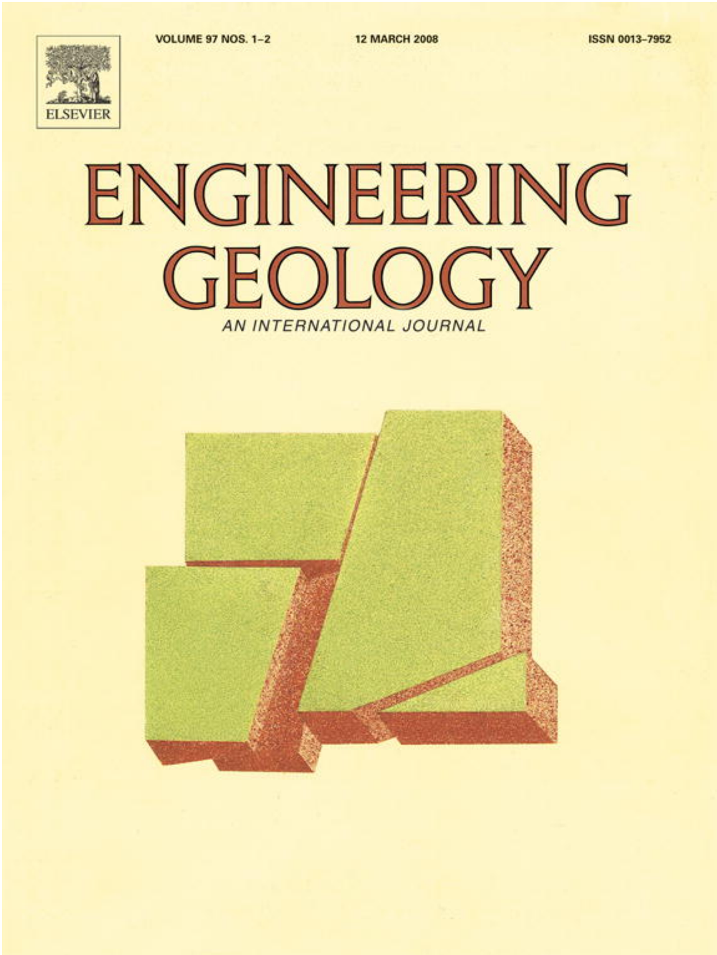
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# Site effect microzonation of Qom, Iran

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**Abstract**

As an important step in effectively reducing seismic risk and the vulnerability of the city of Qom to earthquakes, a site effect microzonation study was conducted. Seismic hazard analysis for a return period of 475 years was carried out. Data from 160 borings was collected and analyzed, geophysical surveys were conducted and microtremor measurements taken in more than 60 stations throughout the city. The study area was divided into a grid of 1 × 1 km$^2$ elements and the sub-surface ground conditions were classified into 59 representative geotechnical profiles. Site response analyses were carried out on each representative profile using 30 different base rock input motions. Distribution maps of site periods and peak ground acceleration throughout the city were developed, providing a useful basis for land-use planning in the city.


*Keywords:* Qom; Microzonation; Site effect; Microtremor; Natural period; Dynamic period; Peak ground acceleration; Land-use planning; Seismic risk

## 1. Introduction

Ground shaking and its associated damage to engineered structures can be strongly influenced, not only by source and path effects, but also by surface and sub-surface geological and topographical conditions in the vicinity, known as "local site effects". Evidence of this can be found in the 1990 Manjil–Rudbar and the 2003 Bam earthquakes, two major seismic events in Iran in the past two decades that resulted in a large number of casualties. Although these cities had comparatively low populations, the lack of suitable development and earthquake risk management led to high human and physical costs. These tragedies prompted the government to implement earthquake risk mitigation measures, including seismic hazard zonation and microzonation of vulnerable cities, to facilitate urban planning.

The historic city of Qom, which archaeologists estimate has been inhabited since the 5th millennium BC, enjoys special status in Iran because it is the site of the shrine of Hazrat-e Masumeh, an important spiritual centre. It is home to a number of advanced theological schools and an array of rich Islamic architecture. The city is situated 120 km south of Tehran (Fig. 1) and covers an area of approximately 180 km$^2$. In the past two decades, it has experienced a sizeable increase in population.

In 2002, Ramazi (2002) carried out a seismic hazard zonation study of Qom Province. He estimated the horizontal peak acceleration for basement rock without considering soil types, based on the tectonics and seismicity of the Qom province using the Cornell approach. He showed that the seismicity of Qom is not only affected by well-known major faults lying between the cities of Tehran and Kashan, but also by some minor but active–or potentially active–faults under the city itself. These results prompted the local Qom government to implement immediate measures to prevent the kind of destruction seen in previous earthquakes.

As part of the program, the International Institute of Earthquake Engineering and Seismology (IIEES) carried out a seismic microzonation study of Qom in 2005. The goals of this investigation were to prepare guidelines for further land-use planning and to provide data for future studies of existing urban systems and seismic rehabilitation processes. The geotechnical

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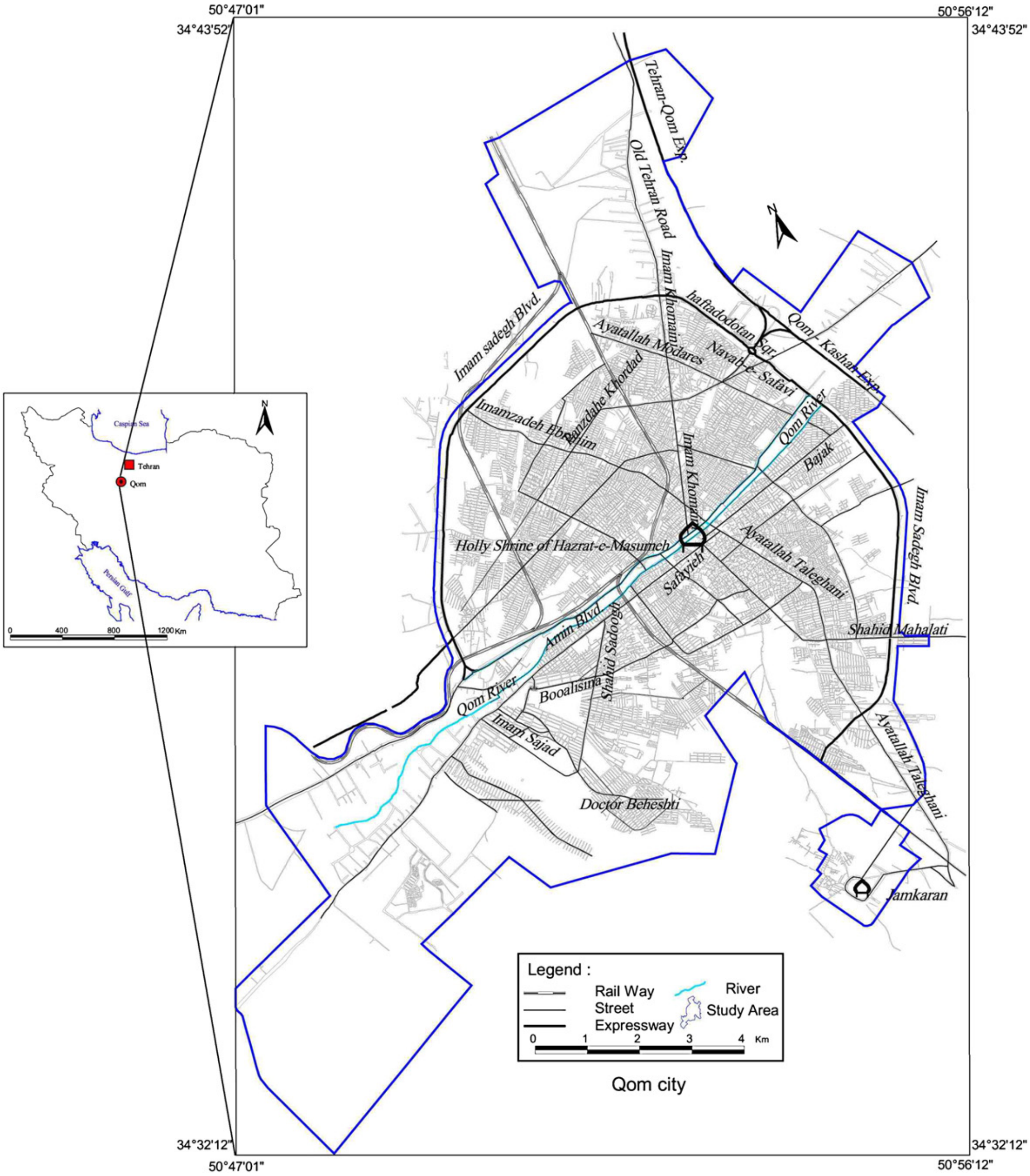


Fig. 1. Location of Qom and study area limits.

aspects of the program were divided into two parts: site effects estimation and geotechnical hazards evaluation. This paper presents the major results obtained during the site effect microzonation study.

## 2. Methodology

The methodology of site effect microzonation adopted in this study falls into the category of Grade-3 zoning methods of the Japanese TC4 Zoning Manual (1999). After dividing the city into a grid of $1 \times 1$ km$^2$, the following steps were taken:

- Preparation of a seismic hazard map of the study area for a return period of 475 years;
- Gathering and investigation of the existent geological, geotechnical and geophysical data of the study area, including field observations and aerial photo studies;
- Conducting complementary geophysical investigation, as well as microtremor measurements, throughout the study area;
- Preparation of representative geotechnical profiles of the city based on the geological, geotechnical, geophysical and microtremor data;
- Estimation of strong ground motion characteristics using one-dimensional site response analysis of the representative geotechnical profiles;
- Preparation of the final site periods and peak ground acceleration (PGA) maps of the study area in the Geography Information System (GIS) media.

