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ADVANCEMENT IN DYNAMICS OF MONOPILE FOUNDATION: ANALYTICAL AND EXPERIMENTAL INSIGHTS

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ABSTRACT

This study explores the dynamic response and vibration control of monopile-supported systems under lateral dynamic loads, incorporating advanced modeling and experimental techniques. Initially, the dynamic impedance properties of a monopile placed within in homogeneous and soil/ soil and rock layered conditions are developed using a spectral element formulation. The results reveal that the presence of a rock layer significantly enhances system stiffness, while increasing rock-socketing depth reduces horizontal amplitudes but increases resonant rocking amplitudes. Incorporating resonator-based vibration control, a novel approach is proposed to integrate periodically linked spring-mass resonators along the monopile, forming a "metapile." Analytical results show that resonators effectively attenuate vibrations within specific frequency ranges, while lumped masses broaden the frequency response range. For wind turbine systems, four configurations are examined: conventional, resonators in the tower, monopile, and both. Experimental tests on a scaled model validate the analytical predictions, highlighting substantial vibration reduction in configurations with resonators, particularly when placed in both tower and monopile. This research underscores the efficacy of resonators in enhancing dynamic performance, demonstrating their potential for reducing vibrations in monopile-supported structures under varied soil-rock conditions, with implications for onshore wind turbine design.

KEYWORDS: Monopile Foundation; Spectral Element Formulation; Resonators; Local Resonance; Soil Shear Modulus

INTRODUCTION

Monopile foundations are widely used in onshore and offshore structures, particularly in wind turbine installations, Pezeshki et al. 2022; He et al. 2022; Wei et al. 2022), due to their structural simplicity and cost-effectiveness. However, their dynamic behavior under lateral loads, including wind and wave forces, Alzabeebee et al. (2022), poses challenges in terms of performance, stability, and durability. Understanding and optimizing the dynamic response of monopile foundations embedded in various soil conditions is crucial for ensuring the safety and efficiency of these systems, Kaynia (2019).

The dynamic stiffness and damping characteristics of monopiles are significantly influenced by the surrounding soil and the depth of rock-socketing Novak (1974); Novak (1978); El Naggar (1996). In layered soil-rock systems, stiffer rock layers enhance the overall stiffness, while increasing the rock-socketing depth reduces horizontal displacement amplitudes but can increase rocking resonant amplitudes (Yu et al. 2013; Anoyatis 2017). These findings underscore the need for advanced analytical approaches to capture the complex interactions between the monopile and the soil-rock system accurately. Spectral element formulations, which allow frequency-dependent analysis, provide a robust framework for studying these interactions. Beyond understanding the inherent dynamic response of monopiles, mitigating excessive vibrations is critical for the longevity of wind turbines. Resonators,

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strategically placed along the monopile or within the turbine tower, have emerged as a promising solution. These devices leverage local resonance phenomena to attenuate vibrations within specific frequency ranges. Unlike conventional mass-damping approaches, resonators enhance stiffness near their natural frequencies, offering a targeted and efficient vibration control mechanism.

This study integrates analytical modeling and experimental validation to investigate the dynamic behavior and vibration control capabilities of monopiles. By examining different configurations of resonators within the wind turbine system, the research aims to provide insights into optimizing the design of monopile-supported structures. The findings have broad implications for enhancing the resilience and performance of wind turbine foundations in diverse soil conditions, addressing critical challenges in renewable energy infrastructure.

DERIVATION OF THE EQUATION OF PILE

This study considers the coupled horizontal translation and rotational motions of the monopile, while disregarding vertical motion dynamics (Novak, 1974). A schematic in Figure 1a illustrates a pile positioned within a mixed soil and rock layer. Figure 1b depicts the monopile linked to a spring-dashpot model, representing the visco-elastic properties of the surrounding soil and rock, which are used to assess the dynamic characteristics of the pile-soil-rock system. The underlying rock layer is represented using a visco-elastic framework that incorporates variations in shear wave velocity and mass density. Both the soil and rock strata are considered uniform, exhibiting linear and isotropic behavior, with material damping properties that adjust based on the excitation frequency.

To derive the governing equation for the pile, the principles of force and moment equilibrium are utilized on the free-body diagram depicted in Figure 1c. The interaction between the pile and the surrounding soil is represented using visco-elastic spring elements. For a pile segment with a height of 'dz' experiencing a horizontal displacement u(z, t) at any elevation 'z,' the horizontal soil reaction can be described as per Novak (1974): $K = G(S_{u1} + iS_{u2})u(z,t)$. The shear modulus of the surrounding soil is represented by G, while the parameters S_{u1} and S_{u2} depend on the dimensionless frequency Additionally $a_0 = \omega r\sqrt{\rho/\mathrm{G}}$., the Poisson's ratio μ determines the specific values of S_{u1} and S_{u2}. Consequently, the governing differential equation for the monopile is simplified and expressed as:

$$\rho_{\mathrm{p}} A \frac{\delta^2 u(z,t)}{\delta t^2} + E_p I_p \frac{\delta^4 u(z,t)}{\delta z^4} + G(S_{u1} + i\,S_{u2})u(z,t) + P\frac{\delta^2 u(z,t)}{\delta z^2} = 0 \quad (1)$$

