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Site Effect Microzonation and Seismic Hazard Analysis of Kermanshah Region in Iran

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Abstract: As an important step in effectively reducing seismic risk and the vulnerability of the city of Kermanshah to earthquakes, a site effect microzonation study was conducted. Seismic hazard analysis for a return period of 475 years was carried out. Data from 113 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 14 representative geotechnical profiles. Site response analyses were carried out on each representative profile using 14 different base rock input motions. Distribution maps of amplified acceleration for a return period of 475 years and peak ground acceleration throughout the city were developed, providing a useful basis for land-use planning in 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 0.8 to 1.5 Hz (period interval of 0.6 to 1.1s) 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.

Key words: Kermanshah, microzonation, site effect, natural period, peak ground acceleration, seismic risk, land-use planning

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. It is well established that local site conditions and, to a more limited extend, irregular surface topography can substantially influence the amplitude, the frequency content and the duration of ground motion and consequently can exert a crucial influence on the severity of the damage caused by the earthquake. Whichever approach to hazard estimation is used, the influence of site conditions needs to be incorporate.

Sitharam (2010) carried out the microzonation studies in different cities of India with different methodologies used by various researchers. The merits and limitations of these studies have also been highlighted. Slob *et al.* (2002) demonstrated that it is possible to make better use of any limited geotechnical, geomorphological and geological information by creating a simplified semi-3D model in a GIS. Through linking of this 3D information in the GIS with a seismic response modeling program - such as the widely used software SHAKE - a more accurate spatial variation of the seismic response can be modeled, which will provide an improved basis for seismic (micro) hazard zonation.

As mentioned above, local site effects on ground motion are considered to be the most significant factor in zoning of ground motions. Local site effects can be defined as the modification of predicted rock outcrop reference motions to give more realistic motions at the local site. The local site effects are evaluated from

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different method depending to the level of accuracy and studying zoning level. The most widely used analytical method for site response is to make use of the multiple reflection models for the propagation of S-wave in a one-dimensional column. The soil column is modeled as a series of horizontal layers. These layers are subjected to base motions that are considered representative of those likely to occur in the region of interest. Nonlinearity of site response is one of the major issues in evaluating site effects as soils exhibit strong strain-dependency of modulus and damping characteristics (Technical Committee for Earthquake Geotechnical Engineering, 1999). Alsouki *et al.* (2008) conducted a research which delineated depositional systems of Strait of Hormuz area (Eastern part of Persian Gulf) included turbidity and Mass Transport Complexes (MTCs) which was characterized on seismic by chaotic reflections, scoured bases and mounded external geometry. Aigbedion (2007) have used 3-D static reservoir models based on the understanding of facies and their relationships, through the integration of all available data to enhance the understanding and qualification of the uncertainties.

In this investigation a site effect microzonation study was conducted. Seismic hazard analysis for a return period of 475 years was carried out. Distribution maps of Amplified Acceleration and peak ground acceleration throughout the city were developed.

General geology: Kermanshah city located within the Zagros fold and thrust belt. The Zagros fold-and-thrust belt stretches from eastern most Turkey to the Oman Gulf. At first sight, it shows a series of large longitudinal folds that affect the Phanerozoic sedimentary sequence of the northeastern Arabian margin (e.g., Stocklin, 1974; Berberian and King, 1981; Koop and Stoneley, 1982). The Main Zagros Reverse Fault (MZRF) underlines the ophiolitic suture zone between the fold and thrust belt in the strictest sense and the Sanandaj-Sirjan zone, a polyphase sedimentary/metamorphic complex that forms the southern margin of the Iranian plateau (Stocklin, 1968, 1974; Berberian and King, 1981). Figure 1 shows geological map of Kermanshah on which, the seismic recording stations have been shown. Kermanshah city in north is part of Sanandaj-Sirjan zone. This zone is located between central Iran and Zagros fold and thrust belt. Sanandaj- Sirjan is a metamorphic zone and like an elongated band. According to the stratigraphy map in Iran Sanandaj- Sirjan from sedimentation and structural pattern is similar with central Iran zone. The general trend of this zone is liked to Zagros. At the northeastern edge of the Sanandaj-Sirjan zone is the Urumieh Dokhtar arc.

Geophysical investigations: This study is part of the seismic hazard assessment project in city of Kermanshah, located West of Iran. The main objectives of geophysical studies, was to estimate shallow seismic structure within the mentioned city which is required for seismic hazard assessment. The ground shallow seismic structure is characterized by body-waves velocity distribution in surface layers and their corresponding seismic natural frequencies.

