

Sedimentary and shallow crustal structure estimation from HVSR analysis: cases in onshore and offshore convergent margins

(HVSR 解析を用いた堆積層及び浅部地殻構造の研究—陸域と海域の2つの収束帯への適用事例—)

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1. Introduction

Sedimentary and shallow crustal structures in onshore and offshore convergent margins significantly influence seismic hazard assessments, engineering applications, and understanding of regional tectonics. The horizontal-to-vertical spectral ratio (HVSR) method has been widely applied for estimating shear wave velocity (V_s) profiles in the shallow subsurface; however, its application for deep crustal investigations, particularly in marine environments, remains limited. This thesis extends the HVSR method beyond traditional limits, successfully estimating deep subsurface structures both onshore in the Bengal Basin, Bangladesh, and offshore in the southern Japan Trench off Fukushima, Japan. This study utilized the newly developed diffuse field theory (DFT), which assumes a seismic wavefield in a diffuse state to reconstruct the Green's function from seismic ambient noise and earthquake coda waves to obtain V_s profiles by forward modeling and inversion. This approach enabled full HVSR investigations at depths previously unexplored by conventional HVSR methods. Methodological innovations include the introduction of the HVSR from S-coda waves (HVSRC) for deep subsurface imaging and the first demonstration of HVSR from ambient noise (HVS RN) instability at frequencies below 0.1 Hz due to high ambient seismic noise energy offshore. The HVSRC approach achieved a lower frequency limit of 0.05 Hz, significantly extending the depth range of HVSR analysis. This study highlights the potential of HVSR techniques for deep subsurface imaging, providing a robust framework for future investigations in onshore and offshore environments. The findings contribute to advancing seismic hazard assessment methodologies, and improving subsurface characterization.

2. Theoretical Background

The theoretical foundations of the HVSR method are explored in this chapter. HVSR is widely recognized for its simplicity, low cost, and effectiveness in identifying shear wave velocity contrasts caused by vertical lithological changes or structural variations. Early HVSR interpretations, however, were limited by an incomplete understanding of the wavefield, preventing the full HVSR from being accurately explained and modeled. The introduction of Diffuse Field Theory (DFA) has significantly advanced HVSR analysis by linking it to the imaginary components of the Green's function, thereby incorporating contributions from body waves, Rayleigh waves, and Love waves.

3. Shear Wave Velocity Estimation in the Bengal Basin, Bangladesh by HVSRN Analysis: Implications for Engineering Bedrock Depth and Seismic Hazard

We estimated 1D V_s velocity models at intermediate depths (<3000 m) beneath 19 seismic stations in the Bengal Basin, Bangladesh, using horizontal-to-vertical spectral ratio of noise (HVSRN) analysis within 0.2–10 Hz. The analysis considers the full noise wavefield and is constrained by available lithological and V_p data. The results provide the first regional assessment of engineering bedrock depth across the Bengal Basin. The deep basin areas generally exhibit deeper bedrock, which could pose significant seismic risk for high-rise buildings, while uplifted regions show shallow (<30 m) bedrock due to tectonic activity. Sensitivity analysis confirms the reliability of HVSR inversion in delineating subsurface structures at various depths. A response spectrum at DHAK was simulated for an MW 7.3 earthquake, revealing a predominant acceleration period of ~0.8–1 s, suggesting that multistory buildings in the region may be vulnerable to strong ground motion. The study highlights the potential of the HVSR method for retrieving subsurface information beyond typical near-surface applications. A key uncertainty is the spatial mismatch between seismic stations and available borehole lithologs or V_p profiles, as geological variations can occur over short distances. Future joint inversion with dispersion curves could enhance robustness. Despite these limitations, the estimated V_s profiles and engineering bedrock depth offer valuable insights for seismic hazard assessment and future exploration. Increased seismic monitoring and borehole investigations in urban areas are recommended to mitigate seismic

risk. Future work will include site response estimation throughout the Bengal Basin and earthquake simulations from different directions at the SHL reference site.

