

Seismic Behaviour of Skirted Ring Foundations Under V-H Loading in Layered Soils for Offshore Wind Turbine

Pratik Goel, Kaustav Chatterjee

Indian Institute of Technology Roorkee, India, pratik_g@ce.iitr.ac.in

ABSTRACT: The overreliance on non-renewable energy sources presents pressing global challenges, driving the need for sustainable energy alternatives such as wind, solar, and geothermal power. Offshore wind farms, located in seas and oceans, are increasingly favoured for their advantages, including higher wind speeds, consistent directions, reduced land-use conflicts, and minimal disturbance to local populations. However, offshore foundations, which account for approximately 30% of wind farm project costs, face complex loading conditions from turbines, waves, earthquakes, scour, and climate change impacts. Skirted foundations have gained prominence as a cost-effective and efficient solution for offshore applications. This study investigates the seismic stability of skirted ring foundations in layered soils, specifically loose sand over clay, using advanced numerical techniques. The analysis is conducted with Abaqus, a 3D finite element program. Both the soil layers are modelled using the Mohr Coulomb elastic perfectly plastic constitutive model. The skirted ring foundation is modeled as linear elastic. Seismic forces were applied using a pseudo-static approach, converting seismic effects into equivalent static forces using horizontal seismic acceleration coefficient k_h . V-H failure envelopes are developed to evaluate the performance of skirted ring foundations under combined vertical and horizontal loading in seismic conditions to replicate harsh offshore environment. The results were benchmarked against established findings in the literature to validate the model and highlight the potential of skirted ring foundations as a sustainable, cost-effective solution for offshore wind farm foundations. The results demonstrate that increasing the skirt length enhances the size of the failure envelope, indicating improved load-bearing performance, whereas higher seismic acceleration coefficients exhibit a detrimental effect on foundation stability. This research provides valuable insights for enhancing the design and resilience of offshore foundations, addressing critical challenges posed by seismic forces and layered soil conditions in marine environments.

KEYWORDS: Pseudo-static approach, V-H failure envelopes, skirted ring foundation, sustainable energy.

1 INTRODUCTION

The rapid, sustainable, and cost-effective deployment of offshore wind turbines (OWTs) is becoming increasingly vital to meeting the global demand for renewable energy. As the pace of the global energy transition accelerates, nations are striving to expand offshore wind capacity to reduce reliance on fossil fuels and lower carbon emissions. However, the rapid scaling of OWT technology—both in turbine size and power output—poses significant challenges for foundation design, construction logistics, and long-term performance. The newer generation of OWTs, often exceeding 15 MW in capacity with hub heights over 150 m, impose enormous vertical, lateral, and overturning loads on their supporting foundations. These demands are further amplified in deeper waters and harsh marine environments, where conventional foundation solutions often become economically or technically infeasible.

Traditional offshore foundation systems such as monopiles, gravity-based foundations, and jacket structures have proven successful in many existing wind farms. Nevertheless, their application faces several limitations when scaled up for next-generation turbines. Monopiles, for instance, encounter design challenges beyond water depths of about 40 m due to excessive bending moments and installation difficulties. Gravity-based foundations require large volumes of construction materials, leading to high fabrication and transportation costs, as well as considerable environmental disturbance during installation. These drawbacks highlight the need for innovative, sustainable, and adaptable foundation concepts that balance cost efficiency, constructability, and environmental compatibility while maintaining superior mechanical performance.

In this context, Skirted Ring Foundations (SRFs) have emerged as a promising alternative to conventional shallow and monopile foundations for offshore applications. SRFs combine the geometric efficiency of a ring foundation with the enhanced bearing and confinement characteristics of peripheral skirts. The ring foundation, characterized by its hollow circular geometry, offers several advantages: reduced material

consumption, lower self-weight, and efficient load distribution, all while maintaining excellent structural integrity. By integrating skirts—vertical extensions projecting downward from the foundation's periphery—the system benefits from improved confinement and increased interaction with the surrounding soil. The skirts act as shear keys, transferring load to deeper and stronger soil strata, thereby improving both vertical and lateral load-bearing performance. These attributes make SRFs particularly suitable for offshore wind installations, where foundations must withstand combined vertical, horizontal, and moment loads under cyclic and dynamic environmental actions.

