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DETERMINATION OF SHEAR WAVE VELOCITY PROFILE OF SEDIMENTARY DEPOSITS IN BAM CITY (SOUTHEAST OF IRAN) USING ONE-POINT MICROTREMOR MEASUREMENTS

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ABSTRACT

Site effect has been known as the major cause of large ground amplifications during several recent catastrophic earthquakes. Consequently, the evaluation of site effect is an important factor that must be considered in mitigation of earthquake hazards. Shear wave velocity is a key parameter that controls seismic response of a site. Hence its profile must be identified down to the seismic bedrock. Generally geotechnical or even geophysical methods are expensive and time consuming for this purpose. As an economical and practical substitute, microtremor measurements can be used. In order to investigate the reliability of shear wave velocity (V_s) profiling by using microtremors, a series of one-point microtremor measurements have been conducted in Bam city (southeast of Iran) which experienced the damaging earthquake of December 2003. Microtremor measurements included 49 one-point observations distributed throughout the city. Based on the H/V spectrum of microtremors, shear wave velocity profiles were determined at the measurement sites using nonlinear inverse analysis. Reliability of the method was investigated, comparing results of microtremor measurements and seismic refraction method. Ultimately, using all inverted profiles, seismic microzonation maps were developed for Bam city.

Keywords: Microtremor Measurements, V_s Profile, H/V Spectral Ratio, Nonlinear Inverse Analysis

INTRODUCTION

The effects of geometry of subsoil structure, soil types and variation of their properties with depth and surface topography on ground motion are technically referred to as site effects. Site effects have been known to be the most influencing factor causing large amplifications of ground motion and hence intensive damage during several past destructive earthquakes (e.g., Michoacan 1985 Mexico, Loma Prieta 1989 California, Kobe 1995 Japan and Kocaeli 1999 Turkey). Therefore, the evaluation of site effects is one of the key factors that must be considered when discussing prevention or mitigation of seismic hazards.

Present approaches to site effect evaluation are either empirical or theoretical. Theoretical modeling requires accurate knowledge of the geometry and the shear wave velocities (V_s) of sedimentary deposits and the basement as the key parameters controlling seismic response of the site. Most of the field tests currently used for determining V_s require boreholes and therefore, may not be economical and practical in all cases. Moreover, some methods that use the characteristics of surface waves have received increasing interest in recent years. These methods can be done conveniently on the ground surface without the need of boreholes. Surface wave methods are divided into two major categories i.e.

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active and passive methods. At the present, microtremor measurements are used as an economical and practical tool in site effects studies. In a number of studies, the frequency-wavenumber (f-k) spectral analysis (Capon, 1969) and the spatial autocorrelation (SPAC) analysis (Aki, 1957) of microtremor array measurement have been used successfully to extract the Rayleigh wave dispersion characteristics. Additionally, it has been revealed that the V_s profile of a sedimentary deposit can be successfully obtained by the inverse analysis of the dispersion curve of Rayleigh waves (e.g., Horike, 1985; Matsushima and Okada, 1990a; Tokimatsu et al, 1992b; Kavand and Ghalandarzadeh, 2006). However, microtremor array measurements may encounter some difficulties especially in urban areas. Besides, microtremors have received most interest due to the convenience of their measurements at the ground surface. In a number of recent studies, use of microtremor one-point measurements for V_s profiling have been studied (Arai and Tokimatsu, 2004), in addition to their conventional usage including determination of site natural site period and amplification factors.

In this paper, the possible use of one-point microtremor measurements for determining the shear wave velocity profile of sedimentary deposits in Bam city is investigated. For this purpose, 49 one-point microtremor measurements were performed in Bam city, which experienced the destructive earthquake of December 2003. Identification of local site conditions in Bam city is very useful in determination of their effects on ground motion and building damage distribution during the 2003 Bam earthquake. By using microtremor from one-point measurements, V_s profiles of sediments were determined through an analytical procedure. This procedure employs the nonlinear inverse analysis of H/V spectral ratio of microtremors. Finally, the reliability of the method is investigated, comparing inverted V_s profiles with results of other methods in the area.

