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GEOPHYSICAL PROSPECTING USING MICROTREMORS TO ESTIMATE 1-D SHALLOW SHEAR WAVE VELOCITY PROFILES IN THIMPHU, BHUTAN

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ABSTRACT

Microtremor measurements were conducted at 25 sites in Thimphu to obtain 1-D shallow shear wave velocity (Vs) profiles. The Vs profiles were obtained from the inversion of the phase velocities using the microtremor Spatial Autocorrelation method. The averaged Vs values in the upper 30 m obtained at 16 sites are categorized under "class C (dense soil and soft rock)" of the NEHRP classification. The horizontal-to-vertical spectral ratios of the observed microtremors were also obtained and compared to the theoretical ones calculated from the inverted Vs profiles. Almost all sites showed a flat characteristic of the spectral ratios between 1 Hz and 15 Hz. The computed site amplifications showed most sites in Thimphu have predominant frequencies above 4 Hz.
We also performed microtremor array surveys at six sites in South Ibaraki, Japan, using the same method and sensors used in Thimphu to corroborate the applied methods and to understand the effects of geology/geomorphology on the results obtained. The results obtained in Thimphu and South Ibaraki showed clear distinctions in the Vs profiles and predominant frequencies. Thimphu City, located on mountainous terrain, showed higher values of Vs30 and dominant frequencies than most sites in South Ibaraki, which is located on a deep sedimentary basin.

Keywords: Microtremors, Thimphu, SPAC method, Vs30, H/V spectral ratio.

1. INTRODUCTION

The seismicity of Bhutan is low in normal times, but the recent paleoseismic studies revealed the existence of a significant event with a magnitude of 8±0.5 in the 18th century (Le Roux Mallouf et al., 2016). Since then, the only noticeable event was the 2009 Mongar earthquake (Mw6.1) in the east, which caused local damage and claimed 12 lives. Significant events located outside the territory, such as the 2011 Sikkim earthquake (Mw6.9), have caused considerable damage in the country (Diehl et al., 2017). Bhutan falls under the "category Zone V (highest risk zone)" in the Indian seismic zonation system, indicating a Peak Ground Acceleration value of 0.36*g*. However, this estimation is much lower than the recent hazard results (Stevens et al., 2020). Most of the buildings in Bhutan consist of traditional styled rammed earth and stone masonry houses, and these structures do not follow any building code.

Generally, significant seismic risks arise from the probable collapse of buildings and other structures. For this reason, Bhutan faces high vulnerability in terms of both hazard and risk. Seismic hazards need to be understood well to eliminate risks as far as possible. Seismic wave amplification

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occurs depending on local geological conditions (e.g., thickness and physical properties of subsurface sedimentary soils), and effects of amplification at the subsurface soil are different from site to site and are controlled by the geological condition. Studying local site effects and understanding the subsurface profiles is essential for understanding the impact of subsurface geology on the strong ground motion for earthquake hazard assessment and risk mitigation.

Geophysical exploration using microtremors (ambient seismic noise) is a reliable and straightforward technique to understand subsurface structures and deduce soil characteristics. In this study, we will use the microtremor array data measured in the city of Thimphu to construct 1-D subsurface Vs profiles. The study also uses microtremor array data measured in South Ibaraki, where geological information, PS loggings and Vs30 information are available, to validate the techniques applied and confirm the results. The geological and geomorphological difference of Thimphu and South Ibaraki will also be helpful to understand the effects of different environments on microtremors.

2. METHODOLOGY

2.1. SPAC method

The primary method used in this study is the Spatial Autocorrelation (SPAC) method, which uses microtremor array recordings to estimate the characteristics of the subsurface Vs profile from the Rayleigh-wave phase velocities. The technique was first proposed by Aki (1957, 1965) and completed by Okada (2003).

