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Frequency-Based Comparative Analysis of Ground Vibration Spectra at Multiple Monitoring Locations Under Soil-Rock Impact Conditions

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Abstract

Ground vibration characteristics provide valuable information regarding dynamic soil behavior and potential instability in riverbank and near-surface geological environments. This study presents a frequency-based comparative analysis of vibration signals measured at nine monitoring locations subjected to soil–rock impact excitation. Three-directional vibration signals (transverse, vertical, and longitudinal) were recorded and processed using bandpass filtering and Fast Fourier Transform (FFT)-based spectral analysis. The measured signals were segmented and normalized to evaluate temporal and spatial variations in dominant frequency behavior. Comparative spectral analyses revealed significant differences among monitoring locations, particularly in the low-frequency range associated with soil softening and reduced stiffness conditions. The results demonstrate that dominant frequency shifts and spectral broadening can effectively identify spatial heterogeneity and localized dynamic instability zones. The proposed methodology provides a simple and practical framework for vibration-based assessment of soil degradation and instability in riverbank environments.

Keywords: Ground Vibration, FFT Analysis, Dominant Frequency, Soil Instability, Spectral Analysis, Riverbank Monitoring, Soil-Rock Impact

1. Introduction

Ground vibration monitoring has become an important technique in geotechnical engineering for evaluating soil dynamic behavior, wave propagation characteristics, and instability mechanisms under external excitation [1, 2]. Dynamic soil properties such as shear modulus and damping ratio are strongly affected by soil structure, stress conditions, and material degradation processes, resulting in significant variations in vibration response behavior [3, 4].

Previous studies have demonstrated that wave propagation and spectral amplification in soils are closely related to local stiffness and subsurface heterogeneity [5, 6]. In soil and weak rock environments, external impact loading may induce complex vibration transmission patterns associated with anisotropic and heterogeneous ground conditions [7, 8]. Soft or dynamically degraded soils generally exhibit lower dominant frequencies and broader spectral responses compared with relatively stable ground conditions [2, 9].

Microtremor and ambient vibration techniques have been widely used for seismic site characterization and dynamic soil assessment because frequency-domain characteristics are highly sensitive to local geological conditions [10, 11, 12]. Surface-wave propagation studies have further shown that vibration energy redistribution and attenuation behavior can provide indirect indicators of soil degradation and localized instability zones [13, 14].

Ground vibration analysis has also been extensively applied in practical engineering problems involving construction activities, blasting operations, and impact-induced loading [15, 16]. Under soil–rock impact conditions, vibration spectra and dominant frequency characteristics may vary significantly among monitoring locations due to differences in soil stiffness, material composition, and structural heterogeneity. Therefore, comparative spectral analysis provides an effective approach for identifying dynamically sensitive zones and evaluating spatial variations in soil behavior.

Among available signal processing techniques, Fast Fourier Transform (FFT)-based spectral analysis is widely used because of its computational efficiency and capability for identifying dominant frequency characteristics in vibration signals [17]. Welch spectral estimation methods further improve spectral stability and reduce noise effects in nonstationary vibration measurements [18]. These methods enable reliable comparison of normalized vibration spectra among multiple monitoring locations.

Despite considerable progress in vibration-based geotechnical investigations, comparative analyses involving multiple monitoring points under soil-rock impact conditions remain limited. In particular, the spatial variation of normalized vibration spectra and dominant frequency characteristics across different monitoring locations within the same soil region has not been sufficiently investigated. Understanding these variations is important for evaluating dynamic heterogeneity and identifying potentially unstable zones.

Therefore, this study presents a frequency-based comparative analysis of ground vibration spectra measured at nine monitoring locations under soil–rock impact conditions. Three-directional vibration signals, including transverse, vertical, and longitudinal components, were processed using bandpass filtering and FFT-based spectral analysis. The normalized spectra were compared among monitoring locations to investigate spatial variations in dominant frequency behavior and vibration response characteristics.

The main objectives of this study are summarized as follows:

- To evaluate spatial variations in vibration spectra among multiple monitoring locations.
- To identify dominant frequency characteristics associated with different soil conditions.
- To compare directional vibration responses using three-dimensional monitoring data.
- To demonstrate the applicability of FFT-based spectral analysis for practical assessment of dynamic soil behavior under soil–rock impact conditions.

2. Methodology

2.1 Data acquisition and monitoring configuration

Ground vibration measurements were conducted at nine monitoring locations under soil-rock impact conditions. The monitoring system recorded three-directional vibration signals corresponding to the transverse (Tran), vertical (Vert), and longitudinal (Long) directions. Each monitoring point produced time-series vibration data stored in CSV format for subsequent signal processing and spectral analysis. The vibration signals were sampled at a frequency of 1024 Hz, enabling high-resolution analysis of dynamic responses within the investigated frequency range. The measured amplitudes were converted from inch-based units into SI units. The collected data from all monitoring locations were organized into separate folders corresponding to different experimental groups.