The applied methods were refraction seismic, Spectral Analysis of Surface Waves SASW and H/V spectral ratio for estimation of P-wave velocity, S-wave velocity and natural frequency, respectively. Kermanshah area was covered with 70 recording stations for seismic measurements. The H/V technique was applied in all stations but refraction and SASW methods were done at 50 out of 70 points. There are 113 old and new boreholes in the city, so, the seismic stations have been mostly distributed in areas which have less or no boreholes. However in a few points, seismic recording have been done close to borehole to calibrate seismic data with geological data. Figure 2 shows the location map of geotechnical boreholes and geological cross-section stations. The ground natural frequency was calculated using H/V spectral ratio analysis of seismic microtremor data. Figure 3 shows the location of boreholes and seismic recording station in Kermanshah. The results of this analysis have been presented in Fig. 4 a qualitative frequency map.

The results of refraction analysis include average P-wave velocity and depth of surface layers up to bed rock depth. These data have been presented in the form of depth-velocity graphs at different stations, velocity contour maps of sediment layers and bed rock and depth contour map of bed rock surface (bed rock topography). SASW method was applied to calculate S-wave velocity structure. The results yielded by this technique have been shown by depth-velocity graphs, velocity contour maps at different depth ranges and depth contour map of bed rock surface. At the final stage, the geophysical results were compared with surface geology and borehole data to give a more accurate and trustable earth model for seismic hazard estimation.

Geotechnical investigation: Reliable modeling and evaluation of site effects is the key problem in seismic microzonation especially in high seismicity areas, with complex geology and highly heterogeneous soils. Hence, a detailed model of the surface geology and geotechnical characteristics, properly oriented for seismic hazard

