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ESTIMATION OF SHEAR-WAVE VELOCITY STRUCTURE USING MICROTREMOR MEASUREMENTS

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Due to the recent construction boom in Ulaanbaatar city (UB), Mongolia, newly urban areas are rapidly expanded to the surrounded area of the city. According to the previous researches and reports, the thickness of the sedimentary basin in UB reaches 120m at the maximum in the area along the Tuul river. Therefore, the evaluation of site amplification is one of the essential parts of the estimation of earthquake hazard in this area. In this paper, the shear-wave velocity (Vs) structures in UB are estimated from single microtremor observations with the existing microtremor array observations. We carried out the microtremor observations at 50 sites and computed horizontal-to-vertical (H/V) spectral ratios. Inversion analysis is performed to the observed H/V spectral ratios based on the diffuse field approach (DFA) to determine the Vs structures. The site characterizations are evaluated from the amplification factors of the Vs structures.

Keywords: H/V spectral ratio, Inversion technique, Soil model, Site effect.

1 INTRODUCTION

Ulaanbaatar (UB), the capital city of Mongolia, exhibits dynamic urban and industrial development with a rapidly increasing population. Since the population of UB has grown approximately three times larger in the last two decades, the urbanized areas have been expanded to all parts of the city area. Especially in the last six years, moderate- and high-rise buildings have been newly constructed in the Tuul riverside areas located in the southern part of UB. UB is located at the valley of the Tuul river widely covered with alluvial deposits with 30 km length and 4-10 km width. According to existing borehole data and geological map, the thickness of the deposit is around 10-80 meters in most of the area.

According to the previous seismicity studies in Mongolia, the Emeelt fault located approximately 20 km from UB in the west-south-west direction has been one of the active faults that would provide great impact to UB (Adiya 2016). In order to consider countermeasures against the earthquakes, the evaluation and prediction of the strong ground motions due to the earthquakes are indispensable. The evaluation of the site amplification effects is one of the important issues in evaluating the seismic hazard and risk because the earthquake ground motions at the surface strongly depend on the site effects. Recently PS-logging surveys and spectral analysis of surface wave (SASW) method were conducted and the shear-wave velocity (Vs) profiles were estimated at around 40 sites in UB (JICA 2013). However, since the depths of the investigations were much less than 30 m (less than 10 m in most of the sites), the detailed Vs structures including much deeper profiles are not obtained in UB.

The use of microtremors (ambient noise) is a low-cost and handy method for site characterization. Nakamura (1989) has introduced this technique to estimate the fundamental resonant frequency of sediments using horizontal-to-vertical (H/V) spectral ratio at a single station. Microtremor H/V spectral ratio has been used to estimate Vs profiles by assuming that the microtremors are mainly composed of surface waves (Arai and Tokimatsu 2005). Recently, diffuse field theory has been proposed to understand the theoretical background of H/V spectral ratio by assuming a diffuse wavefield containing all types of elastic waves (Sánchez-Sesma *et al.* 2011). Based on the theory, the H/V spectral ratio is computed from the horizontal-to-vertical ratio of imaginary parts of Green's function.