MICROTREMOR MEASUREMENTS

Microtremor measurements were performed in Bam city including 49 one-point and 5 array observations distributed over the area. However, in this paper, only the one-point measurements data are considered. Locations of microtremor observation points are shown in Figure 1. The equipment used to record the microtremors was a seismometer with natural frequency of 0.5 Hz. Seismometers consist of three-component velocity sensors, which can record the horizontal motion (in both longitudinal and latitudinal directions) and the vertical motion. Ground motions were observed for 2 minutes and the sampling frequency was 100 Hz for each point. The orientation of equipments in all locations was N-S.

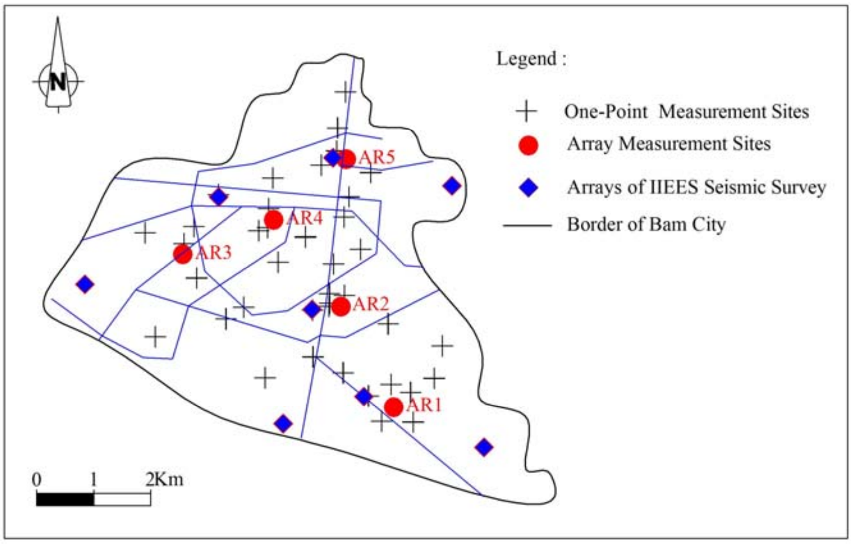

Figure 1. Microtremor measurement points in Bam city

MICROTREMOR H/V ANALYSIS FOR DETERMINATION OF V_S PROFILE

The evaluation of V_s profile from one point microtremor measurements consists of three main stages:
(1) determination of observed H/V spectral ratio of microtremors
(2) determination of theoretical H/V spectral ratio of microtremors
(3) estimation of shear structure based on nonlinear inverse analysis of microtremor H/V spectra

Observed microtremor H/V Spectral Ratio

In the first stage, observed microtremor H/V spectra were obtained at one-point observation points. To process microtremor data, a computer program was developed in MATLAB, using the Signal Processing Toolbox. Based on the Nakamura's technique (Nakamura, 1989), the H/V spectral ratio is defined as:

$$(H/V)(\omega) = \sqrt{\frac{F_{NS}(\omega) + F_{EW}(\omega)}{F_{UD}(\omega)}} \tag{1}$$

in which F_{UD} is the Fourier amplitude of microtremor vertical motions. Also, F_{NS} and F_{EW} are the Fourier amplitudes of the two orthogonal horizontal copmonents.

In order to find the best processing method, authors gave a special emphasis to the processing procedure of microtremors as signals. Based on the study of Motamed and Ghalandarzadeh (2002), on the processing of microtremors, a time window length of 20 seconds with an overlapping value of 10% and a Hamming window type were used in the development of observed H/V spectra.

Sample H/V spectra obtained at sites MT49 and MT28 are shown in Figure 2. Primarily, based on the obtained results at different points, iso-period and iso-amplification maps of Bam city can be developed.