The coherence function between sensor pairs is derived based on a stochastic approach. This approach assumes that: 1) Microtremor propagates as a sum of the individual sources and reaches the array as a plane wave. For this assumption, the sources of microtremors are located distant from the array; 2) Microtremors propagate uniformly and continuously from all directions, and the distribution of signals from source to sensors is uniform (Aki, 1957). Based on the assumptions, the SPAC coefficient between a sensor pair can be linked by fitting it to the Bessel function of the first kind of zero order.

$$\rho_{AB}(r,\omega) = \frac{1}{2\pi}\int_0^{2\pi} \frac{Re[S_{AB}(r,\omega)]}{\sqrt{|G_A(\omega)||G_B(\omega)|}}\, d\theta \cong J_0\left\{\frac{\omega r}{c(\omega)}\right\} \tag{1}$$

where $\rho_{AB}(r,\omega)$ is the coherence function between sensors A and B, $S_{AB}(r,\omega)$ is the cross-spectrum of the sensor pair, $G(\omega)$ are the power spectrum of the microtremor, and r, ω, and $c(\omega)$ are the sensor-to-sensor distance, the angular frequency, and the phase velocity, respectively. After we obtain the dispersion curves of Rayleigh-wave, we apply a heuristic inversion technique to estimate 1D subsurface Vs profiles. An initial velocity model consisting of horizontal layers is assumed and each layer thickness and Vs value are determined. After the inversion we obtain a Vs structure model which optimally fits the observed phase velocities.

2.2. H/V spectral ratio (HVSR) method

The horizontal-to-vertical (H/V) spectral ratio of microtremors is calculated using three-component microtremor data at a single station. This method was first developed by Nakamura (1989), which described that the spectral ratios of the horizontal to vertical component corresponds to the site amplification characteristics. There are discussions regarding the physical interpretation of the H/V ratios, and recent works show that the H/V represents the predominant frequency of the subsurface soil (Pierre-Yves et al., 2008). The H/V spectral ratio can be defined as

$$\frac{H}{V}(f) = \sqrt{\frac{P_{NS}(f)+P_{EW}(f)}{P_{UD}(f)}} \tag{2}$$

where P_i indicates the power spectrum.

3. DATA

The Thimphu city expands in the N-S direction along the valley and is divided by Wang River that runs from north to south. The populated area is entirely located within the valley deeply carved by Wang River, with the settlements built on the valley slopes.

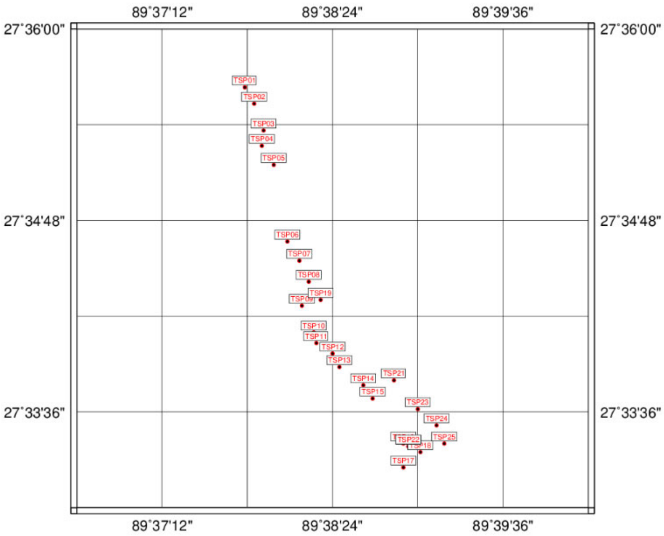

Figure 1. Location of microtremor array sites in Thimphu.