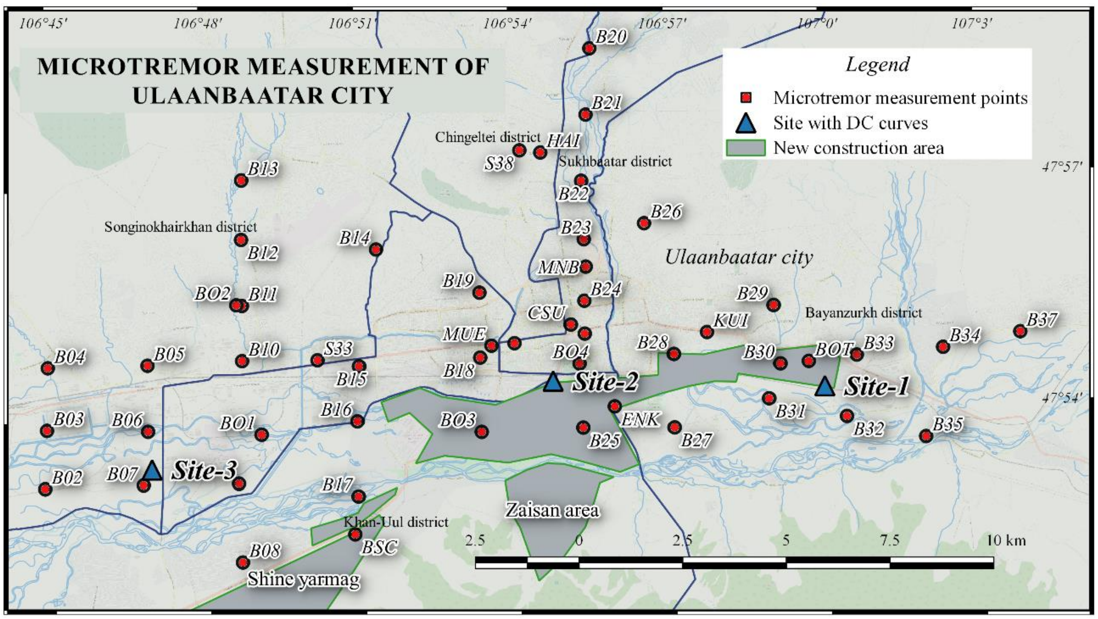

Figure 1. Microtremor observation points at Ulaanbaatar city with reference site-1, 2 and 3.

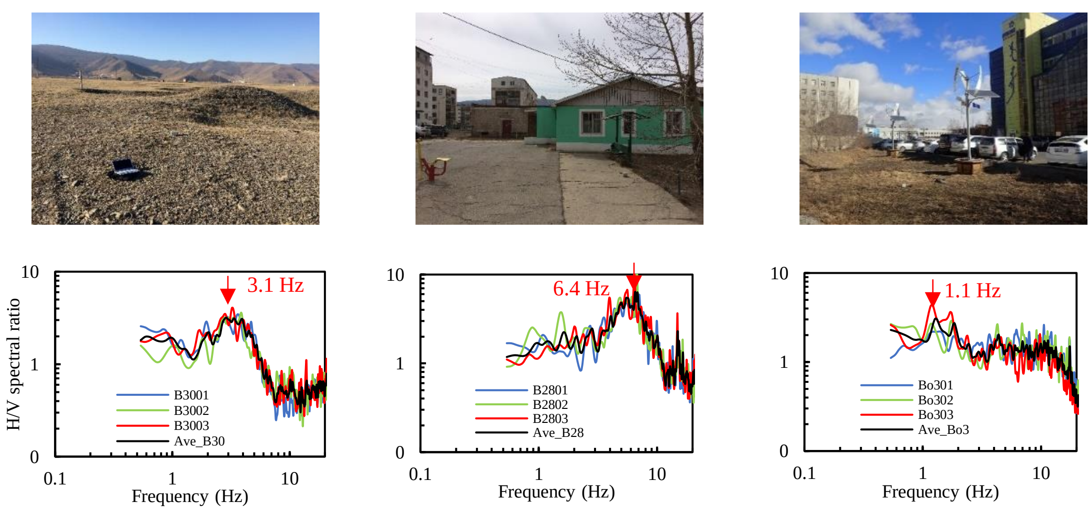

Figure 2. Typical site observation photos and observed H/V spectral ratios at B30, B28 and BO3.

In this paper, microtremor observations at multiple sites in UB are performed, and the inversion analysis based on the diffuse field theory is applied to the observed data in order to identify the Vs structures and to characterize the site amplification in the city.

2 OBSERVATION OF MICROTREMOR IN UB

Figure 1 shows the distribution of the microtremor observation sites in UB. Totally 50 sites are selected over the UB area. The Site-1, 2 and 3 in Fig. 1 are the reference sites where surface wave dispersion curves (DC) were obtained from microtremor array observations (Odonbaatar 2011). Due to the heavy traffic in the central part of UB during the daytime, most of the measurements are conducted in early mornings. Ground photographs for the observation condition and the observed H/V spectral ratios at typical sites are illustrated in Figure 2. The shapes and the predominant frequencies of the spectral ratios largely vary at site-by-site, indicating the variability of the site conditions in UB.

3 INVERSION ANALYSIS OF MICROTREMOR DATA

In this study, first joint inversion analysis is applied at the Site-1 to 3 based on the previously obtained DC curves by Odonbaatar (2011) and the observed H/V spectral ratio to avoid non-uniqueness of Vs and thickness during the inversion process. Second, considering the results of the joint inversion and the existing PS-logging data, single inversion analysis of H/V spectral ratios is applied to the rest of the sites.

Table 1. Initial inversion parameter ranges.

