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Application of Ground Vibration Analysis and Damping Ratio in Predicting Riverbank Landslides

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Abstract
Riverbank landslides pose significant threats to residential areas, infrastructure, and agricultural production. Conventional prediction approaches primarily rely on hydrological and static geotechnical parameters and therefore do not fully capture the dynamic response and progressive mechanical degradation of soils prior to observable deformation. This study proposes the use of ground vibration characteristics and damping ratio as complementary indicators for assessing riverbank slope stability. Field recorded ground vibration signals are processed using frequency domain analysis to identify characteristic frequencies and frequency dependent energy distribution. The damping ratio is determined using the half-power bandwidth method to quantify the energy dissipation capacity and micro scale deformation behavior of soils. Results indicate that riverbank sections with higher landslide susceptibility exhibit a systematic redistribution of vibrational energy from high frequency to low-frequency bands, accompanied by a pronounced increase in damping ratio, reflecting stiffness degradation and enhanced energy dissipation within the soil skeleton. The integration of these vibration based indicators with conventional geotechnical analysis enables early identification of mechanically vulnerable riverbank zones prior to the onset of visible failure, thereby supporting early warning and sustainable riverbank management.

Keywords: Riverbank Landslide, Ground Vibration, Frequency Domain Analysis, Damping Ratio, Energy Dissipation, Early Warning

1. Introduction

Riverbank landslides are among the most common geotechnical hazards, particularly in areas where the soil is weak or consists of loose sand. These events not only cause damage to property and the environment but also pose a direct threat to human safety and riverside infrastructure [1, 2]. Due to the complex nature of riverbank soils and the continuous influence of flowing water, predicting such failures requires dynamic soil assessment methods that are both accurate and sensitive to pre-failure changes. One modern approach involves analyzing ground vibrations in combination with damping ratios to evaluate soil stability. Ground vibrations provide insight into the dynamic state of the soil, reflecting its stiffness, elasticity, and energy dissipation capacity [3, 4]. The damping ratio, which represents the soil's ability to absorb vibrational energy, may vary as the soil structure weakens or its resistance to sliding decreases, making it a sensitive indicator of landslide risk [5, 6].

Field vibration tests such as hammer excitation, mechanical shakers, or ambient vibration measurements combined with spectral analysis, enable the identification of natural frequencies and damping ratios at multiple locations along the riverbank [7, 8]. Variations in these parameters over time or across different positions can reveal instabilities within the soil layers, providing a basis for developing rapid and reliable prediction models for riverbank failure [9, 10].

This study focuses on analyzing ground vibrations and damping characteristics in riverside areas to propose a dynamic-based approach for early identification of landslide prone zones. Unlike conventional studies that rely mainly on static geotechnical properties or hydrological conditions, this work explores the distribution of vibrational energy in the frequency domain and the variation of damping ratios as direct indicators of mechanical degradation in the soil. By integrating spectral analysis with the half power bandwidth method applied to field vibration data, the study clarifies the relationship between stiffness degradation, energy dissipation capacity, and slope instability risk. This approach offers a highly sensitive dynamic assessment framework capable of detecting subtle changes in soil behavior, thereby complementing traditional methods and supporting the development of early warning systems for riverbank landslides.

2. Methodology

2.1 Conceptual approach

Ground vibration analysis is widely used to assess the dynamic behavior of soils and foundations. This method is based on recording vibration signals typically in terms of velocity or acceleration in three orthogonal directions and analyzing them in the frequency domain. From this process, key dynamic parameters such as natural frequency, vibration amplitude, and damping ratio (ζ) can be obtained. Changes in these parameters may signal underlying instabilities within the soil layer.

2.2 Fourier spectrum analysis (FFT)

The Fast Fourier Transform (FFT) is a mathematical tool used to convert a signal from the time domain into the frequency domain. By analyzing the frequency spectrum of vibration signals, it becomes possible to identify characteristic frequencies f_n and the corresponding vibration amplitudes of the ground. The general form of the Fourier transform for a signal $x(t)$ is given by:

$$X(\omega) = \int_{-\infty}^{\infty} x(t)e^{-i\omega t}dt \qquad (1)$$

Where:

- $X(\omega)$ is the frequency spectrum of the signal;
- $x(t)$ is the time-domain signal;
- ω is the angular frequency;

In practice, for discrete data collected from sensors, the Discrete Fourier Transform (DFT) and the FFT algorithm are employed to obtain the frequency spectrum. This spectrum reveals the dominant frequencies within the signal, allowing the identification of the soil's natural frequency.

