was established for the purpose of performing the analysis using QUAKE/W. The model was established considering a representative soil profile at the accelerograph station considering the soil stratigraphy and the geotechnical and geophysical data presented in Table 1 and Fig. 3.

Dynamic Properties of Soil

The dynamic soil properties that are needed in an equivalent-linear type ground response analysis are the small strain shear wave velocity, V_s, shear modulus, G, and the modulus reduction curve, G/G_0-γ (Fig. 5) describing the degradation of soil shear stiffness with increasing amplitude of cycle shear strain, γ (G_0 = low strain amplitude shear modulus, i.e. for $\gamma \leq 10^{-5}$, G = higher amplitude shear modulus). The variation of soil damping, D, with the strain level is characterized by the curve D-γ (Fig. 5). The measured shear wave velocities shown in Fig. 3 are high indicating the high shear stiffness of soil formations at the study region of the city. The shear modulus, G, was determined from the measured shear wave velocities, V_s, i.e.,

$$G = V_s^2 \gamma / g \quad (1)$$

Poisson's ratio, υ, was assumed to be between 0.28-0.39 based on the soil profile. Young's modulus was then determined from the following relationship:

$$E = 2G(1+\upsilon) \quad (2)$$

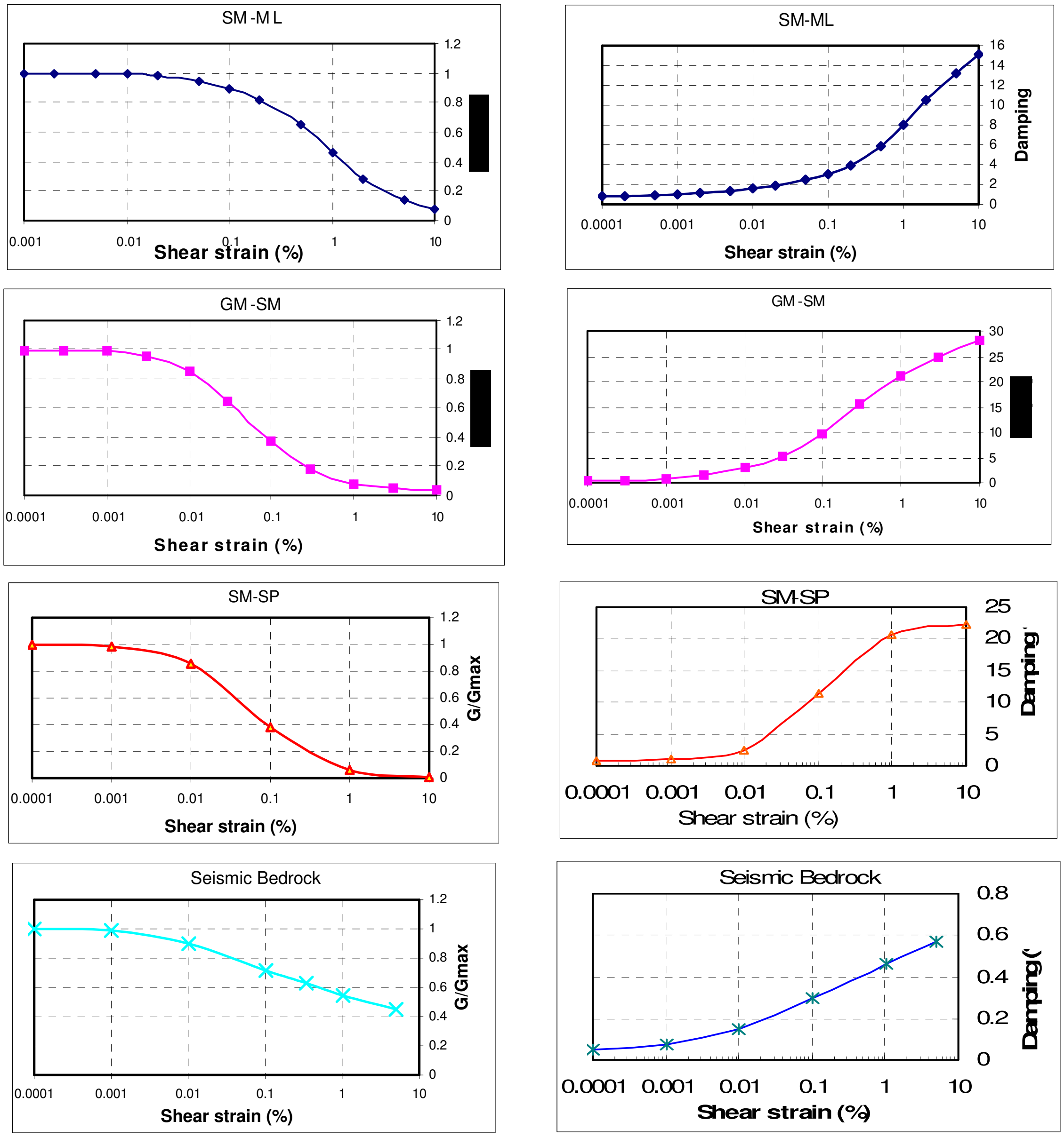


Figure 5. G/G_0–γ and D–γ curves used in the seismic ground response analysis.

Table 2 summarizes the input data. The G/G_0–γ and D–γ curves are usually obtained through laboratory cyclic loading tests. No such experimental data are available, however, for the soils of Bam area. Therefore, the empirical relation reported by Ishibashi and Zhang (1993) for similar soils was used in the analysis. These relations allow the determination of G/G_0–γ and D–γ curves