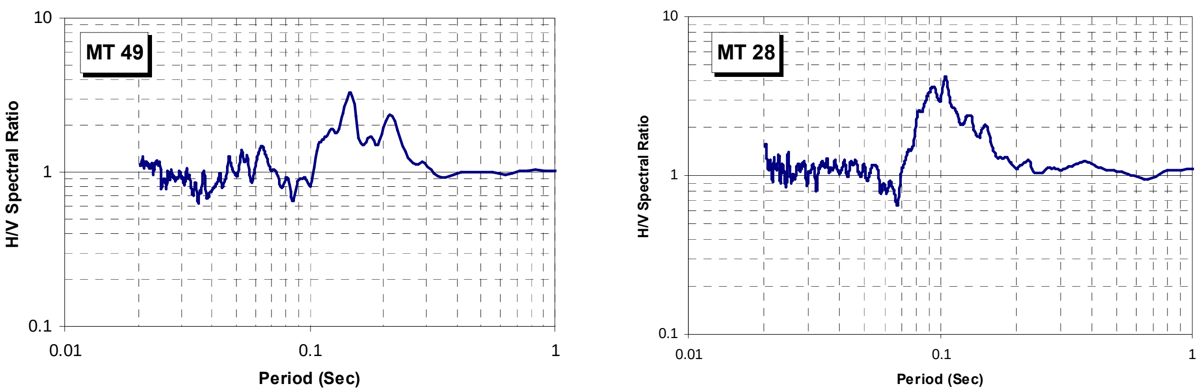

Figure 2. Sample microtremor H/V spectra at sites MT49 and MT28

Theoretical microtremor H/V Spectral Ratio

For the inversion process it is necessary to have the theoretical H/V spectral ratio. Here, the theoretical formulation of H/V is reviewed. According to Arai and Tokimatsu (2000), the H/V ratio of surface waves for simulating the H/V spectral ratio of microtremors can be expressed as:

$$(H/V)_S(\omega) = \sqrt{\frac{P_{HS}(\omega)}{P_{VS}(\omega)}} = \sqrt{\frac{P_{HR}(\omega) + P_{HL}(\omega)}{P_{VR}(\omega)}} \tag{2}$$

in which $(H/V)_S(\omega)$ is the H/V spectral ratio of surface waves. $P_{HS}(\omega)$ and $P_{VS}(\omega)$ are the horizontal and vertical powers of surface waves, $P_{HR}(\omega)$ and $P_{VR}(\omega)$ are those of Rayleigh waves and $P_{HL}(\omega)$ is the horizontal power of Love waves. Knowing the soil model parameters including the thickness, density, P-wave and S-wave velocities of layers, theoretical H/V ratio of microtremors can be obtained using equation (2). Sample theoretical H/V spectra obtained at sites MT49 and MT28 are shown in Figure 3 in solid lines. These spectra are obtained using the soil model parameters at the end of inversion process which will be described in next part.

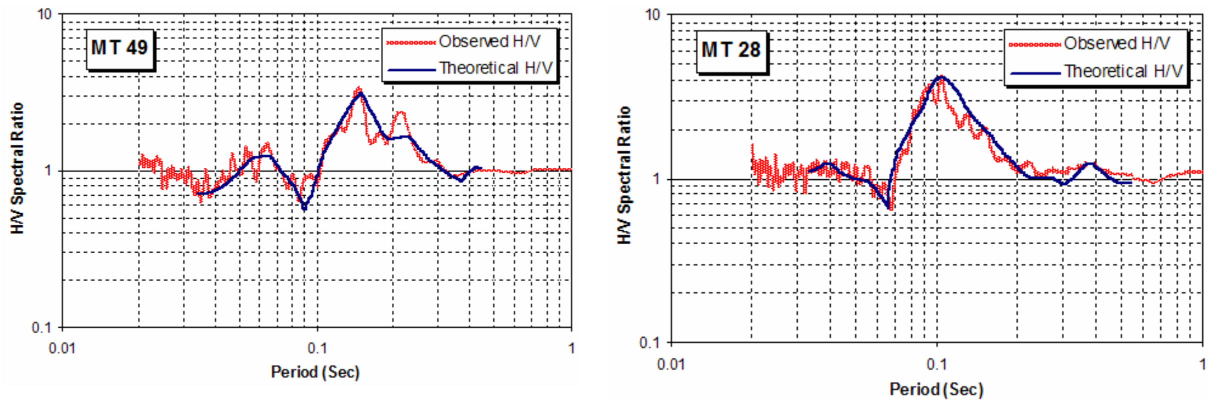

Figure 3. Sample theoretical microtremor H/V spectra at sites MT49 and MT28 (solid lines)