The potential of ring and skirted foundation systems has been extensively validated through both experimental and numerical investigations. Boushehrian and Hataf (2003), Birid and Choudhury (2021), and Goel and Chatterjee (2025) demonstrated that ring foundations exhibit optimal performance when the ratio of internal to external radius (R_i/R_o) lies between 0.2 and 0.4, ensuring a balance between stiffness and material economy. Traditionally, ring foundations have been deployed for onshore axisymmetric structures such as silos, tanks, and chimneys; however, Eranti et al. (2011) explored their potential for offshore environments, paving the way for broader applications in renewable energy infrastructure.

The beneficial influence of skirts in improving the behaviour of shallow foundations has also been well documented. Experimental studies by Micic et al. (2003) and Eid (2013) reported up to a threefold increase in load-carrying capacity for skirted footings on soft clays compared to unskirted ones. Similarly, Wakil (2013) observed improvements as high as 6.25 times, underscoring the effectiveness of skirts in enhancing bearing capacity and reducing settlement. Li et al. (2014) further reinforced these observations through finite element simulations, capturing the influence of skirt length, embedment ratio, and soil strength parameters on the ultimate capacity. Collectively, these studies highlight that the integration of skirts provides both mechanical and

environmental advantages by improving performance without excessive material use.

The combination of ring geometry and skirts thus presents a rational, lightweight, and structurally efficient solution for next-generation OWT foundations, especially in layered or heterogeneous soil conditions. In such systems, the skirts not only increase the effective embedment but also enhance the soil–structure interaction mechanism, resulting in greater rotational stiffness and resistance against lateral displacement. These features make SRFs particularly attractive for sandy–clayey profiles, where the upper sand layer provides high stiffness and the underlying clay offers additional damping and confinement.

However, the foundation behaviour of OWTs is not governed by static loads alone. Offshore wind structures are frequently subjected to combined vertical and horizontal (V–H) loading, arising from complex combinations of wind, wave, and operational forces. Understanding the interaction between vertical and lateral capacities is essential for reliable design, as these load components are not independent but influence each other through nonlinear soil response mechanisms. The situation becomes even more complex under seismic loading conditions, where transient inertial forces and cyclic degradation of soil strength may significantly alter the load transfer mechanism and the resulting failure envelope.

Recent damage observed in offshore wind farms due to earthquakes or extreme loading events—such as typhoons and severe storms—has highlighted the need for a deeper understanding of foundation performance under seismic excitation. Conventional analytical approaches, including those based on classical plasticity or limit equilibrium theory, often fall short of capturing the full spectrum of soil–structure interaction (SSI) effects in non-homogeneous, anisotropic, or layered soils. These limitations necessitate the use of advanced numerical modeling techniques, such as three-dimensional finite element (FE) analysis, which can account for complex geometries, material nonlinearities, and dynamic soil behaviour.

The present study addresses this research gap by undertaking a comprehensive numerical investigation into the V–H interaction and seismic performance of Skirted Ring Foundations embedded in a layered soil profile consisting of dense sand overlying soft clay. The analysis is conducted within a three-dimensional finite element framework using Abaqus, allowing precise representation of soil stratification, foundation geometry, and dynamic loading conditions. The study systematically examines the effect of varying horizontal seismic acceleration coefficients (k_h) on the foundation response and aims to develop dimensionless V–H failure envelopes applicable to performance-based design.

Through this investigation, the study contributes valuable insights into the mechanisms governing the seismic behaviour of SRFs, providing a foundation for optimizing embedment depth, skirt length, and interface properties for enhanced seismic resilience. The outcomes not only advance the current understanding of offshore foundation design under combined and dynamic loading but also support the broader goal of developing sustainable and cost-effective solutions for the next generation of offshore wind energy infrastructure.

2 NUMERICAL MODEL METHODOLOGY

2.1 Model Geometry and Constitutive Relation

A three-dimensional finite element (FE) model of a skirted ring foundation embedded in a layered soil profile is developed in Abaqus/Implicit (Dassault Systèmes, 2023) to perform the present analysis, as illustrated in Fig. 1. The foundation,

comprising the ring and the surrounding skirt, is idealized as a linear elastic material, representing the mechanical behaviour of reinforced concrete. A reference point (RP) is defined at the centroid of the ring’s base, in contact with the soil, to facilitate load application and monitoring of foundation response.