Before performing frequency-domain analysis, the vibration signals are preprocessed to reduce noise and ensure spectral stability. The recorded acceleration signals are first detrended and segmented to isolate stable portions of the signal after the impact excitation. A band-pass filter is then applied to remove low-frequency drift and high frequency noise.

The computed power spectrum is subsequently smoothed using a moving average window to enhance the identification of spectral peaks. These preprocessing steps help suppress spurious spectral fluctuations caused by environmental noise and improve the reliability of damping ratio estimation using the half power bandwidth method, particularly under conditions of soft and heterogeneous riverbank soils.

2.3 Damping ratio (ζ)

The damping ratio is a dimensionless parameter that describes the ability of a system to dissipate vibrational energy. For soils, it reflects the capacity to absorb dynamic energy and may vary as the soil structure weakens or undergoes deformation [11]. Therefore, it serves as a sensitive indicator of landslide risk. In this study, the damping ratio is estimated using the half power bandwidth method. This approach is based on the frequency spectrum of vibration signals and is widely applied in dynamic analysis. The damping ratio using the half power bandwidth method is calculated as:

$$\zeta = \frac{f_2 - f_1}{2f_n} \qquad (2)$$

Where:

- f_n is the natural frequency (the peak frequency in the spectrum);
- f_1 and f_2 are the frequencies at which the amplitude drops to $\frac{1}{\sqrt{2}}$ of the maximum value f_n;

The half power bandwidth method is applicable under small strain conditions, where the dynamic behavior of the soil can be reasonably approximated as linear. Under these conditions, resonance peaks in the frequency spectrum are clearly defined, and the damping ratio can be reliably estimated from the spectral bandwidth at the half power level. In this study, the damping ratio is primarily used as a relative index to compare different measurement locations, in order to assess variations in the energy dissipation characteristics of the soil, rather than as an absolute material property.

A high damping ratio indicates that the soil has a strong capacity for energy dissipation, often associated with loose structure, high porosity, or the presence of water. In contrast, a low damping ratio suggests higher dynamic stiffness and lower energy dissipation capacity, which generally corresponds to more stable ground conditions [12].

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

The FFT spectral analysis results show that the characteristic vibration frequencies range from 39-57 Hz in the horizontal directions (X, Y) and from 45-68 Hz in the vertical direction (Z). This difference clearly reflects the mechanical heterogeneity of the soil at the investigated locations.

From the spectral results in Figure 2, the lowest vibration frequency in the X direction (parallel to the river flow) gradually decreases with increasing distance from the excitation source to the measurement points. This indicates that the soil stiffness tends to reduce closer to the riverbank. The dynamic response at all locations can be approximated as a single degree of freedom system.

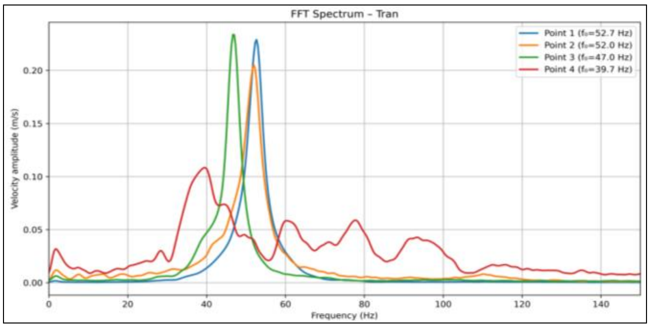

Fig 2: Average FFT spectrum at four measurement points along the X direction

From the spectral results in Figure 3, the decrease in vibration frequency in the direction perpendicular to the riverbank appears to follow an approximately linear trend with respect to the distance from the river. The farther from the riverbank, the higher the soil stiffness. This suggests that river water influences the softening of the soil, leading to the initial separation of soil layers near the bank. The soil behavior in areas adjacent to the river can be characterized as a multi degree of freedom system. This is a promising indicator for monitoring soil degradation that may eventually lead to riverbank failure.

From the spectral results in Figure 4, vertical ground vibrations also reveal the weakening of the soil. The closer the soil is to the river, the more pronounced the separation between soil layers becomes, leading to an increase in the number of frequency peaks. The difference between the highest and lowest frequencies also becomes larger as the soil approaches the riverbank.