Here, m, I_p and E_p represent the mass per unit length, the area moment of inertia, and the Young's modulus of the pile, respectively. For steady-state dynamics, the displacement $u(z,t)$ is assumed to take the form $u(z,t) = U(z)\,e^{i\omega t}$.

$$E_p I_p \frac{\delta^4 U(z)}{\delta z^4} + P\frac{\delta^2 U(z)}{\delta z^2} - \left(\rho_{\mathrm{p}} A\, w^2 - G(S_{u1} + i\,S_{u2})\right) U(z) = 0 \quad (2)$$

Considering $U(z) = e^{\lambda z/\mathrm{L}}$, and performing proper substitution to the equation above:

$$\frac{\lambda^4}{L} E_p I_p e^{\lambda z/\mathrm{L}} + P\frac{\lambda^2}{L} e^{\lambda z/\mathrm{L}} + \left(\rho_{\mathrm{p}} A\, w^2 - G(S_{u1} + i\,S_{u2})\right) e^{\lambda z/\mathrm{L}} = 0 \quad (3)$$

Where,

$$\lambda_{1,2} = \frac{1}{\sqrt{2}}\sqrt{\mp\frac{PL^2}{E_p I_p} + \sqrt{\left(\frac{PL^2}{E_p I_p}\right)^2 - 4L^4\left(\frac{-\rho_{\mathrm{p}} A\,\omega^2 + G(S_{u1} + i\,S_{u2})}{E_p I_p}\right)}} \quad (4)$$

The two resulting solutions are represented as λ_1 and λ_2. Therefore, the final differential equation can be simplified as:

$$U(z) = C_1\left(\cosh\lambda_1\frac{z}{L}\right) + C_2\left(\sinh\lambda_1\frac{z}{L}\right) + C_3\left(\cos\lambda_2\frac{z}{L}\right) + C_4\left(\sin\lambda_2\frac{z}{L}\right) \quad (5)$$

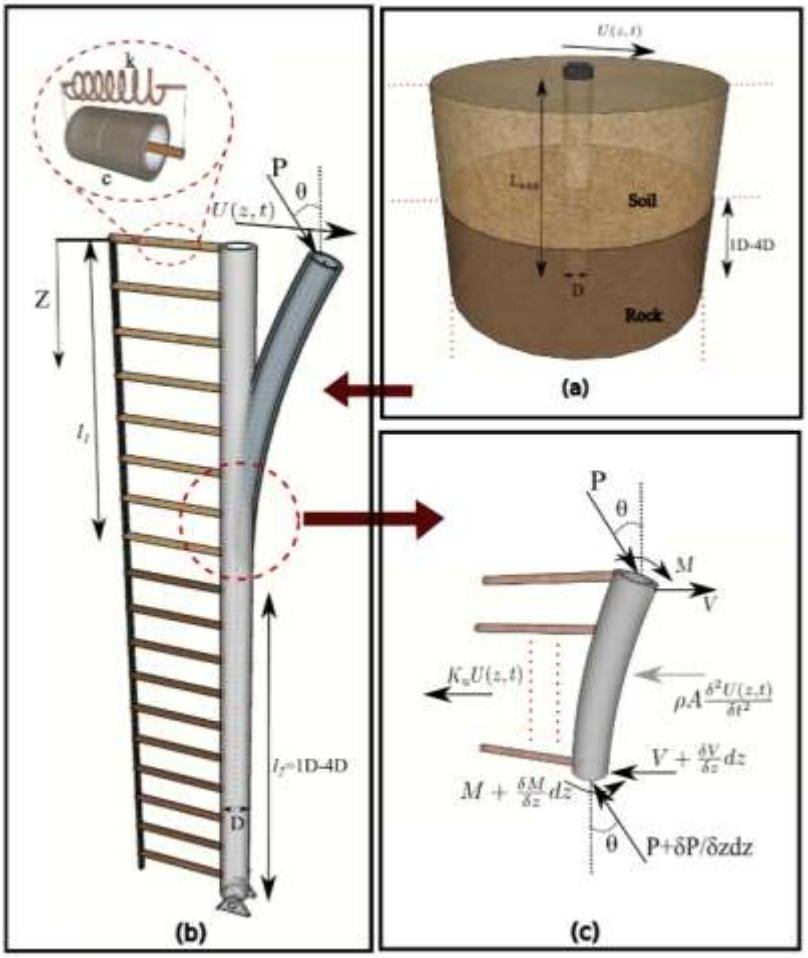

Fig. 1 Schematic representation of the pile-soil-rock models: (a) Pile embedded in a semi-infinite homogeneous layered soil; (b) Mathematical model of the soil-pile-rock system; (c) Free-body diagram of a small pile element

The spectral element method (SEM), though similar to the conventional finite element approach, incorporates a key difference: it employs a direct Fourier transform to transition the pile's response from the time domain to the frequency domain. The soil's material properties are embedded within the parameter λ, effectively allowing the spring-pile configuration to be modeled as a single pile with behavior governed by λ. After deriving the spectral element for a single segment of the pile-soil model, impedance functions are generated, and modal analyses are conducted for a block foundation, as outlined by Das et al. (2023).