The surrounding soil is modeled as a cylindrical domain with a diameter of $15D_o$ and a depth of $18D_o$, where D_o is the outer diameter of the skirted ring foundation. These domain dimensions are selected based on preliminary mesh and boundary sensitivity analyses to ensure negligible boundary influence on the stress distribution and failure mechanisms. The internal diameter of the ring, i.e., D_i , is kept constant at $0.4D_o$.

The stratified soil profile is modeled using the Mohr–Coulomb constitutive model with a non-associated flow rule, providing a more realistic depiction of shear-dominated deformation and failure behaviour. The soil and foundation material properties are summarized in Table 1.

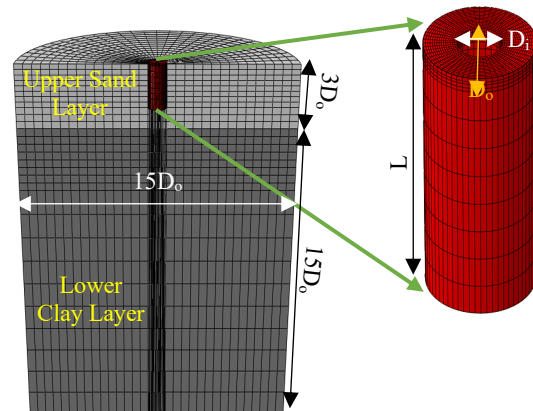


Figure 1. Numerical model of soil and SRF.

2.2 Boundary Conditions and Interaction Properties

The semi-infinite extent of the surrounding soil in the numerical domain is represented through the application of appropriate boundary conditions that effectively minimize artificial confinement and reflection effects. Along the lateral boundaries of the soil domain, roller supports are employed to restrain all horizontal displacements while allowing vertical movement. This boundary configuration ensures that the soil can deform naturally under the applied loads, replicating the behaviour of an unbounded medium, while simultaneously preventing unrealistic lateral confinement that might otherwise influence the load transfer mechanism around the foundation.

At the base of the soil domain, all translational and rotational degrees of freedom are fully constrained. This boundary condition provides a stable reference plane for the numerical model, preventing rigid-body motion and eliminating potential numerical instabilities during both static and dynamic simulations. Such treatment of the base boundary also ensures that stress wave reflections and vertical settlements are minimized, yielding a realistic representation of foundation–soil interaction under loading.

The interaction between the soil and the foundation skirts is modelled using a surface-based contact formulation that captures both normal and tangential contact behaviours. The normal behaviour is governed by a hard contact law allowing separation but preventing interpenetration, while the tangential behaviour is defined through a frictional model governed by the interface friction angle (δ). The value of δ is expressed as a fraction of the soil’s internal friction angle (ϕ) using an empirical relation (Eq. 1), following the methodologies reported by Goel et al. (2024), Goel and Chatterjee (2024a, b),

Kumawat et al. (2024), and Chatterjee et al. (2025). This approach enables an accurate simulation of shear transfer mechanisms along the skirt–soil interface, ensuring realistic representation of interface sliding, mobilized shear resistance, and soil–foundation interaction effects under both static and seismic conditions.

Table 1. Numerical model properties

Property	Value
<i>Foundation</i>	
Outer Diameter (D_o)	100 mm
Internal Diameter (D_i)	$0.4D_o$
Unit weight	24 kN/m^3
<i>Upper sand layer</i>	
Friction angle	32°
Dilation angle	2°
Unit weight	7.85 kN/m^3
Poisson's ratio	0.2
Elastic modulus	60 MPa
Cohesion	1 KPa
<i>Lower clay layer</i>	
undrained shear strength (S_u)	25 kPa
Unit weight	7.40 kN/m^3
Poisson's ratio	0.49
Elastic modulus	$500S_u$

To prevent mesh locking and stress concentration at the contact zone, a finer mesh is adopted near the foundation–soil interface, gradually coarsening away from the region of interest. Additionally, appropriate contact penalty stiffness and frictional parameters are calibrated through preliminary sensitivity analyses to achieve convergence without compromising accuracy.