Layer	Vs (m/s)	Vp (m/s)	Depth (m)	Density (kg/m^3)
1	200-600	350-1400	0-15	1600-1800
2	250-1000	450-2400	0-50	1700-1900
3	1200-1500	2600-2950	0-100	1800-2000
4	1800	3280		2000-2200

3.1 Joint Inversion of H/V Spectral Ratio and Dispersion Data

In the joint inversion of the DC curves and H/V spectral ratio, the misfit between the observed values and the theoretical values is minimized by changing Vs and thickness through the iteration based on the Heuristic approach such as Simulated Annealing technique. We performed ten times inversions at each site with different initial sets and selected the best model with the smallest misfit. The Vs of the bedrock in UB is assumed to be 1800 m/s considering the previous study by Odonbaatar (2011). Table 1 shows the parameter ranges for Vs, thickness, Vp and density in the inversion analysis. We assumed five or six-layer model for the initial models. If closer values of the shear-wave velocities in adjacent layers are estimated in the inversion, we reduced the number of layers and applied the inversion calculation again.

Figure 3 shows the observation data of the DC and H/V spectral ratio at the Site-1 to 3. Figure 4 shows the estimated Vs structures by the joint inversion analysis. The theoretical values from the estimated Vs structures are also shown in Fig. 3. Although the theoretical values from the Vs structures by Odonbaatar (2011) could not reproduce the H/V spectral ratio, the theoretical values of this study show good agreement with the observation data for not only the DC but also the H/V ratios. The results show that the depth to the bedrock is estimated at 50 m to 80 m at the sites.

3.2 Single inversion results of the H/V spectral ratio

We apply the single inversion analysis for the rest of the sites using the H/V spectral ratios. The inversion analysis is not applied to the sites where the peak value of the H/V spectral ratio did not reach a factor of 2 because reliable Vs structure could not be estimated by the inversion due to the uncertainties of the observed values.

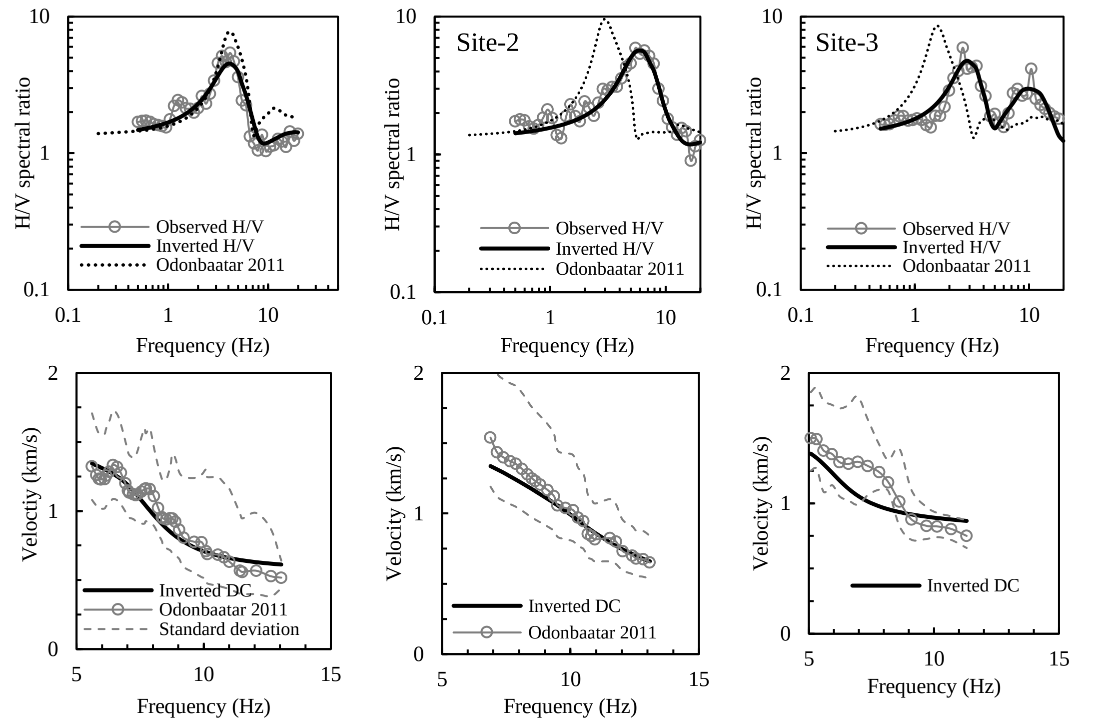

Figure 3. Theoretical and observed H/V spectral ratio and DC curve of joint inversion at Site-1, 2 and 3.

