Local Site effects for ground motion acceleration and amplification at Bahrah, Saudi Arabia.

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Abstract

The soil conditions variability at site strongly influence ground motions during earthquakes. The disastrous earthquakes have shown that the local site conditions are the essential factors that impact surficial ground motions. In present study, local site effects are evaluated for ground motion acceleration and amplification at Bahrah. The town is situated on quaternary alluvial wadi deposits. The ground motion time series are obtained through Spectral matching technique.. The ground motion time series and shallow Geophysical data are utilized to carry out One-dimensional simulation for equivalent linear seismic response analyses for soil layers. Results of One-dimensional site response analysis are interpolated to generate maps that account for ground motion accelerations and amplifications at top of the soil for selected spectral periods (PGA, 0.1, 0.2 and 2) for 475 years return period. The maximum value of amplification ranges upto 3.46 and acceleration upto 0.86 g. The undulation of bed rock topography and existence of deep soft sediments are reflected considerably on the results of the study area.

Keywords: Ground acceleration; ground amplification; local site effect; spectral matching; site response analysis.

1. Introduction

Natural Hazards and Disasters have asserted huge number of lives and damage to infrastructure (Rehman & Harbi, 2018). Local site characterization is inevitable procedure for sustainability against the natural disasters which results in huge number of mortalities and infrastructure destruction. Site characterization can be achieved systematically by evaluating the response of soil layers to earthquake vibrations (Nejad *et al.,* 2018; Tempa *et al.,* 2020). Soil layers under the effect of dynamic forces can act quite contrarily as compared to static conditions. Earthquake vibrations are affected by soil layers as they pass through them (Akkaya & Özvan, 2019). Local site effects are caused by local unconsolidated sediments which result in significant enlargement of the amplitudes earthquake ground motions (Kuo *et al.,* 2018; Rezaei & Choobbasti, 2018; Touhami *et al.,* 2020; Sadiq *et al.,* 2021). The thickness and degree of stiffness of soil deposits are two major geological characteristic that control the earthquake shaking. In order to evaluate the soil layers behavior for derivation of 1-D layered ground models, surface wave dispersion curves and elastic properties of the soils has been extensively used. (Navarro *et al.,* 2014; Hassan *et al.,* 2020). The severity of damage to buildings can vary dramatically at shorter distances across a city due to variation in the spatial distribution of earthquake response which is controlled by local site characteristic (Ding *et al.,* 2004; Kamalian *et al.,* 2008; Lee *et al.,* 2012; Talhaoui *et al.,* 2004). On the other hand, subsoil structures drive the damage to buildings and ground motion over relatively short distances (Anastasiadis *et al.,* 2001). The few of subsoil controlled most horrible examples include the Michoacan, Mexico 1985 event, the Spitak Armenia 1988 event, the Loma Prieta 1989 earthquake and the Dinar, Turkey earthquake (Ansal *et al.,* 2001; Kanlı, 2006).

The fundamental approach in evaluation of local site effects actually comprises of three steps; probabilistic seismic hazard assessment (PSHA), local soil dynamic properties evaluation, and site response analysis. The PSHA provides unified hazard spectrum for a specific return period (Rehman *et al.,* 2019b). The local soil properties enable the illustration of soil dynamic behavior by site response analysis. The results of site response analysis provide the soil amplification and acceleration at various spectral periods (Rehman *et al.,* 2016a; Rehman *et al.,* 2017). Besides spectral matching, geotechnical and geophysical techniques are employed to incorporate local soil effect (Rehman *et al.,* 2016a). Multichannel analysis of surface wave is mainly used geophysical technique. (Anukwu *et al.,* 2018; Karslı *et al.,* 2017; Rehman *et al.,* 2018a). The shear wave velocity and density information for first 30 meters are obtained by surface wave surveying (Ezzelarab *et al.,* 2018; Rehman *et al.,* 2016b). Spectral matching results, subsurface shear wave velocity and density information in addition to lithological data are utilized to carry out site response analysis. Site response analysis provides surface ground motion parameters. These parameters include spectral acceleration and ground amplifications at various spectral periods (Anbazhagan *et al.,* 2013; Rehman *et al.,* 2016a).

Rapid urbanization presents challenges for governments and stake holders. The one of challenging issue is Aseismic structures including residential as well as commercial centers. The site response analysis is fundamental component in earthquake risk assessment or hazard mapping. In the current study, local site effects are evaluated for Bahrah, a rapidly growing town located in western Saudi Arabia mid-way between Makkah and Jeddah City (Figure. 1). Jeddah is one of the major urban center of the central western coast of Saudi Arabia (Rehman & El-Hady, 2017; Rehman *et al.,* 2019a). Bahrah is located in close proximity to the Red Sea active tectonics controlling seismic hazard to whole area. The town is situated on quaternary alluvial wadi deposits. Undesired dangerous amplification of earthquake shaking had been noticed for most of sites characterized by this type of sediments (El-Hady *et al.,* 2012).

2. Methodology

2.1 PSHA and Deaggregation:

PSHA provides the ground motion characteristics which is carried out by this scheme, is mainly based on the historical and recorded seismicity, and earthquake motion data (Anbazhagan *et al.,* 2009; Mihalić *et al.,* 2011; Muço, 2012).

Deaggregation technique has been proved significantly essential approach to understand seismic hazard. This process helps to precisely identify the controlling earthquake magnitude size and distance range that stems to site hazard (Bazzurro & Cornell, 2004; Halchuk & Adams, 2004; McGuire, 1995).

This process enables the identification of seismicity attributes, i.e., distance to site and magnitude, accountable for seismic hazard (Fauzi & Fauzi 2013; Goda & Atkinson, 2009; Sosson *et al.,* 2010). Normally, PSHA is deaggregated in provisions of two variables: source to site distance and magnitude (El-Hussain *et al.,* 2012).

