Numerical modelling of the performance of a hybrid monopiled-footing foundation

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ABSTRACT
Foundations for offshore wind turbines are subjected to horizontal loads and moments due to wind and waves, in addition to vertical self-weight. This study proposes an alternative foundation composed of a shallow footing with a central monopile. This combines the advantages of traditional offshore foundations with the potential for reducing installation costs and time. Finite element analysis indicated that interaction between the components generates high lateral load resistance, in some cases greater than purely summing the resistance of the individual elements. The lateral load resistance was found to rely on vertical loading, roughness of the soil-pile interface and footing width-to-pile length. This research suggests that the new system may improve the lateral resistance of wind turbines.

RÉSUMÉ
Des bases pour des turbines de vent en mer sont soumises aux charges horizontales et les moments devant s'enrouler et les vagues, en plus du l'individu-poids vertical. Cette étude propose une base alternative composée de pose peu profonde avec un central monopile. Ceci combine les avantages des bases en mer traditionnelles avec le potentiel pour réduire des coûts et le temps d'installation. L'analyse par éléments finis a indiqué que l'interaction entre les composants produit de la résistance de charge latérale élevée, dans certains cas plus considérablement que purement additionnant la résistance des différents éléments. La résistance de charge latérale s'est avérée pour se fonder sur le chargement vertical, la rugosité de l'interface de sol-pile et la longueur de largeur-à-pile de pose. Cette recherche suggère que le nouveau système puisse améliorer la résistance latérale des turbines de vent.

1 INTRODUCTION

Recently there has been a worldwide increase in the development of green energy technologies. Wind energy represents the most mature of these renewable energy sources. Progressing from onshore wind turbines, many countries are now switching to large offshore farms. This strategic evolution involves complex environmental, economical and social aspects.

Foundations for offshore wind turbines are subject to combined loading conditions consisting of horizontal loads (H) and moments (M) due to wind and wave forces, in addition to vertical self-weight (V) of relatively low magnitudes. Mitigating problems of such complex loading combinations has lead to a range of analytical and technological approaches being proposed by many researchers. For example, Gottardi *et al.*, (1999) proposed a plastic model to describe the behaviour of circular footings on sand under general planar loading conditions. Martin and Houlsby (2000) conducted a series of laboratory tests on spudcan foundations on clay under general planar loadings and extended their work to cover a full numerical analysis for the same problem in (2001). Further studies have investigated support structures for offshore wind turbines (eg. Byrne and Houlsby, 2002 and 2003; Stone *et al.*, 2007; Ward, 2006).

Foundations for offshore wind turbines can be separated into two major groups: a) monopiles and b) gravity base structures. Monopiles are typically very large with diameters of 3 to 4m or more and lengths of 20m to 35m. These are usually installed by drilling and grouting, or by driving (or a combination of both methods). Gravity bases are also quite large, with diameters of 10-20m being typical. Both foundation types can be expensive to install and this often constitutes the major component of the costs. Since both foundation types require substantial equipment, jack-up barges or ship hire, any time delays can be a significant problem for a project. There are also issues associated with preparation of the seabed, scour and refusal of the pile driving process due to buried obstructions. Hence a reduction in the width or length of foundations to resist these complex loading cases has significant economic benefits.

Given the aforementioned demands, foundation designers are seeking alternative solutions to ensure safe and economical designs. The current study proposes an innovative hybrid foundation system composed of a relatively small shallow footing provided with a central monopile. The new hybrid system combines many of the advantages of its predecessor traditional offshore foundations, with the potential of reducing the installation costs and time.

In the proposed hybrid system, the presence of a shallow footing insures a rigid connection with the pile able to provide rotational restraint at the pile head. Previous studies by Mokwa and Duncan (2003) indicated that the presence of a rigid cap restrained the rotation at the pile head and consequently improved the lateral resistance of the pile and reduced the lateral deflection by up to 75% compared to free head piles. Since the typical dimensions of pile caps are smaller than those of the shallow footings used in the proposed hybrid system, the hybrid system is expected to produce a much higher resistance. Mokwa and Duncan (2001) concluded that an additional contribution in the lateral resistance is also achieved through the development of passive soil wedges behind thick caps, or thick footings. Thus the combination of a smaller gravity base structure combined with one or more short piles is expected to significantly improve the response of offshore foundations subjected to combined general planar loadings. The geometry and assumed loading state for the proposed system are shown in Figure 1, where a single central pile is employed. The pile diameter and length are (D) and (L) respectively, and the footing width is (W). The assumed lateral earth pressures are also shown in the figure.