## 3. General geology

From a geomorphologic point of view, the city of Qom is situated on a flat area of Quaternary deposits connected to the prominent salt lake to the east and to the southeast. The southern part of the city is constructed at the piedmont of a chain of low latitude mountains with a series of parallel anticlines and synclines. To the north and west, the city is surrounded by very low and sparse hills.

The predominant rock formations are the Qom and Upper Red Beds, consisting mainly of marl, conglomerate, limestone and some andesitic lava flows (Fig. 2). Based on previous geo-

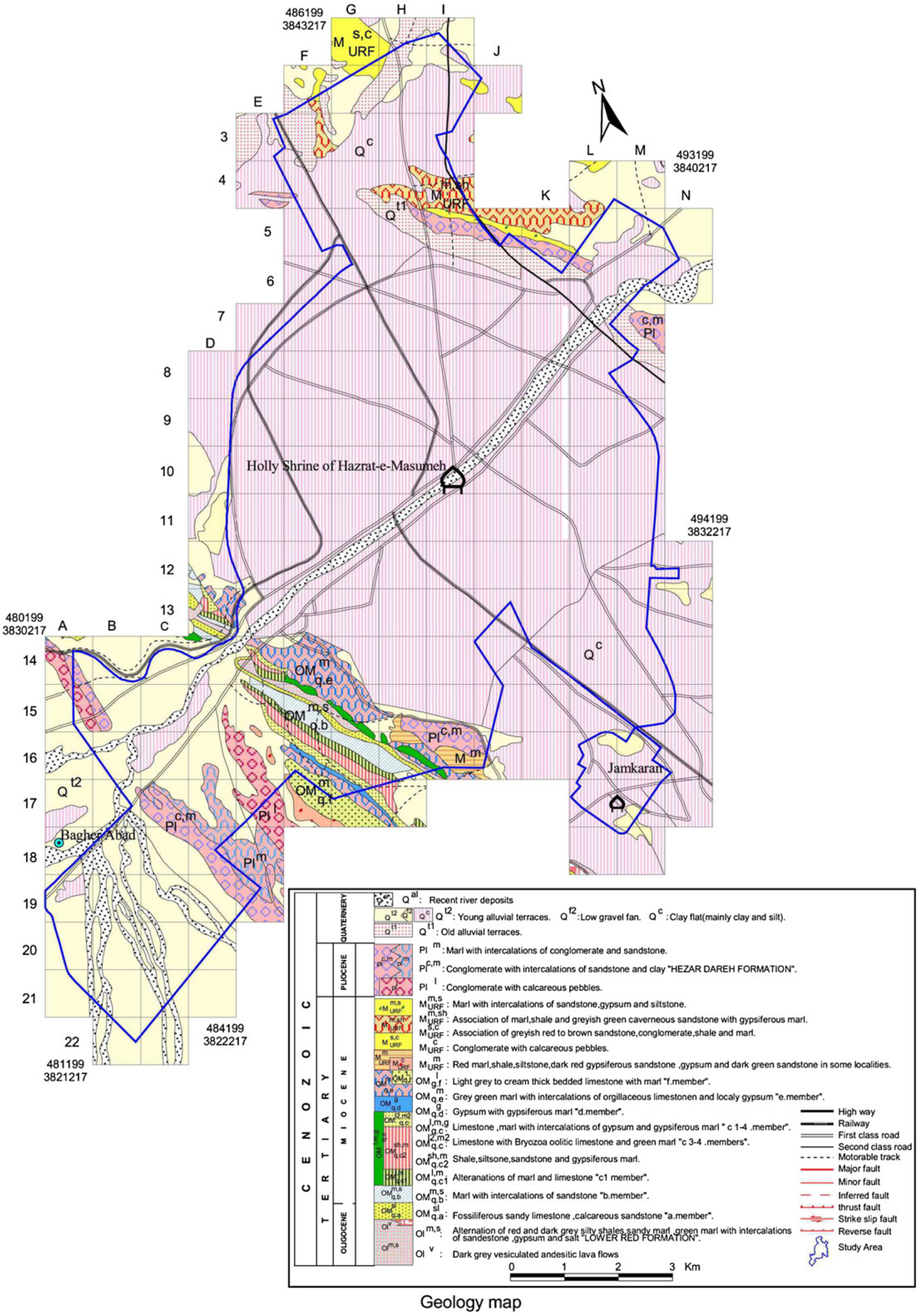


Fig. 2. Geologic map of study area (GSI, 1993).

electrical profiling (WRAO-PM, 1981), these rock units are largely covered with deep (more than 200 m) Quaternary deposits at the city site. The Quaternary deposits are both ancient (Q1) and recent (Q2) alluvial terraces, as shown in Fig. 2, with outcroppings on the north and south edges of Qom and are mainly gravelly and sandy layers with interlayers of fine grained deposits. The terraces in the middle of the studied area are covered by relatively shallow soft silty clay (ML-CL) and lean clay (CL), presented as Qc, which were mostly deposited by floods during the Holocene period. The thickness of alluvial deposits increases from northwest to southeast of the city and the soil grains become finer.

The ground water level has a depth of less than 10 m in north and northeast of the city, deepens toward the south and finally reaches a depth of about 40 m, which constitutes a free aquifer in the Quaternary deposits of the Qom alluvial. The construction of the Panzdah–Khordad dam and the augmentation of water pumping have affected the ground water level in the recent years, deepening it from levels measured 40 years ago (WAO-QP, 2004).

## 4. Seismicity and seismic hazard

Qom is situated in the central Iranian seismotectonic unit. Central Iran is not a linear seismic zone. It is characterized by scattered seismic activity with large magnitude earthquakes, long recurrence periods and seismic gaps along several Quaternary faults. Fig. 3 shows the major active faults around Qom. Hessami et al. (2003) published the characteristics map of active faults around Qom. The most important faults outside the city are the Indis, North Tehran, North Ray, South Ray, Garmsar, Pishva, Robatkarim, Ivanaki, North Eshtehard, South Eshtehard and Siahkoh faults having reverse mechanisms, and the Koshk-e-Nosrat and Kahrizak faults having strike slip mechanisms and reverse components (Hessami et al., 2003).

The Shadgoli, Koeh Khezr and North Qom faults are the most important active Quaternary faults within the city, having caused surface displacements in the Holocene or Pleistocene period. The lengths of these three Quaternary faults are 18, 22 and 40 km and their maximum estimated moment magnitudes are 6.5, 6.7 and 6.9, respectively. The focal mechanisms of earthquakes are mostly reverse with left lateral strike slip components.

The shocks in central Iran are generally shallow and are usually associated with surface faulting. The only historical earthquake close to Qom was the 1495 earthquake with a magnitude of 5.9 (Fig. 3). A few instrumentally located events of small magnitude have been observed around Qom. The instrumental seismicity shows that at least 14 earthquakes have occurred within a 100 km radius of Qom with magnitudes of less than 6.0.

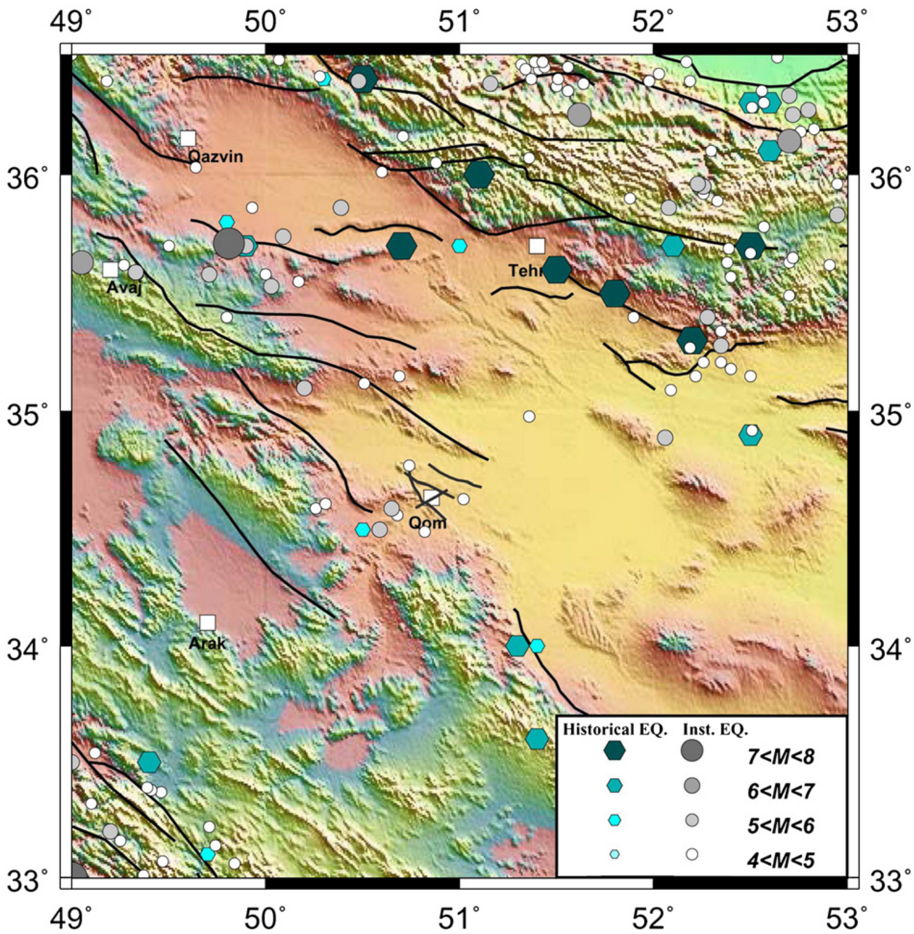


Fig. 3. Major active faults and seismicity.