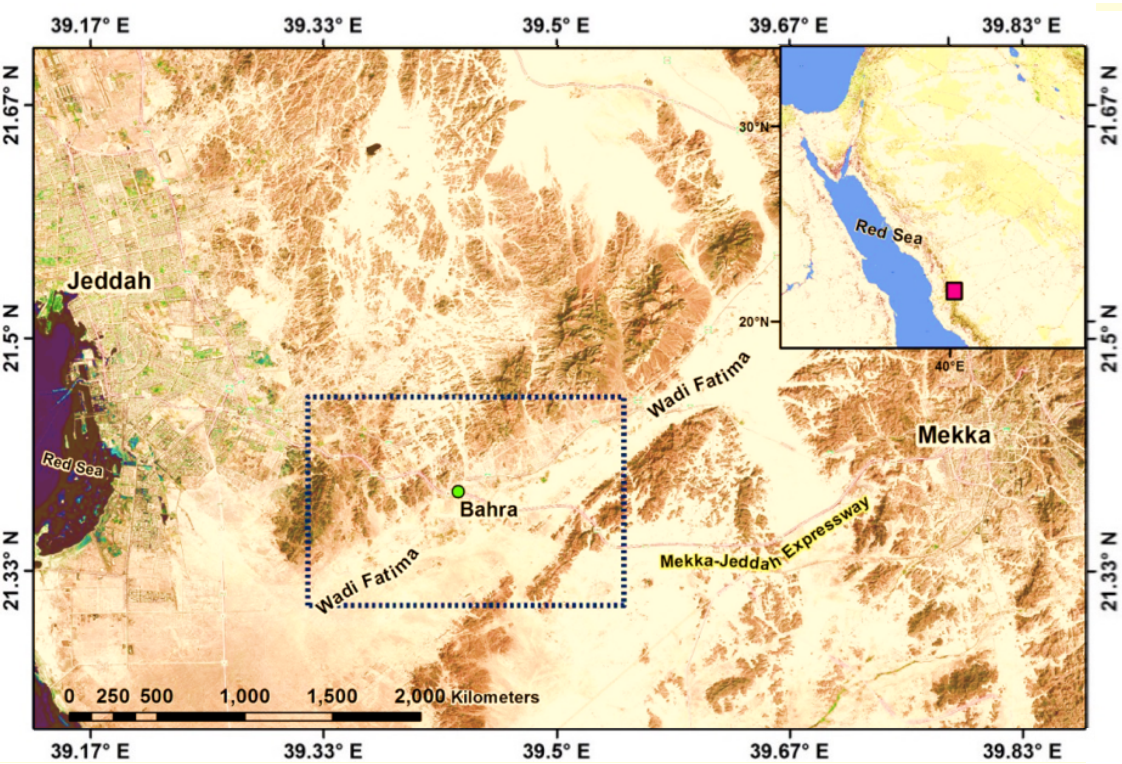

Fig. 1. Location map of the study area.

In the current study deaggregation is carried out to select an appropriate earthquake scenario with specific distance to site and magnitude. Deaggregation is carried out for PSHA result of Rehman et al. (2018b) for return periods of 475 years at selected spectral periods PGA and 0.1s, 0.2s and 2s. Deaggregation results assist the selection of controlling earthquake scenario in terms of magnitude and distance from the site (Figure. 2).

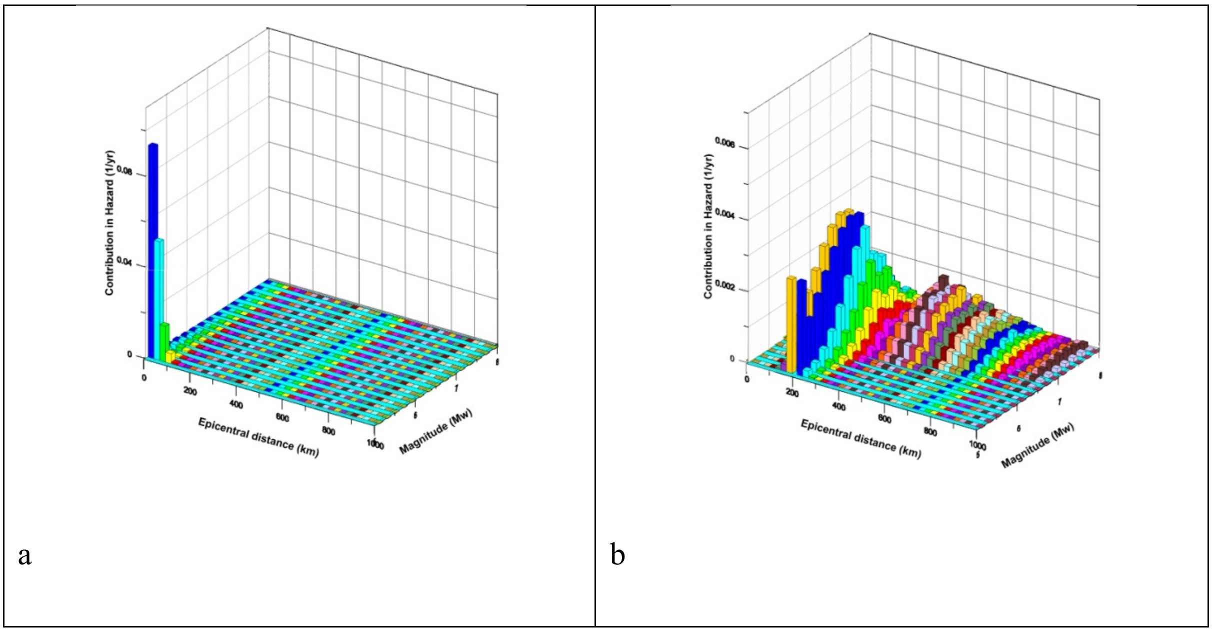

Fig. 2. Deaggregation results. a) PGA , b) Spectral Period 2 sec

2.2 Spectral Matching:

Spectral Matching is the process to generate synthetic/artificial ground motion acceleration time histories having shapes virtually indistinguishable to the predetermined target spectrum (Fahjan and Ozdemir, 2008). This technique is used to estimate nonlinear structural response. It is generally accepted that lower dispersion is present in spectral matching results in most of the cases (Kang *et al.,* 2014). The generation of artificial time histories can be done iteratively in two major domains: Frequency-Domain-based (FD) and Time-Domain-based (TD) matching (Carballo and Cornell, 2000).

In this study, spectral matching is carried on the basis of deaggregation results. The standard search parameters selected for near field effects are 20 seconds duration and for far field are 80 seconds duration. The magnitude is set to of 5.5, while the distance is set to around 25 km from the site for short period duration earthquake. However the long duration far field search parameters for spectral matching involve a distance to site of more than 175 km and a magnitude of 7.5 earthquake (Figure. 2).

Ez-Frisk software ver.7.52 is used for database search and for spectral matching procedure. The available database of strong motions record includes PEER NGA7.3 and USNRC CEUS. The Ez-Frisk software is utilized to search target ground motion record for the study area. The input time histories are matched with unified hazard spectra of Bahrah for the 475 and 2475 years return periods for near and far field effect.

The RspMatch algorithm, developed by Al Atik and Abrahamson (2010) for spectral matching, is applied for preservation of non-stationary frequency content of selected ground motion record. The response spectrum for site response analysis achieved by spectral matching is shown in Figure. 3 for 475 years return period.

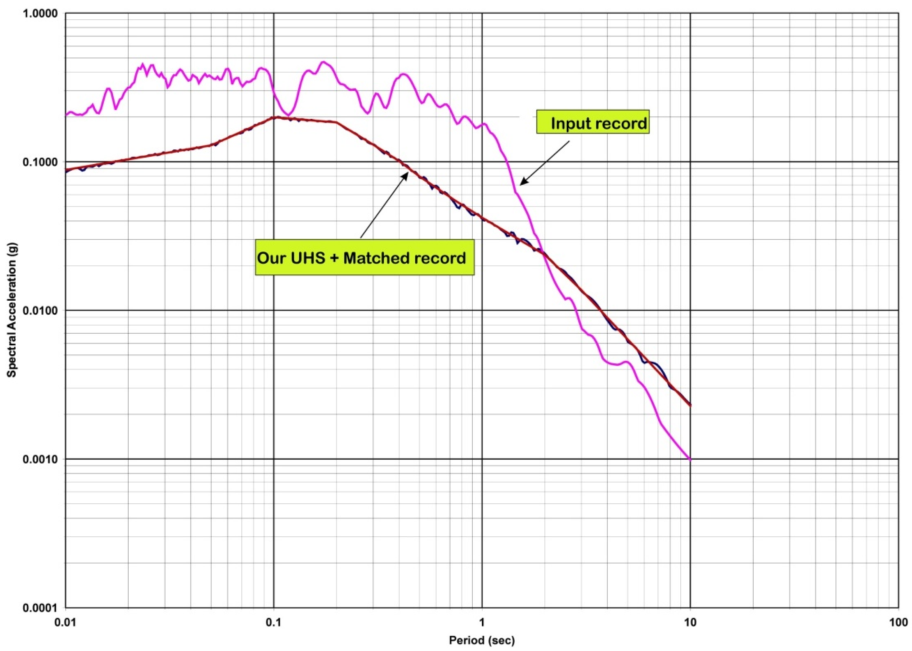

Fig. 3. Response spectrum achieved by spectral matching for 475 years.