The microtremor array measurements were carried out in the northern region of Thimphu at 25 sites (Figure 1). For most measurements, a triangular array with four sensors was applied. We measured microtremors using arrays with radii of 5 m and 10 m. At sites where space was restricted for the 10 m array measurement, linear arrays consisting of two sensors were deployed. The regional geological map of Bhutan categorizes all arrays to be on the Lower metasedimentary unit of the Greater Himalayan Zone (Neoproterozoic-Cambrian) (Long et al., 2011), which mainly consists of metasedimentary rocks such as quartzite, biotite-muscovite-garnet schist, and paragneiss (Long and McQuarrie, 2010). A detailed geological map of the area is not available at present.

South Ibaraki Prefecture, Japan, is situated in the northeastern corner of the Kanto Basin, the largest sedimentary basin in Japan. The maximum depth of sediments reaches approximately several hundred meters to 1~ km in the region. Mt. Tsukuba lies to the north of the basin, whose geology is mainly comprised of mainly gabbro and granite rocks. The sedimentary soil thickness gradually decreases from south to North, and recorded ground motions show areal variations of seismic wave amplification. We took microtremor measurements at six different sites in South Ibaraki (Figure 2). The six sites were distributed on different geomorphological units. Except for site MT (Mt. Tsukuba), which was located on a hillside at an elevation of 170 m above sea level, the other five sites, IS, KZ, KA, SH, and TH were located on a low-lying sedimentary basin. Strong-motion observation stations operated by National Research Institute for Earth Science and Disaster Resilience (NIED) (KiK-net: sites KA, MT, KZ; K-net: sites SH, IS) or Japan Meteorological Agency (JMA) (site TH) were installed at all sites. PS-logging data are available at four sites; IS, KA, MT, and SH. The calculated Vs30 values and the PS-logging data for these sites will be used to corroborate the results of observed values obtained from the array measurements and validate the microtremor survey technique applied in this study. The measurements were taken using four array radii: 5 m, 10 m, 15 m, and 20 m.

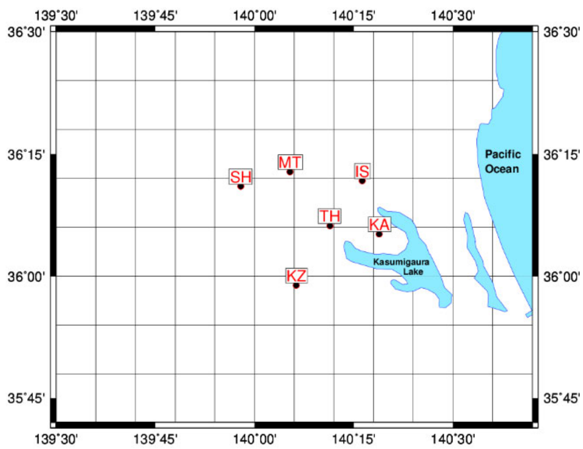

Figure 2. Location of microtremor array sites in South Ibaraki.

4. RESULTS AND DISCUSSION

4.1. South Ibaraki

In this study, data processing of the SPAC method is carried out using software SPAC2021 developed by Dr. Toshiaki Yokoi (2021), and horizontal-to-vertical spectral ratio analysis was carried out using software Prochv developed by Dr. Takumi Hayashida (2021).

The observed phase velocities at South Ibaraki sites were compared with the theoretical ones computed using available PS-logging information (see Figure 3). The PS-logging values were available down to 20 m depth at sites IS and SH, 400 m at site KA, and down to 92 m at site MT. The comparisons between the observed and the theoretical phase velocities dispersion curves are similar at sites IS, KA, and SH in the higher frequency side, representing the phase velocities in shallow depth soils (Figure 3). In the lower frequency side, the theoretical curves show discrepancies; the observed phase velocities are much higher than the theoretical ones, possibly due to a lack of deeper structural information in the logging data. At site MT the dispersion curve shows similarity in the lower frequency side but discrepancies in the higher frequency side. This could be due to the soft velocity layers of the PS logging (~100 m/s) for the top 2 m layer. All sites show rough correlations between the observed and theoretical phase velocities.