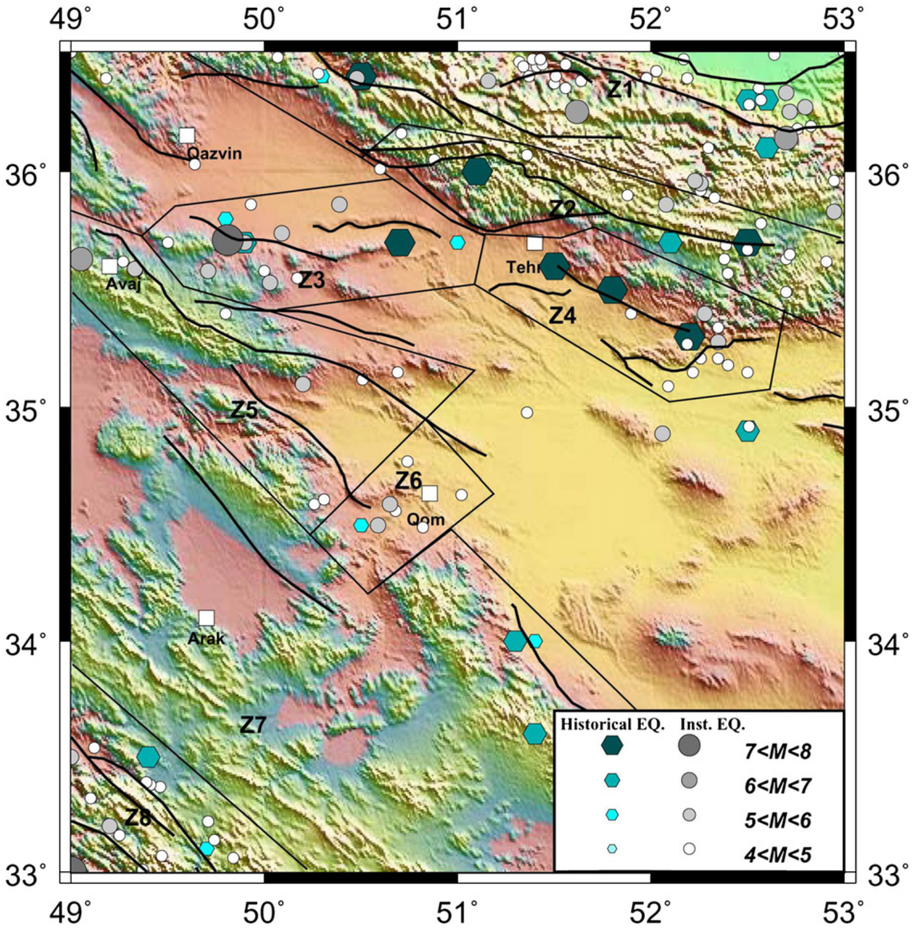


Fig. 4. Seismic sources in Qom region.

This study presents a probabilistic seismic hazard analysis (PSHA) based on the tectonic position and seismicity of the Qom region. The PSHA is based on the Cornell approach. Area sources were identified on the basis of geological and seismological studies (Fig. 4). For each source zone, seismicity parameters have been estimated after omitting foreshocks and aftershocks from the catalogue. Each source zone is characterized by an earthquake probability distribution. A maximum or upper bound earthquake was chosen for each source zone representing the maximum event to be considered. The seismicity parameters, including the Gutenberg–Richter parameter ($\beta$), maximum possible earthquake ($M_{max}$) and mean activity rate ($\lambda$) for each seismic zone used for the PSHA are given in Table (1). The depth of the earthquakes was considered as 10 km based on the depth of strong-to-large earthquakes in Iran.

A reliable assessment of seismic hazard in a region requires knowledge and understanding of both the seismicity and the attenuation of strong ground motion. Some of the larger uncertainties in earthquake hazard analysis are caused by uncertainties in seismic wave attenuation. Several studies have been carried out to obtain attenuation relationships of peak ground accelerations for different regions of the world. The use of different data bases and published empirical attenuation relations for peak ground acceleration brings about widely varying results. Thus, it becomes difficult to select a relationship that can be considered appropriate for a specific application. Furthermore, the use of a particular relationship for an area with different geological and tectonic features may lead to results that differ significantly from the actual values. Therefore, three proper attenuation relationships proposed by Boore et al. (1997), Zare (1999), and Campbell and Bozorgnia (2003) have been considered. The attenuation relation given by Zare (1999) is based on the Iranian strong ground motion data. Those introduced by Campbell and Bozorgnia (2003) and Boore et al. (1997) are observed to be more similar to measured peak ground acceleration in Iran. All three attenuation relationships were used and a logic tree scheme with equal weight was applied.

Table 1
Parameters of seismic zones used for the PSHA

| Zone | $\beta$ | $M_{max}$ | $\lambda(4.5)$ |
|---|---|---|---|
| Z1 | 1.64 | 7.9 | 0.54 |
| Z2 | 1.60 | 7.8 | 0.52 |
| Z3 | 1.40 | 7.7 | 0.058 |
| Z4 | 1.22 | 7.4 | 0.059 |
| Z5 | 1.58 | 6.8 | 0.07 |
| Z6 | 1.68 | 6.5 | 0.06 |
| Z7 | 1.48 | 7.1 | 0.12 |
| Z8 | 2.23 | 7.6 | 0.59 |

The effects of earthquakes of different sizes, occurring at different locations in different earthquake sources for different probabilities of occurrence were integrated into one curve that shows the probability of exceeding different levels of ground motion at the site during a specified period of time. Fig. 5 shows the distribution map of peak rock acceleration (PRA) in Qom for a return period of 475 years. As can be seen, the PRA value varies from 0.31 g to 0.39 g, mostly due to data from the Koeh Khezr, North Qom and Shadgoli faults.

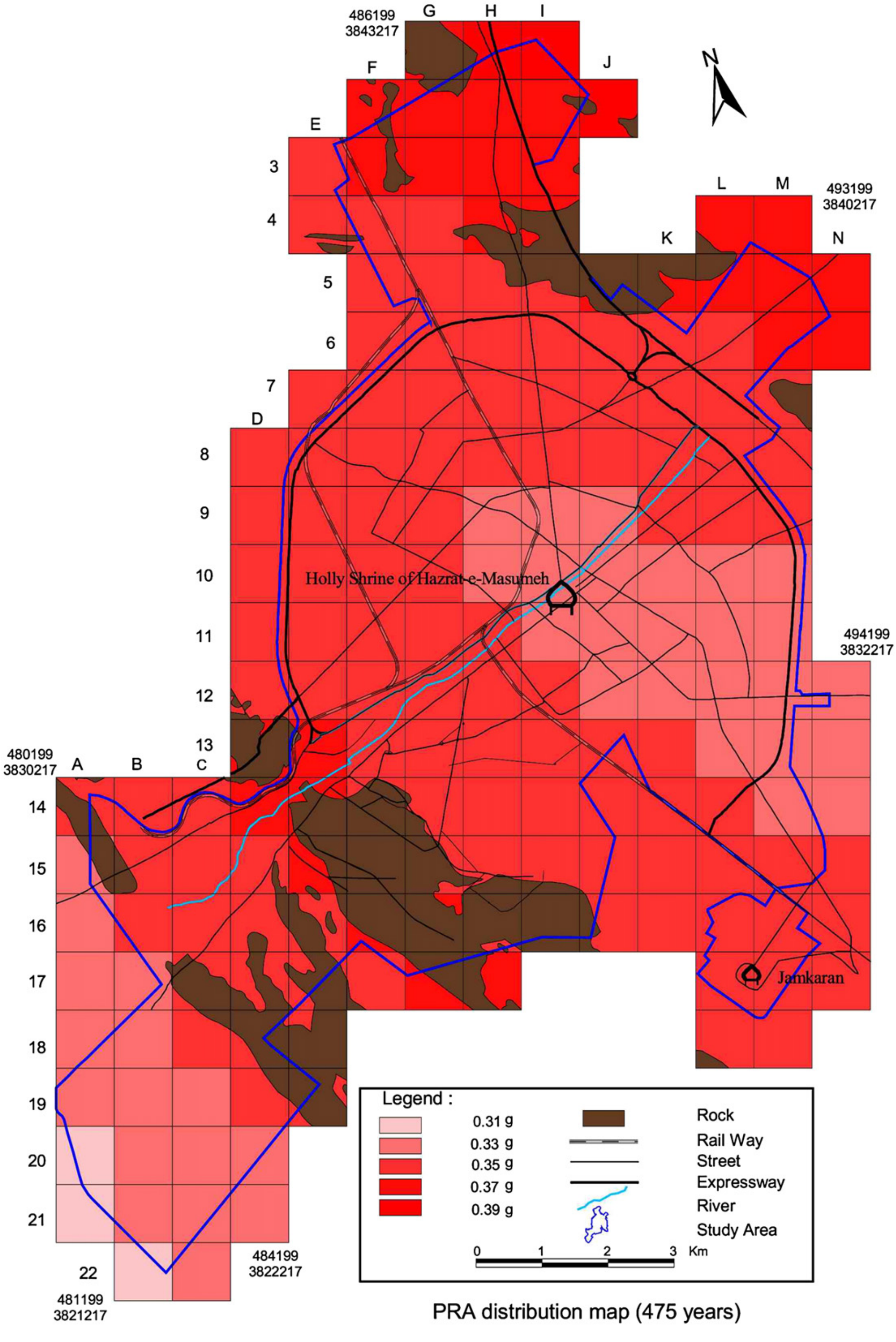


Fig. 5. Distribution map of PRA for a return period of 475 years.