$$\delta = \frac{2}{3} \tan \phi \quad \text{Eqn.1}$$

2.3 Loading Methodology

The development of vertical–horizontal (V–H) failure envelopes for shallow and embedded foundations represents a fundamental aspect of geotechnical design, particularly for offshore and seismic applications where foundations are subjected to combined and multidirectional loading. These envelopes provide a quantitative measure of the load–interaction mechanisms and the ultimate strength characteristics of the foundation–soil system. Broadly, two methodological frameworks are adopted for the construction of V–H failure envelopes in numerical and experimental studies: load-controlled and displacement-controlled approaches. Each framework has its own merits and limitations depending on the complexity of the soil–structure interaction, loading conditions, and numerical formulation employed.

In the load-controlled approach, also referred to as the load probe test, the vertical and horizontal loads are incrementally applied to the foundation until a failure criterion—typically defined by peak load or a specified deformation limit—is satisfied. Although this method is conceptually straightforward, it frequently encounters convergence difficulties, numerical instability, and inconsistent identification of the ultimate state in finite element analyses, particularly when the soil exhibits strong nonlinearity or strain-softening behaviour. Studies such as those by Fan et al. (2023) and Suryasentana et al. (2020) have highlighted that the principal drawback of this method lies in its inability to stably trace the post-peak portion of the load–

displacement curve. As soil stiffness rapidly degrades near failure, load-controlled analyses often diverge or terminate prematurely, leading to an underestimation of the true ultimate capacity. Furthermore, in layered soil systems or under seismic excitation, the soil–foundation response becomes highly nonlinear, making it difficult to maintain equilibrium under load-controlled conditions. Consequently, while the load-controlled framework remains useful for preliminary assessments or small-strain analyses, it is generally unsuitable for large-deformation problems involving complex interaction mechanisms and cyclic or seismic effects.

In contrast, displacement-controlled approaches have proven to be more stable and robust, offering improved numerical convergence and a more realistic depiction of foundation behaviour under ultimate and post-ultimate conditions. In these methods, prescribed displacements are applied in one or more directions, and the corresponding reaction forces are recorded to determine the load-carrying capacity and failure envelope. Fan et al. (2023) comprehensively evaluated several displacement-based techniques—such as the displacement-controlled probe test, side swipe test, sequential swipe test, and enhanced swipe test—and demonstrated that these approaches provide superior control over the failure path and clearer identification of the limit state compared with load-controlled frameworks. Among these, the side swipe test offers an optimal balance between computational simplicity, efficiency, and accuracy, making it particularly suitable for large-deformation analyses of skirted and shallow foundations.

In the present study, the side swipe method (illustrated in Fig. 2) is adopted for constructing the V–H failure envelope of the skirted ring foundation. The procedure involves two sequential stages following the establishment of the initial geostatic stress field. First, a vertical displacement is applied to embed the foundation to the target depth, allowing the soil to mobilize realistic bearing and frictional resistance while establishing confining stresses around the skirts. After reaching equilibrium, the vertical displacement is fixed, and a horizontal displacement—representing lateral loading—is imposed on the foundation base to simulate side-swipe action. The horizontal load response is recorded until the mobilized reaction reaches a plateau or exhibits softening, signifying the attainment of ultimate capacity. This two-stage displacement-controlled framework provides an efficient means to capture the coupled response of vertical and horizontal load transfer mechanisms, enabling precise delineation of the V–H failure envelope under both static and seismic conditions.

The magnitude of the applied displacement plays a crucial role in ensuring accurate and consistent capacity estimation. A displacement that is too small may not fully mobilize the soil resistance, while an excessively large one can lead to unrealistic deformations and numerical instability. Based on the extensive parametric studies by Gourvenec et al. (2006) and Martin and Randolph (2006), a normalized displacement of $0.1 D_o$ (where D_o denotes the outer diameter of the foundation) has been established as sufficient to fully mobilize the ultimate bearing and lateral capacities in both skirted and shallow foundation systems. Adopting this convention ensures that the full load–displacement behaviour, including pre-peak and post-peak phases, is captured without introducing computational artifacts.

Accordingly, in this study, both vertical and horizontal displacements are set to $0.1 D_o$, providing a consistent and reliable benchmark for evaluating the foundation performance across various seismic acceleration coefficients (k_i), embedment depths, and interface friction conditions. This methodology ensures the development of robust and reproducible V–H failure envelopes, which serve as essential

tools for understanding the interaction effects and the relative contribution of vertical and lateral resistance mechanisms.