2.3 Shallow Geophysical Survey:

The shallow geophysical techniques are most commonly used for near surface investigations (Adesola *et al.,* 2017; LI *et al.,* 2020). The geophysical techniques are cost-effective and rapid the way to obtain sub soil properties (Karslı *et al.,* 2017; Rehman *et al.,* 2016a: Olasunkanmi *et al.,* 2020). Shallow geophysical techniques are usually applied to investigate the Depth, thicknesses, composition and dynamic behavior of subsurface sediments and soils. Multichannel analysis of surface waves (MASW) is a geophysical technique for shallow subsurface exploration that has been effectually utilized for local site effects evaluation (Anbazhagan *et al.,* 2013; Kanlı *et al.,* 2006; Mahajan *et al.,* 2007; Miller *et al.,* 1999a; Miller *et al.,* 1999b; Rehman *et al.,* 2016b; Rehman *et al.,* 2018a; Xia *et al.,* 2000 ; Anukwu *et al.,* 2018; Liu *et al.,* 2020; Mogren, 2020; Tap *et al.,* 2020).Recent advancements in data processing especially application of genetic algorithm has enhanced the subsurface visualization.

In the current study, 13 seismic refraction and 66 MASW profiles acquired in study area are utilized (Figure. 4a). The refraction profiles are acquired at different locations in the study area. The refraction profile total length is 115 meters with five shots for each profile. The major goal of the MASW survey is to calculate the one-dimensional (ID) shear wave velocity of soil layers and density information. The MASW data is acquired using 4.5 Hz geophones with help of sledge hammer as source. The 24 channel Geometrics system (StrataVisor seismograph) is employed for data recording. The geophone spacing is kept one meter and the length of each MASW profile is 63 meters. The dispersion curves are generated and inverted to obtain one dimensional shear waves profile for subsurface. One dimensional shear wave velocity profiles are generated to be used for site response analysis (Figure. 4b & 4c).

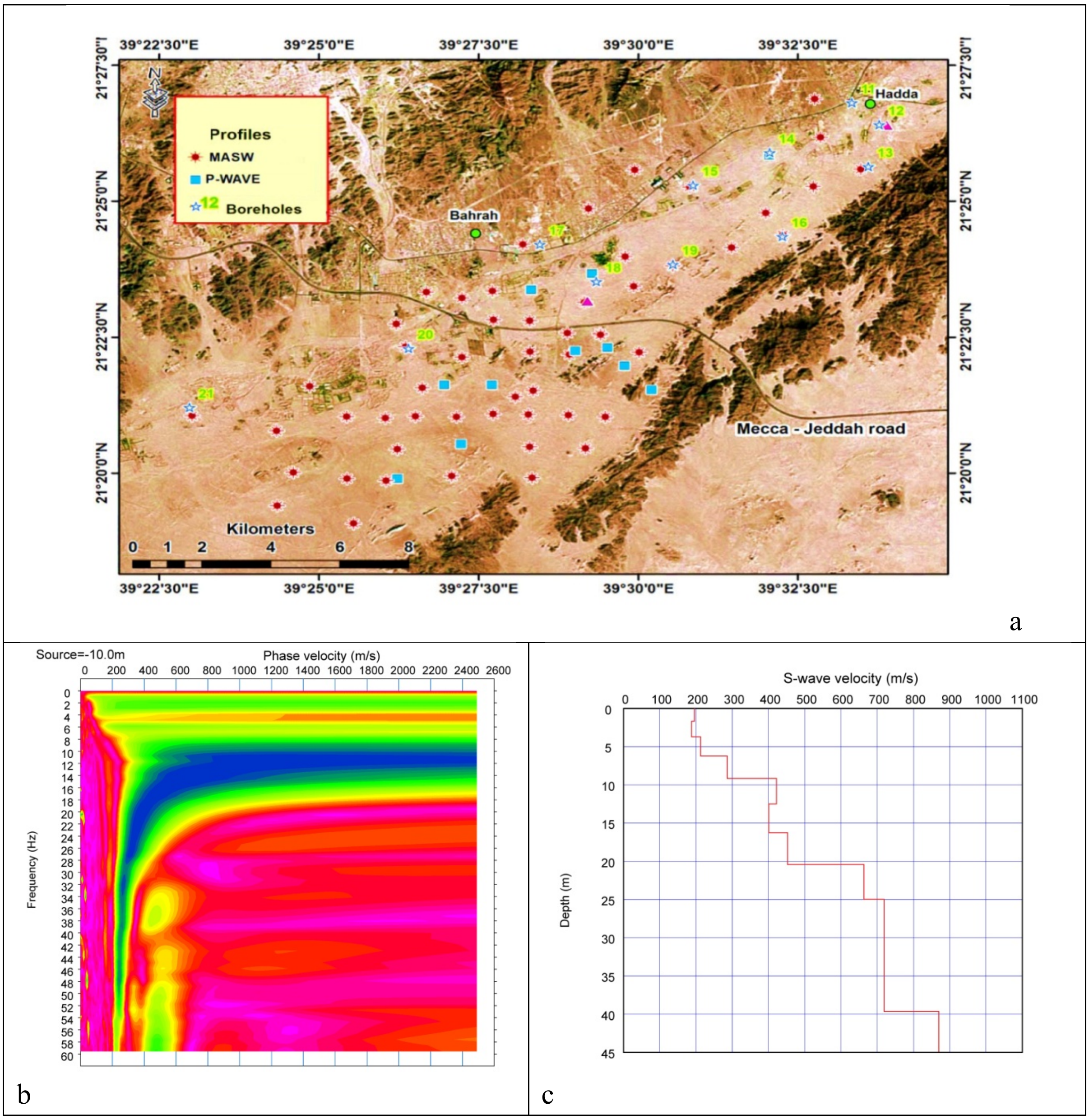

Fig. 4. a) Location map of shallow geophysical survey, b) Dispersion curve for acquired MASW Profile, c) 1D shear wave velocity profile

2.4 Site Response Analysis:

Site response analysis is one of the important steps in evaluating soil conditions under earthquake excitation. It yields site based ground vibration characteristics resulting from earthquake excitation. The site response analysis is mainly conducted for estimation of the site's ground amplification factor, peak ground velocity (PGV), and peak ground acceleration (PGA), or spectral accelerations (SA) (Anastasiadis *et al.,* 2001; Ding *et al.,* 2004; Pitilakis *et al.,* 2004).

The input of site response analysis include, strong motion earthquake data, surface and subsurface lithological information, thickness of subsurface lithologies, shear waves velocity, density information of subsurface lithologies and depth to bedrock at the site. Unfortunately, for Bahrah area, there is a lack of strong motion data records. This problem was solved through deaggregation and spectral matching for PSHA result of Rehman *et al.,* (2018b) . The results obtained from the spectral matching serve as input parameter for site response analysis.

The other input parameters are 1D shear wave velocity profiles (MASW results), subsurface density information (seismic refraction profiling), and lithological information.

