Evaluation of Site Effects by Soil and Sediments in Karaj, Iran

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Abstract. As an important step in effectively reducing seismic risk and the vulnerability of the city of Karaj to earthquakes, a site effect microzonation Study was conducted. Seismic hazard analysis for a return period of 475 years was carried out. Data from 66 borings was collected and analyzed, geophysical surveys were conducted and seismology and geoelectric measurements taken in more than 17 stations throughout the city. The study area was divided into a grid of 500*500m² elements and the sub-surface ground conditions were classified into 9 representative geotechnical profiles. Electric resistivity was measured in close to 20 geotechnical boreholes and surface and sub-surface sediments were collected and analyzed. 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 and old and new texture buildings throughout the city were developed, providing a useful basis for land-use planning in the city.

1. Introduction
Ground shaking and its associated damage to engineered structures can be strongly influenced by source and path effects (depth and type of bedrock, soils and underground sediments) and geomorphologic conditions, known as “local site effects”. Iran is one of ten countries with most unexpected events in the world. Evidence of this can be found in two major seismic events in Iran in the past two decades -1990 Manjil–Rudbar and the 2003 Bam earthquakes-that resulted in a large number of casualties [1, 2]. These tragedies prompted the local researchers and government to implement earthquake risk mitigation measures, including seismic hazard zonation and microzonation of vulnerable cities, to facilitate urban planning. Also, 96% of cities are located on alluvial sediments around Iran and such researches are necessary for them. The industrial and economic of Karaj city, with 3 million inhabitant and huge and important factories, is situated 30 km west of Tehran, capital of Iran (Figure 1) and covers an area of approximately 250 km². In the past two decades, it has experienced a sizeable increase in population. In previous studies [1-4], carried out a soil and sediment quality microzonation study of Bam, Mobarakeh and Qom cities from seismic hazard point of view. They estimated the horizontal peak acceleration for basement rock based on the tectonics and seismicity with considering soil types. As a new research, we carried out a site effect microzonation study of Karaj in 2015. The goals of this investigation were to prepare guide lines for further land-use planning and to provide data for future studies.

2. Methodology
The methodology of soil and sediment quality and site effect microzonation adopted in this study falls into the category of Grade-3 zoning methods of the Japanese TC4 Zoning Manual [5], and Revised Manual for Zonation on Seismic Geotechnical Hazards, [6] and previous experiences of author.
After dividing the city into a grid of 500×500 m², the following steps were taken: 1-Preparation of a seismic hazard map of area for a return period of 475 years; 2-Gathering and investigation of the existent geological, geotechnical, sedimentological and geophysical data; 3- Conducting complementary geophysical investigation, as well as geoelectrical and seismology measurements and sedimentological studies; 4- Several experimental analyses on soil and sediment samples in Kharazmi university laboratory. 5- Preparation of representative geotechnical profiles; 6- Estimation of strong ground motion characteristics using one-dimensional site response analysis; 7- Preparation of the surface and subsurface grain size maps of the study area in GIS media and cross sections in N-S and W-E directions. 8- Preparation of the final site periods and peak ground acceleration (PGA) maps in GIS.

3. Study area

Geomorphologically, Karaj city is situated on an alluvial fan of Quaternary deposits. The predominant rock formation in north of city is Karaj Eocene formation, consisting mainly of Tuff, Shale and sandstone (Figure 1, 2). Water table level in this area fluctuates between 5 to 90 m [7], (Figure 2). The thickness of alluvial deposits increases from north to southwest of the city and the soil grains become finer toward south [8]. Tectonic situation of area is very active. Karaj is situated between the Alborz and central Iran seismo-tectonic units. The most important faults are the Abyek-Firuzkuh and Baghestan faults having strike slip mechanisms and reverse components [9, 10]. The instrumental seismicity shows that at least 6 earthquakes have occurred within a 100 km radius of Karaj with magnitudes of less than 7.0 (Figure 2). This study presents a probabilistic seismic hazard analysis (PSHA) by Cornell approach based on the tectonic position and seismicity of area. Area sources were identified on the basis of geological and seismological studies (Figure 2). For each source zone, seismicity parameters have been estimated. Each source zone is characterized by an earthquake probability distribution. The seismicity parameters, including the Gutenberg–Richter parameter ($\beta$), maximum possible earthquake ($M_{\text{max}}$) 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. Here, three proper attenuation relationships proposed by [3, 11, 12] have been considered. The attenuation relation given by [3]. Figure 3 right shows the distribution map of peak rock acceleration (PRA) in Karaj for a return period of 475 years, the PRA value varies from 0.21g to 0.59g. Figure 3 left presents the locations of the existing geological and geotechnical data as well as those of the complementary geophysical 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. [2, 4, 5].

Figure 1. Location of Karaj in Iran and Seismic risk zone of study area
Distribution maps of sub-surface sediments, depth of the seismic bedrock (Figure 4), as well as some geotechnical sections (Figure 5) were compiled using the accumulated data.