Overall, the displacement-controlled side swipe method offers a numerically stable, physically representative, and computationally efficient framework for assessing the seismic performance of skirted ring foundations, facilitating the development of rational design guidelines for offshore and seismic geotechnical applications.

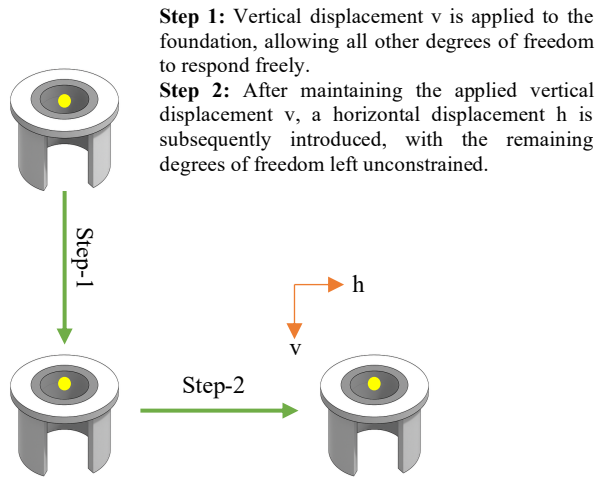


Figure 2. Methodology of the side swipe test

2.4 Mesh detailing

The soil and foundation domains were discretized using the sweep meshing technique available in the Abaqus library, utilizing 8-node reduced integration brick elements (C3D8R), as depicted in Fig. 1. This meshing approach is consistent with the methodologies employed by Gavin et al. (2014) and Goel and Chatterjee (2025). To ensure an optimal balance between computational efficiency and solution accuracy, a detailed mesh sensitivity analysis was performed, the results of which are presented in Fig. 3. Based on this assessment, a discretization comprising approximately 35140 elements was identified as the most suitable configuration and was subsequently adopted for all simulations conducted in this study.

3 VALIDATION OF THE NUMERICAL METHODOLOGY

The reliability of the numerical model is verified through validation against experimental data. Given the scarcity of experimental and field studies on skirted ring foundations (SRF), the methodology is benchmarked using the experimental investigation of laterally loaded caisson foundations in clayey soils conducted by Kumar and Rao (2011).

Their study examined caissons with varying length-to-diameter (L/D) ratios, and the lateral capacity corresponding to $L/D=4$, $S_u=19.2\text{kPa}$, unembedded length to diameter ration $(e/D)=105$ and $D=105\text{mm}$ is adopted for comparison in the present analysis. The numerical results showed good agreement with the experimental findings, with an average deviation of about 12.57%, as depicted in Fig. 4.