Results from spectral matching, 1D shear wave velocity, density information from MASW, and lithological information from available borehole data are integrated to run site response analysis in Shake 91+ code, available in the Ez-Frisk 7.52 software. The site response results are used to generate soil maps in terms of amplification and ground acceleration at top soil (Figure. 5 a & b).

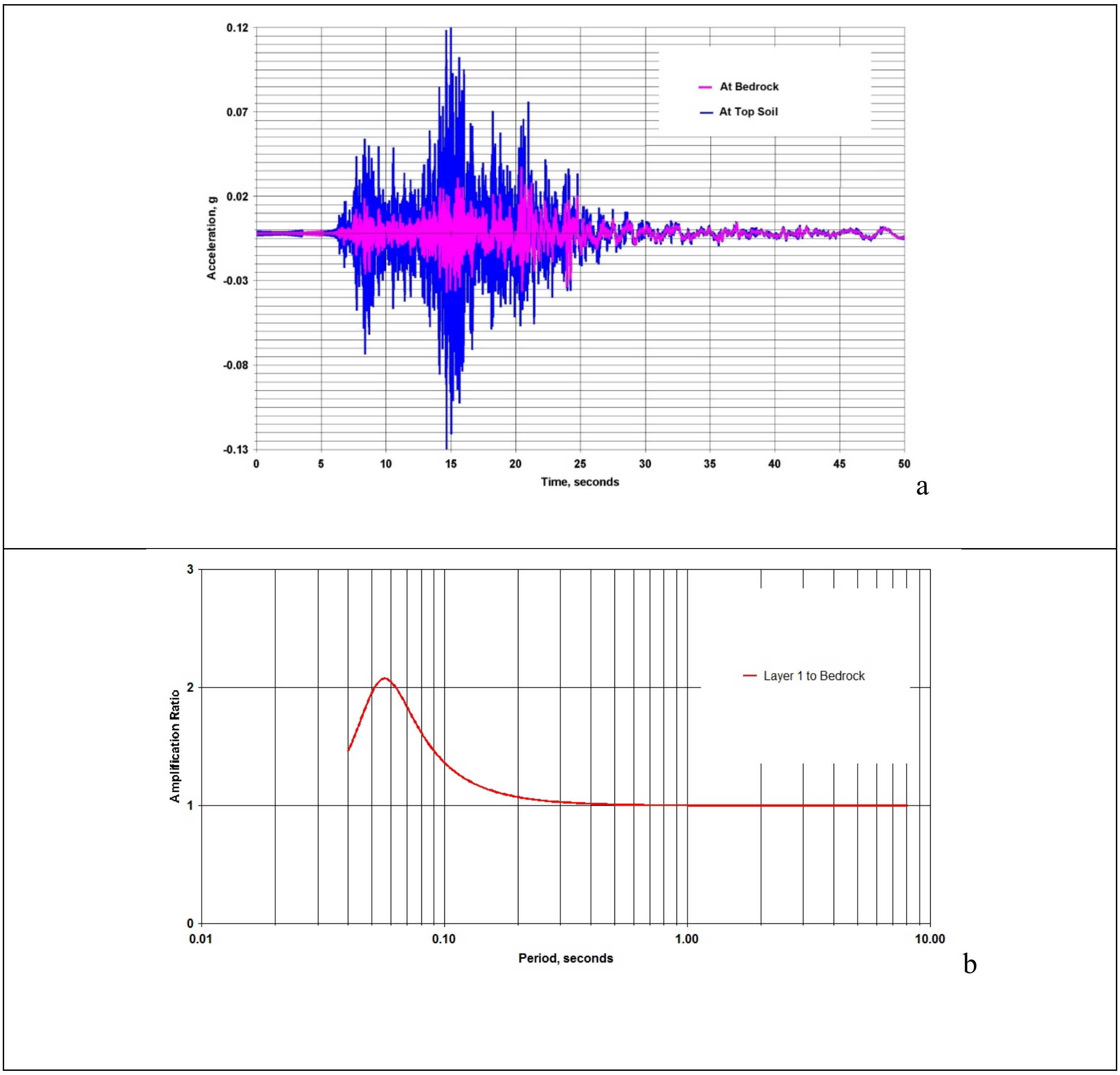

Fig.5. a) Result of site response analysis for ground motion acceleration in a site near borehole, b) resultant site amplification at top of soil for same location

3. Results and Discussion

The site response analysis is carried out for 475 years return periods. The final output for amplification and acceleration is obtained by averaging the near and far field effect calculations for 475 years return period. This task is achieved by making two runs for each site point for 475 years return periods for PGA, 0.1s, 0.2s and 2s seconds. The site response analysis provided ground accelerations and site amplifications at selected spectral periods. The results of site response analysis are interpolated to generate maps in terms of ground acceleration and ground amplification at top soil for various spectral periods.

The site response analysis requires strong motion records at the site. The study area lacks strong motion records. In order to obtain strong motion record compatible with PSHA results, spectral matching is carried out. Spectral matching requires a controlling earthquake scenario which stems hazard to the site. The deaggregation is applied to PSHA results to obtain the controlling earthquake scenario. Spectral matching in the current study is conducted using the Ez-Frisk 7.52 software. The spectral matching results, 1D Vs profiles from geophysical survey, and subsurface lithological information are used as inputs in the SHAKE91+ code to obtain the soil effect. The site response outcome is site amplifications and ground motion accelerations at soil surface with a critical value of 5% damping.

Most of the amplification factors calculated for 475 years return period at PGA (Figure. 6) ranges from 1.0 to 2.7 and spectral period 0.1 second (Figure. 7) ranges from 1.0 to 3.46. Higher amplifications are noticed along the valley trend at spectral period 0.2 second and spectral period 0.3 second. The soil amplifications factor at spectral period 0.2s (Figure. 8) ranges from 1.0 to 3.4, and 0.3s (Figure. 9) ranges from 1.0 to 3.2.

The ground response spectra with a critical value of 5% damping are also calculated by site response analysis in SHAKE 91+ beside amplification factors. The ground acceleration at PGA (Figure. 10) for 475 years returns period ranges from 0.09 to 0.22g. The soil accelerations (acceleration at the surface of the soil) for spectral period 0.1 second (Figure. 11) ranges from 0.20 to 0.66g. The ground acceleration for the top soil at 0.2 second (Figure. 12) and 0.3 second (Figure. 13) for 475 years return period nearly adopts the trend of PGA. The acceleration ranges from 0.18 to 0.5g for 0.2 second and 0.33 to 0.86 g for 0.3 second. The higher accelerations are observed northeast to southwest.

Rehman et al. (2016b) carried out site characterization for study area (Figure. 14). Soil classification maps are correlated with our results of site response analysis. The amplification character varies throughout the site area. The high amplification character can be attributed to D class sites and the lower limit of C class for the majority of the investigated site points at nearly all spectral periods. Significantly higher amplifications are present in the southern part of the valley. These higher amplifications at this spectral period are attributed to deep bedrock and a possible site belongs to lower limit of C class. However few sites at the upstream of the valley, northeast direction indicate high amplifications. The trend for higher acceleration is nearly aligned along the main valley trend. This affinity is linked with deep sediments and lower range of C class.

