

Preliminary Seismic Microzonation of Bam

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ABSTRACT: After the devastating earthquake of 26 December 2003 in Bam, a discipline was followed to prepare a preliminary site effect microzonation map for the city. Seismic hazard studies for two return periods, geological studies accompanied by geophysical surveys and aftershock and microtremor measurements were carried out to provide site classification and PGA distribution maps. The results of this study show that reasonable agreements exist between the 2475 years PGA distribution map and the damage distribution map for the recent earthquake. The 475 years PGA microzonation maps could also be used as a preliminary useful hint in reconstruction and urban planning of the totally destroyed city.

Keywords: Bam; Seismic microzonation; Site effect; Microtremor; Shear wave velocity; Peak ground acceleration; Urban planning

1. Introduction

Nowadays it is well established that ground motions are strongly influenced by source, path and local site effects. The city of Bam in the south-eastern part of Iran was hit by an earthquake of M_s 6.5 at a local time of 5:26 am on 26 December 2003. Among many research groups of different disciplines, the authors carried out their investigation on evaluation of site effects on ground motion in Bam city. The main aim of this investigation was to prepare preliminary seismic microzonation maps for the Bam city.

It is well known that the capability of local geologic deposits to amplify strong ground shaking depends on the physical properties of the materials as well as their three-dimensional geometrical distribution. Due to the dominant construction of adobe and low rise buildings in Bam, valuable data on geotechnical properties and three-dimensional distribution of materials were not available throughout the city in sufficient detail. Consequently the microzonation maps were developed using the distribution of geologic materials as mapped at the ground surface, geophysical surveying, microtremor

and aftershock measurements. The methodology of the site effect assessment throughout the study area adopted in this study, consisted of the following steps:

1. Preparing the seismic hazard maps of the study area for two return periods of 475 and 2475 years;
2. Revising the existent geological map, utilizing field observations and aerial photo studies;
3. Defining the representative geophysical groups, based on the geological map and the geophysical investigations. Non-linear amplification capability of the representative sites were estimated using the latest empirical correlations between the site type and the relative amplification factor;
4. Estimation of the natural frequencies throughout the study area based on the microtremor and aftershocks measurements;
5. Preparing the site classification map, based on the geological map, the representative geophysical groups and the estimated natural frequencies;
6. Preparing the peak ground acceleration (PGA) distribution maps of the study area, by

superimposing the peak ground acceleration (PGA) distribution maps and the site classification map, for the return periods of 475 and 2475 years.

The above mentioned methodology could be incorporated into the category of Grade-2 zoning methods, according to the Japanese TC4 zoning Manual [1]. Finally the prepared PGA distribution map for the return period of 2475 years and also the site classification map were compared to the damage distribution map of 2003 Bam earthquake [2].

2. Seismic Hazard Map

The basis for earthquake hazard analysis is the analysis of seismicity or the occurrence of the earthquake in space and time. The historic records may contain reports of earthquakes that occurred during the hundreds and, in some cases, thousands of years of recorded human history. The instrumental record yields information about those earthquakes for which actual instrumental evidence exists. The 2003 Bam earthquake occurred in southeast of Iran with epicenter close to Bam. The seismicity in Bam did not show any historical and instrumental strong earthquake at least in the last 2200 years ago. The most

important earthquakes which occurred in NW of Bam are the 1981 Golbaf earthquake (M_w 6.6), the 1981 Sirch earthquake (M_w 7.1) and the 1998 Fandoqa earthquake (M_w 6.6).

A reliable assessment of seismic risk in a region requires knowledge and understanding of both the seismicity and the attenuation of strong ground motion. On the basis of geological and seismological studies, the hazard maps for 10% and 2% probability of exceedence in 50 years have been developed for Bam region, see Figures (1) and (2). These hazard maps correspond to return periods of 475 and 2475 years, respectively. The effects of all the earthquakes of different sizes, occurring at different locations in different earthquake sources are integrated into hazard map. The hazard map is generated based on spatially smoothed seismicity [3] and hazard from specific fault sources and attenuation relationships given by Boore et al [4] and Zare [5]. Also a uniform source zone encompassing east central Iran has been considered to quantify possibility of having an earthquake (with magnitude 5.0-7.0) in the area that have potential for damaging earthquake and quiescent historically. Such model has been suggested by different investigators (e.g. [3]).