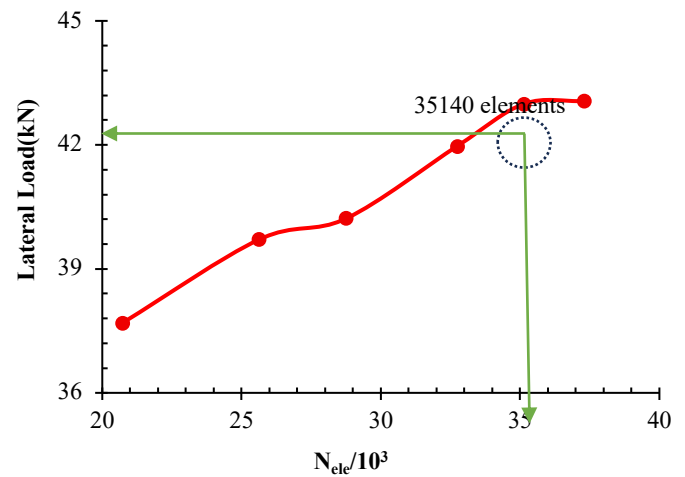


Figure 3. Mesh sensitivity analysis

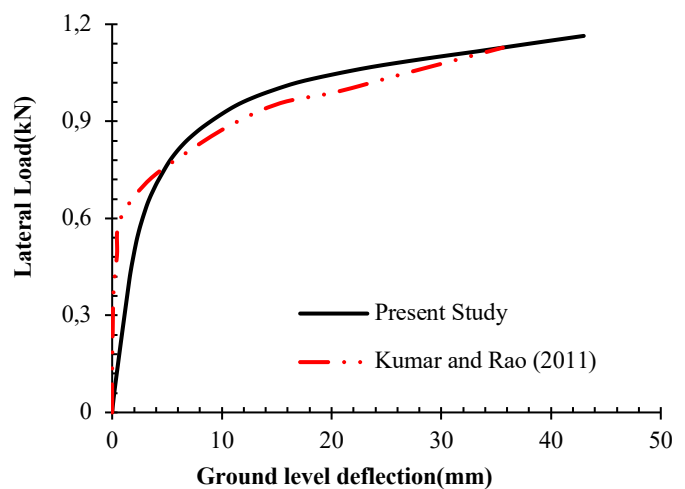


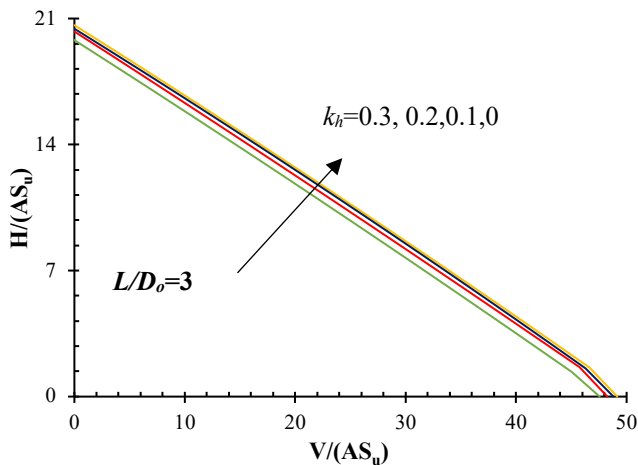
Figure 4. Numerical model methodology validation

4 RESULTS AND DISCUSSION

Fig. 5 presents a comparison of the dimensionless ultimate capacity of the skirted ring foundation for two embedment ratios, $L/D_o=3$ and $L/D_o=2$, under varying horizontal seismic coefficients (k_h). It is observed that both the lateral and vertical ultimate capacities decrease progressively with increasing k_h . This reduction can be attributed to the additional inertial forces generated during seismic excitation, which intensify dynamic soil-structure interaction effects. These inertial forces lead to excessive shear strains and reduced confining stresses in the surrounding soil, thereby weakening the effective stress regime and compromising both the bearing and sliding resistance of the foundation system.

Moreover, the degradation in lateral capacity is significantly more pronounced at higher k_h values. This behaviour stems from the nonlinear amplification of seismic-induced horizontal inertial forces, which result in large lateral displacements and accelerated degradation of passive soil resistance in front of the skirt. In contrast, the vertical capacity is primarily governed by end bearing and shaft friction, mechanisms that are relatively less affected by horizontal seismic acceleration. As a result, the horizontal seismic demand (k_h) has a disproportionately greater impact on lateral capacity, while the reduction in vertical resistance remains comparatively moderate.

Fig. 6 illustrates the normalized load capacity envelope of the skirted ring foundation under the combined action of vertical and horizontal loading. The failure envelopes developed for $L/D_o=2$ and $L/D_o=3$ clearly demonstrate that an increase in skirt length leads to a wider and deeper failure surface, indicating improved load-carrying capacity in both directions. This enhancement is primarily due to the increased embedment depth, which results in improved soil confinement, larger mobilized soil volume, and enhanced development of passive earth pressure along the skirt walls. A longer skirt also increases the contact area with the surrounding soil, enabling greater transfer of both shear and normal stresses at the soil–structure interface.



In addition, the extended skirt acts as a kinematic restraint against horizontal movement, increasing the rotational stiffness and improving the overall stability of the foundation system under seismic loading. The resulting failure envelope becomes more expanded and rounded, reflecting the enhanced interaction between vertical and lateral load-resisting mechanisms. This behaviour underlines the importance of skirt length as a critical design parameter in optimizing the seismic performance of offshore and onshore shallow foundations subjected to multidirectional loading.