**Figure 2.** Geologic and events and Seismic risk zoning maps and Minor and Major faults around study area

The ground conditions of the study were thus categorized according to soil type, layer thickness and depth of seismic bed rock into three distinct zones (Figure 6): Zone 1: south and some parts of southwest of Karaj that is significantly different, with dominant clayey layers (CL) to a considerable depth, Vs less than 300m/s and the depth of seismic bedrock exceeds 90 m. Zone 2: rock outcrops covering the southwest and northeast mountainous regions and granular coarse-grained alluviums (GP, GW) in central parts of study area, Vs is over 700–800 m/s. Zone 3: granular finer grained alluviums (SM, SW, SP) which cover most parts of the central plain and southwest and northeast edges, low to medium dense sub layers have no considerable thicknesses, the depth of seismic bedrock varies from 20-50 m and Vs varies from 350 to 500 m/s. Moving from east to west and from north to south on the plain, the alluvium grain sizes decrease and fine grained soil layers (SM, ML, SC) become dominant. To the southwest of the plain, the thicknesses of low to medium dense sub layers and the depth of seismic bed rock increase and the average shear wave velocity decreases (Figure 4). Considering information currently available on the underlying structure of Karaj, one possible explanation is the existence of a deeper impedance contrast caused by the Quaternary sediments resting at a depth of 100–150 m from the ground surface on hard geological bed rock from the Eocene Tuff Karaj formations.
4. Site response analysis

Non-linear site response analysis was carried out to evaluate the site response of each of the representative geotechnical profiles to the 475-year seismic induced bed rock input motion. The SHAKE program (1997) was used to model the site as a one-dimensional system of horizontal, isotropic soil layers consistent with actual ground conditions. The well-known shear modulus-strain and damping ratio-strain relations proposed by Building Seismic Safety Council [13], were used in the analysis. Since there are no recorded bed rock strong motion time histories for Karaj city, 11 proper Earthquake time histories were selected from available national and international data bases [14] were recorded during earthquakes with approximately the same magnitudes (6.0 to 7.5) and distances (7 to 60 km), as estimated by deterministic approaches (Table 2). Other factors such as the site condition (rocks sites) and style-of-faulting (reverse or strike slip) were also considered [14], [15]. 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 to the normalized 475-year bed rock 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. Figure 8 illustrates the distribution of the natural site period (TN) and the distribution of the dynamic (non-linear) site periods (TD) throughout the city. A comparison of 2 Figs.8 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 behaviour during 475 year strong earthquakes. Figure 8 lower shows the distribution of the 475 year return period PGA throughout the Karaj city. The dense granular alluviums and mountainous rocky sites in north of Karaj experience the lowest PGA values because either their amplification potential is negligible or their PRA values are the lowest. The alluviums experience higher PGA values because of their considerable amplification potential caused by low to medium dense soil layers, [16].

Figure 4. left) Distribution map of soil and sub-surface sediments. right) Distribution map of depth of seismic bed rock

Figure 5. Geotechnical section N-S and W–E directions in Karaj city
Figure 6. left) Distribution of Sediment thickness and right) Distribution map of site types throughout Karaj

Figure 7. Samples of representative geological outcrops and cross sections

Table 2. Specification of selected accelerograms for site response analysis

| No | Earthquake        | Mechanism* | Magnitude | Distance | PGA(g) |
|----|-------------------|------------|-----------|----------|--------|
| 1  | San Fernando-1971 | reverse    | 6.6       | 23.5     | 0.16   |
| 2  | Vendic, Iran-1976 | Strike slip| 6.4       | 10       | 0.17   |
| 3  | Naghan, Iran-1977 | reverse    | 6.1       | 7        | 0.87   |
| 4  | Tabas, Iran-1978  | reverse    | 7.4       | 45       | 0.11   |
| 5  | N. Palm Springs-1986 | Reverse oblique | 6.0       | 45.6     | 0.10   |
| 6  | Northridge-1994   | reverse    | 6.7       | 26.8     | 0.17   |
| 7  | Duzce, Turkey-1999 | Strike slip | 7.1       | 8.2      | 0.51   |
| 8  | Changureh, Iran-2002 | reverse | 6.1       | 28       | 0.43   |
| 9  | Bam, Iran-2003    | Strike slip| 6.5       | 56       | 0.16   |
| 10 | Baladeh, Iran-2004 | reverse | 6.3       | 20       | 0.29   |
Figure 8. Distribution of TN, TD and PGA and throughout Karaj a return period of 475 years

5. Conclusions
This paper presents the most important features of soil, quality, and site effect microzonation studies of Karaj. It was found that two 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. 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 100–150 m from the ground surface on hard rock from the cretaceous limestone formations. This emphasizes once again the important role that site effect microzonation can play in seismic risk mitigation of seismic-prone zones.
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