RESULTS AND DISCUSSIONS

1. Stiffness Coefficients Against Translation and Rocking Motion of the Monopile

The findings have been validated using the example of a pile embedded in soil, ensuring the accuracy of the proposed analytical solution. The half-space consists of horizontal layers, each represented by linear visco-elastic springs. To simplify the calculation of the dynamic stiffness solution, the axial load acting on the pile is assumed to be zero. Consequently, from Equation 4}, λ is expressed as:

$$\lambda_{1,2} = \left(\frac{\rho_p A\omega^2 - G(S_{u1} + iS_{u2})}{E_p I_p}\right)^{\frac{1}{4}} \quad (6)$$

In the same manner, the dynamic stiffness expression for a pile embedded in homogeneous soil is derived. The resulting condensed dynamic spectral matrix contains impedance terms associated with the remaining degrees of freedom.

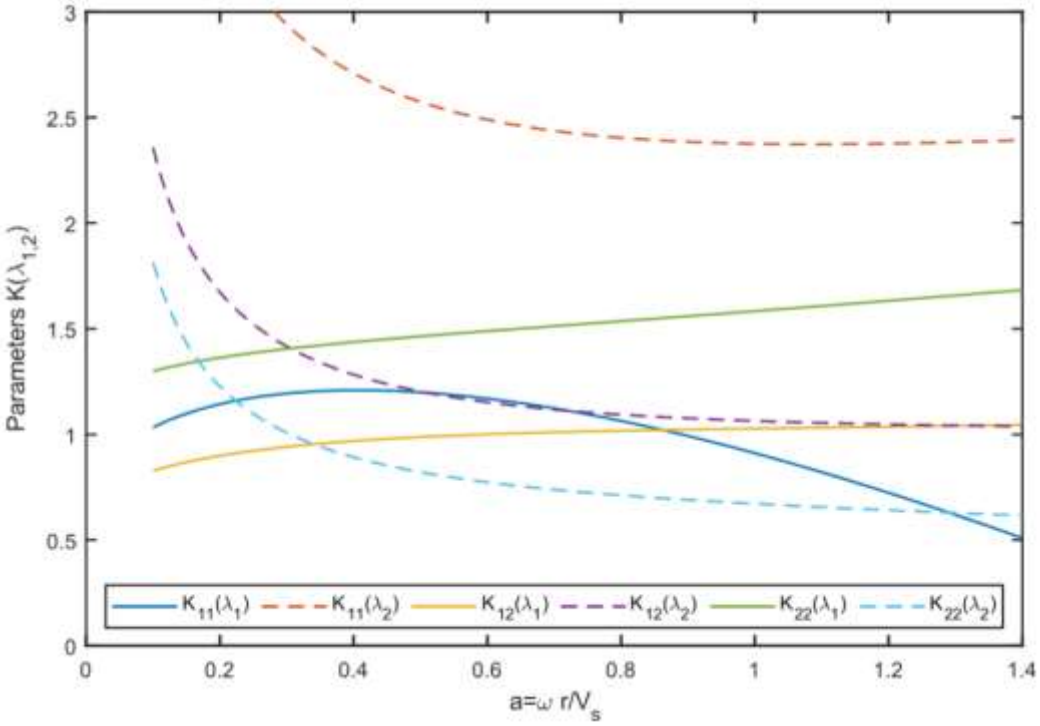

Fig. 2 Impedance functions K showing the dynamic stiffness and geometric damping for horizontal translation, rotational and cross component

The stiffness and damping parameters for different soil-rock-pile interaction cases are determined using the previously outlined equations and approaches. To examine the dynamic stiffness and damping behaviors of the rock-socketed monopile for various rock types and socket depths, a study is carried out on a monopile with a radius of D/2 = 0.75 meters and a height of 12 meters. The depth of the rock socket in the monopile ranges from l_2= 1D to 4D (referencing is1998design). Table 1 provides the shear wave velocity and unit weight for the different cases of rock layers considered in this study.

Table 1: Properties of soil and rock

Medium	Shear Wave Velocity, 'm/s'	Unit Weight, γ
Soil layer	1200	15
Weathered rock	1680	21
Sandstone	1900	22
Shale	2200	23
Limestone	2960	25
Basalt	3700	26