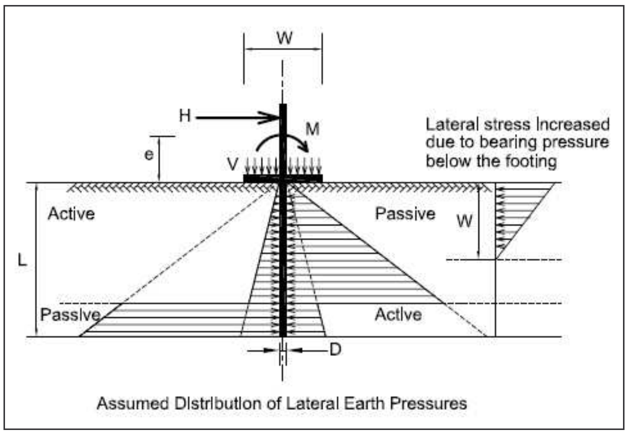

Figure 1. Geometry and definition of the studied problem

2 NUMERICAL MODELING

A numerical study using the finite element code PLAXIS V8 has been performed to characterize the behaviour of the proposed composite system under general planar load combinations (vertical, horizontal and moment loading) typically encountered in the design of offshore foundations. This model helps emphasize the role of each individual component of the composed system and provides guidance for choosing their optimum dimensions. Whilst in practice these hybrid systems will usually be close to circular in plan, an essential precursor to the understanding of the behaviour of circular hybrid systems is the study of the simpler 2-D plane strain problem of a long, rigid strip footing resting on a continuous rigid wall. Therefore the numerical models used in this study are deliberately simple, but are still expected to be capable of capturing the main features required to understand the characteristics of the new hybrid system.

All structural elements and soils have been modeled with 15-noded plane strain triangular elements. The hybrid structural system material is modeled as very stiff, linear elastic, non-porous material with a unit weight of 25 kN/m^3, a modulus of elasticity of 1E10 kN/m^2 and a Poisson's ratio of 0.15. The seabed has been modelled as a loose-medium sand. The properties used in the analysis of the seabed are shown in Table 1 below.

Table 1 Sand Properties, Mohr-Coulomb model

Properties	Value	Unit
Saturated Unit Weight	17.8	kN/m^3
Young's Modulus, E	1E5	kN/m^2
Poisson's Ratio, ν	0.35	N/A
Cohesion Stress, c	0.01	kN/m^2
Friction Angle, ϕ	30	Degree
Dilatancy Angle, ψ	7.00	Degree
Material Model	Mohr-Coulomb	N/A

The mesh used in the analysis is shown in Figure 2 below. The standard fixities which are imposed to the geometry model constrain the lateral displacement at the mesh sides and imply total fixity at the bottom. In the numerical analysis, a constant width (W) of 5m was assigned to the footing, and the pile diameter (D) and length (L) were chosen as ratios of the footing width, where the W/D ratio ranged from 1 to 10 and the W/L ratio ranged from 1/3 to 2. The outer boundaries were chosen to be far enough from the foundation to reduce any boundary effects. Variable mesh density is required to obtain a balance between computer processing time and solution requirements. As shown in Figure 2, local refinements are assigned to areas where large stresses concentrations or large deformation gradients are expected. These include the anticipated location of failure planes underneath and surrounding the strip footing and the continuous wall.

As previously noticed by Frydman and Burd (1997), an important difficulty in the analysis of this problem is associated with the high stress gradients developed at the singularity at the footing edges. Below the footing, the major principal stress acts vertically in the case of the smooth footing and at a variable inclination to the vertical in the rough case. However, just outside the footing edge, the vertical stress at the soil surface is zero and so the shear strength of the sand, and all other stresses, are also zero. Close to the soil surface, the major principal stress acts horizontally. This abrupt transformation in the principal directions at the edge of the footing creates computational difficulties. This problem was addressed by using 10-noded interface elements that extend a little farther than the footing edges together with a concentration of small elements in the region of the footing edge. Furthermore, the interface helped in modeling the interaction between the hybrid system and the soil, which is intermediate between smooth and rough. The roughness of the interaction is modeled using a strength reduction factor (R_{inter}) of 0.67. This factor relates the interface strength to the soil strength ($c'_{inter} = R_{inter} \times c'$ and $\tan \phi'_{inter} = R_{inter} \times \tan \phi'$).