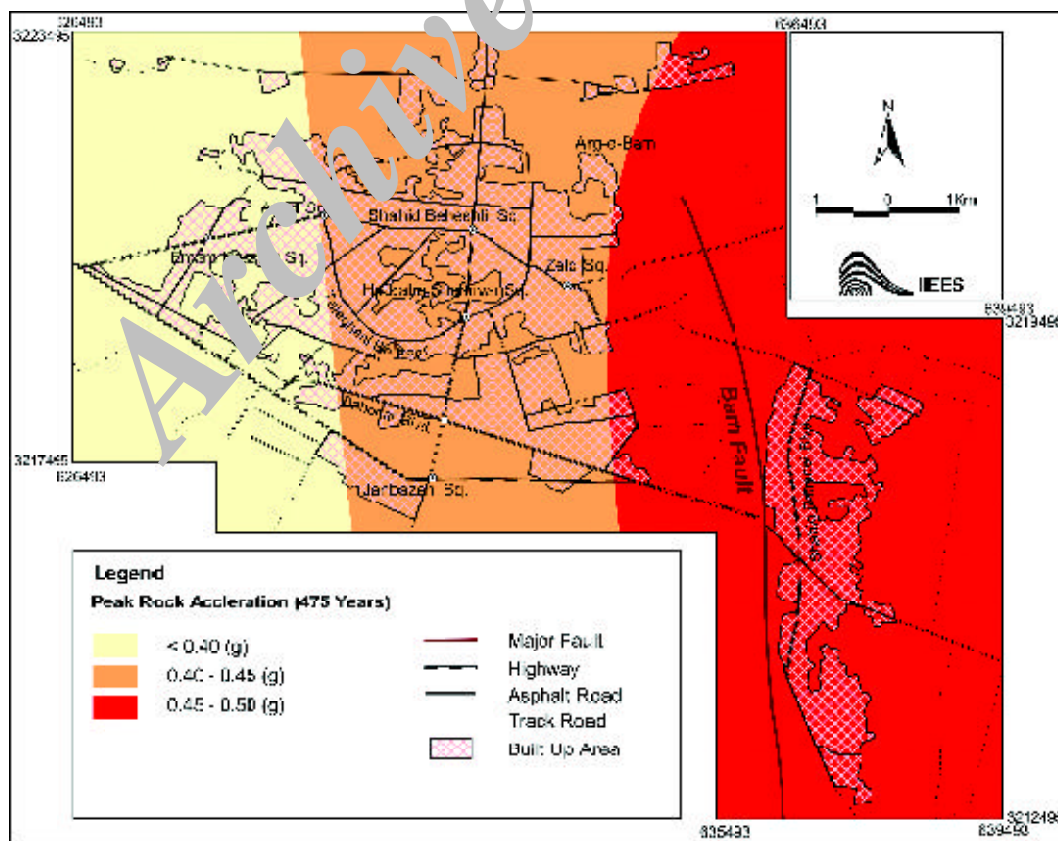


Figure 1. Peak rock acceleration map of Bam (475 years).

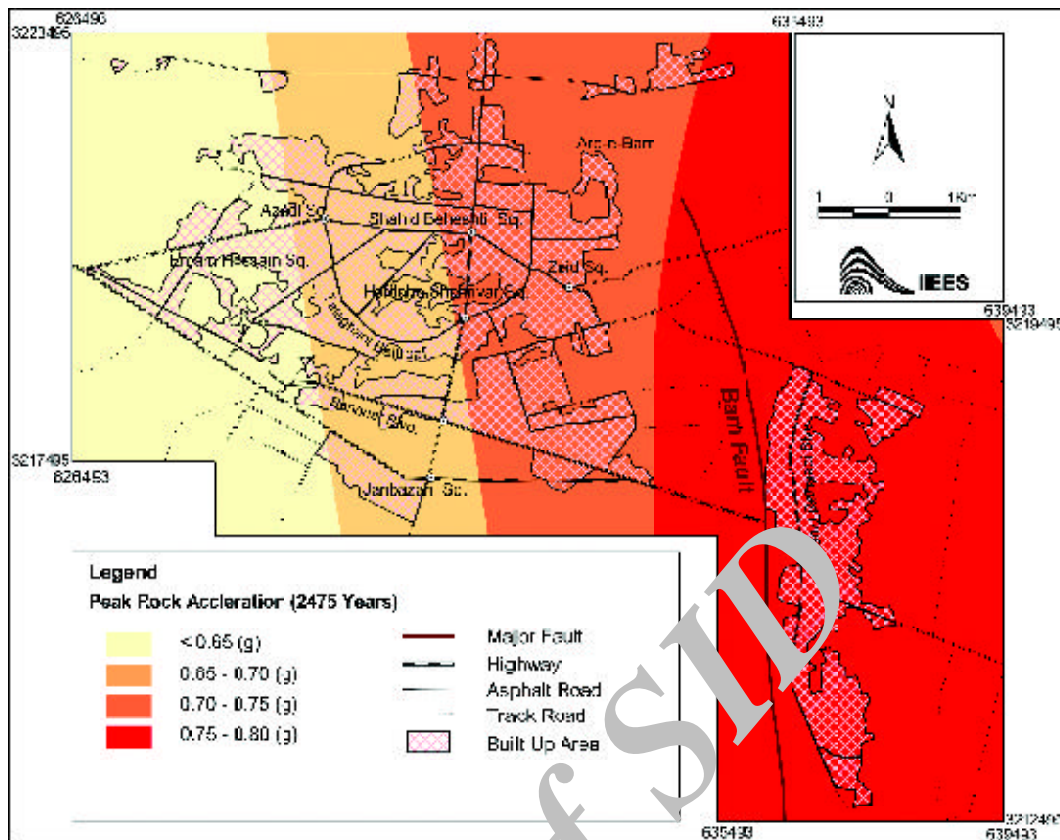


Figure 2. Peak rock acceleration map of Bam (2475 years).

3. Site Classification Map

Underground geological condition plays the main role in seismic microzonation. The site classification map of Bam has been prepared based on the geological map of the study area and also on complementary site investigations conducted by IIEES. These site investigations included geophysical surveys, microtremor and aftershock measurements. In this regard 8 Geo-electrical soundages and 10 seismic refraction profiles were surveyed. Data of 8 temporary seismometer stations accompanied by the 30 minute time window ambient vibration at 18 stations were used for Spectral analysis. Figure (3) presents the location of Geo-electrical soundages, seismic refraction profiles and the seismic stations (including aftershocks and microtremors).

3.1. Geological Map

Figure (3) also shows the geological map of the study area prepared by Geological Survey of Iran [6]. This geological map has been slightly modified using field observations and aerial photo studies.

The geological map shows that most parts of Bam (and Baravat) have been constructed on Quaternary

alluvial. Arg-e-Bam located at the northwest of the city, is the only site where a rock outcrop can be observed. The quaternary materials can be divided into 4 groups based on general and special characteristics. These groups are the recent alluvium in river base (Q^a), late Quaternary alluvium (Q^l), young fan deposits (Q^f), and finally early quaternary materials (Q^m and Q^m). These types of deposits covered nearly most parts of Bam and Baravat. Eocene volcanic rocks are the only outcrops which consist less than 1 percent of surface in the study area.