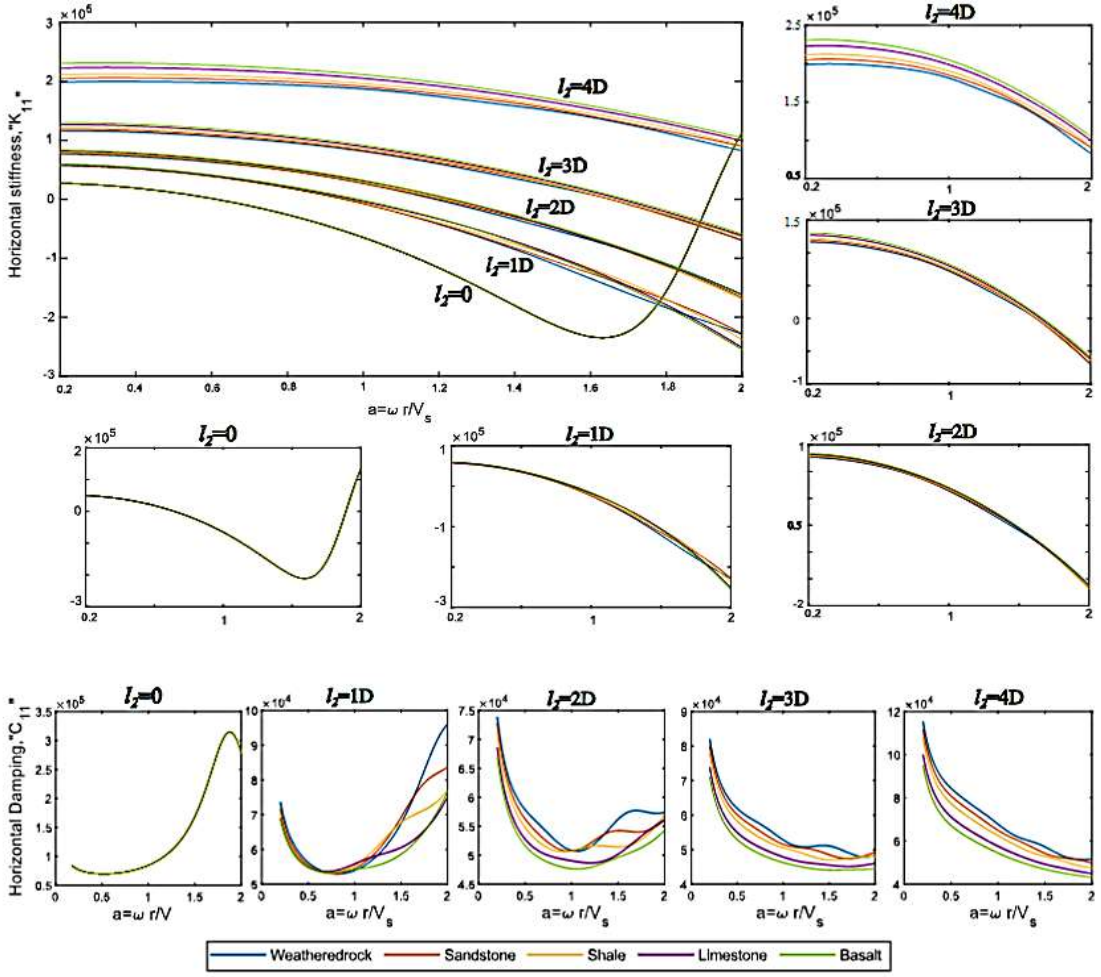

Fig. 3 Changes in the dynamic stiffness K_{11} and horizontal damping C_{11} are observed across a range of dimensionless parameters l/r=16, ρ/ρ_p=0.191, μ=0.4) while varying the depths of the rock socket in the pile

Figures 3 and 4 present the changes in horizontal stiffness (K11) and damping (C11), as well as rotational stiffness (K22) and rotational damping (C22). Notably, the horizontal stiffness exhibits its peak values when the rock layer placed underneath boasts a higher shear wave velocity, exemplified by basalt rock in this investigation, and reaches its nadir when the rock layer possesses a lower shear wave velocity, as observed with weathered rock. Conversely, the dampening property within the system reaches its maximum levels when the rock layer present underneath is less rigid or features a lower shear wave velocity, such as in the case of weathered rock, and declines when the rock layer exhibits significant stiffness, akin to basalt. As a result, a stiffer underlying rock layer enhances the pile's resistance to both horizontal translation and rotation, due to the energy dispersion from the pile into the viscoelastic half-space. Therefore, a more rigid rock layer leads to a stiffer pile-soil-rock system, causing reduced energy dissipation through soil damping. Based on this, the damping of the pile-soil-rock system is lower when the rock has a higher shear wave velocity, such as basalt, while it is more significant in rocks with lower shear wave velocities. Consequently, a pile embedded in a soil-rock mixture will experience greater deflection when the rock's mass density and shear wave velocity are lower. In contrast, piles in soil-rock mixtures with stiffer rock layers, such as basalt with higher mass density, will experience less deflection under lateral dynamic loads. However, piles in a strong rock layer like basalt will exhibit longer oscillations, as the energy dissipation through damping is less efficient compared to piles in weaker, weathered rock.