## 5. Geotechnical aspects of Qom

Most available reports on geotechnical site investigations conducted by national and local governments and public corporations were collected. These comprised approximately 160 boreholes from 45 stations having limited depth (usually less than 30 m) and being unequally distributed in the investigated area. To overcome the problem of insufficiency

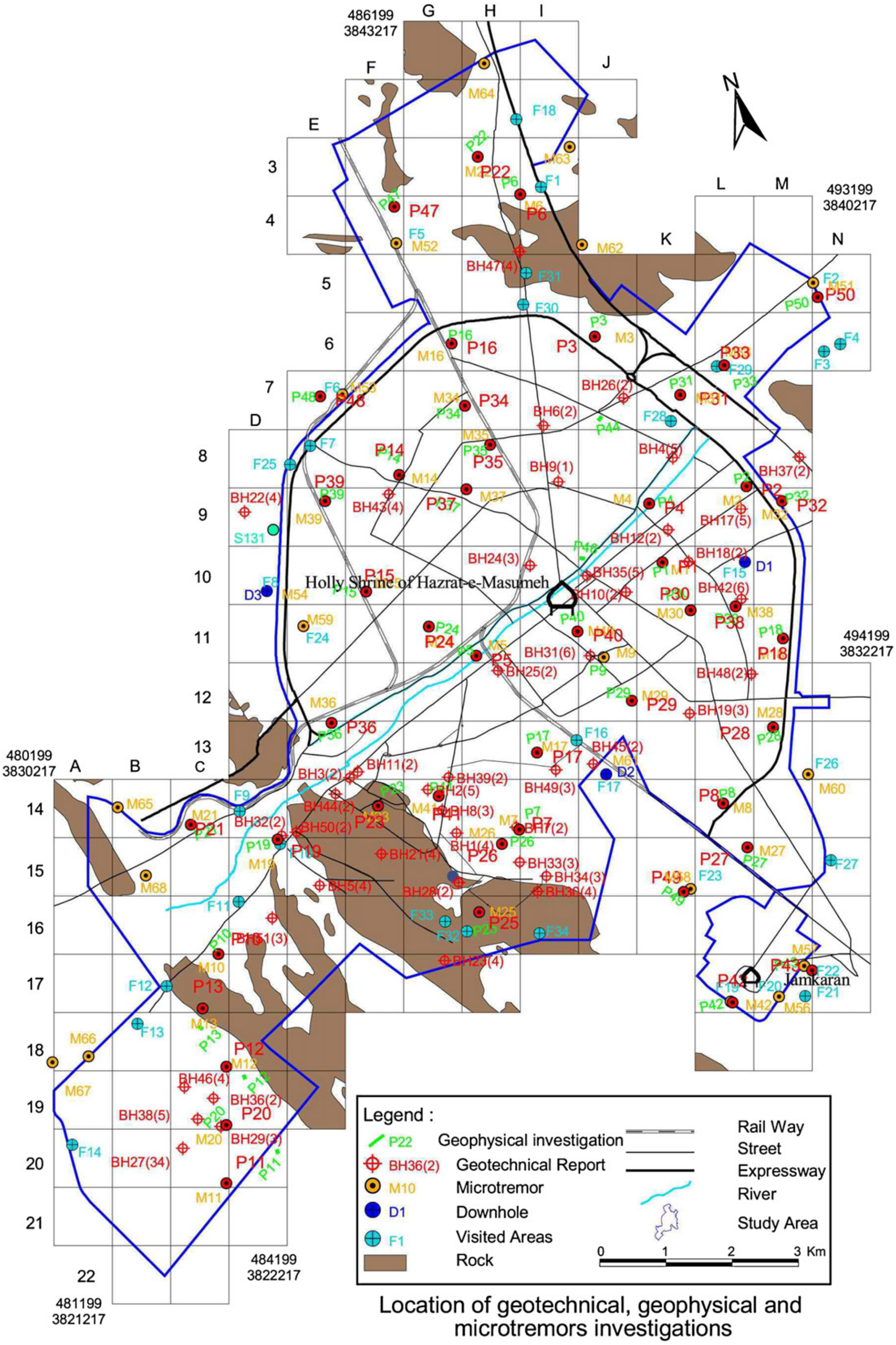


Fig. 6. Geotechnical and complementary geophysical and microtremor stations.

of data, complementary field investigations were designed and conducted. Numerous locations in the study area were selected as being topologically and geologically representative sites for conducting the complementary field investigations. These included seismic refraction surveys at 44 stations, geo-electrical profiling at 49 stations, deep seismic down-hole surveys at three

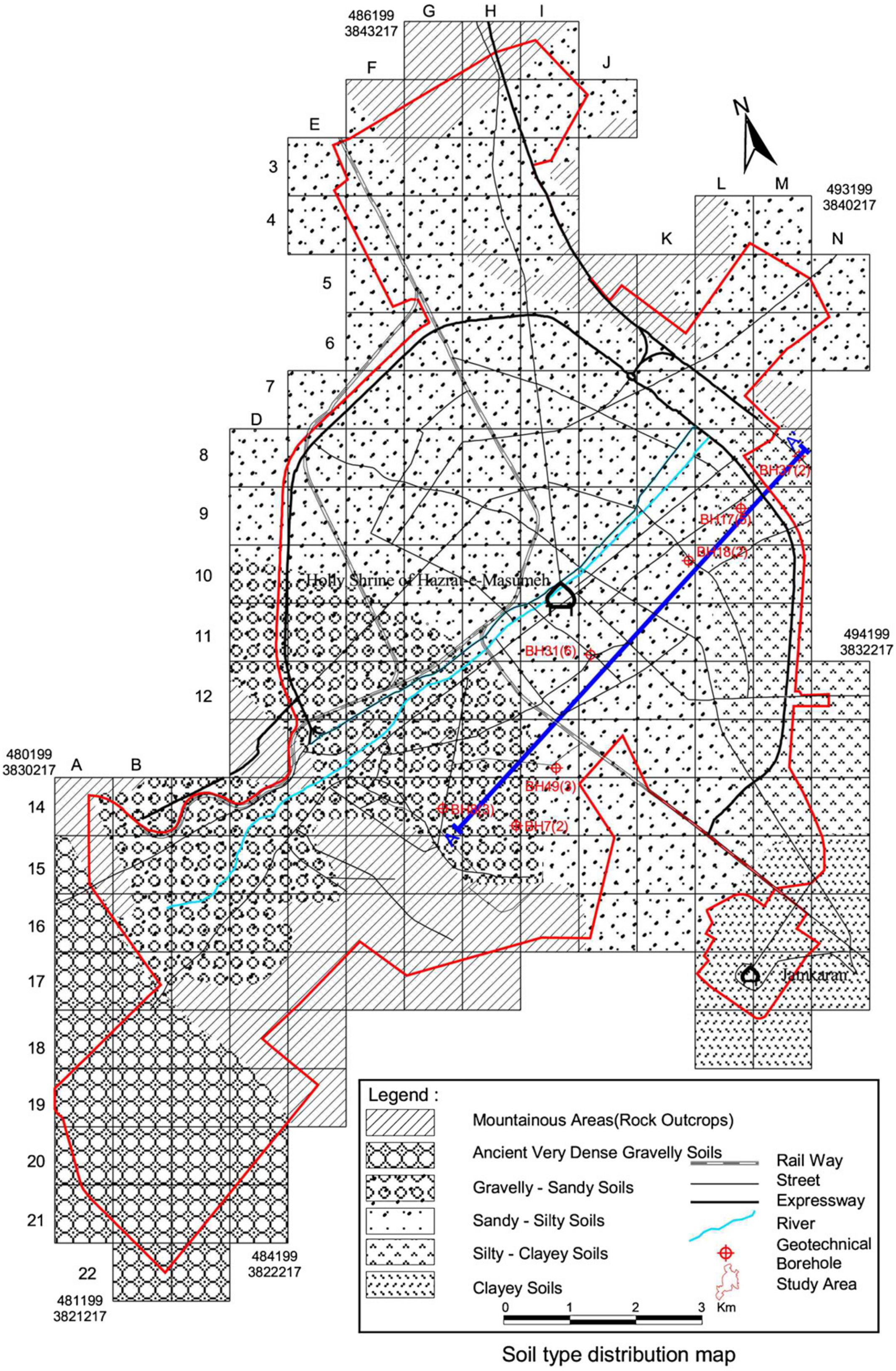


Fig. 7. Distribution map of sub-surface soils.

stations and microtremor measurements at 70 stations. Fig. 6 presents the locations of the existing geotechnical data as well as those of the complementary geophysical and microtremor investigations.