in terms of the plasticity index, PI, and the mean effective normal stress, σ'_0, of a soil element. By taking into consideration four different mean depth levels and four different soil types, four sets of curves were determined for the study site. The determinations were accomplished by using the SHAKE program. All sets of curves (SM-ML, GM-SM, SM-SP, and SB) are shown in Fig. 5. It should be noted that the SB set of curves refers actually to seismic bedrock material and was established by utilizing the values frequently used for bedrock material in the program SHAKE91.

Table 2. Input soil properties for ground response analysis.

Depth (m)	Soil type	Vs (m/s)	γ (kN/m^3)	Poisson's Ratio	G (Mpa)	E (Mpa)
0-6	SM-ML	205	18.8	0.39	81	216
6-15	GM-SM	370	20.0	0.33	278	739.5
15-30	SM-SP	560	21.5	0.30	688	1788
30<	Seismic-bedrock	670	25.0	0.28	955	2546

Seismic Response Analysis

The seismic response analysis of the1-D ground profile was performed by the 1-D dynamic finite element program QUAKE/W. This computer program models the soil as an equivalent elastic material and simulates the non-linear aspect of behaviour by the iterative equivalent-linear method. In order to establish a realistic ground motion data set, the full Bam earthquake data was used.

Since the Bam earthquake record represented the free field motion (the station is situated on a soil profile not outcropping bedrock), deconvolution response analysis was performed to obtain the bedrock motion. The input motion is applied at the surface level of the model in the form of acceleration time history; and the analysis was performed to obtain the bedrock motion, considering vertical propagation of shear waves.

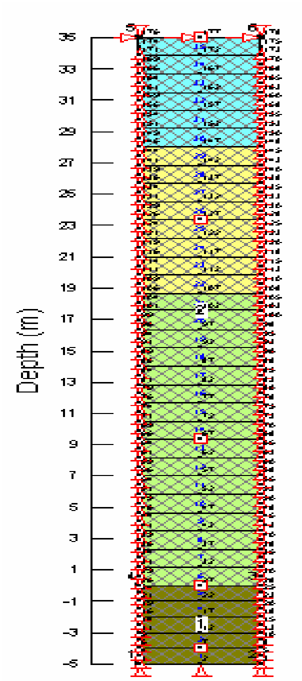


Figure 6. Finite element mesh for ground profile in the Bam station.