The Q^m deposits can be observed along the Bam fault having about 5 degrees dip toward east. The density of this layer is lower than the other deposits, although it is older. The geological map also shows that most parts of Bam and Baravat are covered with Q^m deposits including gravel, sand and silt. There are some thin layers of fine grain sediments as lenses inside these deposits. The thickness of these layers varies from a few meters to more than 50 meters, depending on their location. A weak cementation caused by infiltration of the surface water, can be observed in some parts of these deposits. Shear wave velocity of this layer is about 600m/s at a depth of 5 meters, based on geophysical

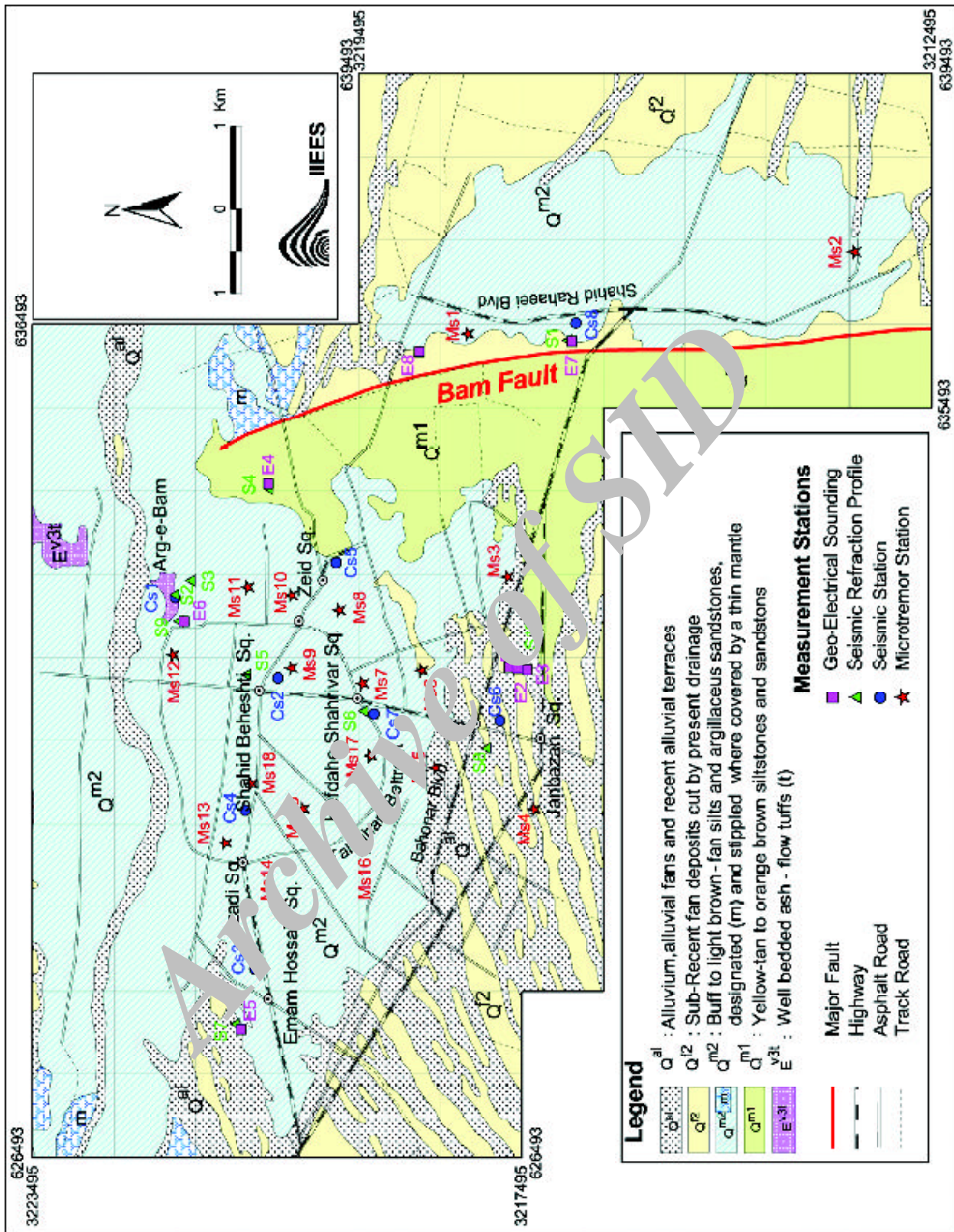


Figure 3. Geological map of Bam, stations of geophysical surveying, aftershock and microtremor measurements.

measurements. The alluvial fan (Q^2) is another quaternary deposits extended at the eastern part of Bam. It is formed by coarse grain sediments having thickness up to 100 meters. Finally, the youngest layers of alluvium at Bam area are alluvium fans and terraces (Q^1) extended along the seasonal river. These sediments are quite loose without cohesion and cementation.

Thickness of deposits increases from north to south generally; although some irregularities at bedrock may exist at southern part of Bam city which is due to volcanic rocks inherent nature and fault effects. The thickness of unconsolidated materials ranges from zero in north to 300 meters in south of Bam. Deep Geo-electrical surveying at the site show the similar subsurface condition at higher depths [7]. The maximum depth of quaternary alluvial in study area is evaluated to be about 300m based on geophysical studies.

