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Nonlinear Analysis of Local Site Effects on Seismic Ground Response in the Bam Earthquake

M. H. T. Rayhani · M. H. El Naggar · S. H. Tabatabaei

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 accelerograph station. Although the highest peak ground acceleration recorded was the vertical component (nearly 1 g), the longitudinal component (fault-parallel motion) clearly had the largest maximum velocity as well as maximum ground displacement. Subsurface geotechnical and geophysical (down-hole) data in two different sites have been obtained and used to estimate the local site condition on earthquake ground motion in the area. The ground response analyses have been conducted considering the nonlinear behavior of the soil deposits using both equivalent linear and nonlinear approaches. The fully nonlinear method embodied in FLAC was used to evaluate the nonlinear soil properties on earthquake wave propagation through the soil layer, and compare with the response from the equivalent linear approach. 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 comparison of results indicated similar response spectra of the motions for both equivalent and nonlinear analyses, showing peaks in the period range of 0.3–1.5 s. However, the amplification levels of nonlinear analysis were less than the equivalent linear method especially in long periods. The observed response spectra are shown to be above the NEHRP building code design requirements, especially at high frequencies.

M. H. T. Rayhani (✉) · M. H. El Naggar
Department of Civil and Environmental Engineering, University of Western Ontario, London, ON, Canada N6A 5B9
e-mail: mrayhani@ce.queensu.ca; mtofighr@uwo.ca

M. H. El Naggar
e-mail: helnaggar@eng.uwo.ca

S. H. Tabatabaei
Geotechnical Department, Building and Housing Research Center, P.O. Box 13145-1696, Tehran, Iran
e-mail: htabatabaei@bhrc.ac.ir

1 Introduction

The powerful earthquake of December 26, 2003 almost destroyed the city of Bam that is located in the southeastern part of Iran. The magnitude of the earthquake was M_w 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% 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 a north–south 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), Northridge (1994), and Loma Prieta (1989) have depicted the role of local site condition in modifying the characteristics of strong motions. Various levels of structural damage have been observed in the same general area depending upon the local site conditions. Damage patterns in Mexico City after the 1985 Michoacan earthquake demonstrated conclusively the significant effects of local site conditions on the seismic ground response. 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 common method in earthquake engineering for modeling wave transmission in layered sites and dynamic soil-structure interaction is "equivalent-linear" method. The equivalent linear method uses linear properties for each element that remain constant throughout the history of shaking. Since the seismic ground response is significantly affected by the nonlinear behavior of the soil profile. Therefore, it is most important to properly model the soil nonlinearity in the dynamic analysis of local site effects during earthquake excitations (Kramer 1996).

In this paper, an attempt was made to perform a true nonlinear analysis of the seismic ground response during Bam Earthquake and compare the calculated free-field ground motion from this analysis with those obtained from the equivalent linear method. The study discusses the effect of local site conditions on earthquake ground motion using nonlinear seismic site response analysis in FLAC program. Nonlinear site response analysis, as well as equivalent linear approach, was used to estimate the site response and study the soil behavior during the earthquake wave propagation. The nonlinear site response was estimated by elasto-plastic constitutive model. The results were compared with those of NEHRP building code provisions for the same soil categories.

2 Geological Setting

Tectonically, Iran is located in the main part of the Alpine-Himalaya orogenic belt. The City of Bam is located in the southern part of the Central Iranian Block. Five different lithologies can be observed in the main geological formations of the Bam area including: (1) Recent Quaternary alluvium, (2) Late Quaternary sandstones and siltstones, (3) Paleogene sedimentary rocks, (4) Eocene volcanic rocks, and (5) Intrusive igneous rocks. The thickness of the sediments having low to medium compaction is about 200 m. The effects of deep erosion can be observed in these sediments (Nadim et al. 2004). 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 Bam accelerograph station is located on thick alluvial sediments.
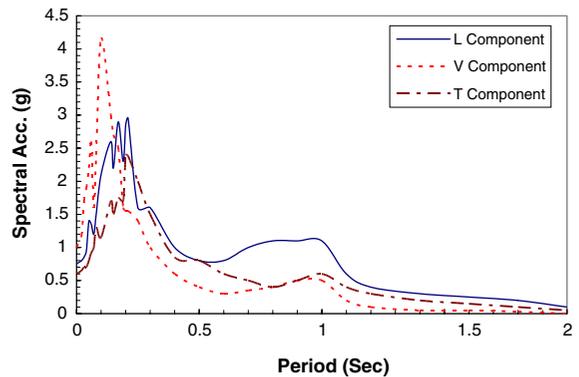
3 Earthquake Ground Motion