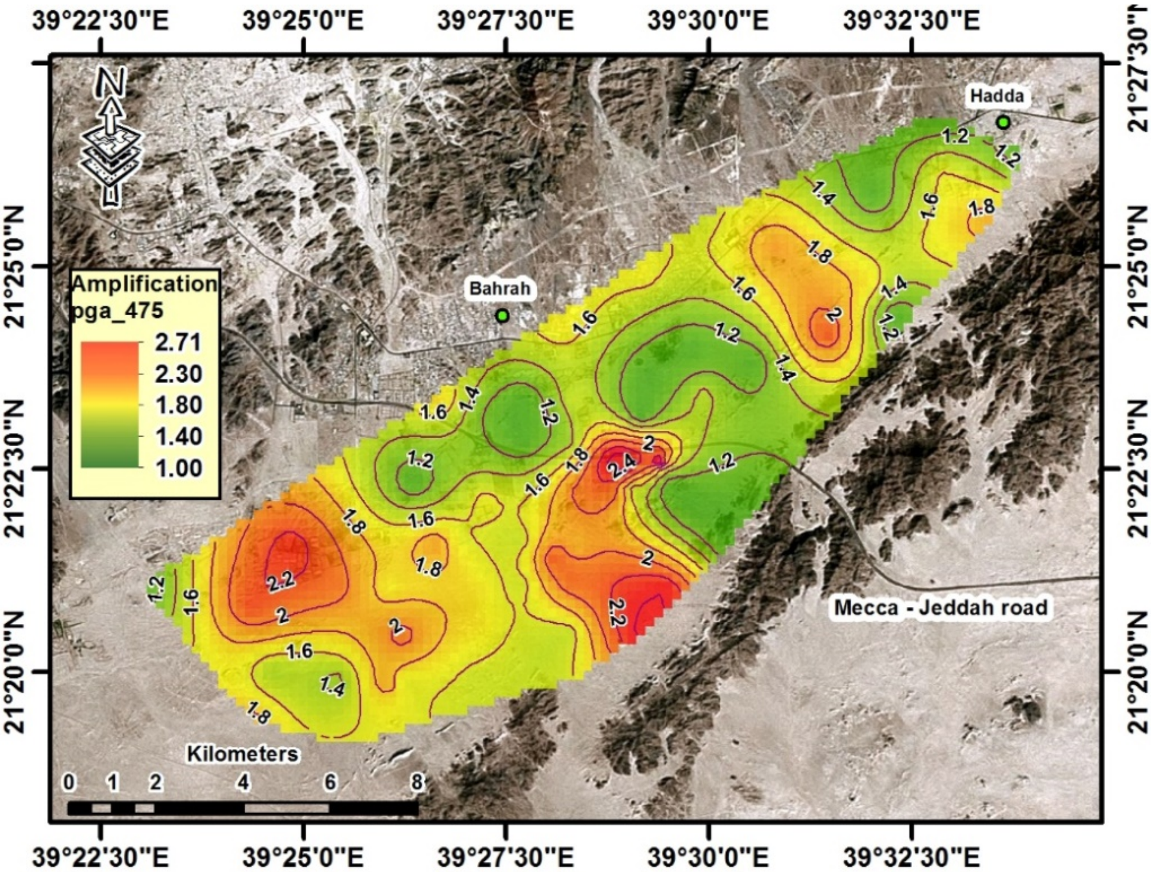

Fig. 6. Soil amplification map at PGA for 475 years return period.

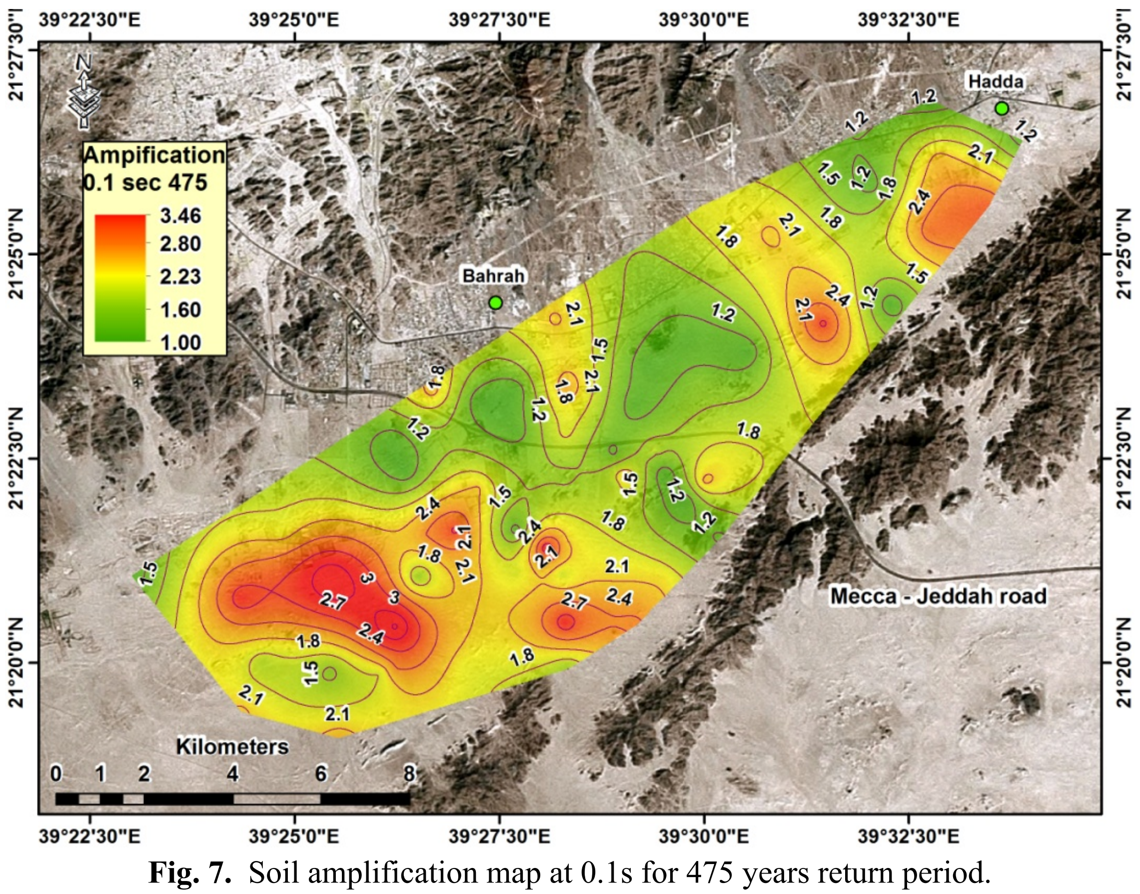

Fig. 7. Soil amplification map at 0.1s for 475 years return period.