3.2. Representative Geophysical Groups

Borcherdt [8] proposed a site classification scheme in which the ground conditions were classified into six distinct classes with acceleration dependent short-period and long-period amplification factors. The site classification scheme adopted by the 1994, 1997 and 2000 NEHRP provisions [9-11], the 1997 Uniform Building Code (UBC) [12] and the 2000 and 2003 International Building Codes (IBC) [13, 14] were primarily based on Borcherdt's scheme. Seed et al [15] proposed a somewhat more detailed site classification scheme that consists of eight main classes and several subclasses with acceleration dependent peak ground surface amplification relative to competent rock sites. All these amplification relationships were based on available empirical data from the 1985 Mexico, 1989 Loma Prieta and 1994 Northridge earthquakes and also on calculations using both equivalent linear and fully nonlinear site response methods.

Figure (4) presents the 10 seismic refraction profiles surveyed in the study area. As can be seen, the resulted shear wave velocity profiles can be categorized into the following four distinct geophysical groups: Group 1 which represents rock like sites with soil thicknesses of less than a few meters; Group 2 which represents stiff shallow sites with a soil thickness of 8 to 15 meters, high shear wave velocity gradients and considerable contrast ratios of 2 to 3 with respect to the seismic bedrock; Group 3 which represents stiff sites with a higher soil

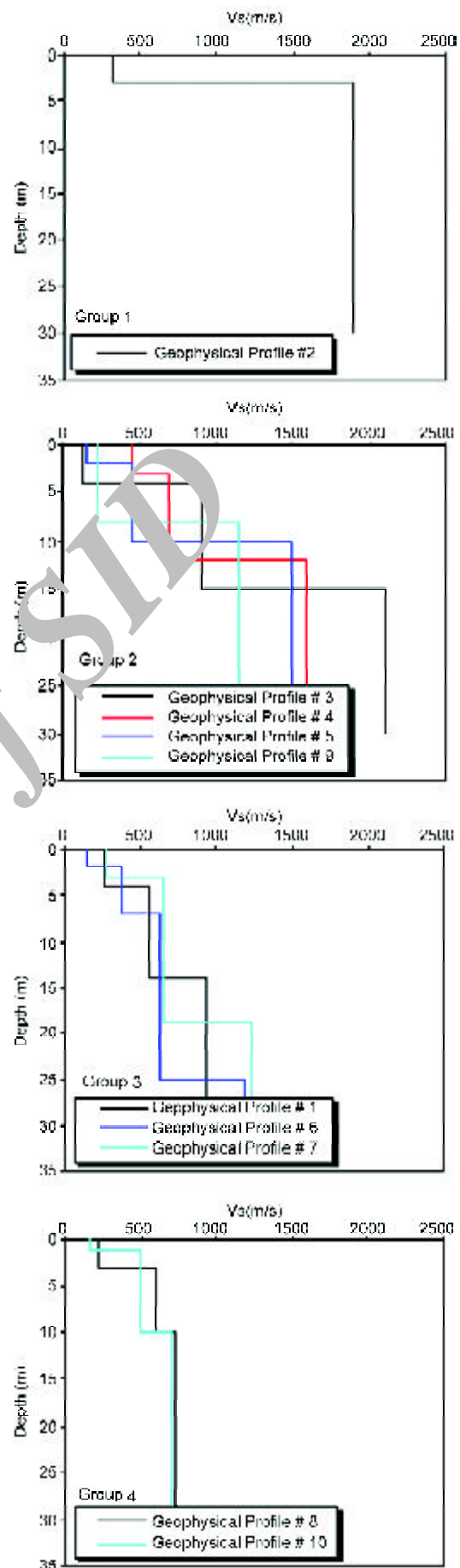


Figure 4. Seismic refraction profiles of Bam.

thickness of 14 to 25 meters, lower shear wave velocity gradients and lower contrast ratios with respect to the seismic bedrock, compared to the second group; Group 4 which represents medium to dense sites with a comparatively high thickness of more than 30 meters, low gradients of shear wave velocity and much lower contrasts with respect to the seismic bedrock. The seismic bedrock is the same as the geological bedrock in geophysical groups 1 and 2, whereas in geophysical groups 3 and 4, the geological bedrock is deeper than the seismic one.

Table (1) indicates that these four geophysical groups can also be categorized according to the above mentioned site classification systems. Figure (5) shows the proposed amplification factors for the geophysical groups 1-4 as functions of peak rock acceleration. Figure (5a) indicates that geophysical group 1, which is the well known competent seismic bedrock introduced by almost all building codes, has an amplification factor of 1.0, irrespective of the *PRA*. Figures (5b) and (5c) indicate that although the amplification factors proposed for geophysical groups 2-4 show some difference with the site classification schemes, but as expected, the amplification factor decreases as the *PRA* increases. Proper curves were fitted to the maximum values of the proposed amplification factors for each of the geophysical groups 2-4. These conservative acceleration dependent correlations provided the required basis for preparing the *PGA* distribution maps of the study area.

Table 1. Representative geophysical group of the study area.

Geophysical Groups	Geophysical Profiles	Site Classification Schemes		
		Borcherdt [8]	NEHRP [9-11], UBC [12] and IBC [13, 14]	Seed et al [15]
1	2	Ib	S _b	A
2	3,4,5,9	II	S _c	A
3	1,6,7	II	S _c	AB2
4	8,10	II	S _c	AB2

3.3. Site Natural Frequencies In Bam

3.3.1. Aftershock and Microtremor Measurements

The portable 3-component Guralp (*CMG-6TD*) seismometers are used in aftershock and microtremor measurements. The frequency operating range of these Mid-band seismometers is approximately 0.1 to 50Hz.