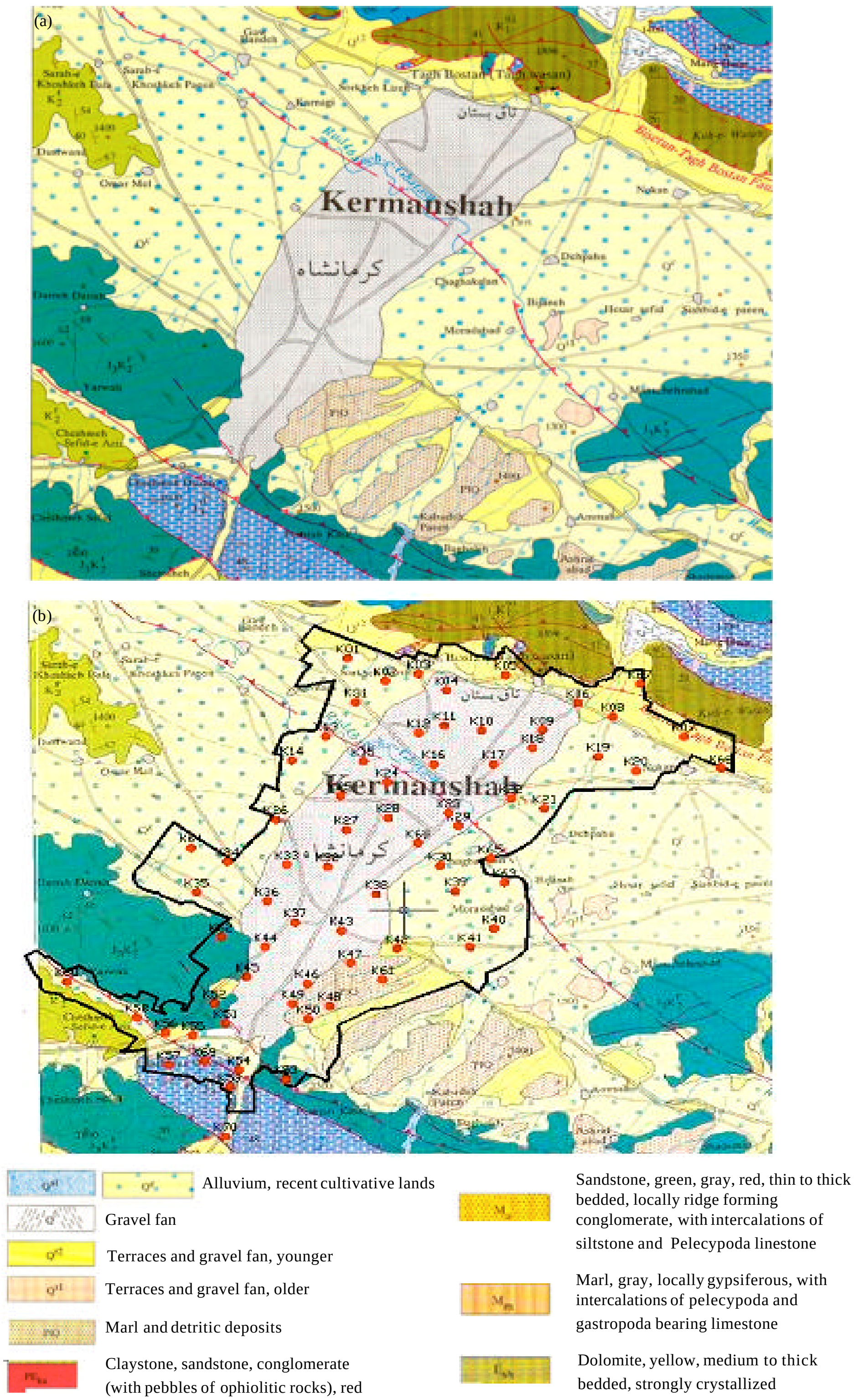

Fig. 1: Geological map of Kermanshah with seismic recording stations

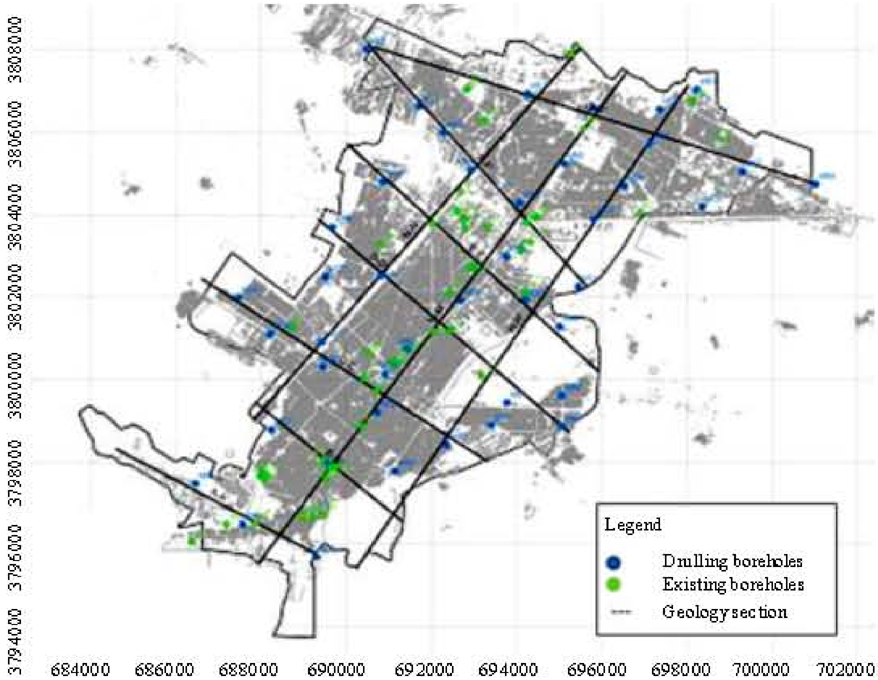

Fig. 2: Geotechnical boreholes and geological cross-sections stations

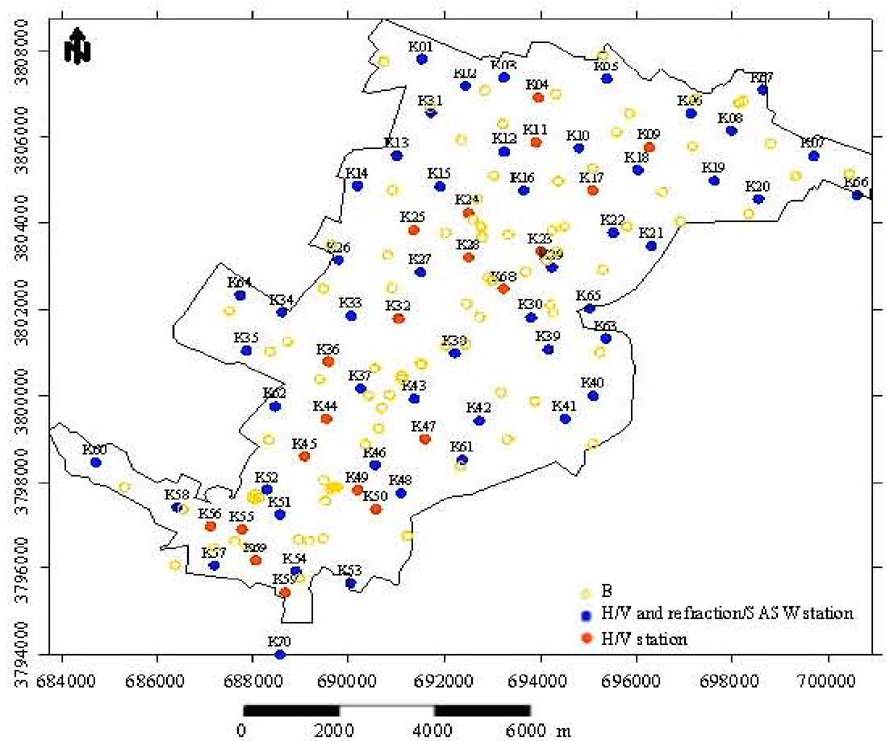

Fig. 3: Location map of boreholes and seismic recording stations in Kermanshah

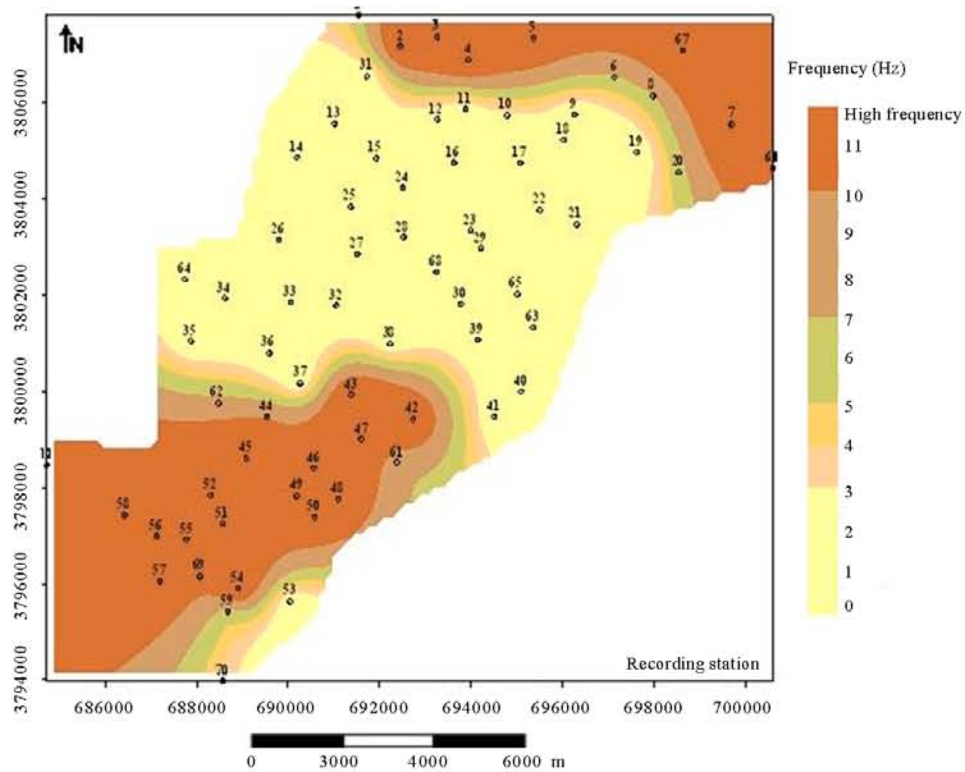

Fig. 4: Natural frequency contour map obtained from microtremor investigation in Kermanshah

studies, has to be generated for the city. The resulted geotechnical maps and cross-section based on data provided by geotechnical investigations (boreholes, SPT's, water wells), geophysical surveys, microtremors measurements, describes the spatial distribution of the soil formation. The thickness of each soil formation is needed to fully describe the subsoil conditions in the city. Among the goals of the present geotechnical zoning was the mapping of the thickness and the lateral spreading of the artificial or hazardous various fills. Their influence on the seismic behavior of modern structures is practically unpredictable.

A general approach to the geotechnical zoning of the urban area should ideally consist of the data collection from public and private sources on the urban area subsoil, creating a GIS, supported geotechnical cross-section across the urban area based on the spatial distribution of boreholes and other field investigation data. The cross-sections depict the geotechnical units, highlighting the shear wave velocity (Vs) values and extending in depth to include the bedrock formation(s) wherever feasible.