For the purpose of the study, seismic bedrock has been defined as rock-like media with shear wave velocities of over 700–800 m/s (Ishihara and Ansal, 1982; ICBO, 1997, 2003; BSSC, 2003; BHRC, 2005), which is suitable for ordinary low

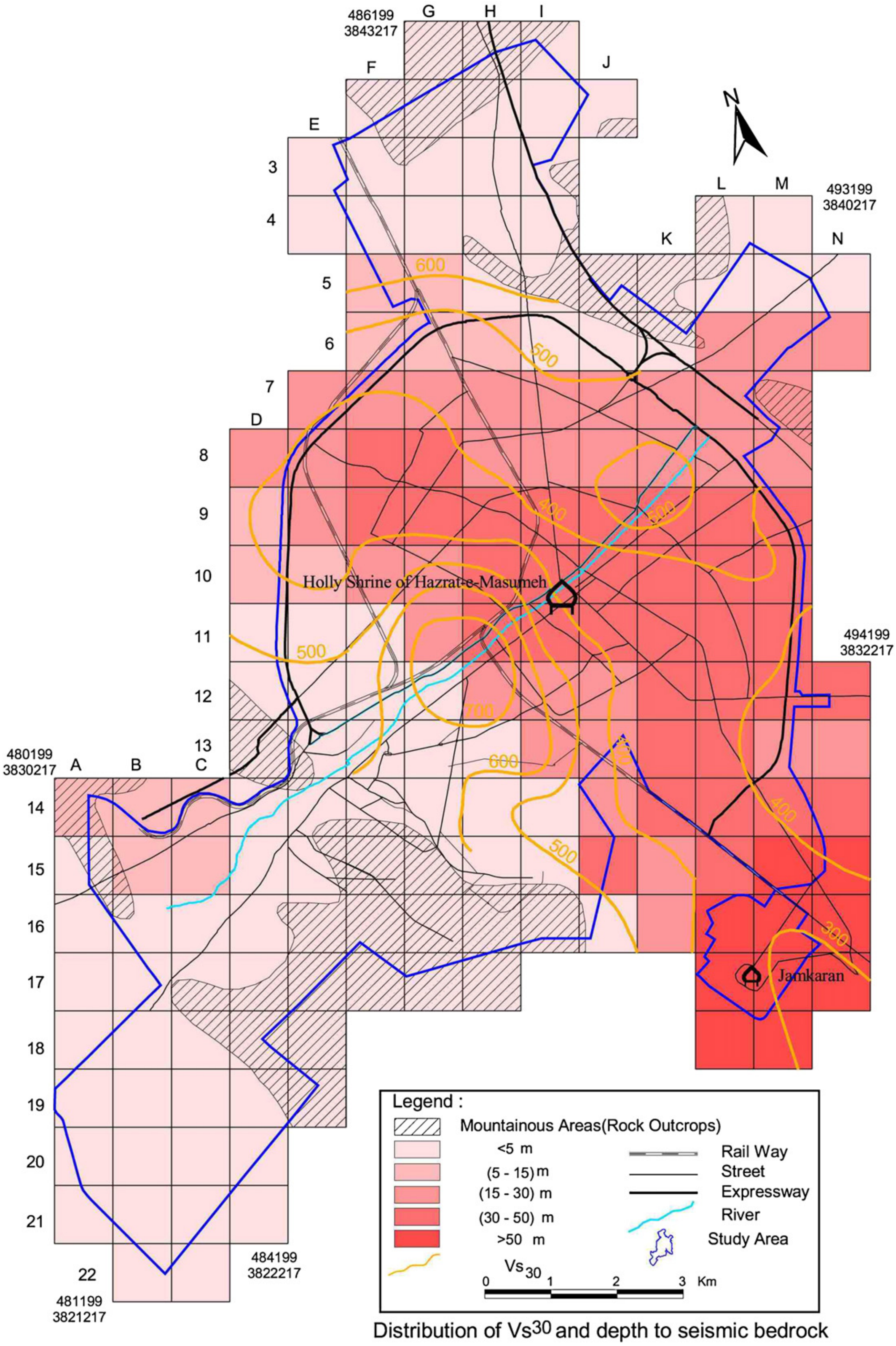


Fig. 8. Distribution map of $V_{s(30)}$ and depth of seismic bedrock.

to medium-rise buildings (TC4, 1999). Distribution maps of sub-surface soils (Fig. 7), average shear wave velocity of the top 30 m ($V_{s(30)}$), depth of the seismic bedrock (Fig. 8), as well as some geotechnical sections (Fig. 9) were compiled using the accumulated data. The maps give clear perspectives on the variability of soil conditions throughout the study area. The ground conditions of the study were thus categorized according to soil type, layer thickness, shear wave velocity and depth of seismic bedrock into five distinct zones (Fig. 10):

- Zone 1: rock outcrops covering the south, west and north mountainous regions. In this zone, low to medium dense sublayers do not exist, the depth to seismic bedrock equals zero and the average shear wave velocity is over 700–800 m/s.
- Zone 2: granular coarse-grained alluviums (GP, GW) covering only the uppermost southwest part of the plain. In this zone, low to medium dense sublayers have negligible thicknesses, the depth to seismic bedrock is near zero (less than 5 m) and the average shear wave velocity is still over 700–800 m/s.
- Zone 3: granular finer grained alluviums (SM, SW, SP) which cover most parts of the central plain. In this zone, low to medium dense sublayers have considerable thicknesses, the depth of seismic bedrock varies from 20 to 50 m and the average shear wave velocity varies from 350 to 500 m/s. Moving from west to east and from south to north on the plain, the alluvium grain sizes decrease and fine grained soil layers (SM, ML, SC) become dominant (Figs. 7, 9). Although some parts of the plain are covered by 2–10 m of alternating surface clayey and non-clayey sublayers, most parts of the plain consist solely of non-clayey sandy and silty sublayers (SM, ML) that change to gravely/sandy sublayers (GP, GW, SP, SW) at the uppermost south region. To the east and southeast of the plain, the thicknesses of low to medium dense sublayers and the depth of seismic bedrock increase and the average shear wave velocity decreases.
- Zone 4: the Jamkaran district southeast of Qom that is significantly different, with dominant clayey layers (CL) to a considerable depth. In this zone, the average shear wave velocity is less than 300 m/s and the depth of seismic bedrock exceeds 90 m.
- Zone 5: south, west and north boundaries of the plain which form a transition zone between Zone 3 and adjacent Zones 1 and 2.

The soil conditions of the zones were classified into 59 representative geotechnical profiles by considering their combinations of soil type, layer thickness, shear wave velocity and depth of seismic bedrock (Fig. 10). Fig. 11 shows typical samples of these representative geotechnical profiles.

Microtremor measurements were also carried out in 70 sites using a Guralp CMG-6TD velocimeter. The horizontal to vertical spectral ratio (H/V) of microtremors was calculated as an average of N/V and E/V spectral ratios. In nearly 90% of the sites, the horizontal to vertical spectral ratios of microtremors indicate a clear peak in the frequency interval of 0.6 to 1.2 Hz, which is equivalent to a period interval of 0.8–2.0 s. (Fig. 12). The origin of this peak is not clear. Considering information currently available on the underlying structure of Qom, one possible explanation is the existence of a deeper impedance contrast caused by the Quaternary sediments underlying the surface soil layers and resting at a depth of 250–350 m from the ground surface on hard geological bedrock from the Qom and Upper Red formations having marked differences in elastic properties. The results of deep down-hole and geo-electrical profiles support this. Another possible explanation is the effect of interaction of the surrounding mountain regions with the 3D basin structure.

## 6. Site response analysis

Non-linear site response analysis was carried out to evaluate the site response of each of the representative geotechnical

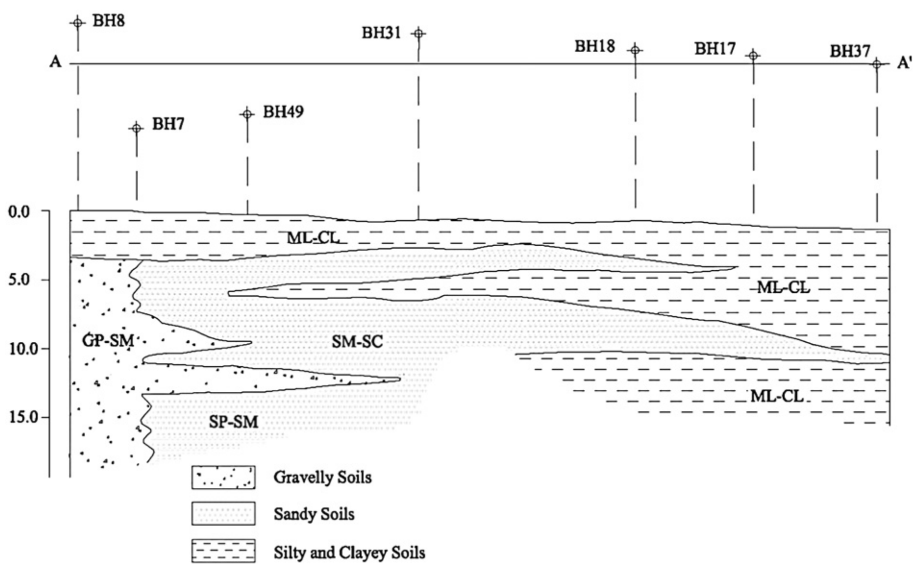


Fig. 9. Geotechnical section A–A' (direction shown in Fig. 7).