Inversion Process

The goal of inversion process is to find a soil layer model that satisfies the least-squares equation defined as follows:

$$\text{minimize}\left[\frac{1}{I}\sum_{i=1}^{I}\left(\frac{(H/V)_i^{observed}-(H/V)_i^{theoretical}}{(H/V)_i^{observed}}\right)^2\right] \tag{3}$$

where $(H/V)_i^{observed}$ is the observed H/V spectrum at frequency i for all I different frequencies obtained from the equation (1). Also, $(H/V)_i^{theoretical}$ is the theoretical H/V spectrum at frequency i, which is introduced in equation (2).

Different nonlinear optimizing methods have been proposed for solving least square equations in case of microtremor array measurements which are dealing with dispersion curves (e.g. Dorman and Ewing, 1962). However due to the complicated variations of H/V spectrum with frequency, only the adopted nonlinear inversion algorithms can be used. In this study the adopted algorithm introduced by Arai and Tokimatsu (2004) is used for inversion analysis of H/V spectra. The inversion process was done with an in-house computer program developed in MATLAB. In the program, the soil layer model was assumed to be horizontally stratified and consists of N layers. Because of the insignificant effects of mass density and P-wave velocity on the theoretical H/V spectrum (Arai and Tokimatsu, 2004), only the shear wave velocities and thicknesses were sought. However the inversion may not be done by considering both V_s and thickness values as unknown parameters. That is because the goal of inversion is a non-dimensional parameter (H/V) and the problem may have many solutions if both V_s and layer thicknesses be considered as unknowns. Thus, the total number of the unknown values, J, was N or $N-1$. The governing equation of the inversion problem in the matrix form is expressed as (Arai and Tokimatsu, 2004):

$$\mathbf{W}_{I\times I}\boldsymbol{\Delta}\,\mathbf{y}_{I\times 1}^{(k)}=\mathbf{W}_{I\times I}\mathbf{A}_{I\times J}^{(k)}\boldsymbol{\Delta}\mathbf{x}_{J\times 1}^{(k)} \tag{4}$$

where $\Delta y_{I\times 1}^{(k)}$ is a column vector that its elements are the misfit between the observed and theoretical H/V spectra at I different frequencies. $\mathbf{A}_{I\times J}^{(k)}$, is a matrix consisting of elements which are a kind of non-dimensional partial derivative of the theoretical H/V spectrum. $\Delta\mathbf{x}_{J\times 1}^{(k)}$, is defined as a normalized correction column vector. Finally, $\mathbf{W}_{I\times I}$, is a diagonal matrix whose elements are weighting factors. Through the inversion process, the correction vector is obtained from the equation (4) and then the soil layer parameters are updated. This procedure is repeated until the soil model satisfies the least-squares equation defined in equation (3).

Geotechnical and geophysical investigations in Bam city generally show that variation of soil layer properties with depth is not very complicated and in most parts of the city, there are three or four layers with different properties (Ghalandarzadeh et al. 2004). Therefore, the analytical soil models in all 49 sites were assumed to consist of four horizontally stratified layers overlying an elastic half-space. In this study, shear wave velocities were sought and the layer thicknesses are assumed to be predefined from the inversion results at array measurement sites (Kavand and Ghalandarzadeh, 2006). As a result the total number of unknown parameters is 4 for all sites. Figure 4 shows the shear wave velocity profiles inferred from the inverse analyses at five sample sites. Seismic bedrock usually is considered as a layer with V_s value grater than 750 m/s. As seen in Figure 4, almost all obtained profiles reached to the seismic bedrock. The theoretical H/V spectra for the inverted soil layer models at sites MT28 and MT49 are also shown in Figure 3 in solid lines, which show a good agreement with the observed H/V spectra of microtremors confirming the soundness of the inversion procedure.