In this Study all the available geological, geotechnical and geophysical data were collected. This has been performed by using the own documentation of Darya Khak Pay and the other private and governmental organizations and data holders. Totally, 19 numbers of 0-10 m bore holes, 45 numbers of 10-20 m bore holes and 7 numbers of 20-30 m bore holes have been collected. Furthermore, after compiling and mapping of the collected information, complementary geotechnical site investigation planned to be performing in the city. So, 3 numbers of 70 m boreholes plus 39 numbers of 20 m boreholes with sampling and in situ tests have been drilled. Boreholes with 70 m depth penetrates in the substratum with Vs>900 m sec^{-1} for at least 15 m. The summary of this complementary geotechnical investigation is shown in Table 1, in addition to depth and density of each bored hole, the velocity of shear wave and classification of soil are presented in this table. Complete drilling operations have been carried out under the supervision of Darya Khak Pay (DKP) consulting engineers. The soil layers have been classified based on the unified system (USCS) according to ASTM (D2487) standard. Sampling in machine-drilled holes has been performed with the SPT test equipments or core - barrel sampler to get disturbed soil and rock samples.

Evaluation and mapping of site effect (Amplification): As described above, the proposed method allows identifying the zones where the seismic response is homogenous and

Table 1: The depth and number of drilled bore holes in Kermanshah city

Boring No.	Depth (m)	Density	Vs (m sec^{-1})	Soil classification
K-D-1	20	Very dense	516	GW\GM\SM
K-D-2	20	Medium dense-very dense	325	GM\GP-M\SM
K-D-3	20	Dense-very dense, medium stiff-stiff	283	GC\SM\CH\CL
K-D-4	20	Medium dense-very dense, medium stiff-very stiff	266	GC\SC\CL
K-D-5	20	Very dense, hard	503	GC\SC\CH\CL
K-D-6	20	Very dense, hard	525	GC\CH\CL
K-D-7	20	Very dense, very stiff-hard	559	GC\SM\SC\CL
K-D-8	20	Very dense, hard	469	GC\GM\SM\ML
K-D-9	20	Very stiff- hard	300	CH\CL\ML
K-D-10	20	Very dense, hard	515	GM\SC\CH\CL
K-D-11	20	Medium dense, stiff-hard	269	SM\CH\CL\MH
K-D-12	35	Very dense, hard	517	GC\SC\SM\CH\CL
K-D-13	20	Medium stiff- very stiff	195	CH\CL
K-D-14	20	Medium dense-very dense, medium stiff-very stiff	219	SC\SM\CH\CL
K-D-15	20	Medium dense, stiff-hard	235	SC\CH\CL\ML
K-D-16	20	Dense, stiff-hard	227	SC\CH\CL
K-D-17	20	Dense, very stiff-hard	282	GC\CH\CL\MH
K-D-18	20	Very Dense, hard	462	GC\GM\CH
K-D-19	20	Medium dense, very stiff-hard	287	SC\CH\CL
K-D-20	20	Stiff-hard	237	CL\MH\ML
K-D-21	20	Very Dense, very stiff-hard	275	SC\CL
K-D-22	20	Very Stiff-hard	257	CH\CL\MH\ML
K-D-23	20	Very Dense, very stiff-hard	324	SW-SM\CH\CL
K-D-24	20	Medium dense, hard	444	SM\CH\CL
K-D-25	20	Dense-very dense, very stiff	412	GC\SC\CL
K-D-26	20	Dense-very dense, hard	380	GC\SC\CL\CH
K-D-27	20	Dense-very dense	617	GC\GM\SC\SM
K-D-28	57.5	Very Stiff-hard	432	CH\CL
K-D-29	20	Very Dense, stiff-hard	385	SM\CL
K-D-30	20	Medium dense- very dense, very stiff	358	GM\SM\CH\CL
K-D-31	20	Very Dense, very stiff-hard	346	SC\CH\CL
K-D-32	20	Very dense, stiff-hard	636	GM\CH\CL
K-D-33	20	Very dense, hard	510	GC\SC\CH\CL
K-D-34	24	Very dense, stiff-hard	392	SC\CL
K-D-35	20	Very dense	570	SC\SC-SM
K-D-36	20	Very dense	941	GM\SM
K-D-37	61	Very dense, very stiff-hard	503	GC\SC\CH\CL
K-D-38	20	Medium dense-very dense, very stiff-hard	389	GM\SC\SM\CH\CL
K-D-39	20	Dense, stiff-hard	247	GM\SM\CL\CH\ML
K-D-40	20	Medium dense-very dense, stiff-very stiff	232	GC-GM\SC-SM\CL\CL-ML
K-D-41	20	Very stiff-hard	314	CH\CL\MH
K-D-42	20	Very dense, stiff-hard	564	GM\SM\CL
K-D-43	45	Dense-very dense, very stiff-hard	426	SC\CL

Source: Author's computation

to furnish for each zone, the specific seismic motion indicates the geological and geotechnical mapping considering the collected data (Fig. 1), checking and corrections of the preliminary results obtained by integrating the geotechnical and geophysical (H/V) field survey. The zones mapping shows the same seismic response.