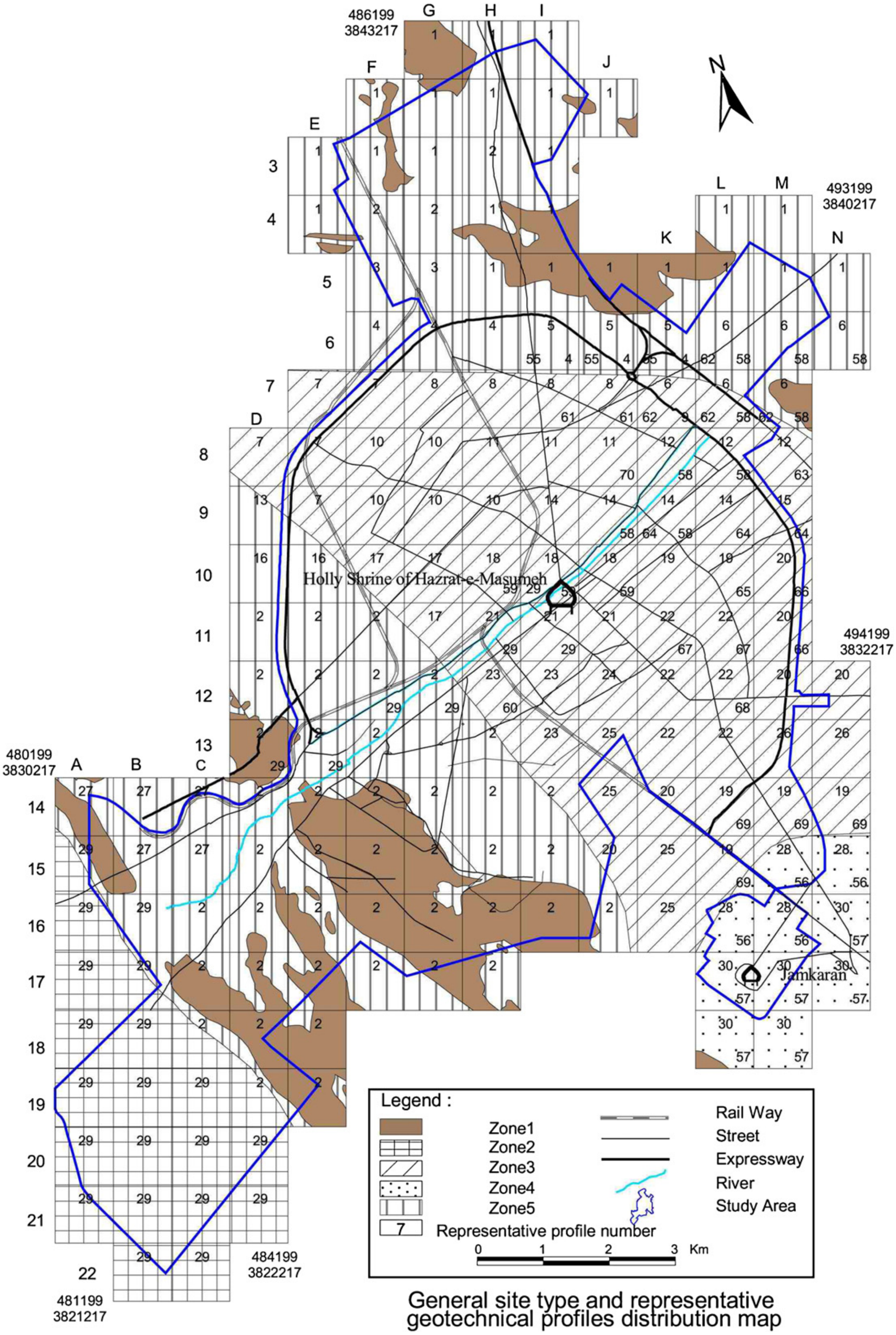


Fig. 10. Distribution map of site types and representative geotechnical profiles.

profiles to the 475 year seismic induced bedrock input motion. The SHAKE program (Schnabel et al., 1972) was used to model the site as a one-dimensional system of horizontal, homogeneous and isotropic soil layers consistent with actual ground conditions in most of the city where the ground surface and surface soil layers are either virtually horizontal or slope gently. The well-known shear modulus-strain and damping ratio-strain relations proposed by Seed and Idriss (1970) for sand and clays were used in the analysis. Since there are no recorded bedrock strong motion time histories for Qom city, thirty proper

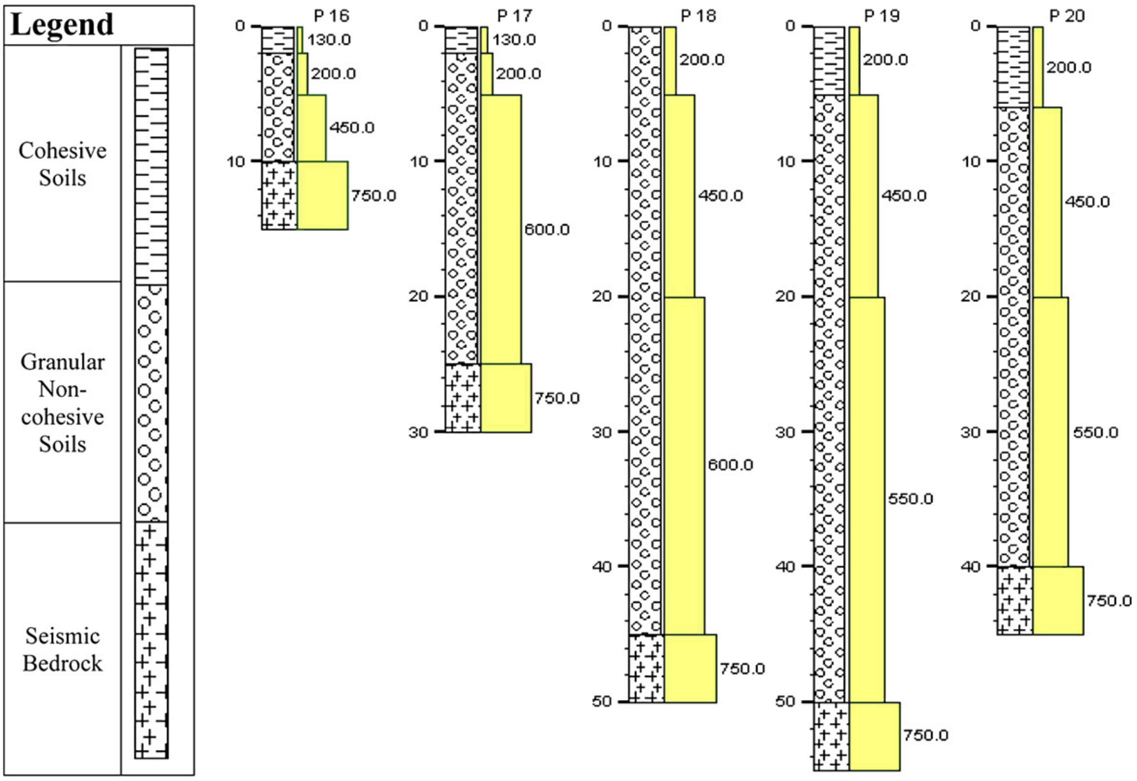


Fig. 11. Samples of representative geotechnical profiles.

earthquake time histories were selected from available national and international databases (Table 2). The selected ground motion records were recorded during earthquakes with approximately the same magnitudes (6.0 to 7.5) and distances (7.0 to 60.0 km), as estimated by deterministic approaches for controlling for earthquakes of well-defined seismic sources affecting the study area. Other factors such as the site condition (rocky sites) and style-of-faulting (reverse or strike slip) were also considered. All selected acceleration time histories were normalized to the 475 year PRA estimated by PSHA. For each grid element, strong ground motion characteristics including natural site period, dynamic site period, and PGA, were computed by subjecting their representative geotechnical profiles to the normalized 475 year bedrock input motions. Once the average results were obtained for each grid element, microzonation maps of the city were created showing the distribution of site amplification characteristics and PGA values throughout the study area.

Fig. 13 illustrates the distribution of the natural site period ($T_N$) throughout the city. As expected, most parts of the city have low natural site periods of less than 0.4 s. Only the southeastern part, Jamkaran district, covered by alluviums with low stiffness and considerable thickness, has medium natural site periods in the range of 0.4 to 0.8 s.

Fig. 14 presents the distribution of the dynamic (non-linear) site periods ($T_D$) throughout the city. A comparison of Figs. 13 and 14 demonstrates that, as expected, the dynamic site periods are higher than the natural site periods because of the shear modulus reduction caused by the soil's non-linear behavior during 475 year strong earthquakes. Most parts of Qom have low dynamic site periods of less than 0.4 s, except for some parts in the center and east of the city, where the thickness of medium dense subsoils and the depth of seismic bedrock increase, which have medium dynamic site periods of 0.4 to 0.8 s. Jamkaran district is the only area that has high dynamic site periods of more than 0.8 s.

Fig. 15 shows the distribution of the 475 year return period PGA throughout the city. The PGA values vary from 0.3 g to more than 0.6 g. Almost 45% of the grid elements exhibit PGA values of 0.45 g to 0.5 g. Only 2% of them experience PGA values of about 0.3 g and approximately 5% exhibit PGA values of more than 0.6 g. The dense granular alluviums in southwest Qom and the mountainous rocky sites in the north of the city experience the lowest PGA values because either their amplification potential is negligible or their PRA values are the lowest. In addition, the Jamkaran district experiences low PGA values since the incident seismic waves are highly damped by its thick alluviums. The alluviums covering the center part of the city and the north and northwest borders of the plain, in particular, experience higher PGA values because of their considerable amplification potential caused by low to medium dense soil layers.

## 7. Conclusions

This paper presents the most important features of site effect microzonation studies of Qom. Evaluations of the ground motion characteristic are based on seismic risk assessment of