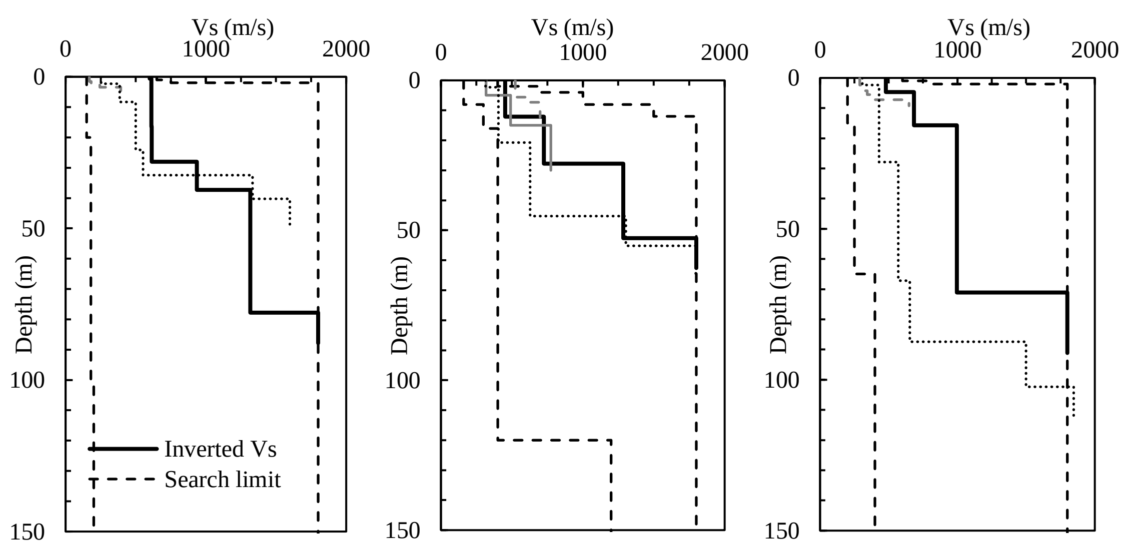

Figure 4. Shear-wave velocity profiles of joint inversion at Site-1, 2 and 3.

The Vs structures at 31 sites are estimated by the analysis. The search limits for Vs and thickness are determined considering the results of the joint inversions and the existing explorations. Figure 5 shows the Vs structures obtained from the inversion analysis. We confirmed that these models well reproduced the observed H/V spectral ratios.

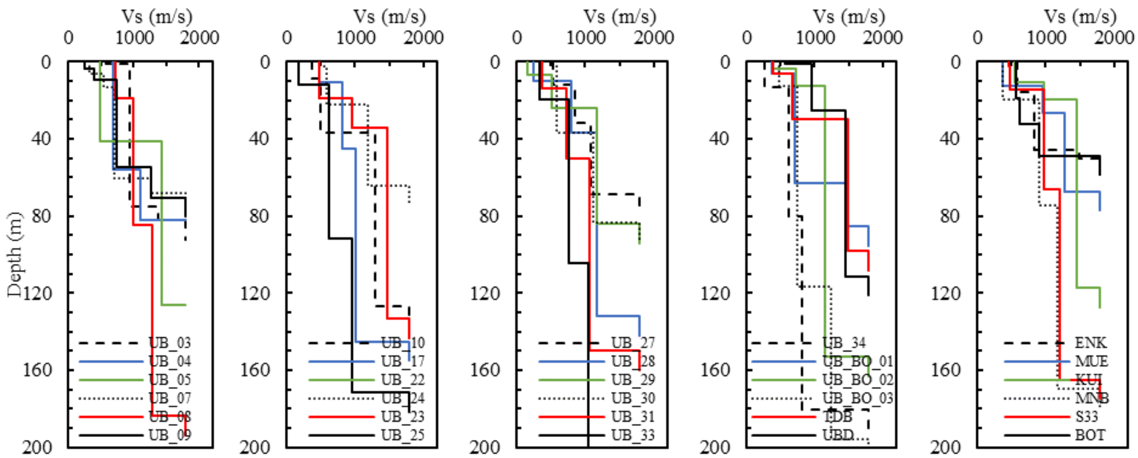

Figure 5. Estimated Shear-wave velocity profiles of all sites from microtremor single inversion.