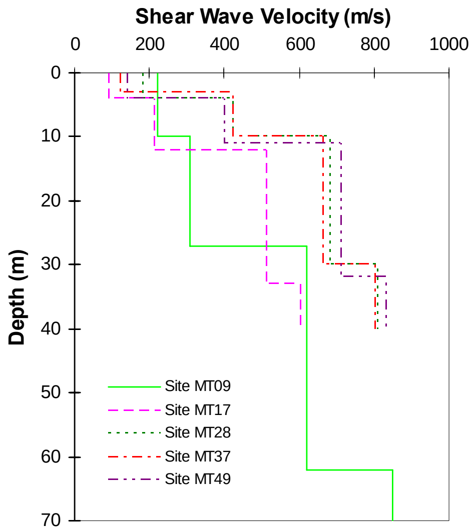

Figure 4. V_s profiles at 5 sample sites obtained from the inverse analyses

RELIABILITY OF V_S PROFILES DETERMINED FROM INVERSION PROCESS

In order to investigate the reliability of the inverted V_s profiles, a comparison was made between results of this study and those of other V_s profiling methods. International Institute of Earthquake Engineering and Seismology (IIEES) has carried out a series of seismic refraction surveys in Bam city. IEES array 2, 4, 7 and 9 are located in less than 100 meter far from sites MT28, MT26, MT42 and MT12 respectively. These data are compared with the inverted soil profiles in Figure 5. As seen in this Figure, inverted profiles at these sites are relatively in agreement with V_s profiles determined by seismic refraction method. The differences between V_s profiles, especially in site MT26 are mostly due to a distance about 100m between microtremor measurement stations and IIEES sites. However, V_s profiles obtained from these two methods at other sites are generally in consistency with each other.

As seen in figure 5, seismic refraction method was not able to detect minor variation of V_s at sites MT26 and MT42 and therefore gave the last layer thickness more that its real value.

It should be noted that microtremor method may not be able to detect the exact number of different geological layers in a site. However, it can give the variation of V_s with depth in a single layer. In practice there is such a variation because V_s values vary with depth even in a single layer. Microtremor method has the advantage of increasing the resolution of obtained V_s profile by simply increasing the number of layers considered in analytical model. It can be concluded that combination of microtremor one-point and array measurements are useful for determination of V_s profile with a reasonable accuracy considering the convenience and speed of this method.