2.2 Signal preprocessing

Prior to spectral analysis, all recorded vibration signals were preprocessed to remove noise and low-frequency drift effects. A fourth-order Butterworth bandpass filter was applied to each vibration signal with cutoff frequencies ranging from 0.5 Hz to 300 Hz. The filtering process was implemented using forward-backward filtering to minimize phase distortion. After filtering, the signals were detrended to eliminate residual linear trends prior to frequency-domain analysis.

2.3 Frequency spectrum analysis

Frequency-domain analysis was performed using Welch's Power Spectral Density (PSD) estimation method. Welch spectral estimation was selected because it improves spectral stability and reduces random noise effects in nonstationary vibration signals. For each vibration signal, the frequency spectrum was computed using a Hann window with overlapping segments. The segment length for spectral estimation was defined as $N_{segment} = 1024$.

The resulting power spectral density was converted into spectral amplitude form according to:

$$A(f) = \sqrt{P_{xx}(f)} \tag{1}$$

Where:

- $A(f)$ is the spectral amplitude,
- $P_{xx}(f)$ is the estimated power spectral density at frequency f.

The analysis focused on the frequency interval between 20 Hz and 250 Hz to emphasize the dominant vibration characteristics associated with soil-rock impact behavior: $20\ \text{Hz} \leq f \leq 250\ \text{Hz}$.

2.4 Spectrum normalization

To enable direct comparison among monitoring locations with different vibration magnitudes, the spectral amplitudes were normalized with respect to the maximum amplitude value of each spectrum. The normalized amplitude was calculated as:

$$A_{normal}(f) = \frac{A(f)}{A_{max}} \tag{2}$$

Where:

- $A_{normal}(f)$ is the normalized spectral amplitude,
- A_{max} is the maximum spectral amplitude within the analyzed frequency range.

Normalization allowed the comparison to focus on spectral shape and dominant frequency behavior rather than absolute vibration amplitude differences.

2.5 Dominant frequency identification

The dominant frequency for each monitoring location was determined from the maximum value of the normalized vibration spectrum. The dominant frequency was defined as:

$$f_0 = argmax(Anorm(f)) \tag{3}$$

Where f_0 represents the dominant vibration frequency.

The dominant spectral peak of each monitoring location was highlighted in the comparison figures to facilitate interpretation of spatial vibration variations.

3. Field Experiment and Results

3.1 Field experiment

Fig 1 shows the experimental layout and monitoring configuration used in this study. Nine measurement points (P1-P9) were arranged with a spacing of 1.5 m to investigate the spatial variation of ground vibration under soil–rock impact conditions. The impact source was generated using a handheld hammer acting on a wooden plate placed near Point P4. Vibration responses were recorded in three directions, including longitudinal (Long), transverse (Tran), and vertical components. The monitoring arrangement was designed to evaluate directional vibration propagation and frequency-dependent spectral differences between measurement locations.

Fig 1: Experimental layout and monitoring configuration for ground vibration measurements under soil–rock impact conditions

3.2 Results

Figures 2-4 present the normalized vibration spectra obtained at nine monitoring locations under soil-rock impact excitation for the transverse, vertical, and longitudinal directions, respectively. The spectral responses reveal clear spatial variability in both dominant frequency and spectral amplitude, indicating heterogeneous dynamic behavior of the investigated ground surface.

In the transverse direction (Fig 2), most monitoring points exhibited dominant frequencies within the range of approximately 40-77 Hz. Points P1, P3, P5, P8, and P9 showed strong spectral peaks concentrated near 60-70 Hz, whereas Points P4 and P7 exhibited lower dominant frequencies around 40-43 Hz. In particular, Point P8 presented a broader high-frequency distribution extending beyond 100 Hz, suggesting stronger high-frequency vibration components and possible local stiffness variation in the subsurface soil layer.