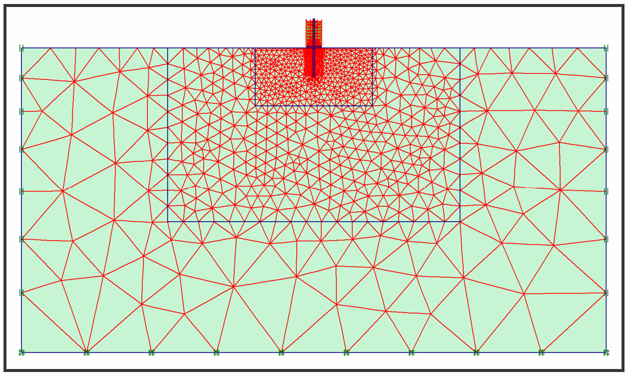

Figure 2. Mesh discretization applied in the finite element analysis

3 MODELING RESULTS

3.1 Purely vertical load resistance

When the hybrid system is loaded, the settlement increases and the pile starts to produce skin friction over its surface area. As the pressure is increased, a failure surface develops initially at the edges of the footing and then extends gradually downward and outward. The same behaviour is expected below the pile tip.

Previous studies (eg. Chalkadis, 2005; Ward, 2006 and Stone *et al.*, 2007) showed that the vertical capacity of the hybrid system is the sum of the individual components (pile and footing). The same behaviour is observed for long slender piles connected to relatively small footings (W/L ratio = 1/2). When a long hybrid system is loaded, settlement is increased and the pile starts to produce skin friction all over its surface area. As the pressure is increased, the failure surface is developed initially at the edges of the footing and then is extended gradually downward and outward.

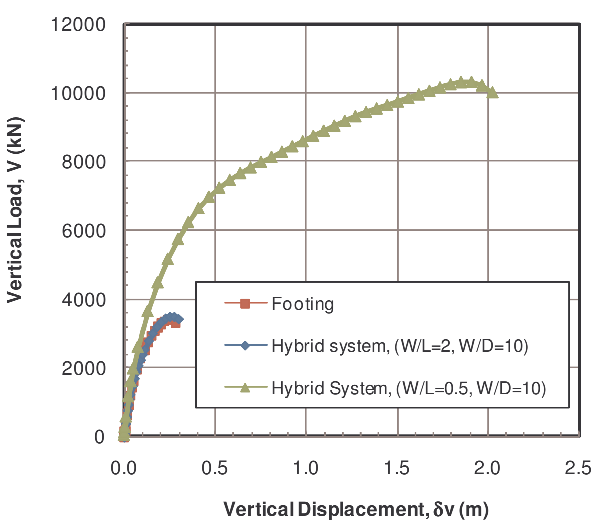

Figure 3. Plot of vertical Load (V) versus vertical displacement (δv)

However for short piles connected to wide footings, the vertical capacity is found to fall below the sum of individual elements, since the stressed soil zones tend to overlap, eliminating the full capacity of individual elements. Figure 3 shows that a hybrid system with a very short pile (W/L= 2.0) provides little gain in the vertical load resistance compared to a shallow footing of the same dimensions.

Figure 4 shows the soil deformation mechanism at failure beneath and adjacent to a shallow footing. The figure shows that the soil mechanism can be approximately separated into three zones [A/B/C], with soil moving downwards (directly beneath the foundation), radially away from this zone (bounded by a log-spiral shaped near stationary soil mass) and out of the soil at angle of approximately 90 degrees minus the angle of friction divided by two. These zones approximate the active and passive triangles, and radial shear zones of classical bearing capacity theory. As seen in Figure 5, the short pile is fully embedded in the moving wedge of soil developed directly below the footing. In this soil wedge, neither significant bearing pressures nor shaft frictions could be developed. This contrasts with the case of the relatively long pile as shown in Figure 6.