The consideration of vertically propagating shear waves constitutes a simplification of the actual phenomenon, especially in the case of near-field events involving complex wave fields. In the case of Bam earthquake, the focal region of the main event seems to lie at a horizontal distance of about 3 km and at a depth of about 8-10Km. By applying Snell's law and utilizing the shear wave velocities of soil strata, it may be shown that at least a significant portion of the seismic waves arrived at the site investigated herein following an approximately vertical direction.

The discretisation of the 1-D ground profile into finite elements is shown in Fig. 6. The four layers were modeled using the equivalent linear approach with the bedrock as equivalent elastic. Considering the input motion as a free field surface motion, it was tried to establish a base motion that when propagated through the 1-D model generates a response at the Bam site similar to the one recorded during the main shock of December 26, 2003. This task (deconvolution) can be conveniently accomplished by using the QUAKE/W code (or other similar codes), which takes into account the non-linear behavior of soil materials. The recorded horizontal accelerations of the Bam station have been applied at the profile surface as a stress function. A comparison of the computed base motion and actual acceleration time history of record at Bam station is shown in Fig. 7. This comparison indicates a good agreement between the two time histories.

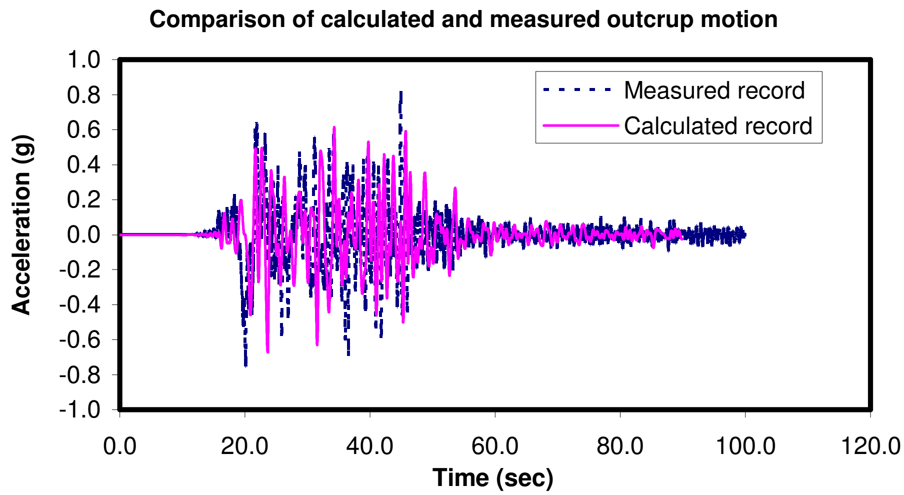
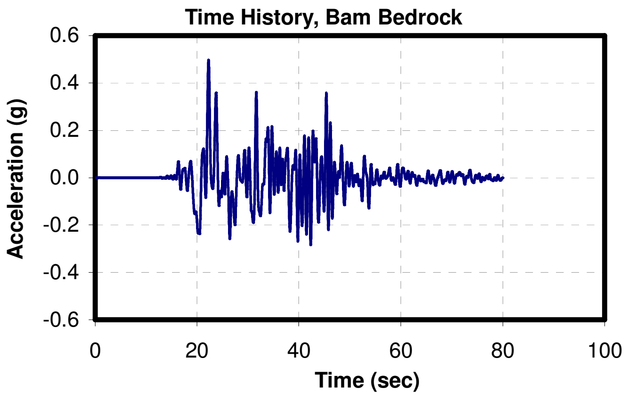