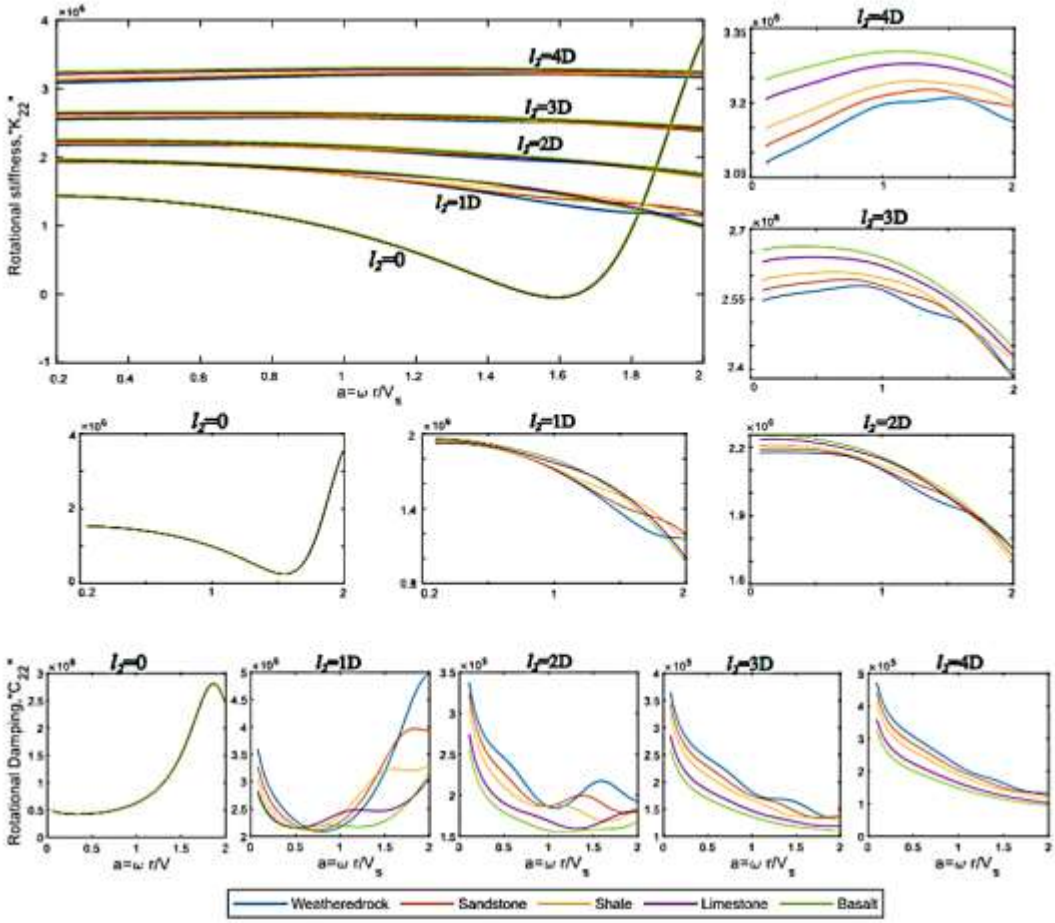

Fig. 4 Changes in the dynamic stiffness K_{22} and horizontal damping C_{22} are observed across a range of dimensionless parameters l/r=16, ρ/ρ_p=0.191, μ=0.4$) while varying the depths of the rock socket in the pile

2. Response of Pile Foundation Plotted against Frequency and Amplitude

The complex factors that influence the horizontal movement, rotation, damping, and stiffness of an individual pile can be used to describe the behavior of a pile-supported foundation system under cyclic loads. To examine the multi-degree-of-freedom (MDOF) nature of this system, a modal analysis is employed. This approach is based on the principle that the dynamic response of a system subjected to time-varying forces can be expressed as a sum of simple harmonic motions, referred to as its natural vibration modes. In a system with 'm' nodes, each having 'n' degrees of freedom, there will be a total of 'm x n' eigenvalues and eigenvectors, or modes, that define the system's behavior. Figure 4 illustrates the actual amplitude of translation, which is also applicable to the rocking amplitude of the foundation block.

Figure 5 illustrates the dynamic response of the pile head, with panels (a, c, e, g) representing the horizontal translation amplitude across various rock types as the pile socketing depth within the rock layer increases. Panels (b, d, f, h) depict the corresponding rocking amplitude as a function of the non-dimensional frequency aa. For a given set of dimensionless parameters, the pile-soil-rock system achieves its initial natural frequency at a lower value when the underlying rock layer is stiffer or possesses a higher mass density, regardless of the socket depth. The maximum translation and rocking amplitudes are observed to be highest for Basalt rock and lowest for Weathered rock at the initial natural frequency. With increasing rock socketing depth, the system's stiffness grows due to the greater impact of the rock layer's properties. While the first natural frequency remains nearly constant, the second natural frequency shifts higher as the socketing depth increases. Basalt, being the stiffest material, exhibits the greatest modal participation in both translation and rocking at the first natural frequency,

followed by sandstone, shale, limestone, and weathered rock. However, the opposite trend is noted for the second natural frequency, particularly when the rock socketing depth exceeds 2D.