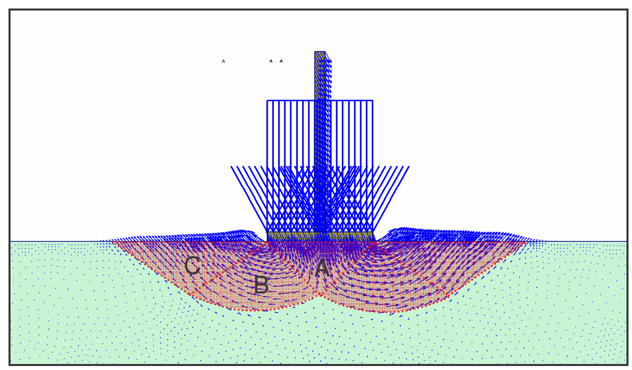

Figure 4. Displacement vectors at failure, for shallow footing

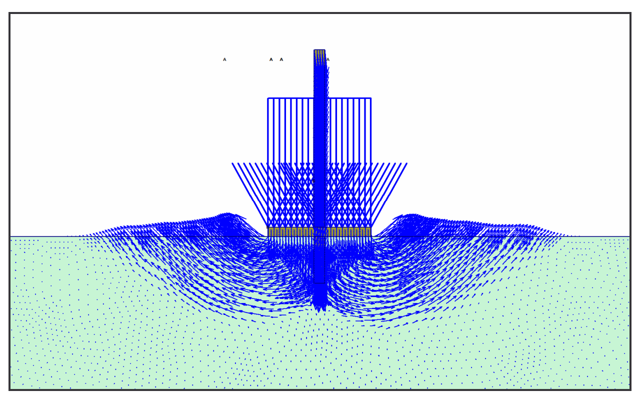

Figure 5. Displacement vectors at failure, for short hybrid system (W/L=2, W/D=10)

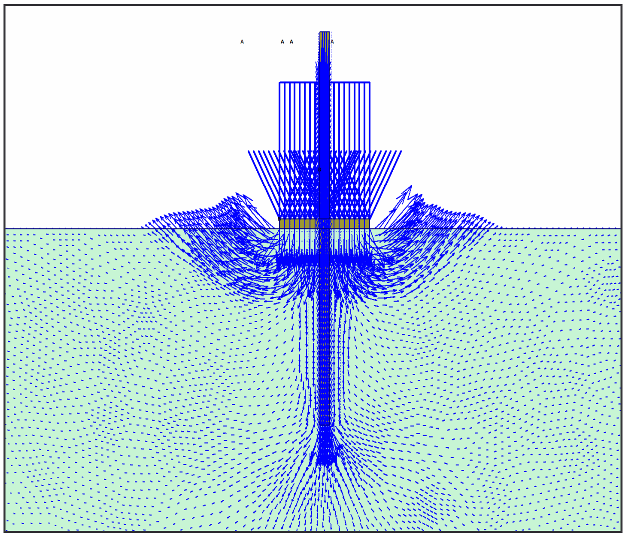

Figure 6. Displacement vectors at failure for long hybrid system, (W/L=0.5, W/D=10)

3.2 Combined vertical and lateral load resistance

Typically for offshore wind turbines, the weight of the structure is relatively very low when compared to the applied horizontal and moment loads derived from the wind and waves. The main role of the proposed innovative system is to resist general planar loading in (V, H and M space). The behaviour of offshore foundations is often dependent on the cyclic loading and associated dynamic phenomenon and their effect on the degradation in soil strength. Also, as mentioned by Byrne and Houlsby (2002), for turbines the accumulation of displacements under lower levels of loading should not exceed the tolerated limits of displacement. However, offshore foundation designs are often based upon monotonic combined loading envelops in (V, H and M) space, which have been found to bound the cyclic loading behaviour (Gottardi *et al.*, 1999). Hence, in this study, we have limited our interest to investigating the monotonic loading behaviour and relative stiffness of the system.

Our main objective is to prove the feasibility of using the hybrid system to improve the lateral resistance over that of traditional gravity base foundations. This target is achieved through a finite element analysis consisting of two main loading stages. In the first loading stage a vertical load, selected based on a percentage (50%) of the ultimate vertical capacity of the shallow footing alone, is applied on the hybrid system. In the second loading stage, the vertical load is maintained constant, and a horizontal load was applied at a determined vertical elevation from ground level (e = 0.5 & 3.0 m). Both the horizontal load and the associated moment load are gradually increased until reaching failure. The results of the finite element models are expressed in Figure 7 and Figure 8 as plots of the lateral load (H) versus lateral displacement (δu). These plots show the increased lateral capacity and stiffness of the hybrid system.