The strong motions were recorded in 18 stations of the Iranian strong motion network (BHRC). The free field record obtained in Bam station (Fig. 1) showed maximum PGA of 0.8 and 0.7 g for the east–west and north–south horizontal components, respectively, and 0.98 g for the vertical component. Although the highest peak ground acceleration was recorded for the vertical component (nearly 1 g), the longitudinal component (fault-parallel motion) clearly had the largest energy flux as well as the largest maximum
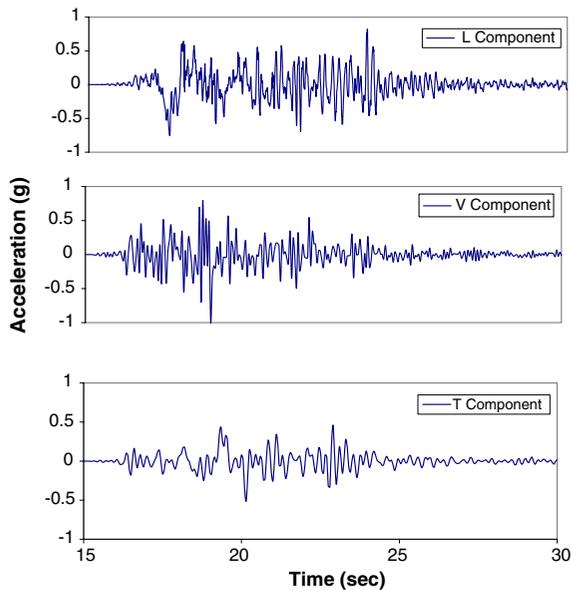
Fig. 1 The acceleration time histories (Longitudinal, Vertical, and Transverse components) recorded at the Bam station

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

velocity and ground displacement. This correlates well with the rupture propagation model and with the overall observation that walls with N–S direction were generally more damaged than E–W trending walls at the recording site. The northwards propagating rupture resulted in a directivity effect with maximum ground motions at the north end of the rupture where Bam is located (Nadim et al. 2004). 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 could be assigned to the Bam earthquake fault rupture, while a strong fault-normal (east–west) motion was created during the main shock as well. The demolished walls and buildings of Bam are representative of such effects in the up–down (vertical) and east–west directions (fault-normal) (Eshghii and Zare 2003).

The acceleration response spectra of horizontal and vertical motion at the Bam station, presented in Fig. 2, show that the peak spectral acceleration of the V-component reached a value of 3.7 g with a predominant period of 0.2 s. It is believed that this period reflects the characteristics of the source mechanism (Eshghii and Zare 2003), whereas the period of a secondary spectral peak (0.8–1.5 s) is

most probably associated with the soil conditions at the Bam accelerograph station. The observed response spectra are shown to be above the Iranian building code design requirements, especially at high frequencies.

4 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 motions 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, 1992.

Due to the combination of large magnitude ($M_w = 6.6$), and being situated on the epicenter of the earthquake, City of Bam was subjected to a strong input ground motion. In addition, the effects of local site conditions, site topography and the thickness of sediments, were significant in many locations. In the location shown in Fig. 3, 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 2004).

Fig. 3 Various damage on different surface deposits in north Bam


5 Soil Properties

Geotechnical drilling was performed near the Bam station, to determine the subsurface layering characteristics and then evaluate the effect of local site conditions on the strong ground motion recorded in the city. The depth of the bore-hole was limited to the top 30 m as per the Iranian code requirement (Standard 2800 2005). However, Rayhani and El Naggar (2007) reported that the seismic local site effects are influenced primarily by the properties of the top 30 m of the soil. A representative soil profile of this region and the measured values of standard penetration test (SPT) blow count (N_{SPT}), based on borings at the Bam station, is shown in Table 1. The table shows that the soil layers consist of stiff/dense sand, silts and gravels characterized by high values of N_{SPT}. The soil profile in the Bam station contains sandy clay on the top, which overlays the dense sand and silty sand at the bottom. Unit weight of the soil varied from 16.8 to 21.2 kN/m³, and the maximum

water content was about 9.5%. The values of SPT blow count was measured about 15 on the top 4 m of the site and increased up to higher than 50 with depth (Table 1). 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 were measured from down-hole tests and shown in Fig. 4. The value of V_s varied between 100 and 670 m/s and increased with depth, indicating high stiffness of soil formations at the study region.