The quantification of site effects is performed by numerical simulation. It is based on a detailed check of the geological and topographical map, then by a good knowledge of the geomechanical and geometrical characteristic of the soils. It is necessary to obtain the width (h) of the superficial formations and the main soil characteristics such as, density and formation type (clay, sand, rock), Shear wave velocity (Vs), damping (D) and evolution of the shear modulus (G) and damping (D) with the strain, for assessing the non linear effects. The level of knowledge or reliability of these collected data is needed to allow approaching the result uncertainties. This is why these calculations are commonly achieved by the mean of parametric approach numerical models. When the geometrical (i.e., the geologic structure) and the mechanical parameters are well known, the calculation of the wave propagation in complex media allows to predict the seismic response of several sites. The numerical model allows calculating, the local transfer function H (f) for linear models and the response spectra taking into account the site effect, once the natural or synthetic accelerograms corresponding to the reference rock spectra have been selected. In this project nonlinear behavior has been considered by using Equivalent-linear Earthquake site Response Analysis (EERA) which is a modern implementation of the equivalent-linear concept of earthquake site response analysis, which was previously implemented in the original and subsequent versions of SHAKE (Schnabel *et al*., 1972; Idriss and Sun, 1991). These calculations take into account the characteristics of the soil column for each soil unit. They give the evaluation of the seismic response to a vertical incidence of (S) shear wave. Figure 5a-g show the