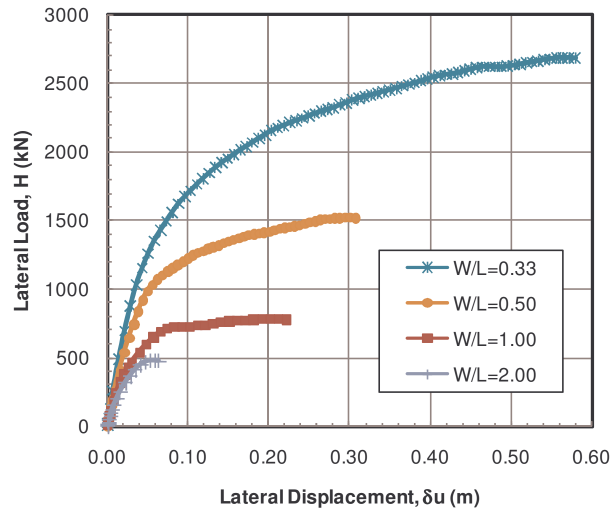

Figure 7. Effect of W/L ratio on the lateral resistance of the hybrid system, for e = 0.5 m. (at W/D=10)

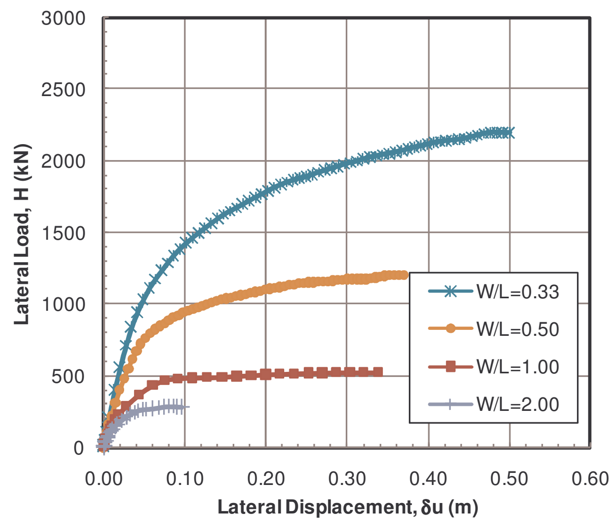

Figure 8. Effect of W/L ratio on the lateral resistance of the hybrid system, for e = 3.0 m. (at W/D=10)

3.3 Effect of W/D and W/L ratios on the lateral resistance

To study the effect of pile diameter-to-footing width ratio, a series of numerical models was carried out at a constant normalized pile length to footing width ratio (W/L=1), and at varying normalized pile diameter ratio (W/D) of 1, 2, 5 and 10. The curves presented in Figure 9 illustrate the slight significance of increasing the pile diameter on the lateral resistance of the hybrid system. The stability gained by increasing the pile diameter is counteracted by the reduction in the pile head fixation. The two curves demonstrate the same pattern of the hybrid system response for the different horizontal loading eccentricities.

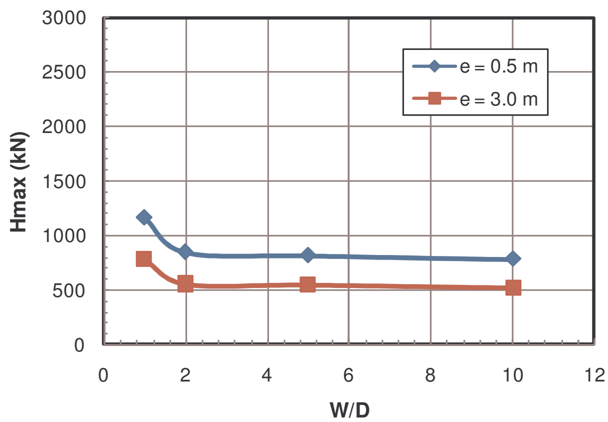

Figure 9. Effect of W/D ratios on the lateral resistance (at W/L = 1.0)

By applying the same methodology, to study the effect of pile length-to-footing width ratio, another series of numerical models is carried out at a constant normalized pile diameter ratio (W/D=10), and varying normalized pile length ratio (W/L) of 1/3, 1/2, 1, and 2. Figure 10 emphasizes the direct impact of the pile length-to-footing width ratio on the ultimate lateral resistance of the hybrid system. The lateral load resistance is increased by up to 4.7 times for low eccentricity (e=0.5m) and up to 6.8 times for high eccentricity (e=3.0m), (for W/L ratio of 1/3).