The seismic network including eight 3-components Guralp (*CMG-6TD*) seismometers were installed

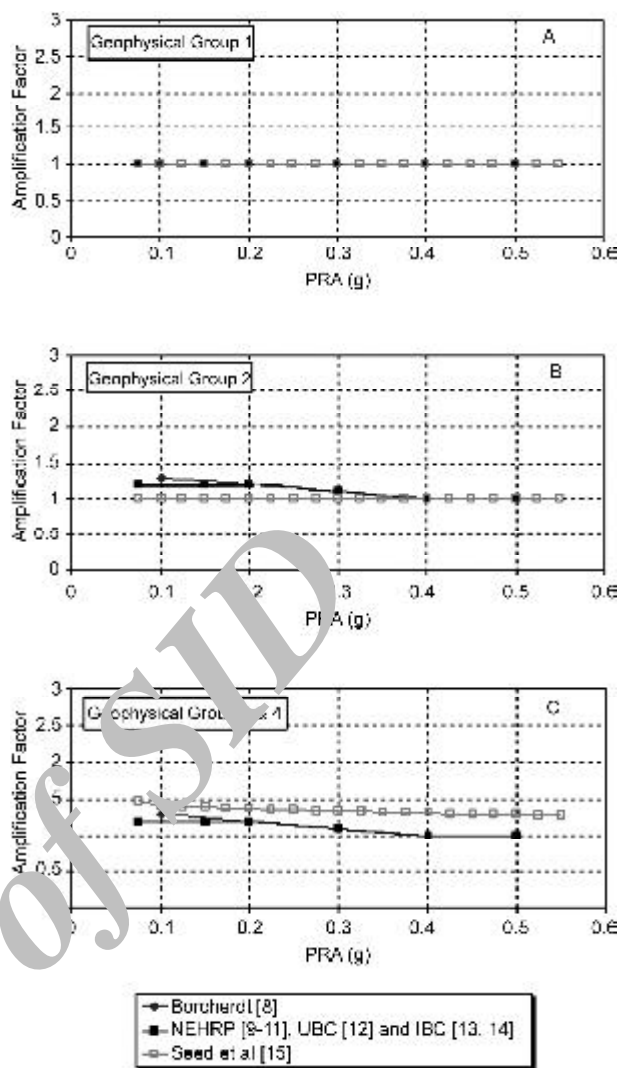


Figure 5. Empirical amplification factors of the representative geophysical groups.

along the main streets in *N-S* and *E-W* directions at Bam City (“Cs” named stations in Figure (3)). One station is also installed at Baravat City, located in southeastern of Bam City. Each seismometer was adjusted to record two horizontal components in *NS* and *EW* directions and one in vertical direction. The instruments were delivered with *GPS* units for synchronization. The network was operating for near two months in the period of 12 January to 30 February, 2004. Due to the high capacity of the flash memory of the seismometers, vibrations including aftershocks and microtremors were recorded continuously with a sampling rate of 100 samples per second. The network recorded more than 2000 aftershocks as well as continues recording of microtremors during day and night. The 30 minutes microtremor vibrations measured at the additional 18 stations (“Ms” named stations in Figure (3)) were recorded by the same above mentioned seismometers.

3.3.2. Data Analysis Procedures

The aftershock data of Bam earthquake were used to analyze site amplification characteristics using spectral ratio analysis. In this analysis, the Fourier spectrum was calculated for 10s time window of seismograms for the whole length of the record started from the beginning of P-wave arrival. The spectra were smoothed using a rectangular moving average window having a bandwidth of 0.4Hz. Then, the ratio of two smoothed spectra was calculated. Two times in succession smoothing were applied to the raw spectra. This number was chosen empirically considering its visual effect on the spectral shape. This procedure was repeated for the spectral ratio of both components (N/V and E/V) and, then the vector average of two ratios was calculated.

The microtremors were also used to identify the site amplification characteristics at the site. In spectral analysis of microtremors, the following steps were processed:

1. Preprocessing: filtering the signal in 0.2-20Hz frequency range.
2. Parameters selection: to maximize the accuracy of computed fundamental frequency, selected parameters for the frequency analysis were required to be optimized. The number of spectral averages (n_d) and the spectral resolution (B_e) are important parameters and, for a finite data record, they are directly related to each other. However, they have a conflicting influence on the error in the spectral estimates [16]. These calculations revealed that a 0.048Hz frequency resolution and a 2048 block length yield the optimum spectrum.
3. The selected time windows were Fourier transformed using cosine tapering before transformation. The spectra were then smoothed with a triangular moving Hanning window (1 time with 15 points).
4. In order to obtain spectral ratios, the spectra of an EW and NS channel at a site were divided by the spectra of the vertical channel and the average of each individual ratio was computed.

3.3.3. Data Analysis Results

Based on the amplification functions obtained by spectral analysis (the spectral peak and corresponding amplification factor), the 26 measurement stations can be classified into the following four distinct categories: Category one, which includes station $Cs1$

(Arg-e-Bam), lies on a rock outcrop and has a fundamental frequency in the range of 0.8-1.2Hz with an amplification factor of greater than 5; Category two, which includes stations $Cs2$, $Cs6$, $Ms2$, $Ms3$, $Ms4$ and $Ms12$ and shows a clear dominant frequency in the low frequency range (less than 3Hz); Category three which includes stations $Cs3$, $Cs4$, $Cs5$, $Ms1$, $Ms5$, $Ms6$, $Ms16$ and $Ms17$ and shows two distinct peaks, one in less than 3Hz and the other in more than 5Hz; Category four, which includes stations $Cs7$, $Cs8$, $Ms7$, $Ms8$, $Ms9$, $Ms10$, $Ms11$, $Ms13$, $Ms14$, $Ms15$, $Ms18$ and demonstrates a single peak in the high frequency range (more than 5Hz). Figure (6) shows the typical amplification functions of the aftershocks and microtremors for the above mentioned 4 categories.