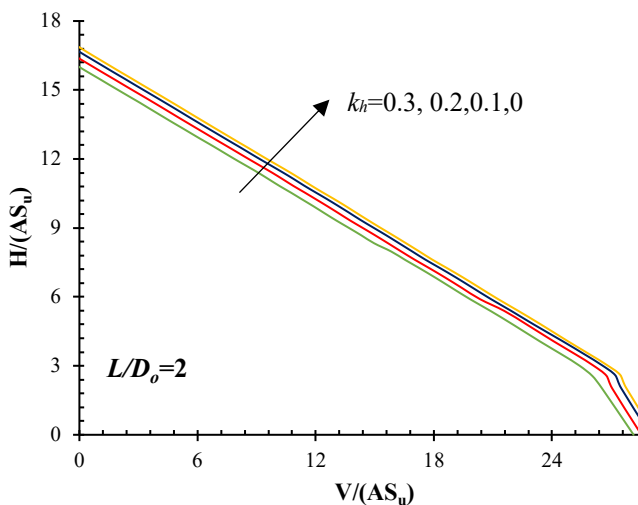


Figure 5. Dimensionless ultimate V-H failure capacity envelope

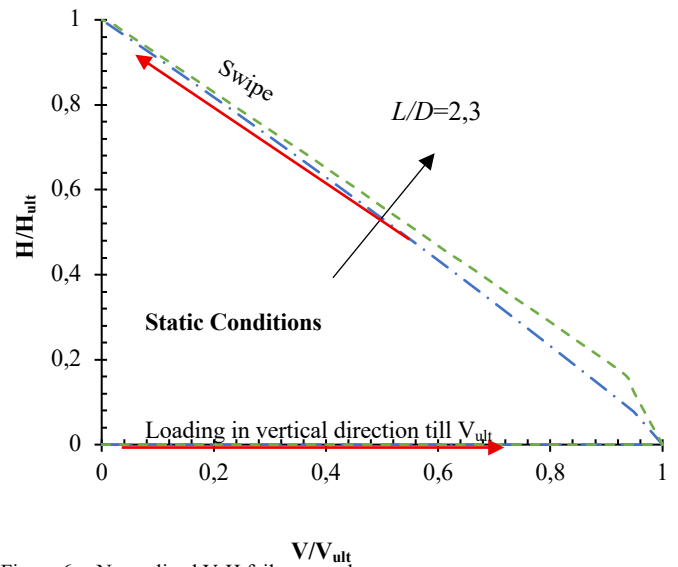


Figure 6. Normalized V-H failure envelope

5 CONCLUSIONS

This study presented a comprehensive numerical investigation into the seismic performance of skirted ring foundations embedded in layered soil, subjected to combined vertical and horizontal (V–H) loading.

The findings clearly demonstrate that the horizontal seismic acceleration coefficient (k_h) has a significant impact on the load-carrying capacity of SRFs. As k_h increases, both the vertical and lateral ultimate capacities reduce due to the generation of additional inertial forces that induce higher soil deformations and reduce effective confining stress. This reduction is particularly pronounced in the lateral direction because seismic-induced shear demands lead to degradation of passive resistance and increased soil softening. Vertical capacity, which is primarily governed by bearing resistance and skin friction, is comparatively less sensitive to k_h though it too exhibits a declining trend under stronger seismic excitation.

Additionally, the study highlights the beneficial influence of increasing skirt length on foundation performance. Increasing the embedment ratio from $L/D_o=2$ to $L/D_o=3$ leads to a substantial expansion of the failure envelope under combined loading. This enhancement arises from improved soil confinement, increased mobilization of passive resistance, and greater engagement of the surrounding soil mass, which collectively enhance both vertical and lateral resistance mechanisms.

The developed V–H failure envelopes under seismic conditions provide valuable insights for the design of offshore wind turbine foundations, where complex loading and layered soil conditions prevail. The results affirm that skirted ring foundations offer a promising solution for next-generation offshore wind applications, combining sustainability, material efficiency, and superior seismic resilience. The study also reinforces the importance of considering interaction effects, embedment geometry, and seismic demand in the rational design of offshore foundation systems.

Future work may involve extending the framework to account for cyclic loading, pore pressure generation, and soil nonlinearity during strong ground motions to further improve the fidelity of seismic design guidelines for such innovative foundation systems.

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