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Frequency-Based Vibration Energy Indicators for Assessing Mechanical Degradation in Riverbank Soils

[1] Bao Quynh Le, [2] Hong Dien Nguyen
[1, 2] Infrastructure Development Department, University of Transport Ho Chi Minh City, Vietnam

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Corresponding Author: **Bao Quynh Le**

Abstract

Progressive mechanical degradation in riverbank soils is associated with gradual reductions in small-strain stiffness and increased material damping under repeated low-amplitude environmental excitation. These processes modify wave propagation within the soil mass and lead to systematic changes in the frequency distribution of vibration energy. This study investigates frequency-based vibration energy indicators as physically grounded measures for assessing mechanical degradation in riverbank soils within a soil dynamics framework. Ground vibration records are analyzed in the frequency domain using power spectral density (PSD) to quantify vibration energy within low-, mid-, and high-frequency ranges. Energy ratios between frequency bands and high-frequency spectral attenuation slopes are employed to characterize stiffness- and damping-controlled components of the dynamic response. Results reveal a consistent redistribution of vibration energy from high- to low-frequency bands along the riverbank, indicating progressive softening of the soil skeleton and enhanced energy dissipation. Increases in the low-to-high frequency energy ratio and stronger high-frequency attenuation are associated with mechanically degraded zones. Because the proposed indicators are normalized in the frequency domain, they reduce sensitivity to excitation amplitude and enable reliable spatial comparison between measurement points, providing a non-invasive approach for identifying mechanically vulnerable riverbank areas.

Keywords: Ground Vibration, Frequency-Domain Analysis, Power Spectral Density, Vibration Energy Redistribution, Mechanical Degradation, Riverbank Soils

1. Introduction

Riverbank soils are inherently vulnerable to progressive mechanical degradation driven by water level fluctuations, seepage, erosion, and repeated low-amplitude environmental loading. These processes gradually alter the soil fabric, leading to reductions in small-strain stiffness and increases in material damping, which weaken bank stability over time. Importantly, such mechanical degradation often develops well before visible deformation or failure occurs, making early-stage assessment particularly challenging [1-3].

Conventional geotechnical investigation methods, including strength testing and deformation monitoring, are primarily sensitive to medium- to large-strain behavior. As a result, they provide limited insight into early degradation processes that occur at very small strain levels under cyclic or ambient excitation [4]. In contrast, ground vibration measurements capture the dynamic response of soils at small strains and directly reflect changes in stiffness, damping, and energy dissipation mechanisms [5].

From a soil dynamics perspective, wave propagation in viscoelastic media is strongly frequency-dependent. Progressive stiffness degradation and increased damping preferentially attenuate high-frequency vibration components while relatively enhancing low-frequency energy, even when excitation amplitude remains nearly constant [6, 7]. This behavior leads to a systematic redistribution of vibration energy across frequency bands, which can be quantified using power spectral density (PSD) analysis. High-frequency energy has been shown to be sensitive to inter-particle contact stiffness and microstructural integrity, whereas low-frequency components reflect the overall dynamic response of the soil mass and boundary conditions [8].

Based on these principles, frequency-based vibration energy indicators—such as band-limited spectral energy, low-to-high frequency energy ratios, and high-frequency attenuation slopes—have emerged as physically interpretable metrics for assessing soil mechanical conditions at small strains [9]. PSD-based approaches further reduce sensitivity to excitation amplitude, enabling spatial comparison between measurement points along riverbanks under similar loading conditions [10]. Nevertheless, a coherent synthesis of these indicators and their relevance for assessing progressive mechanical degradation in riverbank soils remains limited. This study therefore focuses on frequency-based vibration energy indicators as tools for evaluating mechanical degradation in riverbank soils, with emphasis on their physical interpretation and applicability within a soil dynamics framework.

2. Methodology

2.1 Conceptual Approach

This study is grounded in the mechanical principle that reductions in stiffness and increases in energy dissipation capacity of riverbank soils induce systematic changes in ground vibration response at small strain levels. According to soil dynamics theory, material degradation preferentially attenuates high-frequency vibration components and leads to a relative redistribution of vibration energy toward lower frequency bands. Consequently, frequency-domain analysis of vibration energy can be employed as an indirect indicator of progressive mechanical degradation in riverbank soils.

2.2 Spectral analysis and power spectral density

The ground velocity signal $v(t)$ is transformed into the frequency domain using the Fast Fourier Transform (FFT). The power spectral density (PSD) of the signal is computed based on the one-sided spectrum:

$$S_v(f) = \frac{2}{T}|V(f)|^2 \qquad (1)$$

Where $V(f)$ denotes the Fourier transform of the ground velocity signal. The PSD provides a frequency-domain representation of vibration energy distribution and reduces the influence of transient noise present in the time-domain signal.