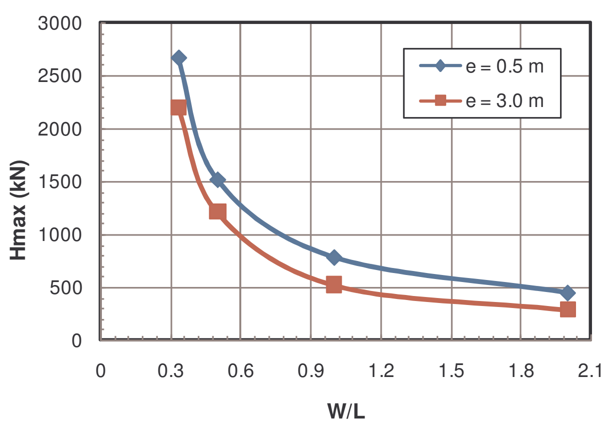

Figure 10. Effect of W/L ratio on the lateral resistance (at W/D=10)

4 LIMIT EQUILIBRIUM ANALYSIS

To provide a relatively simple analytical method for predicting the lateral capacity of this system, the limit equilibrium method has been used. The 2-D plane strain finite element analysis of the laterally loaded hybrid system will be used for comparison. The problem in the 2-D plane is analogous to the analysis of an embedded continuous wall with a stabilizing base previously proposed by Powrie and Daly (2007). The limit equilibrium approach is based on the classical solution of cantilever sheet pile walls, which assumes the presence of a virtual point of rotation lying in the plane of the wall at some point between formation level and the toe. The analysis assumes the development of the failure mechanism by rigid body rotation about that point (this failure mechanism is straightforwardly observed from the finite element analysis shown in Figure 11. Figure 12 shows the proposed limit equilibrium stress distribution adopted in the analytical solution.

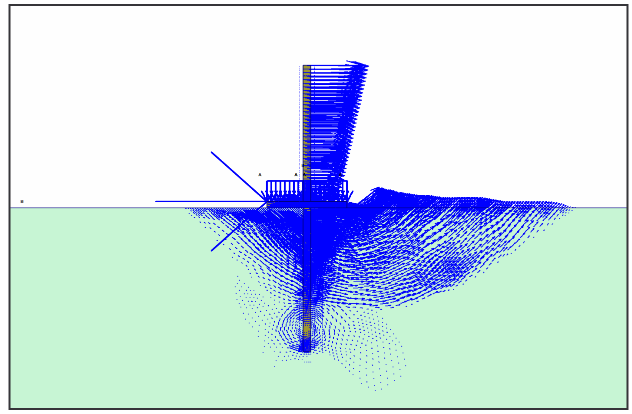

Figure 11. Total Displacement vectors at failure, (W/L=0.5, W/D=10)

When lateral loads are applied to the hybrid system, the footing is subjected to compressive stresses on one side and tensile stresses on the other. Inspection of the studied cases, the deformed meshes and the stress distributions below the footing provided evidence of the development of a gap separating the soil from the tensioned side of the footing (ab in Figure 12). Based on these observations, we proposed in the analysis the assumption of zero bearing pressures beneath the footing side subjected to tension stresses. Beneath the compressed portion, the bearing stresses are assumed to be uniformly distributed with a value equal to the ultimate bearing capacity of a strip footing with half the total footing width.