4. Shear Wave Velocity Structure at the Fukushima Forearc Region Based on HVSR Analysis of Ambient Seismic Noise Recordings by Ocean Bottom Seismometers

We investigated the horizontal-to-vertical spectral ratio of noise (HVS RN) in the Fukushima forearc region of the southern Japan Trench. HVS RN was estimated within the frequency ranges of 0.01 to 10 Hz using broadband seismometers and 0.1 to 10 Hz using short-period seismometers. We assessed the stability and frequency-dependent behavior of HVS RN, focusing on the lower frequency range (<0.1 Hz), where significant instability was observed. HVS RN between 0.1 and 10 Hz remained stable, whereas ratios below 0.1 Hz exhibited high temporal variability, rendering them unreliable for subsurface imaging. The instability was linked to increased ambient seismic noise (ASN) at lower frequencies, probably from tilt and compliance noise affecting the horizontal components. Additionally, V_s profiles were estimated down to 7000 meters below the seafloor (mbsf), revealing a gradual increase in velocity with depth. The study successfully identified key geological layers, including Tertiary and Cretaceous sedimentary sequences, the Tertiary-Cretaceous unconformity as well as the island arc upper crust consistent with prior studies. The impact of the water layer on HVS RN was also explored, showing significant amplitude variations at higher frequencies (>1 Hz), with less pronounced effects at lower frequencies. These findings highlight the potential of HVS RN analysis for detailed subsurface imaging in offshore regions, offering valuable insights into the seismological characteristics of the Japan Trench. The research contributes to enhancing seismic methods for slow earthquake detection and provides a promising approach for high-resolution subsurface imaging in oceanic environments.

5. Shear Wave Velocity Estimation Off Fukushima by Analysis of HVSR From S-Coda Waves

In the previous study here, HVSR from ambient seismic noise (HVS RN) was estimated Off Fukushima, but it exhibited instability below 0.1 Hz probably due to dominant oceanic infragravity waves. To overcome this limitation and extend the investigation depth beyond 7000 m, we estimated HVSR from

S-coda waves (HVSRC) using regional and teleseismic earthquakes recorded at three broadband Ocean Bottom Seismometer (OBS) stations off Fukushima. The results demonstrated that stable HVSRC could be obtained from 0.05 to 10 Hz, whereas HVSRN remained unstable below 0.1 Hz. Under the DFA, forward modeling using known velocity structures down to 10,000 m depth confirmed that the observed HVSRC curves reliably reflect subsurface responses, particularly at lower frequencies. Notably, within the first 7000 m, the results are consistent with those obtained in the previous study. However, by extending the analysis to 10,000 m, we further delineated deeper crustal structures, including the plate interface at ~7000 m depth at one OBS station. This approach significantly improved depth resolution compared to previous studies, capturing detailed variations across sedimentary and crustal layers. The ability to retrieve HVSR at lower frequencies and greater depths highlights the potential of HVSRC for imaging deep offshore structures under the diffuse field assumption. However, the approach requires large-magnitude regional and teleseismic earthquakes with long-duration S-coda waves, which may limit the number of usable events. Despite this constraint, HVSRC provides a robust alternative to conventional HVSR methods, extending frequency coverage and enhancing subsurface imaging in offshore environments and subduction zones.