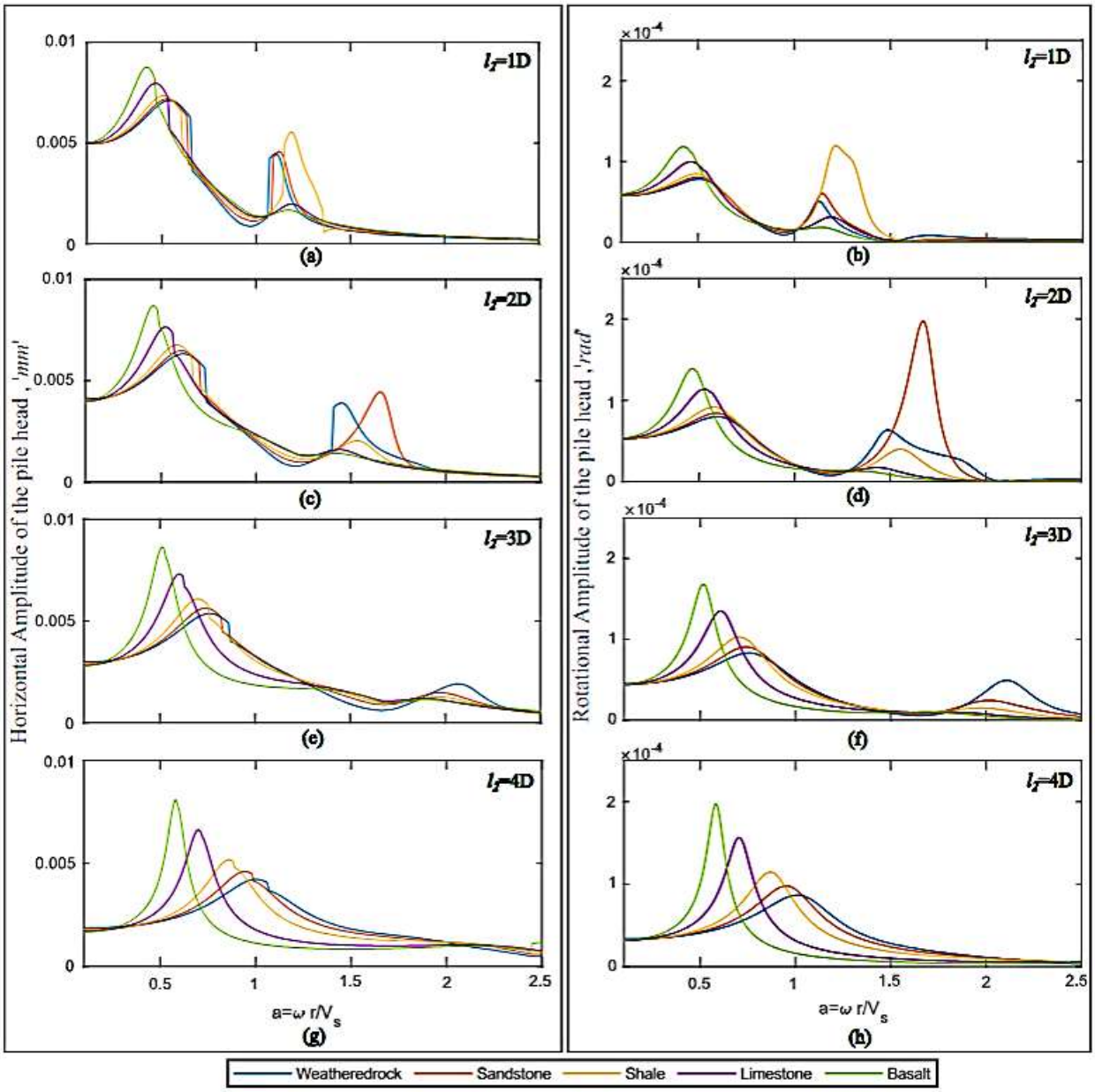

Fig. 5 Horizontal and rotation impedance function of the pile for different non-dimensional frequencies obtained via modal analysis: (a) Horizontal amplitude for $l_2 = 1D$; (b) Rocking amplitude for $l_2 = 1D$; (c) Horizontal amplitude for $l_2 = 2D$; (d) Rocking amplitude for $l_2 = 2D$; (e) Horizontal amplitude for $l_2 = 3D$; (f) Rocking amplitude for $l_2 = 3D$; (g) Horizontal amplitude for $l_2 = 4D$; (h) Rocking amplitude for $l_2 = 4D$

3. Application of the Resonators in Pile Foundation

A novel approach is introduced to address the demands of wind turbine structures and tackle potential challenges: a monopile-supported wind turbine equipped with a series of periodically attached resonators. Analytical and experimental studies are conducted to evaluate and compare the displacement responses at the tower head and monopile head for configurations with resonators distributed along the system's length. Experimental studies on the dynamics of a laterally loaded monopile-supported wind turbine were conducted using Wood's scaling law to replicate full-scale behavior. The setup features a

soil tank lined with a 0.035 m thick foam layer to simulate infinite boundary conditions by damping reflected vibrations. The usable soil volume is 0.53 x 0.53 x 0.68, filled with Yamuna sand at 60% relative density, corresponding to a dry density of 1522 kg/m³. The setup includes the turbine, lateral loading system, and instrumentation. To simulate lateral wind and wave-induced excitations, harmonic loading was applied to the tower using a stringer, sweeping through frequencies under unit displacement. The key innovation of this study lies in the development of a specialized resonator, integrated into both the monopile and wind turbine tower, to enhance the vibration attenuation performance of the entire system while accounting for soil-structure interaction effects. Additionally, two alternative configurations are examined, where resonators are placed exclusively in the tower or the monopile. Finally, the dynamic responses at the tower head and monopile head across all four configurations are compared to identify the optimal design.