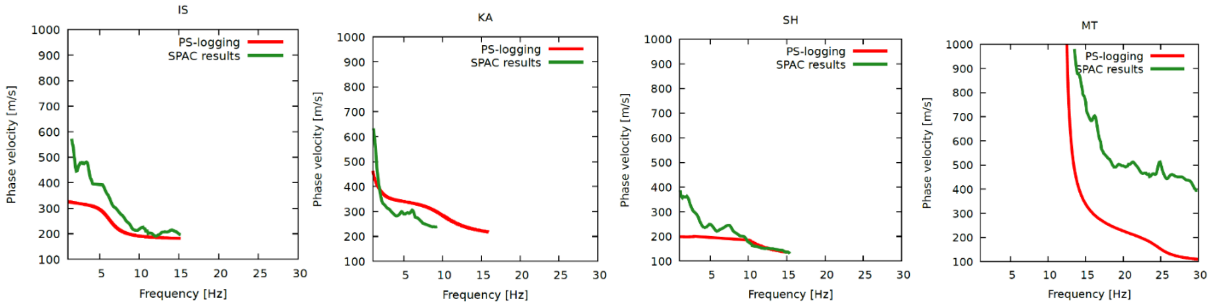

Figure 3. Comparison of the observed phase velocities obtained from SPAC analysis and the theoretical phase velocities obtained from PS-logging data.

The 1-D Vs profiles obtained at the five sites in the basin (IS, KA, KZ, SH, and TH) represent the dispersive characteristics of the Rayleigh-wave phase velocities. The Vs profiles obtained from the microtremors were compared to the theoretical ones derived from PS-logging data. Both data show good correlations. These results suggest that the inversion process was efficient, and the obtained results were reliable.

Table 1. Vs30 values obtained from observed data and PS logging.

Site ID	Vs profiles	Phase velocities	SPAC coefficients	PS logging
IS	285	293	299	246
KA	304	317	301	No logging
KZ	274	274	209	301
SH	671	667	702	692
MT	222	226	221	206
TH	*305*	*370*	329	No logging

The Vs30 values were calculated at all sites using various methods such as CEN (2004), Vs30 values from SPAC coefficients (Hayashida and Yokoi, 2021), and Lamda – 40 m method (Konno and Kataoka, 2000). The Vs30 values obtained from the observed data were also compared to the theoretical values obtained from PS-logging data (Table 1). All the Vs30 values show good correlations with those of the estimated ones from Vs profiles. According to the

National Earthquake Hazards Reduction Program (NEHRP) site classification, MT falls under class C (soft rock) while the rest of the sites fall under class D (stiff soil).

The predominant frequencies of H/V and site amplifications were also calculated. The theoretical site amplifications computed from the Vs profiles at three sites were compared to the amplification models provided by the National Institute for Land and Infrastructure Management (NILIM). For all the sites, the predominant frequencies of the theoretical site amplifications are roughly similar to the frequency of the dominant peaks obtained around 1 Hz in the NILIM models. Theoretical H/V obtained from PS logging and Vs profiles were compared to the observed H/V. All values showed a good correlation for all sites and have almost flat characteristics except for site MT. However, the predominant frequencies of site amplification did not match those of H/V.

4.2. Thimphu

The phase velocities obtained for most sites in Thimphu are lower than South Ibaraki. The frequency ranges and the phase velocities of the dispersion curves varied among sites in Thimphu. Phase velocities below 5 Hz are observed only at three sites. In the lower frequency side, the phase velocities have high variations among the sites.

Vs models in Thimphu are obtained at 22 sites out of 25 sites. The average maximum depth obtained for all sites is about 24 m. The depth reached 30 m at only eight sites.

The Vs30 values were also computed in Thimphu for 22 sites using the same methods in South Ibaraki. Following the National Earthquakes Hazards Reduction Program (NEHRP) classification, six sites in Thimphu are categorized under class D (stiff soil) and 16 sites are classified under class C (dense soil/soft rock).