2.3 Frequency-band energy decomposition

The frequency domain is divided into three characteristic bands:

- Low-frequency band (LF): 1–10 Hz
- Mid-frequency band (MF): 10–30 Hz
- High-frequency band (HF): 30–100 Hz

The vibration energy within each frequency band is quantified by integrating the PSD over the corresponding frequency range:

$$E_i = \int_{f_{i1}}^{f_{i2}} S_v(f)df \qquad (2)$$

where$i \in \{LF, MF, HF\}$. The total vibration energy is defined as:

$$E_{tot} = E_{LF} + E_{MF} + E_{HF} \qquad (3)$$

To reduce the influence of excitation amplitude, the energy in each frequency band is normalized by the total vibration energy:

$$E_i = \frac{E_i}{E_{tot}} \qquad (4)$$

2.4 Mechanical degradation indicators

The ratio between low-frequency and high-frequency vibration energy (LF/HF) is employed as an indicator reflecting the degree of frequency-dependent redistribution of vibration energy:

$$\mathrm{R}_{\mathrm{LF/HF}} = \frac{\mathrm{E}_{\mathrm{LF}}}{\mathrm{E}_{\mathrm{HF}}} \qquad (5)$$

An increase in the RLF/HF value indicates a relative depletion of high-frequency components, consistent with reductions in effective stiffness and an increase in intrinsic material damping of the soil.

High-frequency energy attenuation slope: The attenuation characteristics of high-frequency vibration energy are analyzed using the cumulative energy within the HF band. In log–log space, the HF energy follows a power-law decay with frequency, and the attenuation slope is determined by linear regression. This slope reflects the degree of energy dissipation and scattering within the soil material.

2.5 Directional vibration analysis

The vibration energy indicators are computed separately for each motion component in order to evaluate the sensitivity of individual vibration directions to progressive mechanical degradation. Comparison among different directions helps clarify the role of shear deformation and potential sliding mechanisms in riverbank stability.

2.6 Analysis workflow

The analysis procedure consists of: (i) acquiring three-component ground vibration signals under a fixed excitation source; (ii) performing PSD analysis and frequency-band energy decomposition; (iii) normalizing the band-limited energies and computing the LF/HF ratio and high-frequency energy attenuation indicators; and (iv) conducting spatial comparison of the derived indicators to identify zones exhibiting signs of progressive mechanical degradation.

3. Field Experiment and Results

3.1 Field experiment

This study aims to investigate subsurface soil conditions using a seismic-based approach at a laterally heterogeneous site. A soft riverbank area along the Saigon River was selected, where river water infiltrates the ground predominantly in a direction perpendicular to the river flow, leading to spatial heterogeneity in near-surface soil properties. Impact loading was applied using a handheld hammer in combination with a wooden plate. The wooden plate was employed to distribute the hammer impact energy over a finite area, thereby avoiding localized compressive stress concentration at the vibration source. Hammer impacts are mainly suitable for short source–receiver distances, typically less than 5 m for soil sites and less than 10 m for rock sites. Four measurement points, labeled Point 1 to Point 4, were investigated and evenly spaced at 1.5 m intervals along a line perpendicular to the river flow direction (Fig 1). This configuration was designed to examine spatial variations in soil properties along the potential riverbank failure direction. Free-vibration response data were recorded at each measurement point, corresponding to ten hammer impacts per location.

Fig 1: Ground vibration measurements conducted near the Saigon River

Ground vibration data were recorded along three orthogonal directions, defined as follows:

- X: direction parallel to the river flow;
- Y: direction perpendicular to the riverbank;
- Z: vertical direction relative to the ground surface.

3.2 Results

Fig 2 presents the normalized vibration energy distribution across low-frequency (LF: 1–10 Hz), medium-frequency (MF: 10–30 Hz), and high-frequency (HF: 30–100 Hz) bands at the four measurement points along the riverbank. At all locations, the vibration energy is dominated by the high-frequency band, reflecting the response of near-surface soil layers under short-distance impact excitation. However, clear spatial variations in the relative contribution of LF and MF energy are observed. Point 1 exhibits a strongly HF-dominated response, with negligible LF and MF contributions, indicating relatively intact soil stiffness and limited internal energy dissipation. In contrast, Points 2 and 3 show a modest increase in MF energy accompanied by a slight increase in LF contribution, suggesting the onset of stiffness degradation and enhanced damping effects. The most pronounced redistribution is observed at Point 4, where LF and MF energy fractions increase substantially at the expense of HF energy. This shift indicates a systematic transfer of vibration energy toward lower frequencies, consistent with progressive mechanical degradation of the riverbank soil.