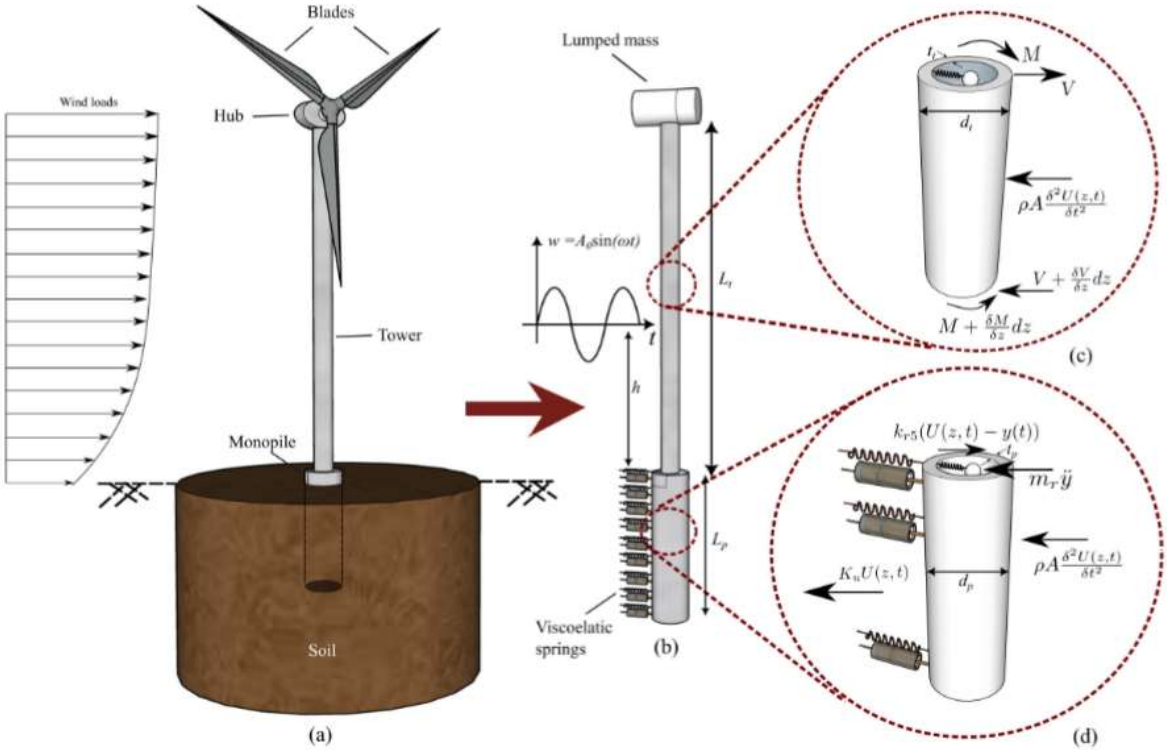

Fig. 6 Schematic of the wind turbine system: (a) Monopile-supported wind turbine configuration; (b) Equivalent numerical represention of the wind turbine setup; (c) Free-body diagram of a tower section with an infused resonator; (d) FBD of a small section of pile with an integrated resonator

- The experimental setup, shown in Figure 6 includes the wind turbine system, lateral load application mechanism, and supporting components. Loading conditions were defined after assembling the turbine. The study focuses on steady-state excitations impacting the turbine, which typically experiences lateral dynamic forces from wind and waves. To simulate this, lateral harmonic excitation was applied to the tower using a stringer connected to a dynamic actuator, inducing unit displacement over a range of frequencies. Figure 7 presents the experimentally obtained transmittance data for each case.
- In Case 2, where resonators are periodically integrated into the tower, transmittance at the tower top decreases significantly (solid yellow line) compared to Case 1. However, the monopile head response increases due to the absence of resonators in the monopile, with a noticeable natural frequency shift to a lower range due to added inertial mass.
- In Case 3, with resonators only in the monopile, minimal changes occur at the tower top, but the monopile head response decreases near its resonant frequency. The dynamic behavior is influenced primarily by the stiffness and damping of visco-elastic springs.

- In Case 4, where resonators are integrated into both the tower and monopile, responses at both the tower top and monopile head significantly decrease compared to Case 1, with a natural frequency shift similar to Case 2. This configuration achieves a 20% reduction in monopile head response and an 11% reduction at the tower top. The system also exhibits lower responses beyond the resonator's natural frequency, confirming the effectiveness of comprehensive resonator integration. Case 4 highlights the potential of this approach for significant response attenuation across the wind turbine structure.