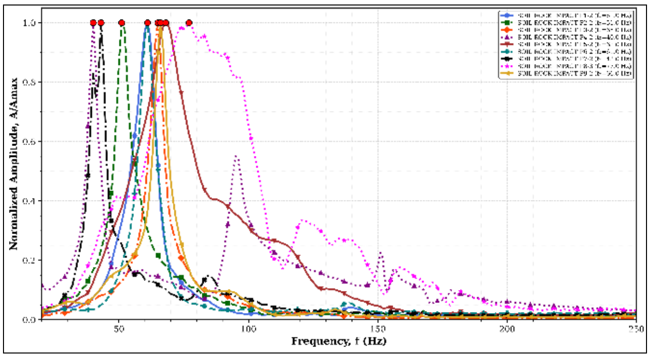

Fig 2: Comparison of normalized ground vibration spectra in the transverse direction at multiple monitoring locations

The vertical direction (Fig 3) demonstrated the largest spectral variability among all three components. Several points, including P4 and P8, exhibited dominant frequencies exceeding 100 Hz, while other locations remained concentrated within the range of 48-87 Hz. Compared with the transverse and longitudinal responses, the vertical spectra displayed wider spectral bandwidths and higher energy persistence over a broad frequency range. This behavior indicates that vertical vibration propagation is more sensitive to local soil heterogeneity and impact energy transmission.

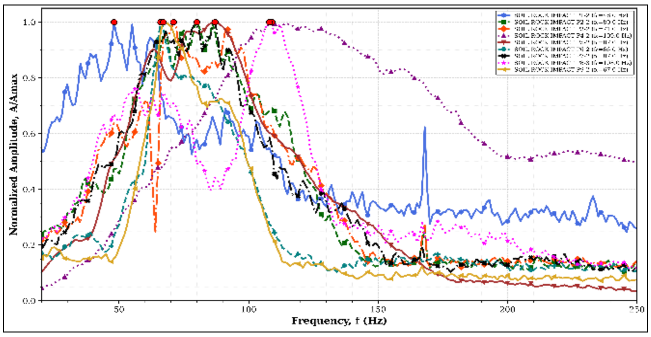

Fig 3: Comparison of normalized ground vibration spectra in the vertical direction at multiple monitoring locations

In the longitudinal direction (Fig 4), the dominant frequencies were mainly distributed between 43 and 71 Hz. Most spectra showed relatively narrow peaks concentrated near 60-70 Hz, indicating a more stable vibration propagation pattern along the primary excitation direction. However, Point P8 again showed a wider spectral distribution with extended high-frequency content, consistent with the observations in the transverse component. This repeated behavior suggests that the subsurface condition near Point P8 differs from the surrounding monitoring locations.

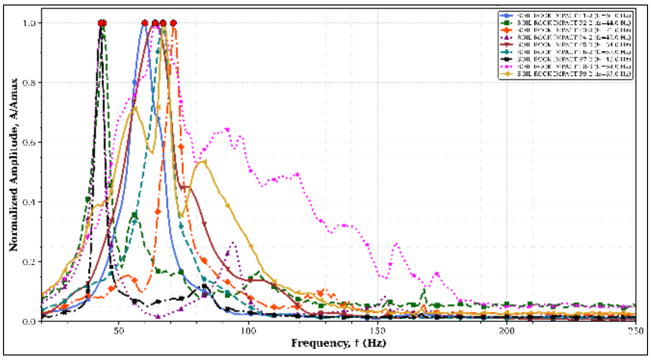

Fig 4: Comparison of normalized ground vibration spectra in the longitudinal direction at multiple monitoring locations

Overall, the spectral comparisons confirm that the vibration response varies significantly between monitoring positions and vibration directions. The observed differences in dominant frequency and spectral shape imply spatial heterogeneity in soil stiffness, density, and wave propagation characteristics across the investigated area. The results demonstrate that frequency-based spectral analysis can effectively identify local variations in dynamic ground behavior under impact loading conditions.

4. Conclusion

This study presented a frequency-based comparative analysis of ground vibration spectra at multiple monitoring locations under soil–rock impact conditions. Ground vibration signals recorded at nine measurement points were processed using bandpass filtering and Welch spectral analysis to evaluate directional vibration characteristics in the transverse, vertical, and longitudinal components.

The results showed that dominant frequencies varied considerably between monitoring locations, generally ranging from approximately 40 to 110 Hz depending on vibration direction and local ground condition. The vertical component exhibited the largest spectral variability and broader frequency distributions, while the longitudinal direction showed more concentrated spectral peaks. Several monitoring points, particularly P8, consistently displayed wider spectral bandwidths and stronger high-frequency responses, indicating localized differences in subsurface stiffness or material composition.

The comparative spectral analysis demonstrated that normalized vibration spectra can effectively capture spatial variations in dynamic ground response under impact excitation. The proposed approach provides a simple and practical method for evaluating heterogeneous soil behavior using multi-point vibration measurements. The findings also suggest that frequency-domain analysis has strong potential for site characterization, dynamic soil assessment, and vibration-based monitoring applications in riverbank and near-surface geotechnical environments.

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