The dynamic soil properties that are needed in a ground response analysis are the small strain shear wave velocity, V_s, shear modulus at low strain, G_0, and G/G_0–γ and D–γ curves describing the degradation of soil shear stiffness and damping with increasing amplitude of shear strain, γ. The dynamic soil properties were estimated from in-situ measurements, e.g., Standard Penetration Test, down-hole seismic survey together with complimentary laboratory tests.

Table 1 Soil characteristics in the study area

Borehole	Depth (m)	Description	W (%)	γ_d (kN/m³)	SPT	LL	PL	PI	V_s (m/s)
BH1	0.0–4.0	SC	6.0	16.80	15	19.8	13.7	6.1	105
	4.0–8.0	SW-SM	9.5	18.10	31	–	–	–	243
	8.0–16	SP-SM	8.3	18.60	50	–	–	–	370
	16–20	SP-SM	7.1	21.20	50	–	–	–	560
	20–26	SP-SM	8.3	18.60	50	–	–	–	612
	26–30	SM	8.8	20.30	50	–	–	–	670
BH2	0.0–1.0	SC	6.3	18.00	43	17.0	12.8	4.2	105
	1.0–10.0	SP-SM	5.7	19.20	50	–	–	–	295
	10.0–20	SM	5.3	20.80	50	–	–	–	435
	20–24	SP-SC	5.0	18.00	50	15.5	12.4	3.1	560
	24–30	GP-GM	6.0	18.40	50	–	–	–	560
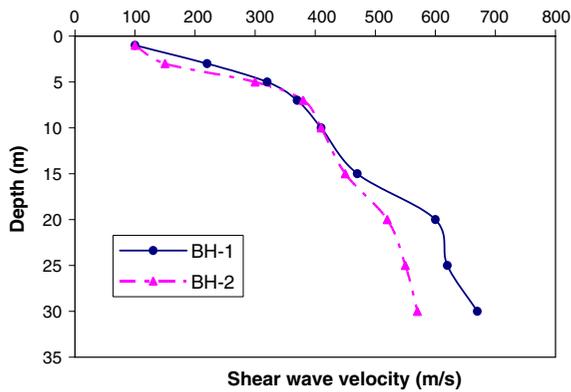
Fig. 4 Shear wave velocity, V_s, versus depth in Bam obtained from down-hole data

The shear modulus, G, was determined from the measured shear wave velocities, V_s, i.e.,

$$G = V_s^2 \gamma_s / g \tag{1}$$

where, γ_s, is soil unit weight. Poisson's ratio, v, was assumed to be between 0.28 and 0.39 based on the soil profile. Young's modulus was then determined from the following relationship:

$$E = 2G(1 + v) \tag{2}$$

The G/G_0–γ and D–γ curves are usually obtained through laboratory cyclic loading tests. However, such experimental data were not available for the soils of Bam area. Therefore, G/G_0–γ and D–γ curves were selected based on soils type and their index properties and the empirical relations reported by Ishibashi and Zhang (1993) for sandy soils. 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.

In this study, four soil types with different mean depth levels were considered for the response analysis. Therefore, four data sets were determined for the study site and are summarized in Table 2. The degradation curves were accomplished by using the SHAKE program (SHAKE91 1992) . All sets of curves (SM-SC, GM-SM, SM-SP, and SB) are shown in Fig. 5. It should be noted that the SB (seismic bedrock) 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.