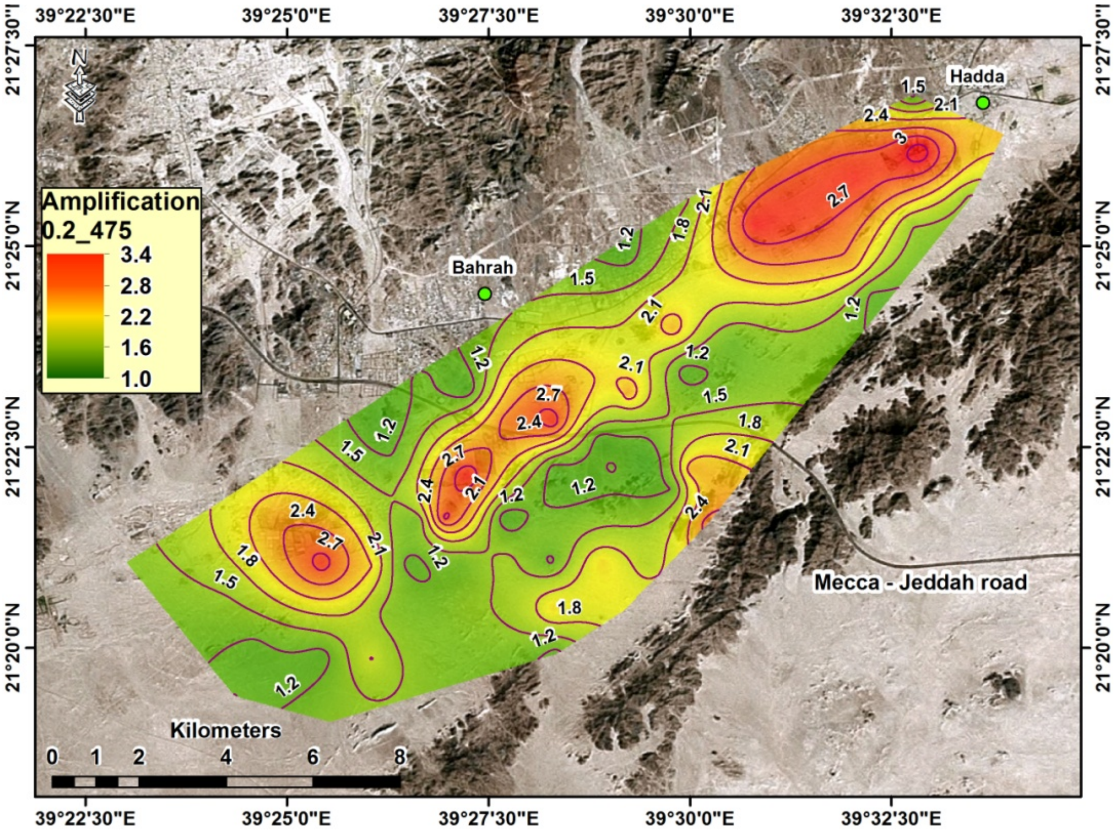

Fig. 8. Soil amplification map at 0.2s for 475 years return period.

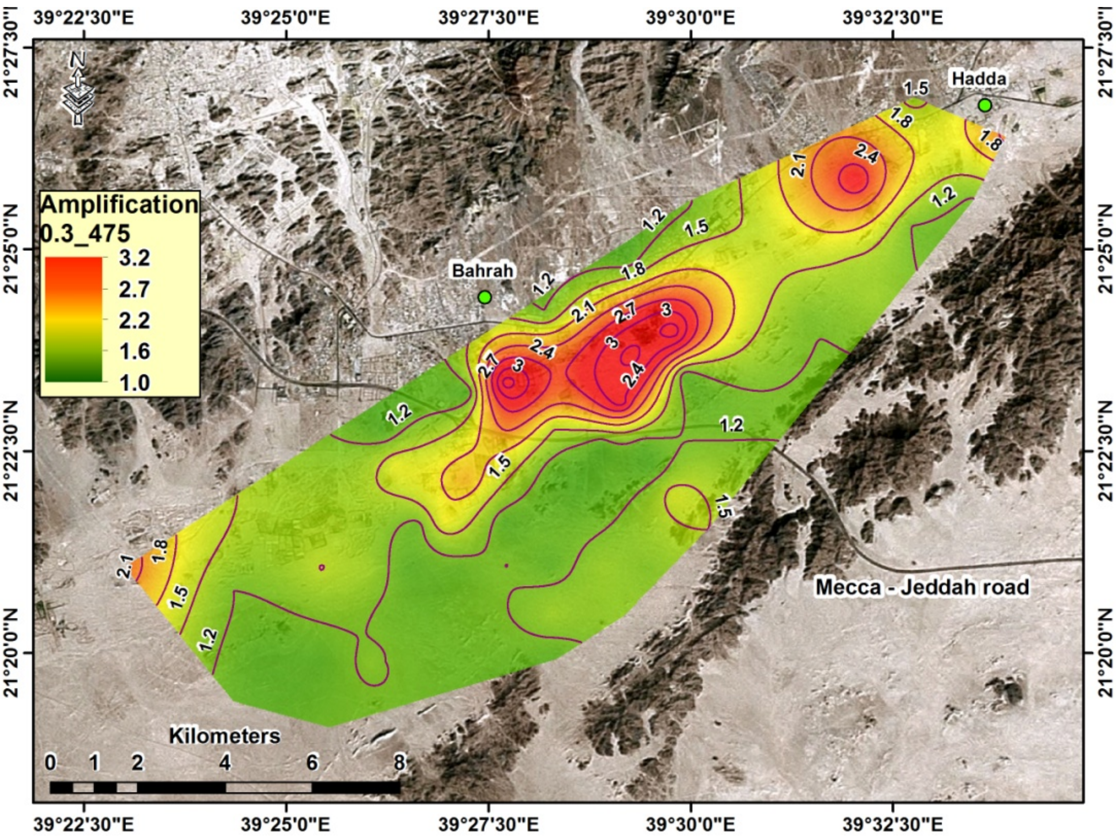

Fig. 9. Amplification map at 0.3s for 475 years return period.

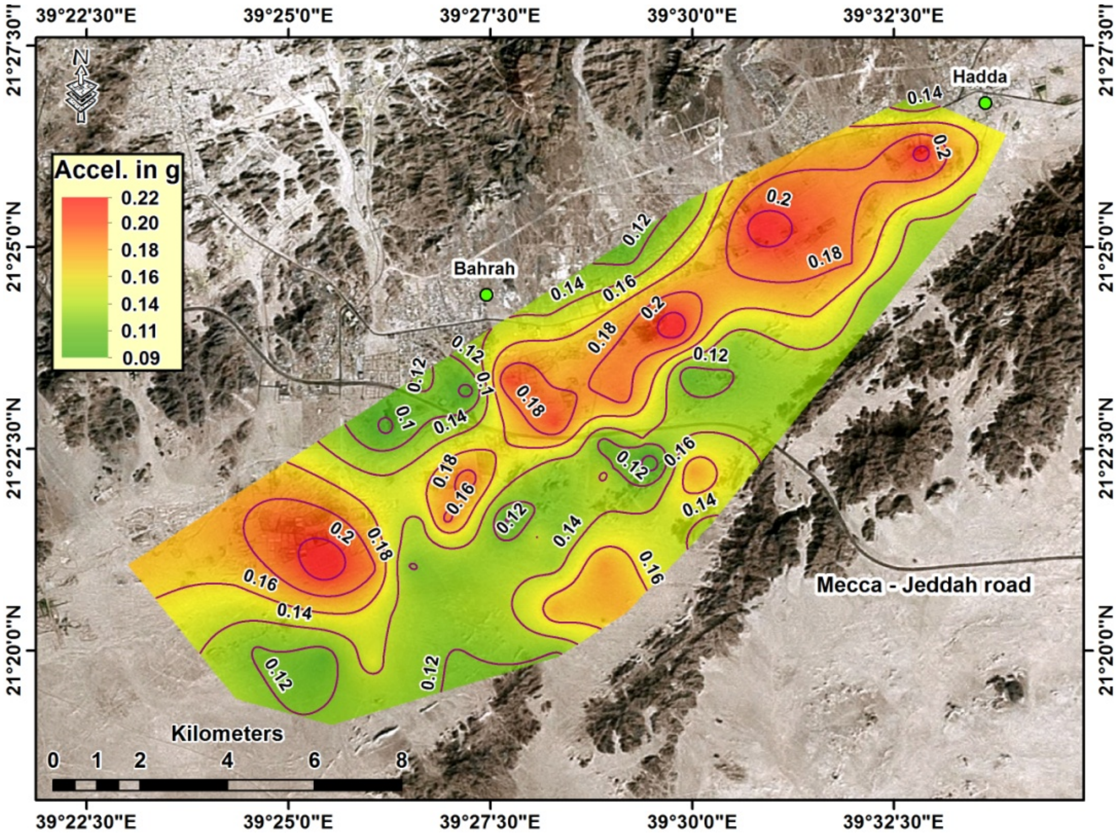

Fig. 10. Ground acceleration map at PGA for 475 years return period.