The theoretical H/V ratios for most sites in Thimphu have flat characteristics. At site TSP016, the theoretical ratios have a dominant peak at 6.6 Hz, whereas the observed H/V ratio has a dominant peak at 5.5 Hz. Site TSP022 has a clear dominant peak for the theoretical ratios at 8.5 Hz, but in contrast the observed ratios have a peak at 1 Hz. The predominant frequencies of site amplification had considerable variation (2-12 Hz) among the sites in Thimphu. This might suggest large range heterogeneity of the shallow subsurface layers in the area. Conducting microtremor measurements with larger array might result in deeper Vs profiles. However, due to constraints in the availability of the open surface in the area, the use of larger arrays is not possible. At most of the sites, the predominant peaks have higher values than those observed at sites in South Ibaraki. Similar to the results in South Ibaraki, the dominant frequencies of site amplification did not match those of H/V at sites in Thimphu either.

4.3. Limitations

The power spectral densities, which indicate microtremor amplitude levels, hold the information of the available frequency range for the analysis. The power spectral densities for the sites in Thimphu were compared to the power spectral densities of the sites in South Ibaraki. The population of Thimphu city is almost 1/10 of South Ibaraki. South Ibaraki is a neighboring region of the capital city, Tokyo, and traffics can be the primary source for the generation of ambient vibrations. Unlike Japan, Bhutan does not use railway transport; trains are also a major source of tremors that are detectable even up to 100 km away (e.g., Brenguier et al., 2019). Therefore, the source of ambient vibrations is much weak in Thimphu.

The lower limit of the phase velocity dispersion curves was set at frequencies for which the SPAC coefficient curves reached their peaks at all sites. This limited the range of phase velocities in the dispersion curves at around 5 Hz. As a result, information about the deep layers could not be obtained at most sites. Using larger arrays, the information of the deeper parts may be obtained. However, as the availability of space is restricted in the current study area, larger arrays could not be observed in this study.

5. CONCLUSIONS

Microtremor measurements were conducted at 25 sites in Thimphu city and six sites in South Ibaraki. The observed phase velocity dispersion curves, Vs profiles, Vs30, H/V, and site amplifications obtained for South Ibaraki are well compared to theoretical ones. This implies that the results obtained in Thimphu using the same methods are acceptable. The effects of different geology and geomorphology on microtremors are also clearly shown by the results obtained. For sites located on the sedimentary basin, reliable phase velocities are possibly obtained in the lower frequency side (~1 Hz) due to deeper sediments. For site MT and the sites in Thimphu, reliable phase velocities were obtained only in the higher frequency range (> 4 Hz), and the obtained Vs profiles were shallow in depth. This implies that the predominant frequencies for Thimphu sites could not be well justified, and a more detailed study of the geology and geomorphology of the area might help corroborate the results obtained. The observed phase velocities in Thimphu ranged from ~180 to 930 m/s in the frequency range of 4 Hz to 30 Hz. In South Ibaraki, a wide range of phase velocities were obtained from 130 to ~2500 m/s in the same frequency range. The observed values in South Ibaraki vary widely owing to the variability in the geomorphology of the sites. According to the NEHRP classification, six sites in Thimphu were located on stiff soil (class D), and 16 sites were located on soft rock (class C).

The dominant frequencies of site amplification could also be well explained. The dominant frequencies of site amplification at sites located on the basin in South Ibaraki have dominant peaks below 2 Hz. Site MT had the dominant peak at ~8 Hz. At sites in Thimphu, the dominant peaks were observed within a wide range frequency (2–12 Hz), and hence the correlation of the dominant frequencies among the sites in Thimphu could not be determined. The shallow depth of the Vs profiles obtained in this study might not properly constrain the characteristics of Thimphu. The observed and theoretical H/V ratios of most sites in Thimphu had almost flat features. They do not match the predominant frequency of site amplification.

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