6. Search For Diffusive Properties in Earthquake S-Coda Waves Recorded at the Ocean Bottom

Understanding the diffusive nature of seismic wavefields is essential for seismological studies, particularly in ocean-bottom environments where data are limited. This study examines the S to P energy ratio in the S-coda waves of nine regional and teleseismic earthquakes recorded by ocean-bottom seismometers off Fukushima to assess energy partitioning and diffusion. S- and P-wave energies were estimated from curl and divergence to estimate the energy ratio within the 0.05–0.2 Hz frequency range. A moving average window of 150 seconds was applied to ensure a stable estimation in the S-coda window. The results show that for six earthquakes, the energy ratio stabilized between 7.5 and 9.18, indicating body wave dominance. For two earthquakes, the lower ratios of 6.14 and 6.92 suggest significant Rayleigh wave contributions, while one event exhibited an anomalously low value of 4.2, likely due to the presence of soft sediments affecting wave propagation. Compared to previous onshore

studies, the delayed stabilization observed in this study may indicate a weakly heterogeneous crust or prolonged scattering. Additionally, the presence of a water layer above the ocean-bottom seismometers may have caused the medium to behave as a full-space, enhancing body wave dominance. These findings confirm that S-coda waves at the ocean bottom exhibit diffusion, similar to the ambient seismic noise wavefield, supporting their use in forward modeling techniques such as the horizontal-to-vertical spectral ratio of coda for inverse problems. However, the variations in stabilization values across events suggest that additional research is needed to better understand the influence of site conditions, crustal heterogeneity, and wave interactions in deep-sea environments.

7. General Discussion

This chapter explores the comparison of near-surface sediment properties and the geodynamics of subduction zones, focusing on the Japan Trench off Fukushima and the Bengal Basin. Through the analysis of shallow V_s profiles, we investigate the differences between onshore and offshore sediment characteristics, emphasizing the effects of sedimentation, physiography, and fluid saturation. The study highlights how the V_s of the top layer off Fukushima is significantly lower than that of onshore Bengal Basin sediments, suggesting a reduced sediment load and unique sedimentary processes in each region. Additionally, the geodynamic processes of the Japan Trench subduction zone are examined in comparison with the Bengal Basin, emphasizing the differences in crustal thickness, sedimentation, and tectonic history, which influence the evolution of the subduction systems in both regions. Further, the chapter delves into the use of passive seismic methods, specifically HVSr, to image subsurface structures. By utilizing ambient seismic noise and earthquake coda, we demonstrate the potential of HVSr for obtaining high-resolution V_s profiles from the near-surface to depths of up to 10 km offshore and 3 km onshore. The study addresses the challenges of using the HVSr method: spatial resolution in lateral imaging, proposing the integration of dense seismic networks for improved spatial resolution. While the HVSr method offers significant advantages, such as cost-effectiveness and wide frequency coverage, it is also subject to the challenge of non-uniqueness in inversion results, which can be mitigated through joint inversion with other geophysical methods.

8. General Conclusions

In this study, we explored the potential of passive seismic methods, particularly the horizontal-to-vertical spectral ratio (HVSr) technique, for subsurface imaging and shear wave (VS) velocity estimation. Our work focused on the Bengal Basin in Bangladesh and the southern Japan Trench off Fukushima, Japan, aiming to bridge gaps in subsurface imaging and improve seismic hazard assessment. We successfully demonstrated the HVSr method's ability to image deeper subsurface structures, reaching depths of up to 10 km, beyond its conventional application to near-surface layers. Key methodological advancements include the first application of HVSr using ambient seismic noise (HVSrN) at the ocean bottom to obtain V_s profiles down to 7 km, and the novel use of earthquake coda (HVSrC) for deeper imaging, achieving a resolution down to ~10,000 m. These new insights provide valuable data for improving subsurface models in both regions. One significant finding was the instability of HVSrN frequencies below 0.1 Hz, attributed to the high temporal variability of ambient seismic noise, which was addressed using S-coda waves. The S-coda approach provided more stable results, confirming the feasibility of using lower frequencies to access deep subsurface structures. Additionally, this study's application of forward and inverse modeling techniques using the diffuse field assumption (DFA) was crucial for improving the reliability of the HVSr method in deep crustal studies. These advancements contribute to our understanding of seismic hazard assessment, particularly in regions with limited seismic data. We recommend further application of these methodologies in other regions to validate and improve these findings, offering a deeper understanding of subsurface structures and their implications for seismic risk mitigation.