6 Seismic Response Analysis

In order to study the effects of local geology on the seismic ground response at the Bam station, 1-D numerical model of the ground profile with 30 m depth was established using FLAC program. The model was established considering a representative soil profile at the accelerograph station using the soil stratigraphy and the geotechnical and geophysical data presented in Table 2 and Fig. 3.
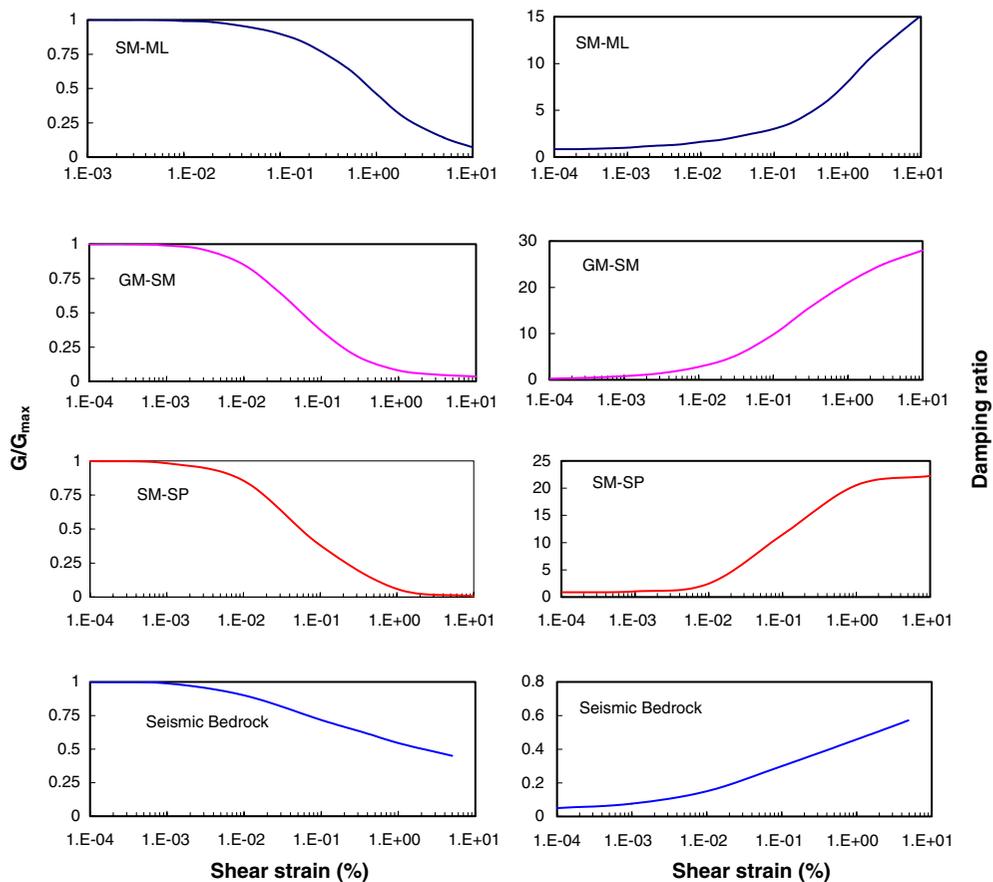
The seismic response analysis of the 1-D ground profile was performed using the commercially available program, *FLAC* (Fast Lagrangian Analysis of Continua), (Itasca 2005). It is an explicit finite difference program that can simulate the behavior of structures built of soil, rock or other materials that may undergo plastic flow when their yield limits are reached. Materials are represented by elements, and each element behaves according to a prescribed linear or nonlinear stress/strain law in response to the applied forces or boundary restraints. The program can model the soil using true nonlinear soil behavior. The discretization of the 1-D ground profile into the model elements is shown in Fig. 6. The four layers were modeled using the equivalent linear approach with the bedrock as equivalent elastic medium.

6.1 Equivalent Linear Site Response

The "equivalent-linear" method is commonly used in earthquake engineering for modeling wave transmission

Table 2 Soil properties for ground response analysis

| Depth (m)	Soil type	V_s (m/s)	γ (kN/m^3)	Poisson's ratio	G (MPa)	E (MPa)
0–6	SM-SC	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	1,788
30<	SB	670	23.0	0.28	955	2,546

Fig. 5 Modulus reduction and damping curves used in the seismic response analysis

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. The full Bam earthquake data was used to establish a realistic ground motion data set. 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 was 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.