3.4. Site Classification Map

Although the number of seismic refraction profiles were not sufficient to prepare the site classification map, but combining them with the results of the microtremor and aftershock measurements enabled this task. Figure (7) shows the distribution of the representative geophysical groups throughout the study area. It seems that moving from north to south of the study area, although the site thickness increases, but both of the shear wave velocity gradient and the contrast with respect to the bedrock decrease. Moving from west to east of the study area, it does not seem that considerable variations exist. Figure (7) also shows the distribution of the measured natural frequencies throughout the study area. As can be seen, most stations in the city indicate a high amplification potential in the high frequency range. Northern and southern parts of the city indicate the existence of high amplification potentials in the low frequency range as well. Based upon these findings, the ground conditions of the Bam city could be classified primarily into the following five distinct sites:

1. Rock like sites in which the soil thickness is less than a few meters.
2. Stiff shallow sites in which only the low frequency range indicates a considerable amplification potential.
3. Stiff shallow sites in which only the high frequency range indicates a considerable amplification potential.
4. Stiff medium depth sites in which both of the high and low frequency ranges indicate considerable amplification potentials.
5. Stiff to medium stiff deep sites in which only the

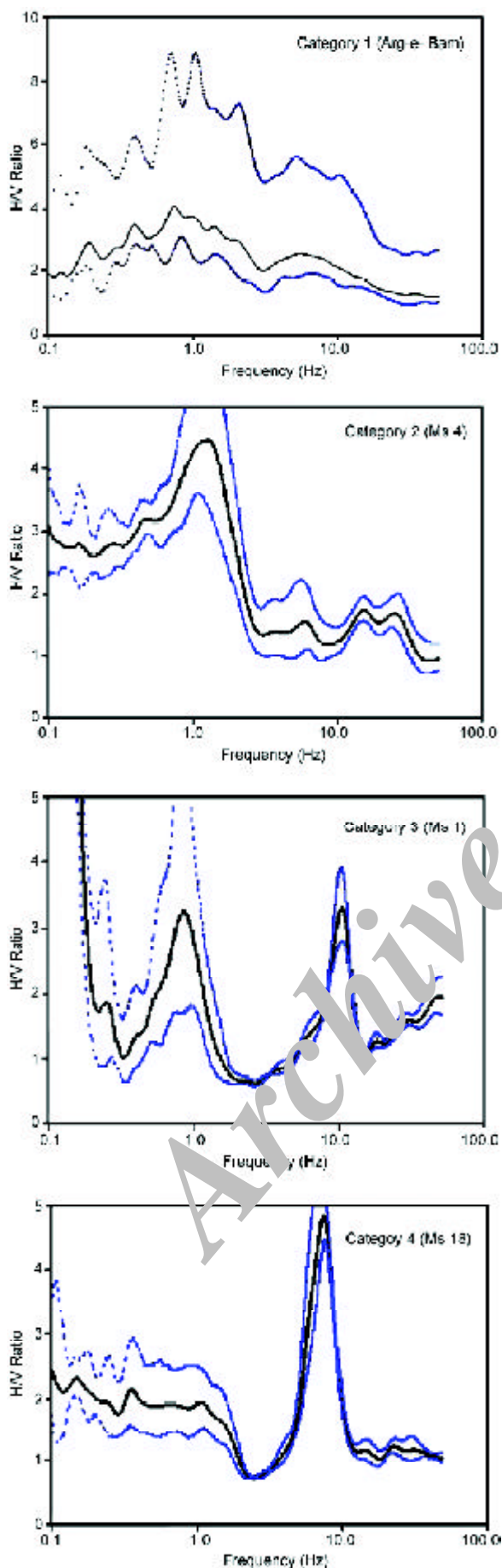


Figure 6. Typical amplification functions of the spectral analysis categories.

low frequency range shows a considerable amplification potential.

Figure (7) shows the preliminary site classification map of the Bam city. As could be seen, the north part of the city is covered with the site classes 1 and 2, the central part is covered with the site classes 3 and 4 and the south part is covered with the site class 5.

4. PGA Distribution Maps

The site-corrected *PGA* distribution maps were constructed as composites of the corresponding *PRA* distribution maps and the site classification map. Figures (8) and (9) present the horizontal *PGA* distribution maps of the study area for return periods of 2475 and 475 years, respectively.

The only accelerometer in the city, located at the governor's building at Hofdahe Shahrivar Square (29.09N, 58.3°E), recorded during the 2003 Bam earthquake (corrected) peak values of 0.79g (799cm/s²) and 1.01g (992cm/s²) for horizontal and vertical components, respectively [17]. According to Figure (8), the estimated *PGA* value for the same location lies also in the range of 0.7g to 0.8g justifying the 2475 years return period selection for comparison with the damage distribution in the affected area.

Figure (8) indicates that in a return period of 2475 years, peak ground accelerations vary from a value of less than 0.7g to a value of 0.9g to 1.0g throughout the study area, depending on distance from the causative faults and type of the underlying geologic deposit. Figure (8) presents also the damage distribution of the 2003 Bam earthquake throughout the study area [2]. As it can be seen, the highest value of the peak ground acceleration occurs in the south-east part of the city, where the highest value of damage percent (80-100) was experienced. The least value of the peak ground acceleration occurs in the north-west part of the city, where the least value of damage percent (20-50) was experienced. Although the north-east part of the city indicates a moderate value of peak ground acceleration, but since the adobe buildings were concentrated in this part of the city, the highest value of damage percent was experienced. Indeed much less shaking intensities would be sufficient to totally destroy these adobe buildings. Of course probable near source effects may be another possible factor explaining the damage concentration in this part of the city, which should be studied in detail later. Although the central part of the city indicates a moderate value of peak ground acceleration too, but since most buildings were