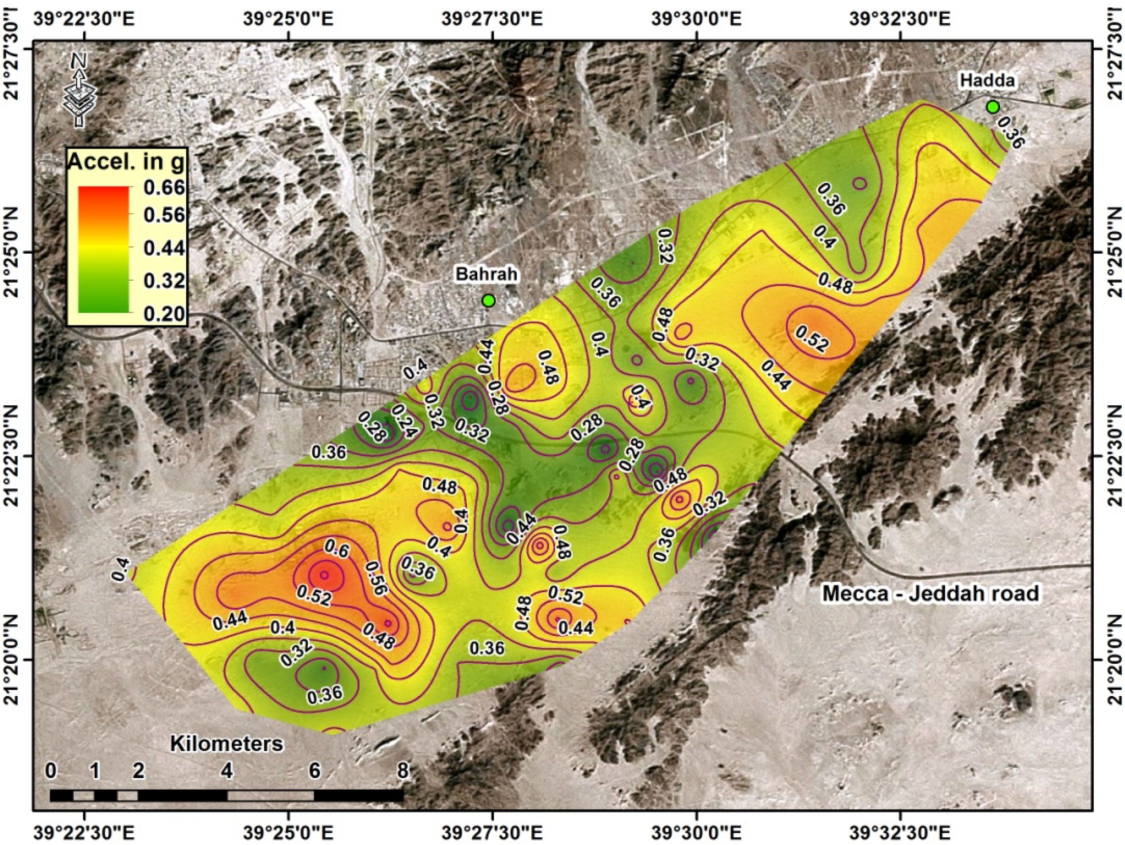

Fig. 11. Ground acceleration map at 0.1s for 475 years return period.

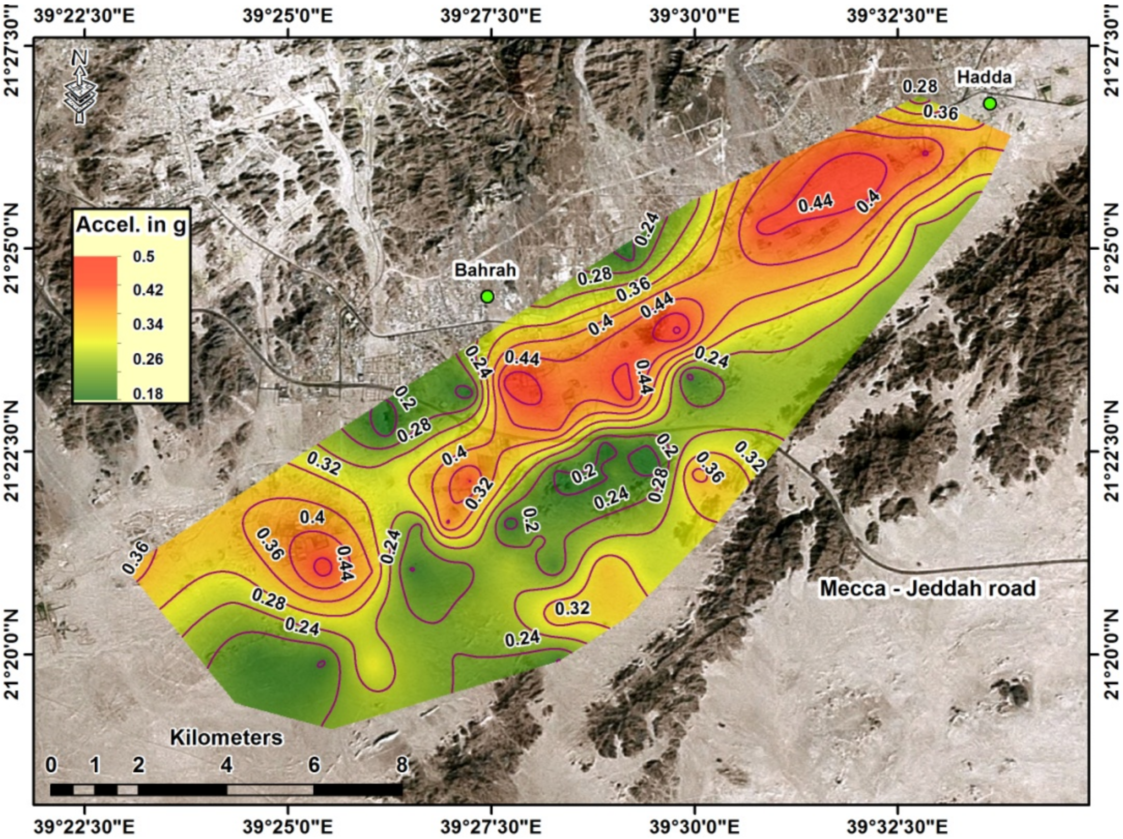

Fig. 12. Ground acceleration map at 0.2s for 475 years return period.