The consideration of vertically propagating SV 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 8–10 km. 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.
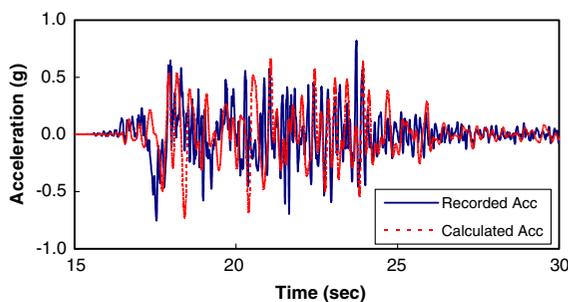
Considering the input motion as a free field surface motion, it was attempted to establish a base motion that when propagated through the 1-D model generates a response at the Bam site surface similar to the one recorded during the main shock of December 26, 2003. This task (deconvolution) can be conveniently accomplished by using the FLAC and Quake/W codes (or other similar codes), which takes into account the nonlinear behavior of soil materials. The recorded horizontal accelerations of the Bam station have been applied at the profile surface as a stress
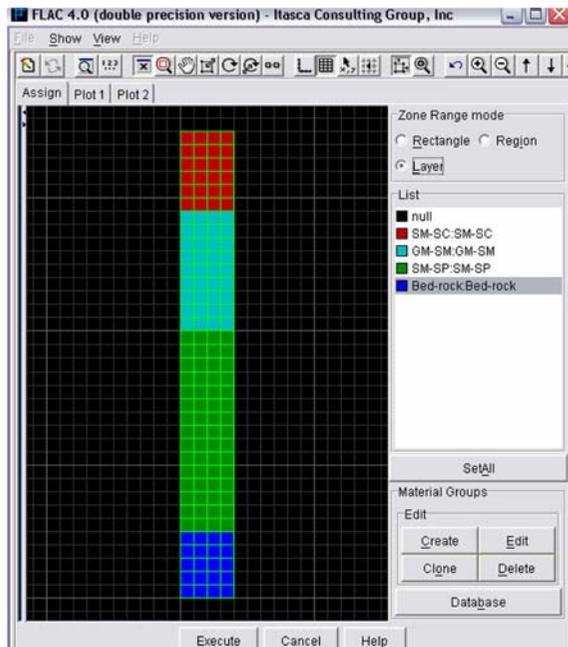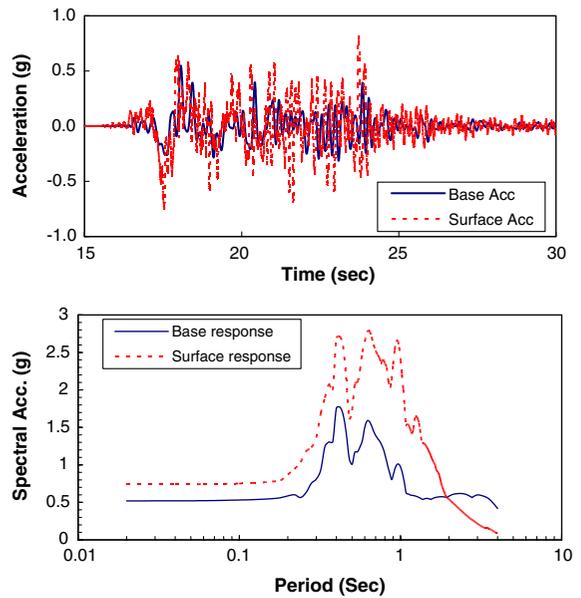
Fig. 6 Finite difference mesh for ground profile in Bam station

Fig. 8 Time history and response spectra of the base motion and surface record

function. The deconvolution site response analysis was performed and the base (bedrock) motion was established. This bedrock motion was then used as input motion to the model and the surface (free field) motion was calculated. A comparison of the recorded (actual) surface acceleration time history and the computed time history of the surface (free field) motion from this process is shown in Fig. 7. This comparison indicates a good agreement between the two time histories.

The base and surface acceleration histories and the response spectra for bedrock and free field motions are presented in Fig. 8. The results indicated that the

peak horizontal acceleration is about 0.55 g at the base compared to 0.78 g at the surface, i.e., an amplification factor equal to 1.4. These results showed that the motion at Bam site was amplified with respect to the base motion by about 40%. The response spectra of the motions showed peaks in the period range of 0.3–1.5 s. The ratio of surface response spectra to the base response (RRS) at the peak response is more than 1.5. This amplification is attributed to the local site effects due to the thick soil deposits at the site of the accelerograph station. It seems that the frequency content of the response spectra at the surface slightly shifted to the longer periods, compared to the base response.