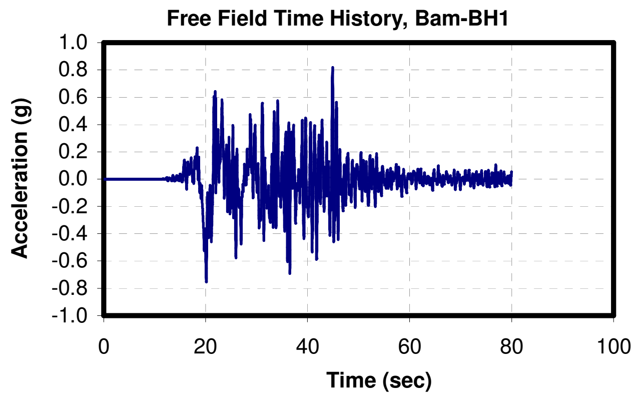
Figure 7. The comparison of calculated and measured outcrop motion in Bam.

The response spectra for bedrock and outcrop motions are presented in Fig. 8. The results indicate that the response spectra of the motions show peaks in the period range of 0.5 to 1.5 seconds. The comparison of the response shows that the surface response is about 1.5 times of base response. This variation is most probably associated with the amplification of soil at the site of accelerogram station.

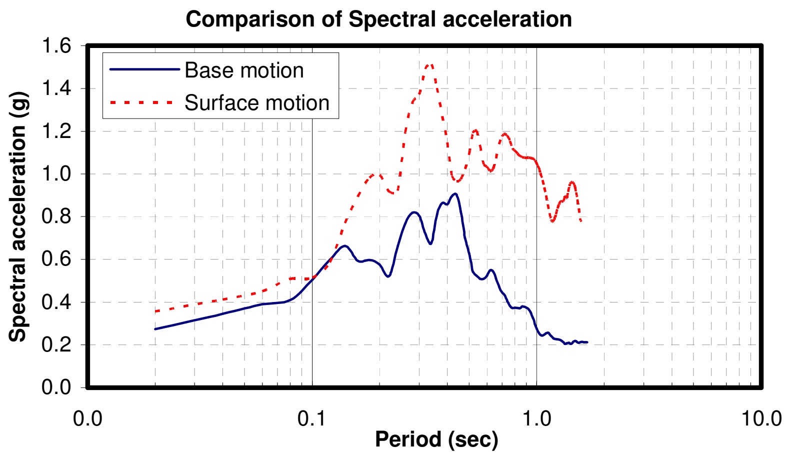
The outcrop response spectra are also shown to be above the NEHRP building code design requirements, especially at high frequencies. Results indicate that in short period, the standard NEHRP design spectra are less than the response spectra of the recorded data. Based on the above results it is concluded that the motion at Bam site was amplified with respect to the base motion (160%). The peak horizontal acceleration is equal to 0.5 g at the base compared to 0.8 g at the surface. It shows a significant amplification (160%).



Base time history



Free field time history



Free field and Base response spectra

Figure 8. Time history and response spectra of computed base motion and surface record.

Conclusions

The effects of local site condition in the Bam 2003 earthquake was studied by establishing a 1-D ground profile at the BHRC station of the city. The response of the ground surface was analyzed by a finite element code (QUAKE W) implementing the equivalent-linear method. It was found that the peak horizontal acceleration of the seismic base of the area was about 0.5 g. This base motion was amplified (160%) at the central region of the city. This behaviour seems to be in agreement with both theoretical results and field measurements and observations presented in reviewing the existing knowledge on the subject as well as with the damage pattern in the city.

The results of response spectra indicate that the response spectra of the motions show peaks in the period range of 0.5 to 1.5 seconds. The comparison of the response shows that the surface response is about 1.5 times of base response. This variation is most probably associated with the amplification of soil at the site of accelerogram station. The outcrop response spectra are also shown to be above the Iranian building code design requirements, especially at high frequencies. Results indicate that in short period, the NEHRP standard design spectra are less than the response spectra of the recorded data. It is therefore concluded that the characteristic local geology of the city played an important role in modifying the intensity of base motion.

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