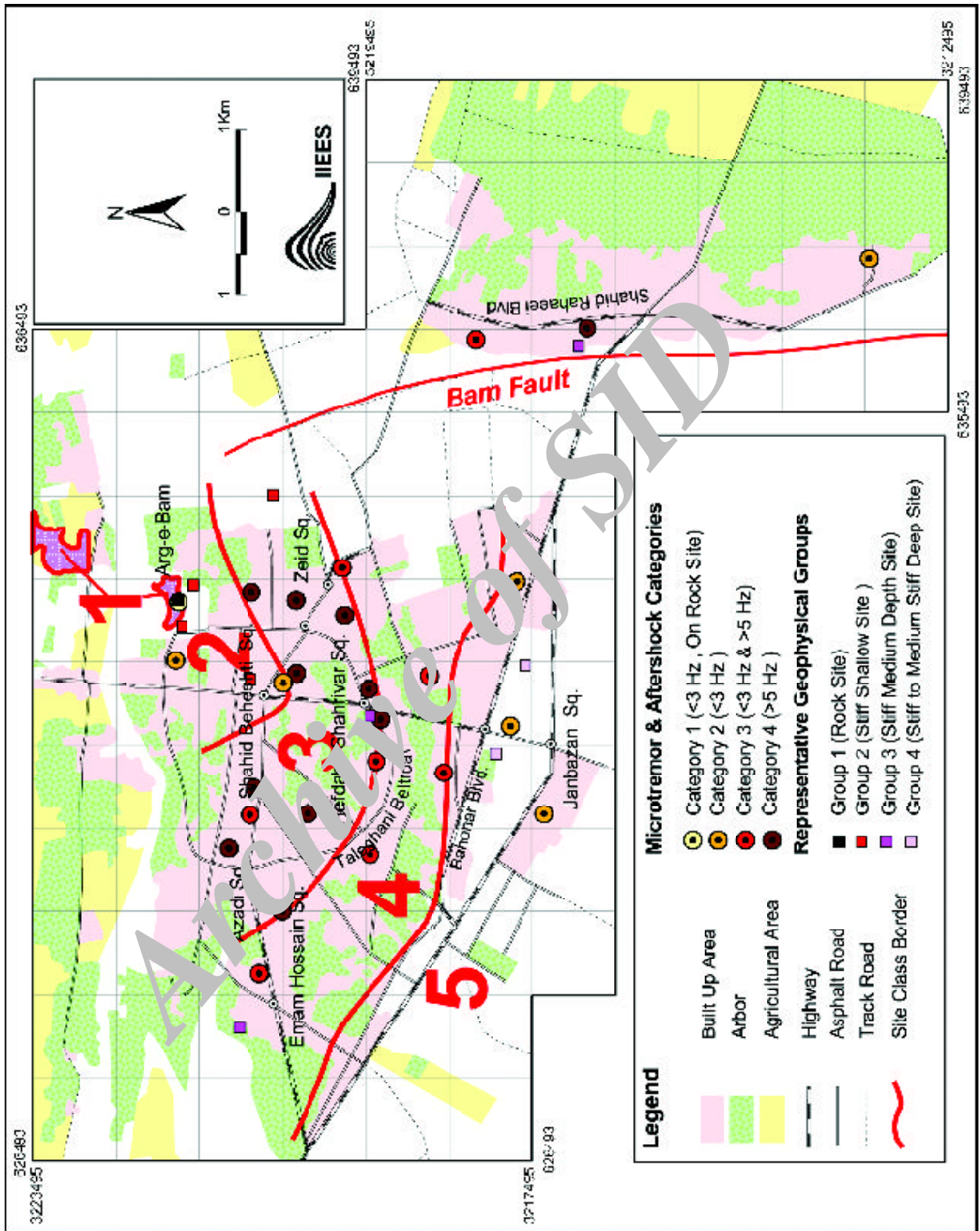


Figure 7. Site classification map of Bam.