To accommodate the presence of the compressive portion of the footing in the limit equilibrium analysis, the following assumptions are made in the analysis: a) a restoring moment resulting from the concentration of the bearing stresses below the footing is introduced; b) bearing stresses are assumed to act as a uniform surface surcharge acting on a strip area. As a result, additional lateral stresses at the wall side are calculated based on the theory of elasticity (Figure 13). Figure 14 shows the calculated lateral stress distribution beneath the edge of the strip adjacent to the embedded wall. In Figure 14, the lateral stress ratio represents the value of the lateral stress at any depth normalized by the initial lateral stress value right underneath the strip edge. The depth is normalized by the total footing width (twice the width of the loaded strip). Figure 14 shows that the lateral stresses tend to diminish with depth and there is no need to consider the lateral stresses below a depth equal to the total footing width. In the proposed analysis, we replaced the calculated distribution by a simplified linear equivalent distribution starting at the ground surface from the initial lateral stress value right underneath the strip edge and reaching a zero value at depth equal to the total footing width.

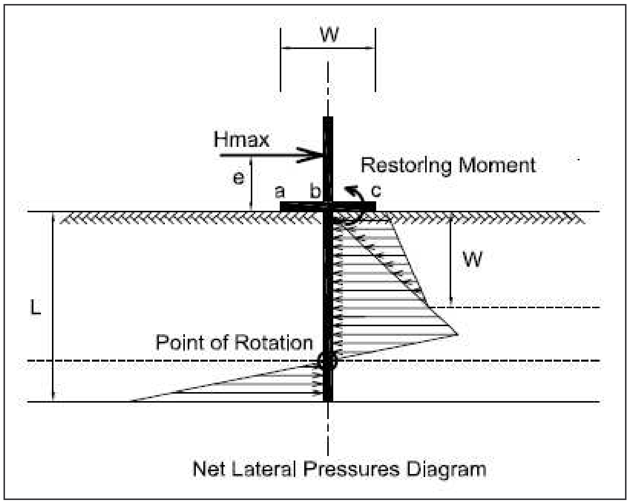

Figure 12. Net lateral pressure distribution applied in the limit equilibrium analysis

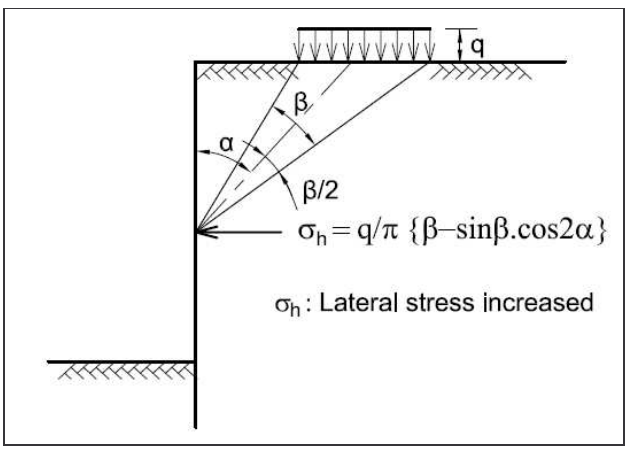

Figure 13. Lateral stress increased due to uniform surface surcharge (after NAVFAC Engineering Manual EM 1110-2-2504)

Shear stresses below the footing are neglected in the analysis. The coefficients of lateral earth pressure are determined from Coulombs equations, with respect to the effective angle of shear resistance ϕ' and soil-structure friction angle δ. Based on the net lateral stress distribution shown in Figure 12, the conditions of horizontal forces and moment equilibrium are used to calculate the position of the rotation point as well as the maximum lateral load value to be resisted by the hybrid system.

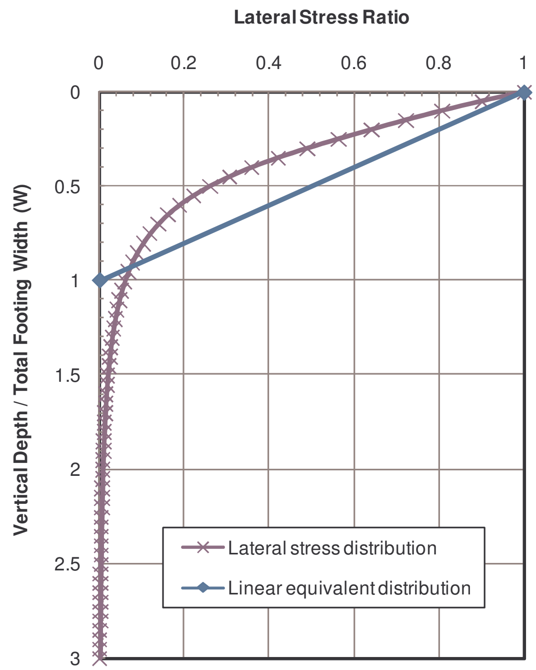

Figure 14. Lateral stresses distribution beneath the edge of uniformly loaded strip area