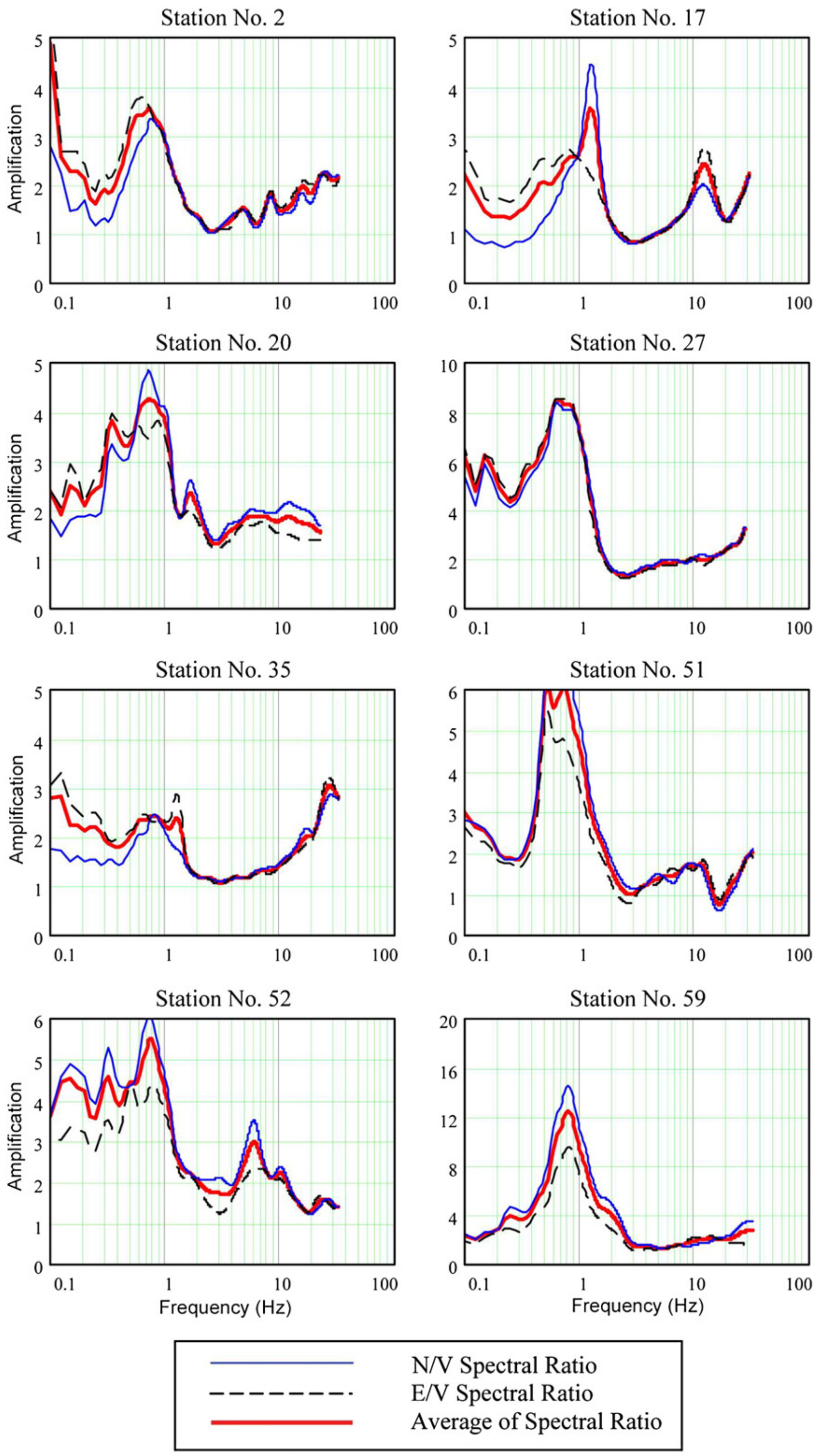


Fig. 12. H/V spectral ratio samples showing long period amplification potential.

the region for a return period of 475 years, and on geophysical and microtremor measurements and one-dimensional non-linear site response analyses of the geotechnical profiles representing the geotechnical model of the city.

It was found that three active or potentially active Quaternary faults with distinct evidence of surface displacements within Holocene or Pleistocene times lay within the city. This implies the necessity of considering surface fault-rupture hazard as well as other near field effects in planning future construction in these neighbourhoods.

The presence of a significant amplification peak in the frequency interval of 0.6 to 1.2 Hz (period interval of 0.8 to 2.0 s) throughout the city is observed by the microtremor H/V display ratios which implies that prospective high-rise buildings (more than 14 stories) may be endangered. The origin of the peak is not clear and cannot be explained by the 1D amplification potential

Table 2
Specification of selected accelerograms for site response analysis

| No. | Earthquake | Mechanism [a] | Magnitude | Distance | PGA (g) |
|---|---|---|---|---|---|
| 1 | San Fernando 1971/02/09 14:00 | R | 6.6 | 23.5 | 0.16 |
| 2 | San Fernando 1971/02/09 14:00 | R | 6.6 | 23.5 | 0.13 |
| 3 | Vendic, Iran 1976/11/07 | SS | 6.4 | 10 | 0.17 |
| 4 | Vendic, Iran 1976/11/07 | SS | 6.4 | 10 | 0.18 |
| 5 | Naghan, Iran 1977/04/06 | R | 6.1 | 7 | 0.87 |
| 6 | Naghan, Iran 1977/04/06 | R | 6.1 | 7 | 0.57 |
| 7 | Tabas, Iran 1978/09/16 | R | 7.4 | 45 | 0.11 |
| 8 | Tabas, Iran 1978/09/16 | R | 7.4 | 45 | 0.09 |
| 9 | N. Palm Springs 1986/07/08 09:20 | RO | 6.0 | 45.6 | 0.10 |
| 10 | N. Palm Springs 1986/07/08 09:20 | RO | 6.0 | 45.6 | 0.13 |
| 11 | N. Palm Springs 1986/07/08 09:20 | RO | 6.0 | 7.3 | 0.49 |
| 12 | N. Palm Springs 1986/07/08 09:20 | RO | 6.0 | 7.3 | 0.61 |
| 13 | Northridge 1994/01/17 12:31 | R | 6.7 | 26.8 | 0.17 |
| 14 | Northridge 1994/01/17 12:31 | R | 6.7 | 26.8 | 0.22 |
| 15 | Northridge 1994/01/17 12:31 | R | 6.7 | 36.1 | 0.23 |
| 16 | Northridge 1994/01/17 12:31 | R | 6.7 | 36.1 | 0.13 |
| 17 | Northridge 1994/01/17 12:31 | R | 6.7 | 8.2 | 0.30 |
| 18 | Northridge 1994/01/17 12:31 | R | 6.7 | 8.2 | 0.43 |
| 19 | Duzce, Turkey 1999/11/12 | SS | 7.1 | 8.2 | 0.51 |
| 20 | Duzce, Turkey 1999/11/12 | SS | 7.1 | 8.2 | 0.97 |
| 21 | Duzce, Turkey 1999/11/12 | SS | 7.1 | 8.5 | 0.13 |
| 22 | Duzce, Turkey 1999/11/12 | SS | 7.1 | 8.5 | 0.15 |
| 23 | Duzce, Turkey 1999/11/12 | SS | 7.1 | 27 | 0.05 |
| 24 | Duzce, Turkey 1999/11/12 | SS | 7.1 | 27 | 0.05 |
| 25 | Changureh, Iran 2002/02/26 | R | 6.0 | 28 | 0.43 |
| 26 | Changureh, Iran 2002/02/26 | R | 6.0 | 28 | 0.44 |
| 27 | Bam, Iran 2003/12/26 | SS | 6.5 | 56 | 0.16 |
| 28 | Bam, Iran 2003/12/26 | SS | 6.5 | 56 | 0.1 |
| 29 | Baladeh, Iran 2004/05/28 | R | 6.3 | 20 | 0.29 |
| 30 | Baladeh, Iran 2004/05/28 | R | 6.3 | 20 | 0.16 |

[a] R: reverse, RO: reverse oblique, SS: strike slip.

of the medium stiff surface layers. It may be attributed to the 3D basin effects or to the presence of thick Quaternary sediments (with shear wave velocity of more than 800 m/s) resting at a depth of 250–350 m from the ground surface on hard rock from the Qom and Upper Red formations.

In almost all parts of the city, estimated 475 year PGA values are higher than the maximum design base acceleration (DBA) of 0.35 g proposed by the Iranian code for regions with very high levels of seismicity. This emphasizes once again the important role that site effect microzonation can play in seismic risk mitigation of seismic-prone zones.

The microzonation maps of the natural site period, dynamic site period and PGA can be useful in land-use planning in consideration of population density, building height and building importance.

It is obvious that more accurate evaluations of ground motion characteristics in the future require more geotechnical and geophysical data as well as consideration of the 3D effects of the surrounding mountain regions and of the sub-surface topography. It should also be noted that the microzonation maps are not intended to replace site-specific investigations for structures such as hospitals and fire departments, which have critical roles in the aftermath of an earthquake.

## Acknowledgments

The preliminary work for this study was conducted for the municipality of Qom; however, these contents do not necessarily reflect municipal policy.