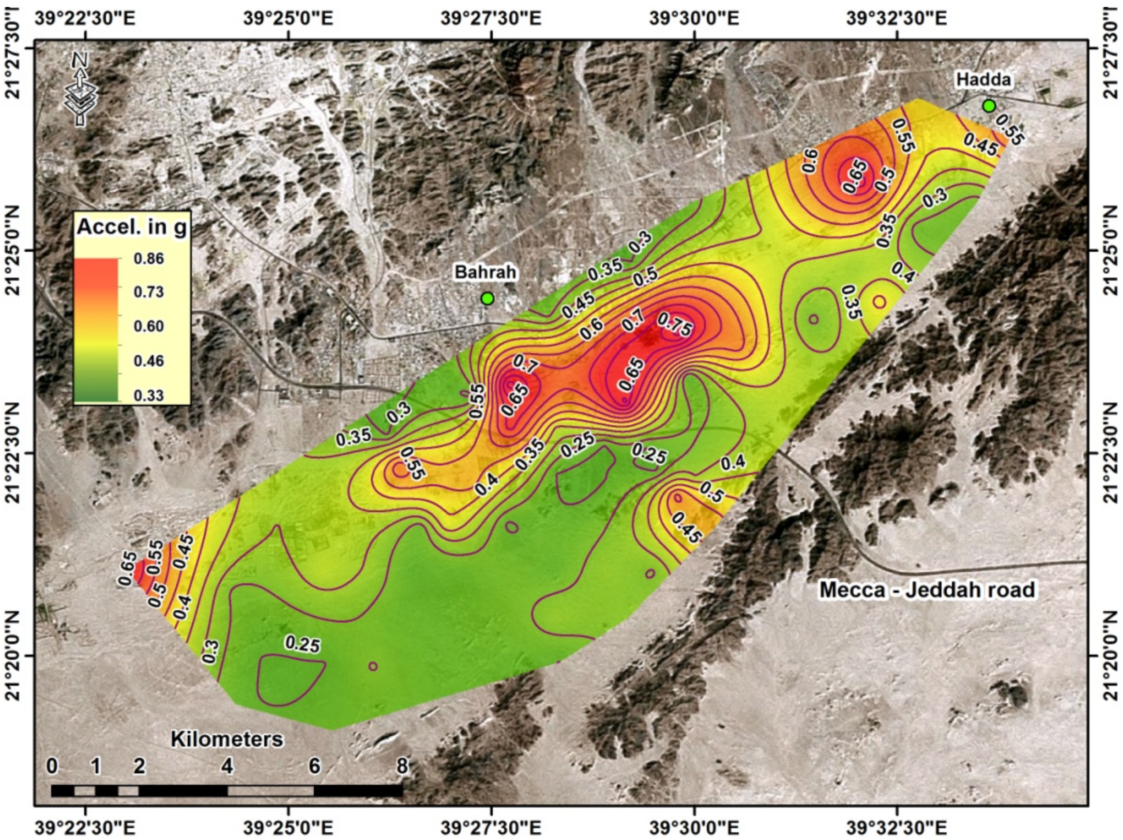

Fig. 13. Ground acceleration map at 0.3s for 475 years return period.

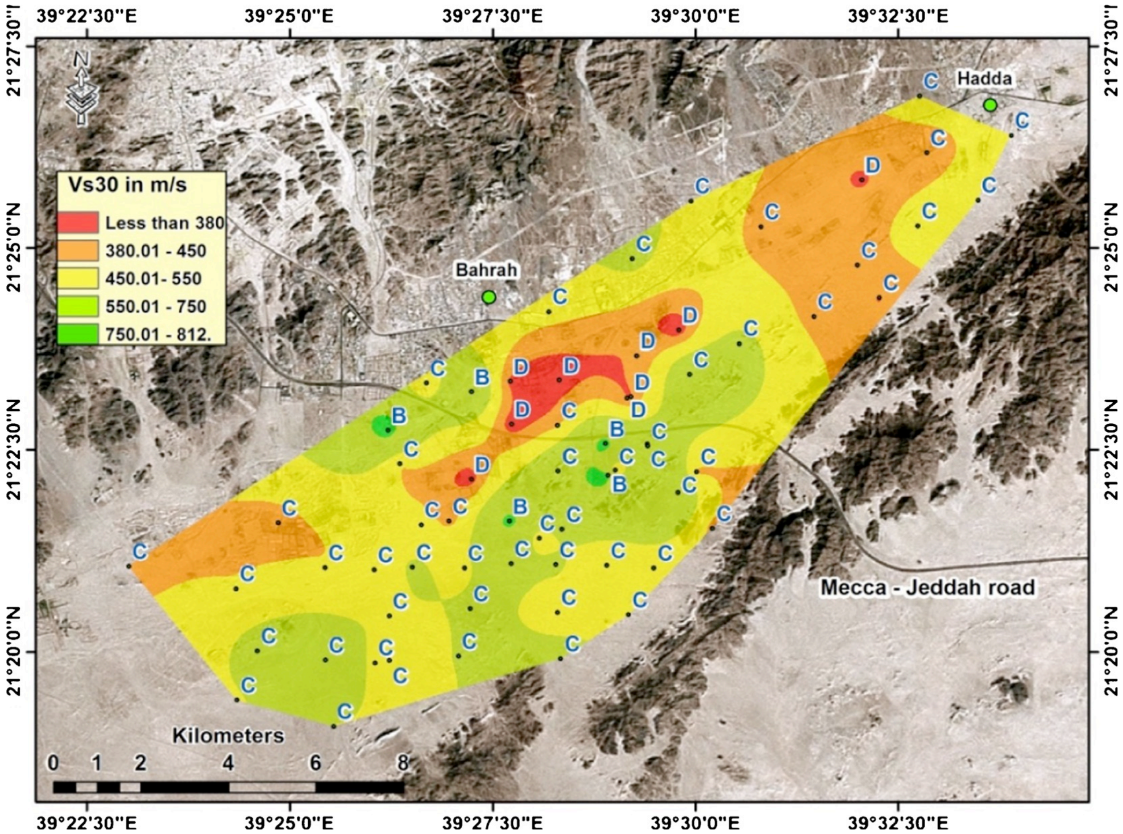

Fig. 14. Soil Classification map for study area [Rehman *et al.,* 2016b]

4. Conclusions

This study provides local site effects in terms of amplification factor and ground surface acceleration maps in Bahrah, western Saudi Arabia. The Bahrah town is approximately located at mid-way between Jeddah and Makkah City. This rapidly growing town in near future can key strategic location for transportation network and urban development. The site response analysis is carried out using the results from spectral matching, 1D Vs profiles, and available borehole data. The SHAKE-91 analysis provides soil amplification character and ground motion acceleration at soil top. Amplification factor for ground vibrations ranges up to 3.5. The maximum surface ground motion values are associated with the 5% damped horizontal spectral acceleration with a period of 0.3 second for 475 years return periods. The amplification character varies throughout the site area. The high amplification character can be attributed to presence of deep sediments for the majority of the investigated site points at nearly all spectral periods. The higher acceleration at different spectral periods is attributed to existence of thick sediment cover and deep bedrock. Significantly higher amplifications are present in the southern part of the valley. However few sites at the upstream of the valley, northeast direction indicate high amplifications.

The study area is uninhabited, which is one of the most important features of this area and has a potential to grow in near future. This study can provide assistance to any civil work opportunity to be carried out in future. These maps will assist in the structural designing of the critical buildings. These maps will assist a better understanding of the potential spatial distribution of seismic risk. These efforts will provide a cogent basis for policy making and planning regarding mitigation of earthquake hazards. These maps produced through this research study can serve as an essential tool for urban planning and to build earthquake crisis rescue plans. The organizations including government sector, private industry, transportation networks, hazardous goods transportations, and storage department, community planners and utility operators can benefit from this information.

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