3.3 Comparison with Borehole Data

In order to validate the obtained Vs structures in this study, the soil profiles are compared with the other data source. The geotechnical map of UB includes the cross-sections of soil profiles. Figure 6 shows the comparison of the soil profiles and the Vs structures obtained in this study. We confirm that the boundary of the Vs structures almost corresponds to the soil layers. The Vs of the gravel with sand or clay near the surface corresponds to 300 to 500 m/s. The Vs of the weak weathered and fissured alevrolit corresponds to 1000 to 1200 m/s.

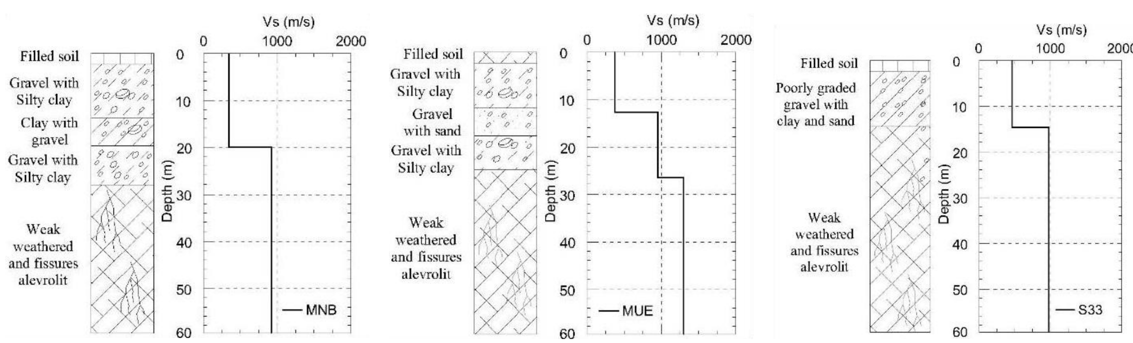

Figure 6. Comparison with estimated Vs profiles and borehole data.

4 SITE AMPLIFICATIONS OF ESTIMATED V_S PROFILES

Site amplifications for SH wave are computed from the estimated Vs structures based on the Haskell's multiple reflection theory. Figure 7 shows the examples of the site amplification at the sites near mountain, central area, and the Tuul river, where the thickest deposits are expected from the inversion analysis and the commercial and residential constructions including mid- and high-rise buildings are newly developed. Most of the old residential apartments are located near the central area. Finally, lowest site amplification is expected near mountain area because of the shallow deposit. The results show that the large amplifications are found at 3 to 10 Hz that would greatly affect the mid-rise buildings.

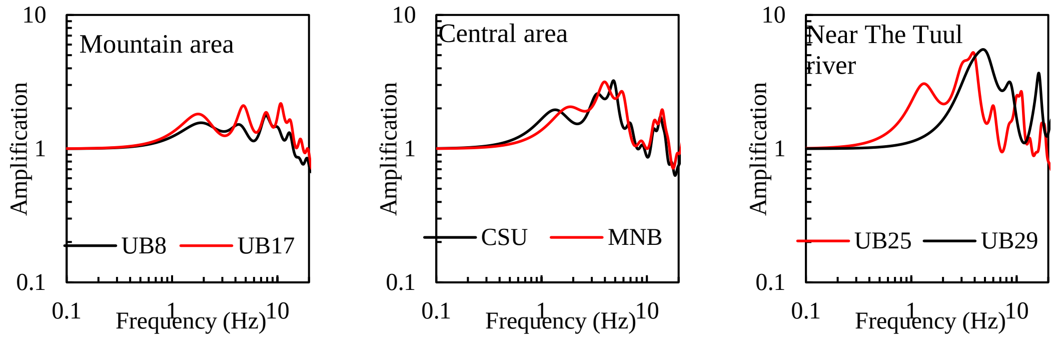

Figure 7. Estimated theoretical site amplification.

5 CONCLUSIONS

In this research, the shear-wave velocity (Vs) profiles of Ulaanbaatar city, Mongolia are estimated by the inversion analysis of the microtremor H/V spectral ratios based on the Diffuse Field Assumption. The joint inversion results with the surface wave dispersion curves are applied to the three sites where the microtremor array observations were conducted in the previous study by Odonbaatar (2011). The single inversion analysis is applied to the rest of the site. From these inversion analyses, the Vs structures up to the bedrock with the Vs of 1800 m/s are estimated, showing good correlation with the shallow borehole data. The site amplifications are evaluated from the estimated Vs structures. The results of this study would be useful for strong ground motion predictions and building damage assessment due to anticipating future earthquakes.

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