6.2 Nonlinear Site Response

The seismic ground response is significantly affected by the nonlinear behavior of the soil profile. Therefore, it is most important to properly model the soil nonlinearity in the dynamic analysis of local site effects during earthquake excitations (Kramer 1996). In this paper, an attempt was made to perform a true nonlinear analysis for the seismic ground response during the Bam Earthquake and compare the calculated free-field ground motion from this analysis with

Fig. 7 The comparison of calculated and measured free field motion in Bam

those obtained from the equivalent linear method. To capture this behavior in a numerical model, the soil properties should be modified with current or accumulated stress history and pore water pressure step by step. The computer program *FLAC* Version 4.0 has been employed to perform the nonlinear site response analysis considering the soil nonlinear behavior. The calculation is based on the explicit finite difference scheme to solve the full equations of motion, using lumped grid point masses derived from the real density of surrounding zones.

The plastic models in *FLAC* are characterized by their yield function, hardening/softening functions and flow rule. The yield functions for each model define the stress combination for which plastic flow takes place. The plastic flow formulation in *FLAC* rests on basic assumptions from plasticity theory that the total strain increment may be decomposed into elastic and plastic parts. The Mohr–Coulomb model was used to simulate the nonlinear soil behavior. In *FLAC*, this model is characterized by its yield function and flow rule. The yield functions define the stress combination for which plastic flow takes place. The model is based on plane strain conditions, and is formulated in terms of effective stresses. The failure envelope corresponds to a Mohr–Coulomb criterion (shear yield) with tension cutoff (tension yield function). The position of a stress point on this envelope is controlled by a non-associated flow rule for shear failure, and an associated rule for tension failure. The Mohr–Coulomb material model requires conventional soil parameters including: unit weight (γ), friction angle (ϕ), cohesion intercept (c), shear modulus (G), and bulk modulus (B). Table 2 presents the soil parameters used in the *FLAC* model.

The soil was modeled as a nonlinear elastic–plastic material using Mohr–Coulomb failure criterion with non-associated flow rule. The dynamic soil properties estimated from the geotechnical investigation were used to match the hysteretic damping parameters for nonlinear analysis in *FLAC*. The shear modulus values of 81–955 MPa were used for soil layers in the model. The damping ratio of 5% and Poisson's ratios of 0.39–0.28 were employed for soil layers based on subsurface soil investigation.

The computed bedrock motion at the Bam station was applied as the base motion and the surface motion was calculated considering the soil nonlinearity using the full nonlinear approach. A comparison of the nonlinear surface response and the equivalent response spectra at the Bam station is shown in Fig. 9. The results indicate that the response spectra from both nonlinear and equivalent linear approaches are similar in terms of frequency content, with slightly higher frequency content in the predictions of the equivalent method at longer periods. However, the amplification level of the equivalent linear response is higher than the nonlinear method. The surface response spectra considering the nonlinear effect on the ground response analysis is slightly less than the equivalent linear response, especially for long periods. The maximum response spectrum of the nonlinear analysis is about 2.4, while the corresponding value in the equivalent linear approach was about 2.7.

The comparison of the nonlinear surface response and bedrock response shows that the free field response is about 1.35 times of base response, i.e., less than that of obtained from the equivalent linear analysis. The equivalent linear method showed peak spectral acceleration of about 15% higher than the nonlinear method. This ratio is even higher in long periods (0.5–1.2 s).

6.3 Comments on the Comparison of Response Analyses

Both nonlinear and equivalent linear methods are used to perform ground response analyses, with quite different formulation and underlying assumptions. Consequently, it is reasonable to expect to find some differences in their results. The nonlinear method requires a reliable stress–strain or constitutive model.
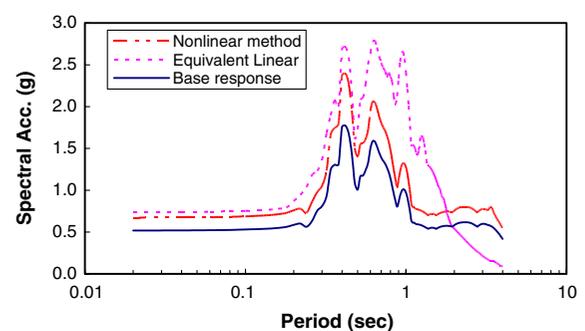
Fig. 9 Comparison of nonlinear and equivalent linear surface response spectra

Table 3 Amplification factors in both equivalent linear and nonlinear analyses

Method	Peak base acc. (g)	Peak surface acc. (g)	Frequency at peak (Hz)	RRS at peak	Amplification factor
Equivalent linear	0.55	0.78	2.4	1.53	1.4
Nonlinear	0.55	0.72	2.4	1.35	1.35

Field/laboratory tests are required to estimate the nonlinear model behavior. Equivalent linear method does not have the capability of incorporating stress-history effects on the dynamic behavior.