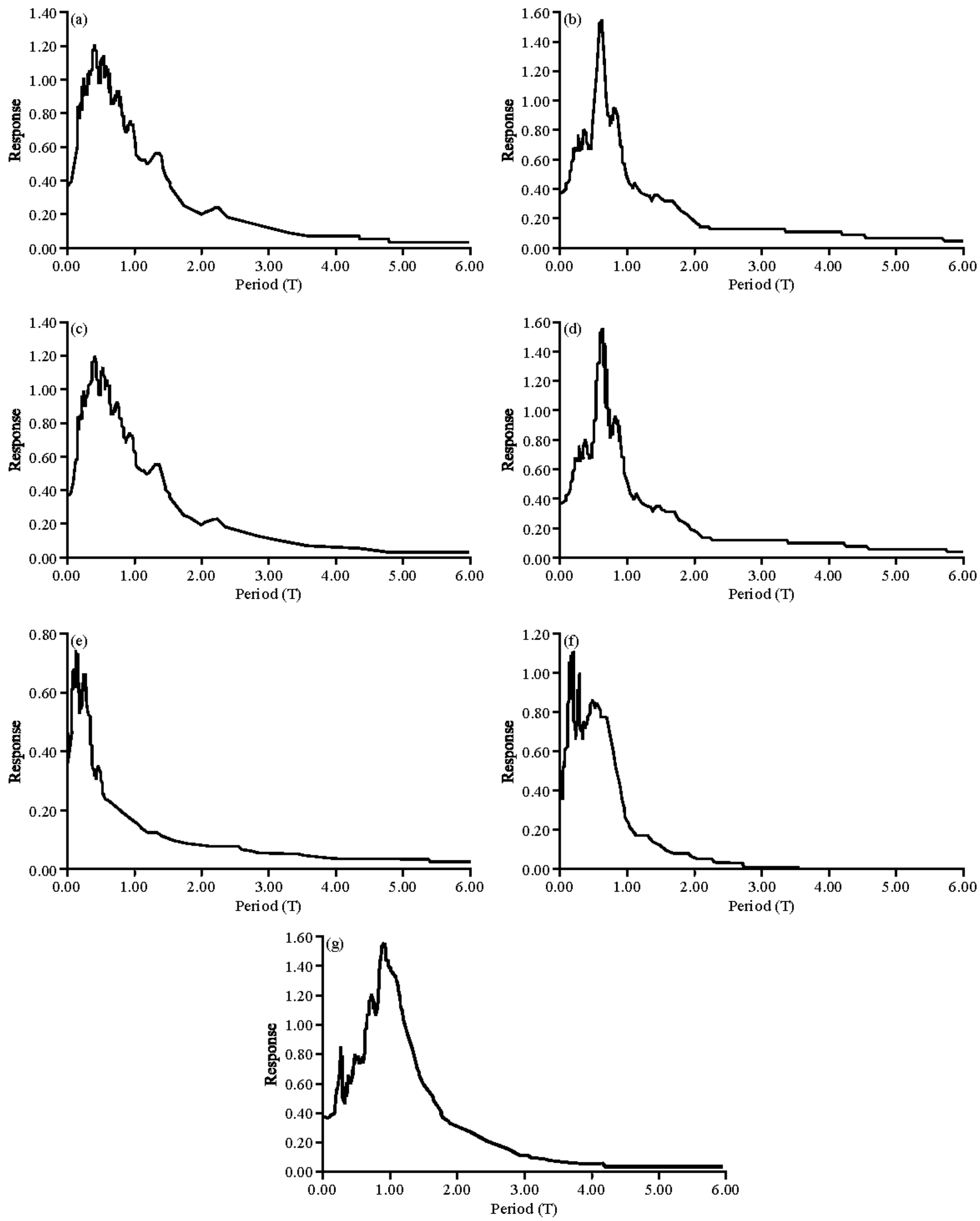

Fig. 5: Response spectral on seismic bedrock. (a) North region earthquake, (b) Coyote alke earthquake, (c) Zanjan earthquake, (d) Firooz abad earthquake, (e) Cape Mendoclio earthquake, (f) Wlilttler narrows and (g) Zarrat earthquake

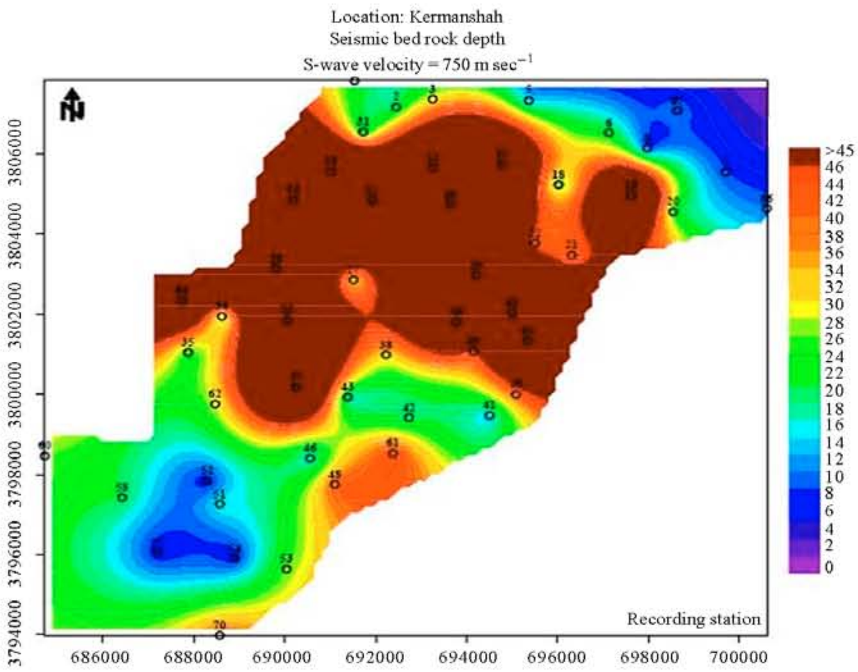

Fig. 6: Seismic bed rock depth

response of bedrock versus period of time for seven different earthquake. The selected ground motion records were recorded during earthquakes with approximately the same magnitudes and distances. Other factors such as the site condition (rocky sites) and faulting mechanism were also considered. All selected acceleration time histories were normalized to the 475 year peak rock acceleration estimated by Probabilistic Seismic Hazard Analysis (PSHA).

In the viewpoint of Earthquake Engineering and Iranian code 2800 of the Building and Housing Research Center (BHRC, 2005), the shallower interface of underlying stratum with 750 m sec^{-1} of the shear wave velocity, has been selected as the seismic bedrock. The both definitions of bedrock are widely used in the field of quantitative strong motion estimation. In the textbook of Earthquake Engineering, Bedrock and sometimes Seismic Bedrock is used in the context where Engineering Bedrock should be used (Fig. 6). In contrast, the textbook of Seismology uses Bedrock where it should be called Seismic Bedrock. It is important to distinguish the definition of the terms where they are used, by the context or the glossary. As mentioned above, these results will be corrected and refined with the H/V field survey results. Finally, we have defined a limited number of spectra showing the same frequencies characteristics, giving a limited number of zones showing a homogeneous seismic response, inside of which the construction rules are the same.