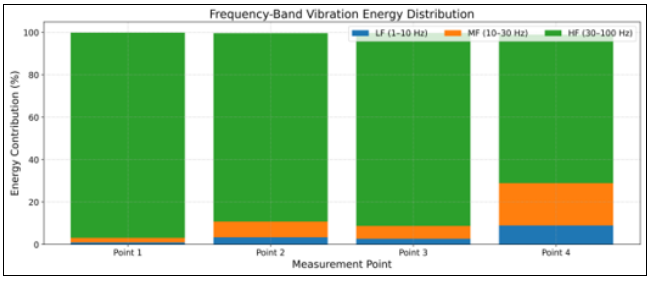

Fig 2: Frequency-band vibration energy distribution

The spatial variation of the LF/HF energy ratio is shown in Fig 3. The LF/HF ratio increases monotonically from Point 1 to Point 4, with a particularly sharp rise at Point 4. This trend reflects a progressive attenuation of high-frequency vibration components relative to low-frequency energy along the riverbank. Low LF/HF values at Points 1–3 indicate a stiffness-dominated dynamic response, whereas the elevated LF/HF ratio at Point 4 suggests a transition toward a damping-dominated regime. This behavior is consistent with increased material damping, reduced effective stiffness, and enhanced microstructural degradation of the soil. The LF/HF ratio therefore serves as a sensitive indicator for identifying zones of advanced mechanical degradation under small-strain conditions.

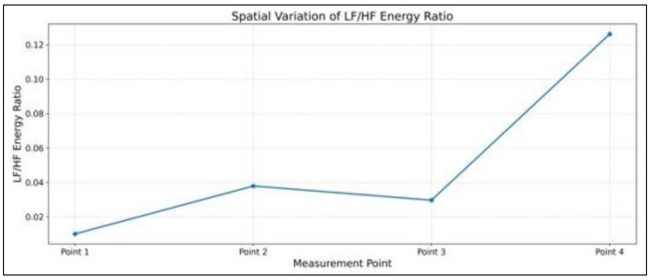

Fig 3: Spatial variation of LF/HF energy ratio

Fig 4 illustrates the spatial variation of the high-frequency energy attenuation slope (β) derived from the cumulative HF energy in log–log space. The attenuation slope is most negative at Point 1, indicating relatively limited energy loss with increasing frequency. Moving toward Points 2 and 3, the slope becomes less steep, reflecting increased high-frequency attenuation associated with enhanced energy dissipation mechanisms.

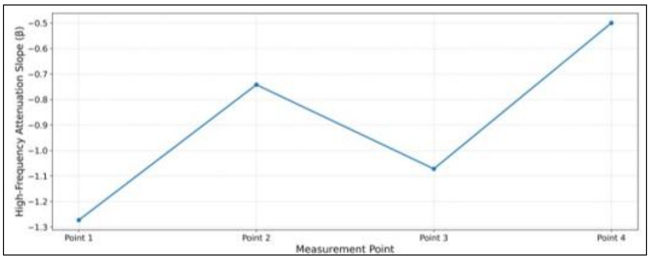

Fig 4: High-frequency energy attenuation characteristics

4. Conclusion

This study demonstrates that frequency-based vibration energy indicators provide a physically meaningful and non-invasive approach for assessing progressive mechanical degradation in riverbank soils under small-strain conditions. By analyzing ground vibration responses induced by controlled impact excitation, systematic changes in vibration energy distribution across frequency bands were identified along the riverbank.

The results reveal a clear spatial redistribution of vibration energy from high-frequency to lower-frequency bands, particularly toward the riverward measurement locations. This redistribution is reflected by a consistent increase in the LF/HF energy ratio, indicating preferential attenuation of high-frequency components associated with reduced effective stiffness and enhanced material damping. In parallel, the high-frequency energy attenuation slope exhibits a progressive reduction in magnitude, highlighting increased energy dissipation and scattering within the soil structure. The consistency between these two independent indicators provides coherent evidence of progressive mechanical degradation along the investigated riverbank section.

Importantly, the proposed indicators are derived from power spectral density analysis, which minimizes sensitivity to excitation amplitude and allows robust spatial comparison between measurement points. This feature makes the approach particularly suitable for field applications involving heterogeneous soils and variable environmental loading. The directional analysis further emphasizes the potential role of shear-related vibration components in capturing degradation mechanisms relevant to riverbank instability.

Overall, the findings confirm that frequency-based vibration energy indicators can effectively characterize early-stage mechanical degradation in riverbank soils prior to the onset of visible deformation. The proposed framework offers a practical and physically grounded tool for riverbank condition assessment and may support early-warning strategies and long-term monitoring of riverbank stability.

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