The comparison of results indicated similar peak response spectra in terms of peak frequency for both equivalent and nonlinear analysis, showing peak responses at a frequency of about 2.4 Hz. Due to the absence of pore water pressure in the soil profile considered in the analysis (the ground water table is at approximately 60 m below ground surface), the ground response results are similar for both nonlinear and equivalent linear methods. However, the amplification levels of nonlinear analysis are less than the equivalent linear method especially in long periods. The amplification factor using the equivalent linear method is about 1.4, while the corresponding factor in full nonlinear method is about 1.35 (Table 3). The maximum spectral acceleration in equivalent linear method is about 15% higher than the nonlinear method. The ratio of surface response to the base response (RRS), at peak response, in equivalent linear method is about 1.53, while this ratio in nonlinear approach is about 1.35. Therefore, based on findings of this research, the equivalent linear method shows higher amplification and higher response spectra compare to the real nonlinear analysis. This difference may be reasonable in the analysis of simple projects, but it is better to use real nonlinear approach in important projects.
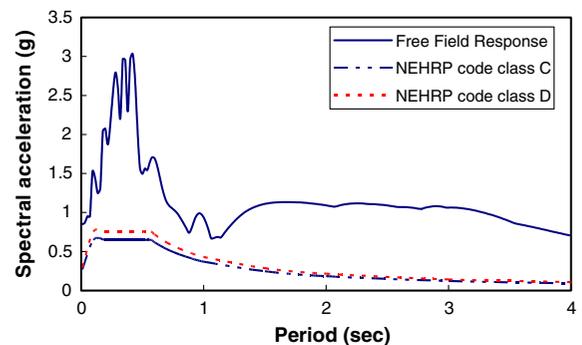
6.4 Comparison with NEHRP Response Spectra

The seismic provisions of building codes incorporate the effects of local soil conditions on design ground motions by classifying the wide variety of possible soil conditions into different categories and assigning a foundation factor, or response spectra, to each category. The response spectra based on the recommendations of the 1997 National Earthquake Hazards Reduction Program (NEHRP) provisions were compared with the response spectra from this study. Based on the shear wave velocity in the upper 30 m, the soil profile in the study area would be classified as site class C. Figure 10 compares the NEHRP response spectra for a site class C and D with the response spectra calculated in this study. The results indicated that the surface response spectra were clearly higher than the NEHRP building code design requirements, especially at low periods. Therefore, it seems the NEHRP code provisions underestimated the response spectra in all periods, especially at resonance periods of the site.

7 Conclusion

The effects of local site condition in the Bam 2003 earthquake was studied by establishing a 1-D ground profile at the Bam station. The seismic response of the ground surface was analyzed using the finite difference code (FLAC) implementing both nonlinear and equivalent-linear methods. It was found that the peak horizontal acceleration of the seismic base of the area was about 0.55 g. This base motion was amplified by 30–40% at the central region of the city. This behavior shows that the earthquake shear waves were amplified during wave propagation from the base to the surface in soil layers. This amplification is

Fig. 10 Comparison of surface response spectra with NEHRP design response spectra

attributed to the local site effects due to the thick soil deposits at the Bam station.

In order to evaluate the effect of nonlinear analysis on the ground response, a series of nonlinear site response analysis has been conducted using the FLAC and compared with the equivalent linear approach. The response spectra, in both nonlinear and equivalent linear approaches, showed peaks in the period range of 0.3–1.5 s. However, the amplification levels of nonlinear analysis were less than the equivalent linear method especially in long periods. The amplification factor using the equivalent linear method was about 1.4, while this factor in full nonlinear method was about 1.35. The maximum spectral acceleration in equivalent linear method was 15% higher than the nonlinear method. Therefore, based on findings of this research, the equivalent linear method showed higher amplification and higher response spectra compared to the full nonlinear analysis. This difference may be acceptable in the analysis of most projects, but it is better to use full nonlinear approach in critical projects.

The free field response spectra were also shown to be above the NEHRP building code design requirements, especially at resonance periods of the site. It is therefore concluded that the characteristic local geology of the city played an important role in amplifying the intensity of base motion.

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