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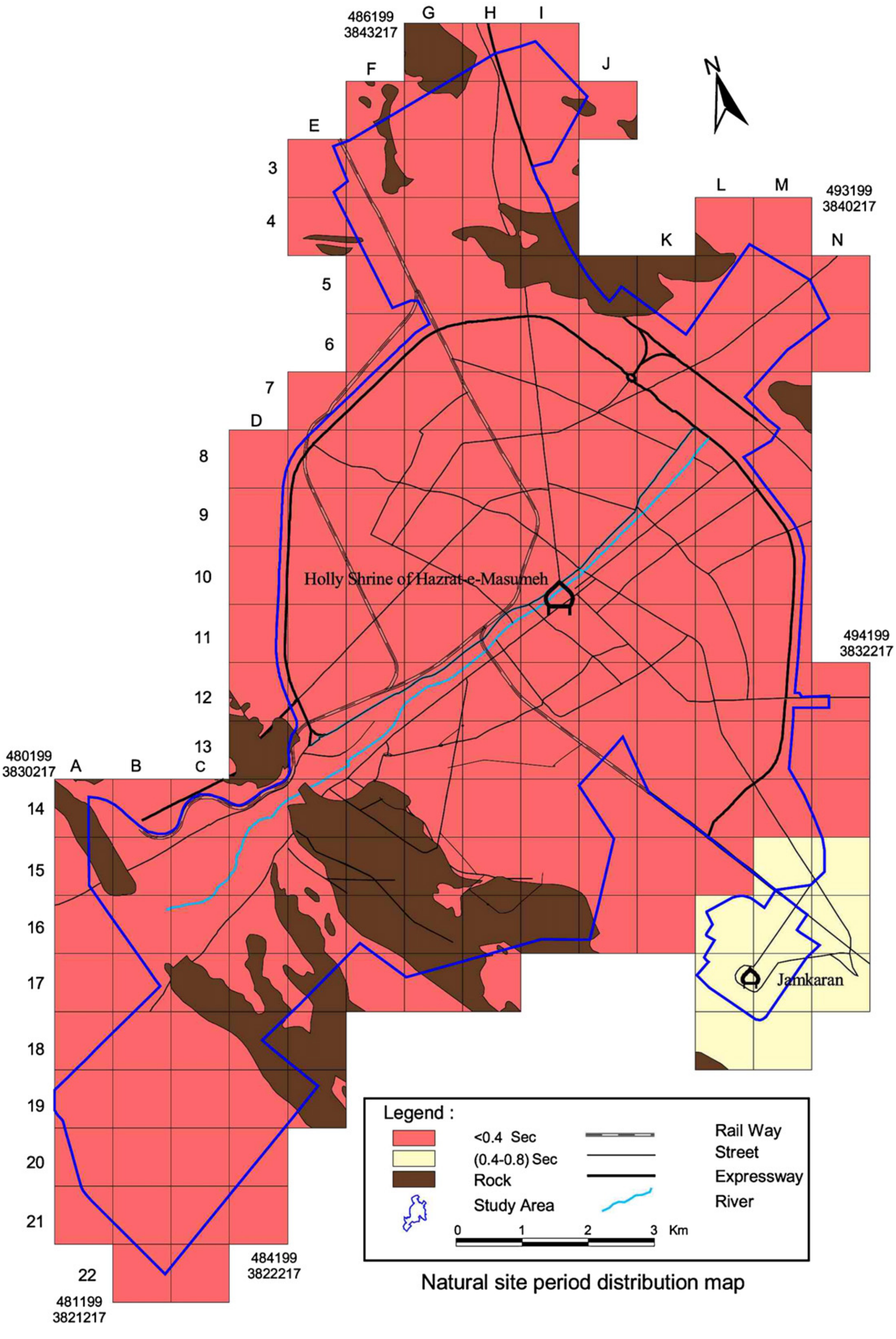


Fig. 13. Distribution of $T_N$ throughout Qom.

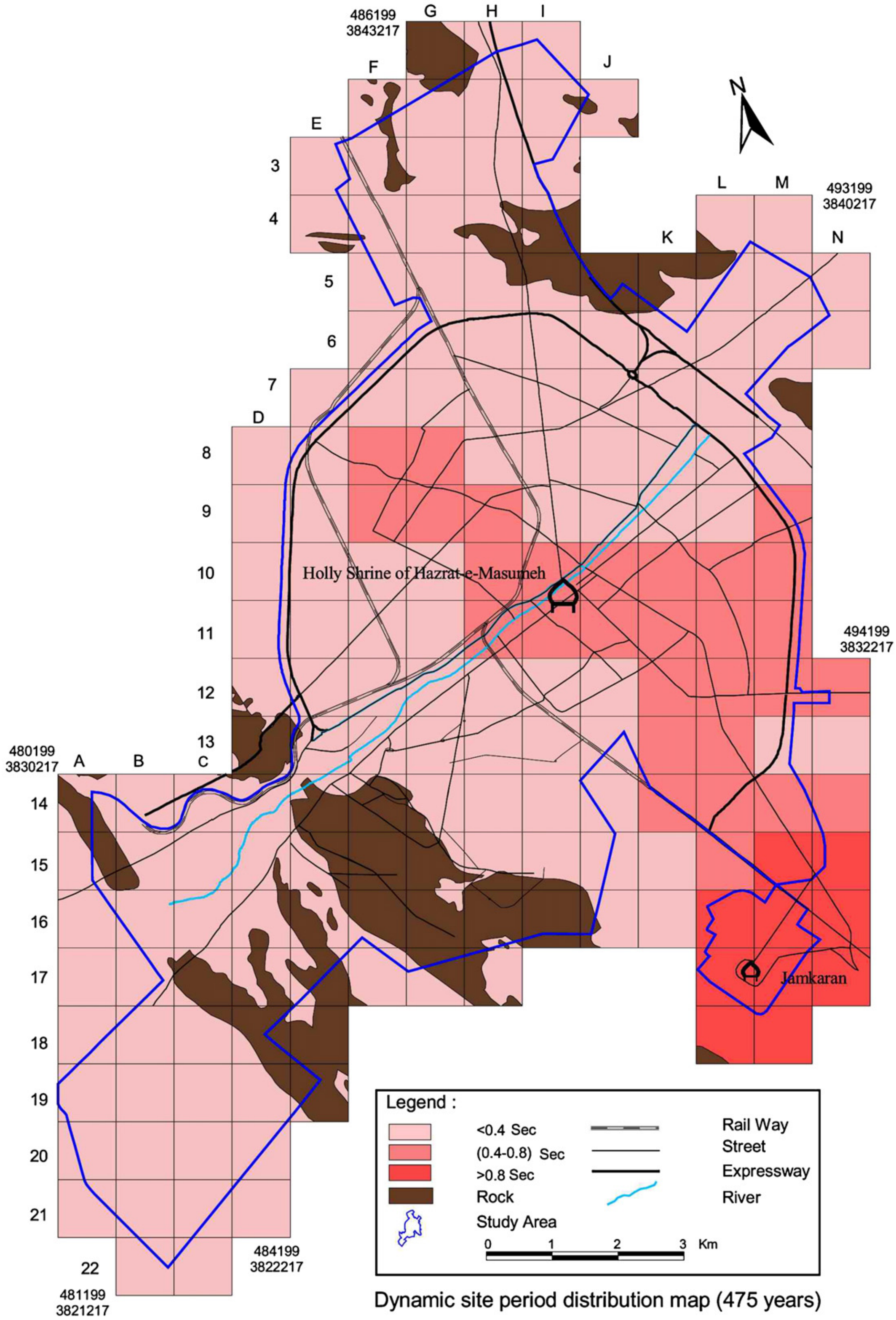


Fig. 14. Distribution of $T_D$ throughout Qom a return period of 475 years.

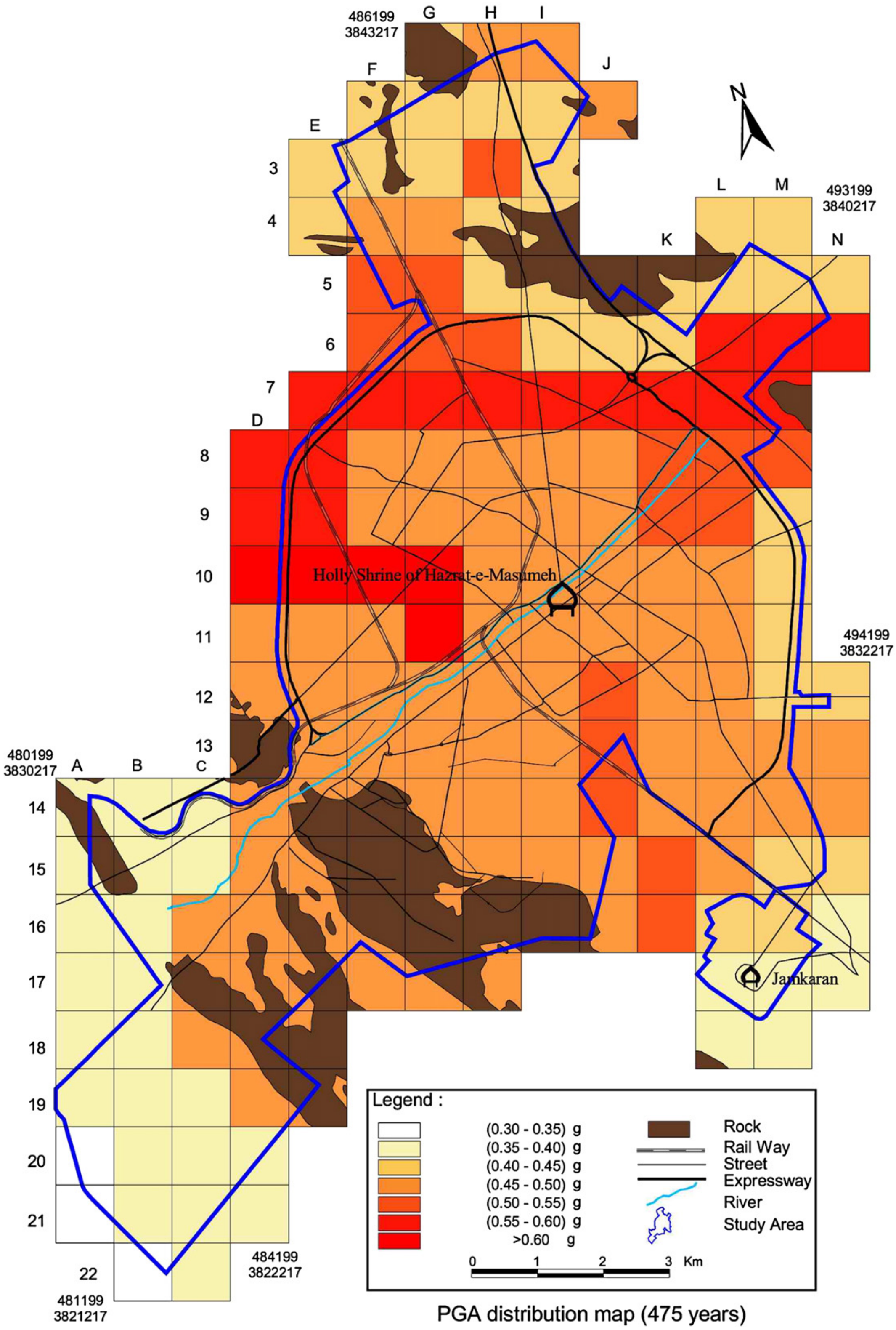


Fig. 15. Distribution of PGA throughout the city for a return period of 475 years.