CONCLUSIONS

This study presents a comprehensive analysis of the dynamic behavior of monopile foundations under horizontal dynamic loads in both homogeneous and layered soil-rock conditions. Further, a novel

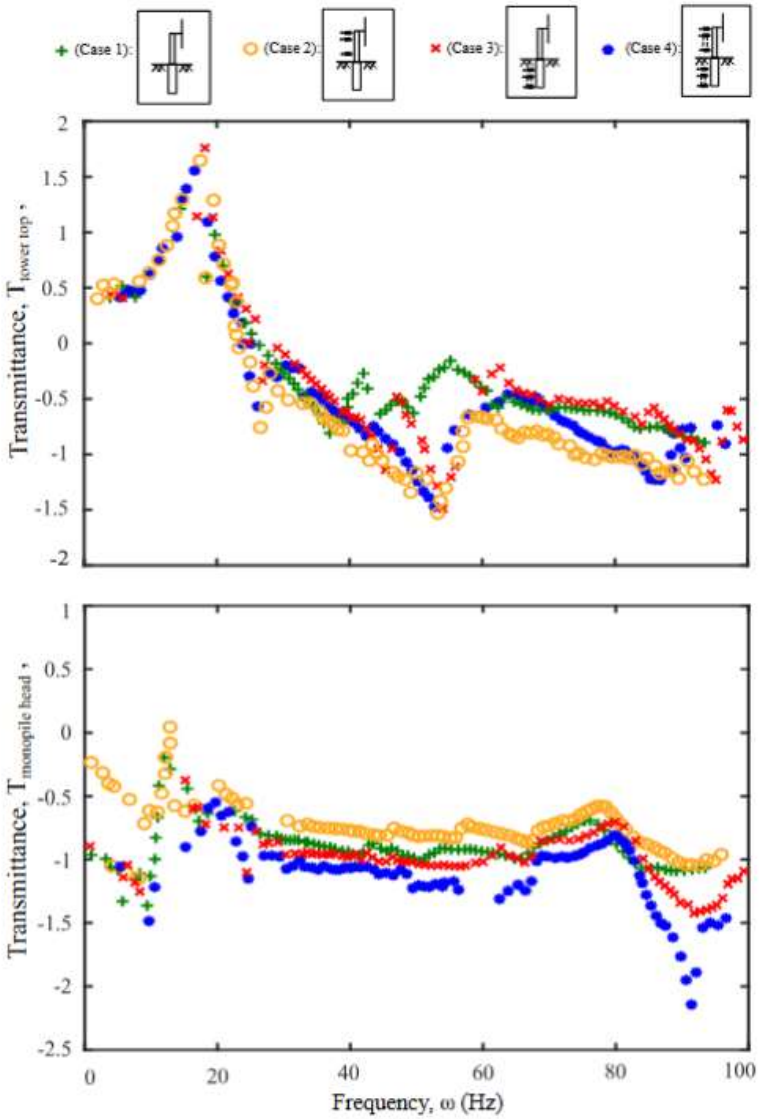

Fig. 7 Experimental transmittance data for four wind turbine configurations: (a) tower top and (b) monopile head responses. Case 1: Traditional monopile-supported turbine; Case 2: Resonators in the tower; Case 3: Resonators in the monopile; Case 4: Resonators in both tower and monopole

approach in incorporating the resonators in pile foundation in order to enhance the vibration attenuation characteristics is experimentally shown for a scaled wind turbine system supported by monopile

foundation. The dynamic characteristics of a monopile are strongly influenced by rock socketing depth. The overall stiffness of the pile-soil-rock system is greatly enhanced by the presence of a stiffer underlying rock layer. The dynamic response of monopile, characterized by horizontal translation and rocking motion, is influenced by the rock-socketed monopile depth. As the socket depth increases, the horizontal amplitude decreases, indicating enhanced stability, whereas the resonant amplitudes for rocking motion show a noticeable increase with greater socket depth. The integration of spring-mass resonators into a monopile (termed "metapile") significantly improves its dynamic stiffness. The dynamic response of a metapile shows reduced amplitudes within a specific frequency range, particularly near the resonant frequency of the resonators.

Further, a comparison between a resonator-infused monopile and a monopile with lumped masses demonstrated that resonators enhance vibration attenuation, with the metapile exhibiting an increased stiffness and a broader effective frequency range. The study explores dynamic vibration control in a monopile-supported wind turbine by strategically placing resonators along the tower and monopile. Four configurations were analyzed: (1) conventional monopile-supported turbine, (2) resonators in the tower, (3) resonators in the monopile, and (4) resonators in both tower and monopile. The results show that placing resonators in both the tower and monopile (Case 4) offers the most effective vibration attenuation, reducing responses at both the tower top and monopile head. Experimental and analytical results indicate significant response reductions, particularly near the resonant frequency, with the tower and monopile head responses diminishing when the excitation frequency exceeds the resonator's natural frequencies.

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