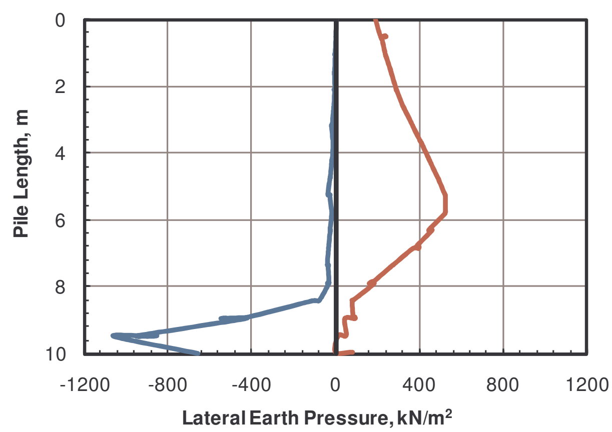

Figure 15. Distribution of lateral pressures as generated from the finite element analysis (for W/L=0.5, W/D=10)

The net lateral stress distribution generated from the finite element analysis is shown in Figure 15. This distribution shows excellent correspondence to the net stress distribution presumed in the limit equilibrium analysis and shown in Figure 12, and creates confidence in the results.

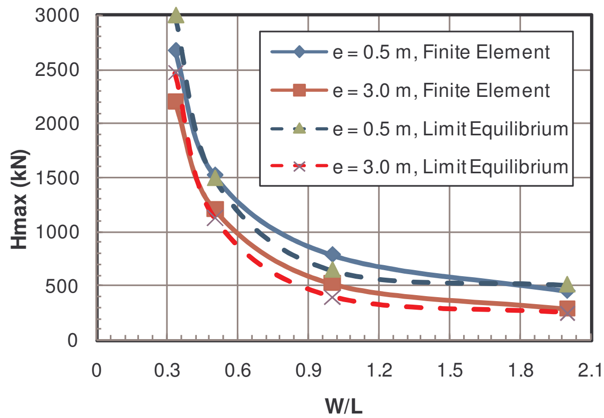

Figure 16. Comparison between the finite element and the limit equilibrium solutions for various W/L ratios.

To evaluate the analysis methodology, the maximum lateral load resistance of the hybrid system at various W/L ratios, as calculated from both the finite element and the limit equilibrium analyses, are plotted in Figure 16. The plotted graphs demonstrate the accuracy of the procedure applied in the limit equilibrium analysis.

5 SUMMARY AND CONCLUSIONS

This study has proposed an innovative shallow footing – monopile hybrid foundation system for offshore wind turbines. The behaviour of the hybrid system under general planar load combinations typically encountered in offshore structures is characterized through numerical modeling. The research has proved the feasibility of using the hybrid system to improve the lateral resistance of offshore foundations.

The finite element modeling shows that the vertical capacity of the hybrid system is highly dependent on the footing width - to - pile length (W/L) ratio. The vertical capacity of the hybrid system ranges from a value equal to the capacity of the unaccompanied footing for high W/L ratios (W/L = 2 or up) to a value almost equal to the sum of the capacities of individual components (pile and footing) for low W/L ratios (W/L < 1/2 to 1/3).

The interaction between the individual components of the hybrid system generates a higher lateral load resistance, greater than summing the resistance of the constituting elements. The lateral load resistance of the hybrid system appears to rely on the initial vertical load acting on the hybrid system, the value of the strength reduction factor (R_{inter}) and the footing width - to - pile length (W/L) ratio. On the other hand, the effect of the footing width to pile diameter ratio (W/D) is less significant.

A simple analytical procedure derived from the limit equilibrium method is also proposed to estimate the lateral capacity of the hybrid system. The proposed methodology is based on the classical solution of cantilever sheet pile walls, which assumes the presence of a virtual point of rotation lying in the plane of the wall at some point between formation level and the toe.

This study suggests that the use of hybrid foundations systems such as the one investigated here may provide viable alternatives to conventional wind turbine foundations systems. However, further work needs to be conducted on a wider range of materials, load cases and for 3D conditions.

ACKNOWLEDGEMENTS

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