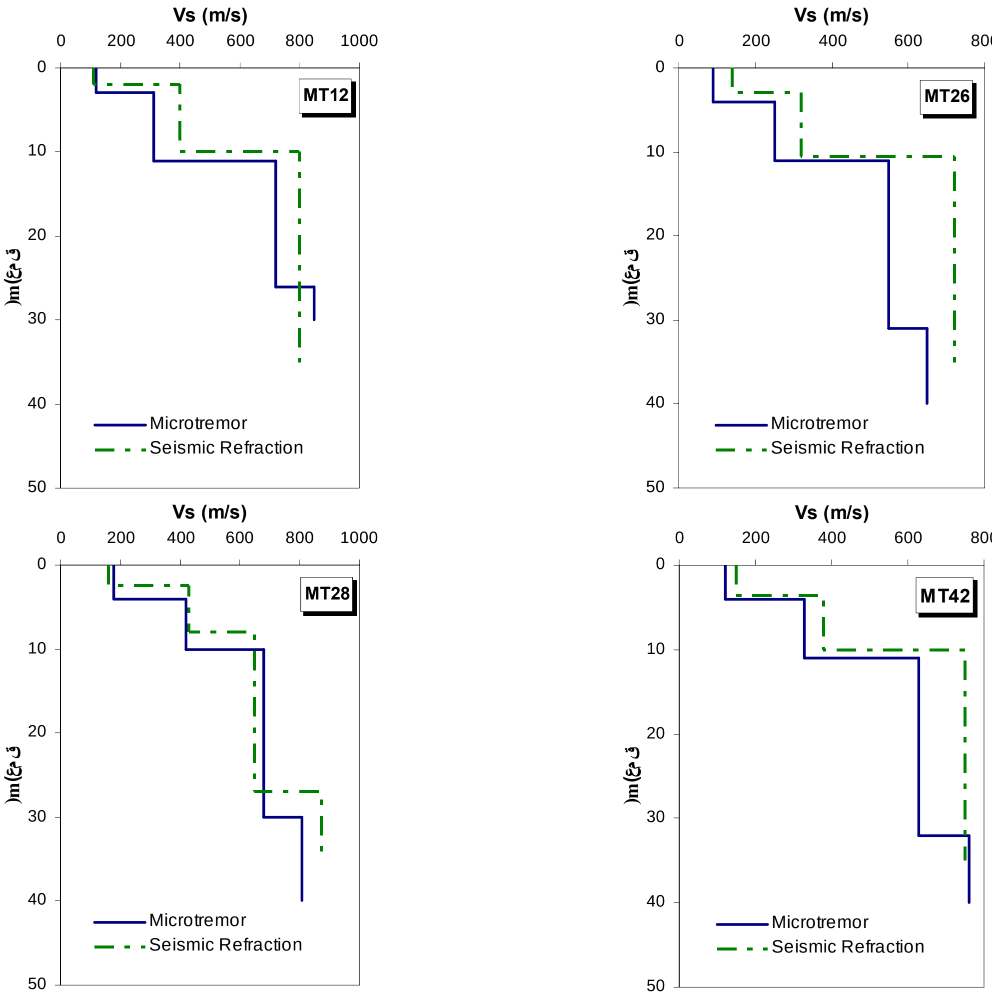

Figure 5. Comparison between inverted soil profiles and results of seismic refraction method

SEISMIC MICROZONATION MAPS OF BAM CITY

Average shear wave velocity at the depth of 30m ($\overline{V}_s^{30}$) has been widely used in most seismic code of practices for classification of sediments. Therefore determination of this parameter is very useful in development of seismic microzonation maps of sediments. Average shear wave velocity is defined as:

$$\overline{V}_s^{30} = \frac{\sum d_i}{\sum (d_i / V_{Si})} \tag{5}$$

in this equation, d_i and V_{Si} are the values of thickness and the shear wave velocity in each layer, respectively. Considering that the microtremor measurements have been done in almost whole regions of Bam city, microzonation map of $\overline{V}_s^{30}$ is developed for Bam city based on the inverted V_s profiles. This map is presented in figure 6. Microzonation map of Bam city for soil classes is also obtained based on the soil classification criteria introduced in Iranian code of practice for seismic design of buildings (Standard No.2800) and presented in figure 7.