CONCLUSIONS

This study presents the most important features of site effect microzonation studies of Kermanshah. Evaluations of the ground motion characteristic are based on seismic risk assessment of 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 (Fig. 7). 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 0.8 to 1.5 Hz (period interval of 0.6 to 1.1s) 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 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 750 m sec^{-1}) resting at a depth of 250-350 m from the ground surface on hard rock from the Kermanshah 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 0.30 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 and PGA can be useful in land-use planning in consideration of population density, building height and building importance (Fig. 8). It is obvious that more accurate

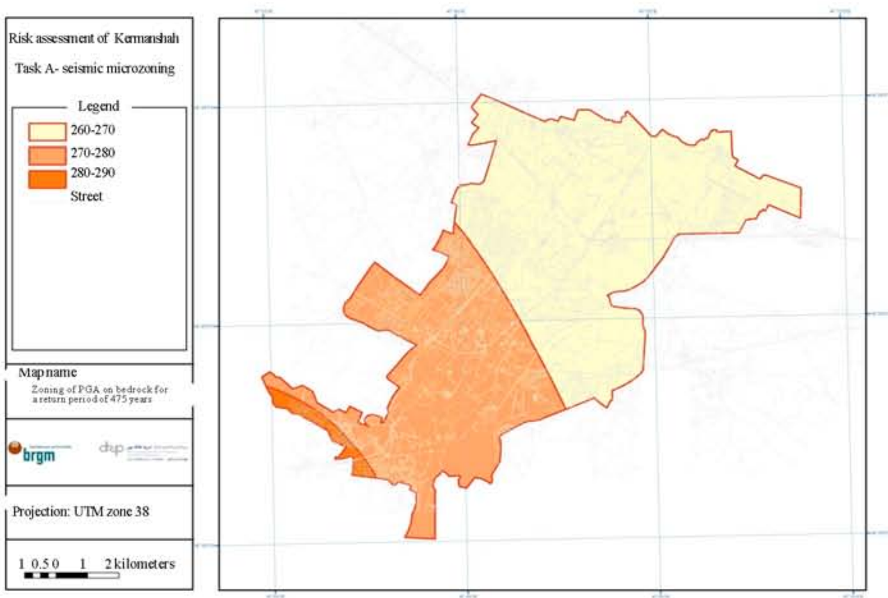

Fig. 7: Mean PGA zoning map in Kermanshah for return period of 475 years

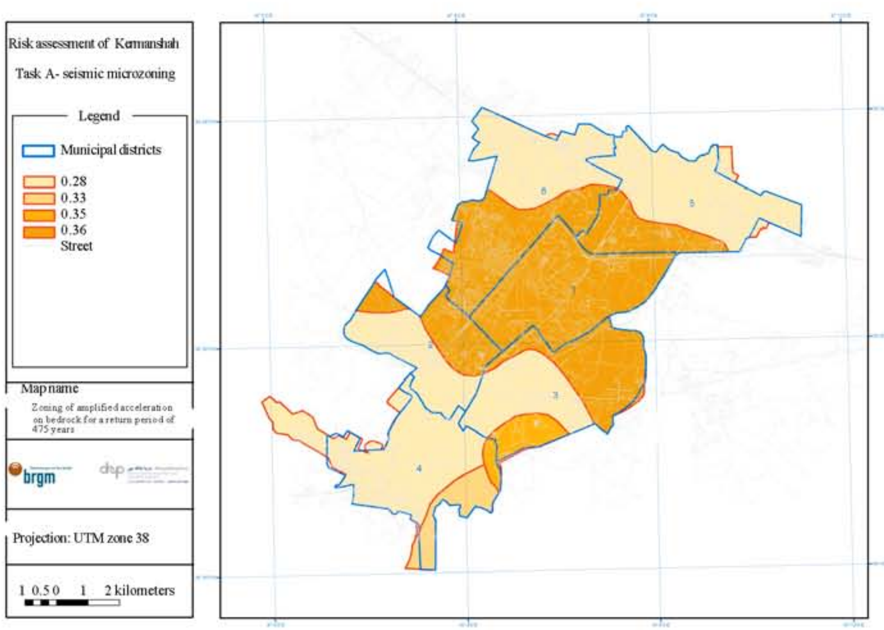

Fig. 8: Zoning of Amplified Acceleration for a return period of 475 years

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.

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