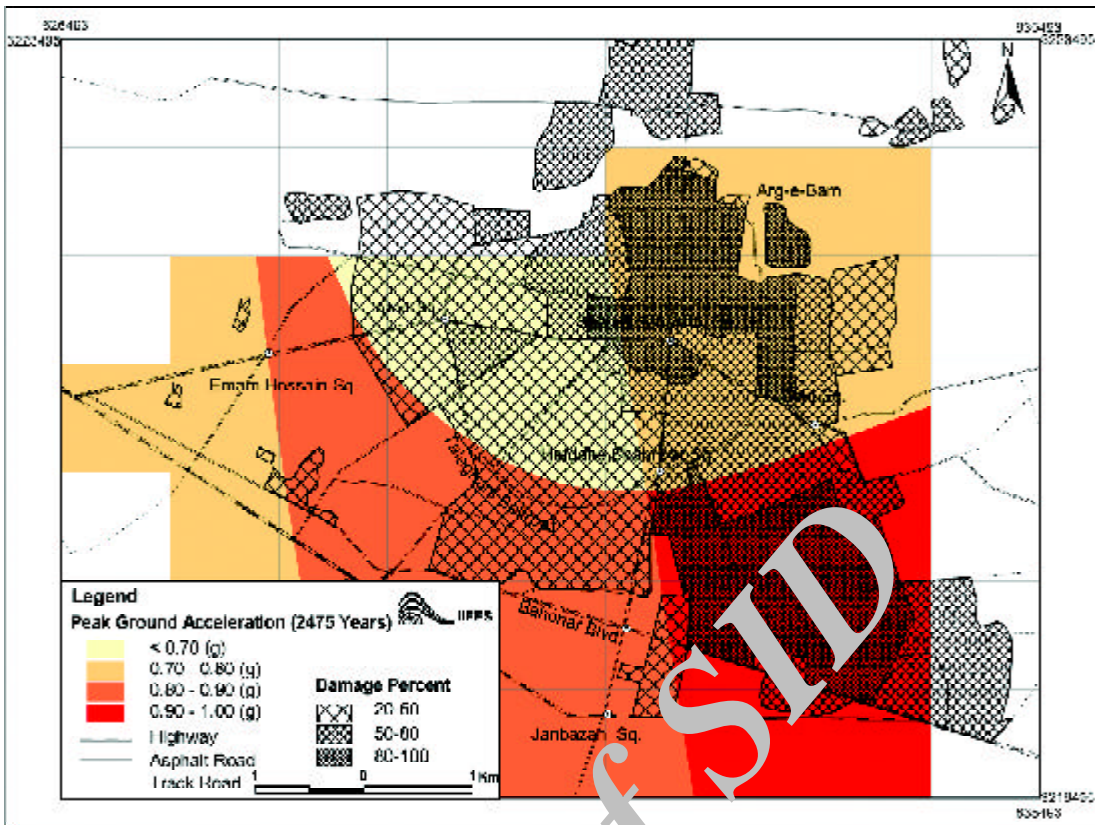


Figure 8. Peak ground acceleration map of Bam (2475 years).

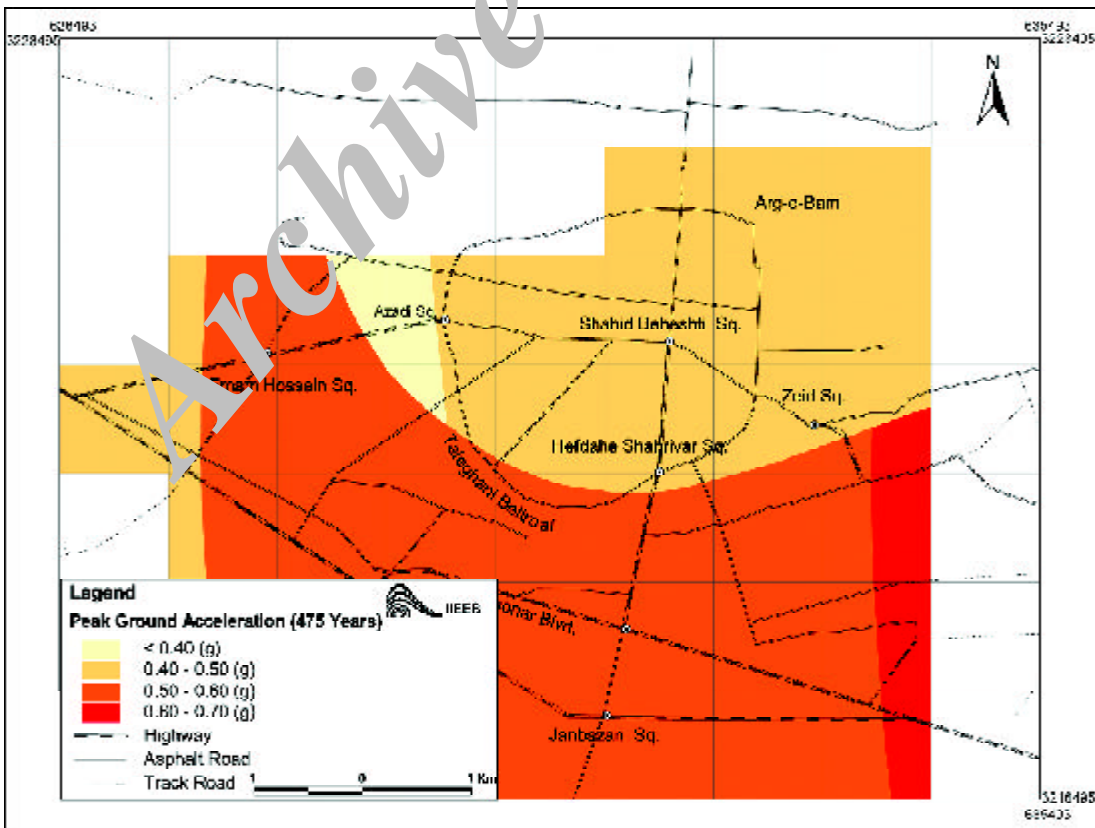


Figure 9. Peak ground acceleration map of Bam (475 years).

designed and constructed on engineering basis, the experienced value of damage percent was the least. The damage distribution of Figure (8) could also be compared with the site classification map of Figure (7). As can be seen, almost all damages of low rise buildings occurred in site classes, which possess a considerable amplification potential in the high frequency range.

Figure (9) indicates that in a return period of 475 years, peak ground accelerations vary from a value of less than 0.4g to a value of 0.6g to 0.7g throughout the study area. Comparison of Figures (8) and (9) shows that irrespective of the return period, the peak ground acceleration increases by moving from north to south and from west to east of the city.

5. Conclusions

After the devastating earthquake disaster in the Bam city of Iran, a discipline was followed to prepare preliminary seismic microzonation maps for this city. This paper presented the preliminary results of seismic microzonation studies of the Bam city. The site effect evaluations were based on geophysical, microtremor and aftershock measurements conducted by *IIEES* in the study area. Good agreements existed between the 2475 years *PGA* distribution map and the damage distribution map of the recent earthquake. Highest values of damage percents concentrated in sites with stiff shallow and medium depth soils, which possessed considerable amplification potentials in high frequency ranges. The obtained microzonation maps could be used as a preliminary useful hint in reconstruction and urban planning of the totally destroyed city. It is obvious that more accurate evaluations of ground motion characteristics require more geotechnical and geophysical data, consideration of multi-dimensional sub-surface topographic effects as well as all possible near source effects.

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