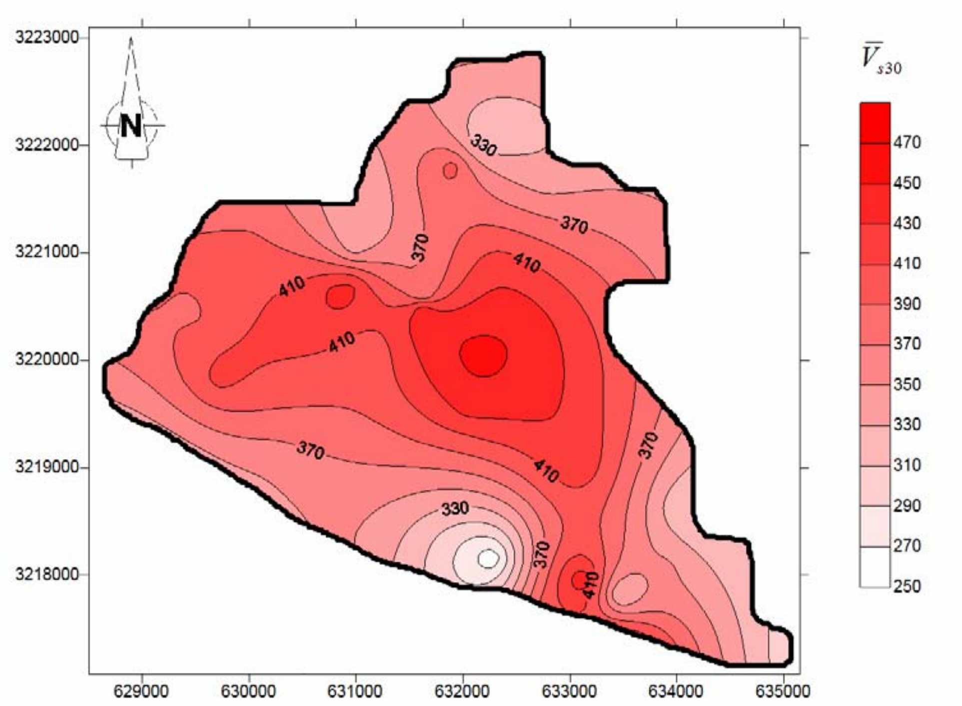

Figure 6. Microzonation map of Bam city for $\overline{V}_s^{30}$

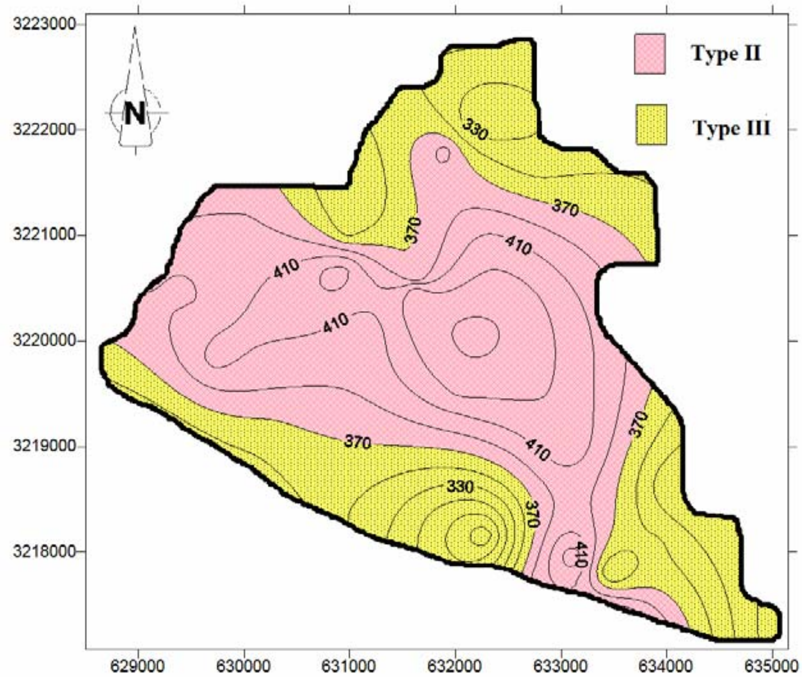

Figure 7. Microzonation map of Bam city for soil classes based on the standard No.2800

CONCLUSIONS

It is already shown that the seismic ground motion amplifications is directly related to the V_s values of the subsurface soil and the bedrock. Furthermore, determination of V_s profiles is one of the key actions of seismic microzonation studies, site response analysis and evaluation of liquefaction potential. As a result determination of V_s profile is very important for evaluation and mitigation of seismic hazards. For this purpose, microtremor measurements can be conveniently used as a simple tool. In this study, the possibility of V_s profiling by use of one-point microtremor measurements was investigated. For this, a series of microtremor measurements was conducted in Bam city. First, observed H/V spectrum of microtremors was obtained. Then, shear wave velocity profiles were determined by using theoretical H/V spectrum and based on a nonlinear inversion process. Ultimately, inverted V_s profiles were compared with other available V_s data in Bam city. The inverted profiles are resonablly in agreement with results of seismic refraction method. Ultimately, based on the inverted V_s profiles at 49 sites, distributed throughout Bam city, seismic microzonation maps of the city were obtained. This shows that microtremor measurements are useful as a simple and economical method for V_s profiling. However, for practical use it should be kept in mind that due to existence of a tradeoff between V_s and layer thickness, both V_s and thickness values can not be taken as unknown parameters or the problem may have many solutions.

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