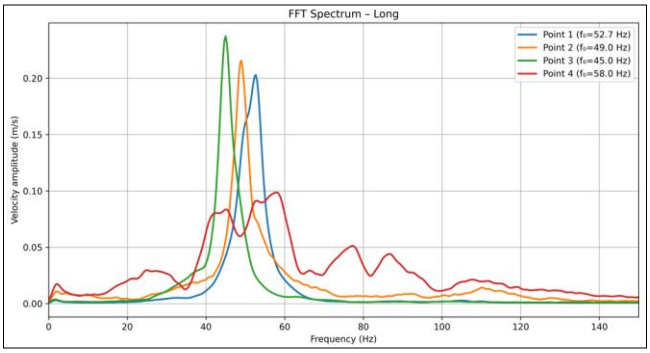

Fig 3: Average FFT spectrum at four measurement points along the Y direction

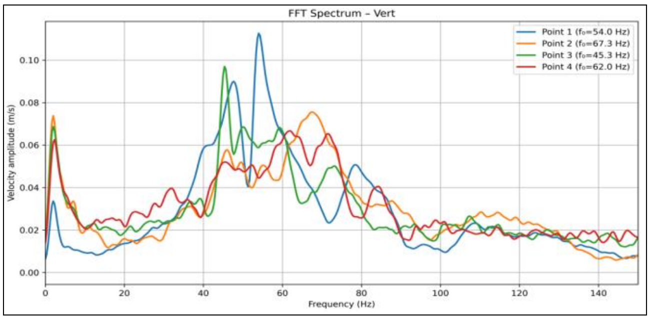

Fig 4: Average FFT spectrum at four measurement points along the Z direction

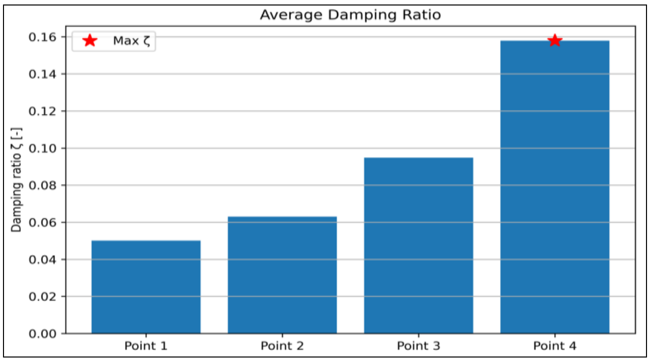

Fig 5: Average damping coefficient of four measurement points

In this study, the interpretation of soil vibration behavior as either a single degree of freedom or a multi degree of freedom system is used in a qualitative sense. Locations where the spectrum exhibits a single dominant and clearly defined peak are considered to behave similarly to a single degree of freedom system, reflecting a relatively uniform dynamic response of the soil layer. In contrast, vibration spectra exhibiting multiple peaks with comparable amplitudes indicate the presence of different vibration modes, often associated with soil heterogeneity, and can be interpreted as behavior equivalent to a multi degree of freedom system.

From the damping ratio results shown in Figure 5, the average damping ratio (ζ) at Point 4 is the highest. This suggests that the soil structure in this area is likely loose, with high porosity or groundwater presence, causing vibrations to dissipate rapidly. This is also a warning sign of potential instability and a high risk of landslides. In contrast, the average damping ratio (ζ) at Points 1 and 2 is the lowest, indicating relatively high soil stiffness and low energy dissipation capacity, which corresponds to better stability. Meanwhile, the average damping ratio (ζ) at Point 3 is at a moderate level, which may reflect softer soil conditions with lower compaction and a higher tendency to absorb vibrational energy.

4. Conclusion

This study conducted ground vibration analysis in a riverside area through field vibration measurements combined with frequency domain signal processing. Based on Fourier spectral analysis, the characteristic frequencies of ground vibrations were identified, while the damping ratio was estimated using the half-power bandwidth method to evaluate the energy dissipation capacity of the soil.

The results reveal significant differences in vibration characteristics among the measurement locations. At several points, the vibration spectra tend to shift toward lower frequency ranges, accompanied by a noticeable increase in the damping ratio. These changes indicate a relative reduction in soil stiffness and an increase in energy dissipation mechanisms within the soil structure, suggesting the potential of vibration based indices for identifying weak soil zones in riverside environments.

The combination of spectral analysis and damping ratio estimation proves to be an effective approach for clarifying the dynamic characteristics of the ground and can serve as a supplementary parameter to traditional geotechnical assessment methods in riverbank stability studies. This approach enables the identification of differences in dynamic responses across measurement locations and provides additional insights for evaluating soil stability conditions along riverbanks.

However, it should be noted that this study was conducted at a pilot scale with a limited number of measurement points and without full integration of geotechnical data such as soil composition, mechanical properties, and groundwater conditions. Therefore, the proposed vibration based indices should be considered as supplementary indicators rather than direct predictors of riverbank stability.

Future studies should expand the survey area, increase the density of measurement points, and integrate long term vibration monitoring with detailed geotechnical data. Such efforts would allow for a more comprehensive evaluation of soil degradation mechanisms and enhance the applicability of vibration based indices in monitoring and managing riverbank landslide risks.

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