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Numerical Analysis of Uplift Resistance for Winged Piles in Sandy Soil

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ABSTRACT: There are several methods that can be used to strengthen the sandy soils and their uplift capacity (Q_b). One of the most effective methods is to use under-reamed piles with wings (hunches) one or more along the stem. This research used Plaxis 3D software to analyse the performance of winged piles in the sandy soils under pull-out forces through numerical analysis. The properties of the soil applied in the simulation were received in the Al-Muthanna Governorate in southern Iraq. The wing positions were mixed in the length of the pile (L) at L, 0.75L, 0.5L and 0.25L to explore their effect on the uplift capacity (Q_{up}). The findings were made against the traditional straight-shaft piles. Results show that winged piles can decrease the vertical movement at all winged positions and increase the earth pressure and skin friction along the pile shaft significantly. The highest was recorded with the wings in the tip of the pile (L) of which tensile bearing capacity was found to be about 95% as compared to a straight-shaft pile at 20 mm vertical displacement. These findings demonstrate the possibility of winged piles to significantly increase uplift resistance in sandy soils.

KEYWORDS: Belled piles, winged Pile, sandy soil, uplift load, PLAXIS-3D Software.

1 INTRODUCTION

The winged piles were initially created in Texas, USA, as a counteraction to the high ground movements due to changes in soil moisture content that frequently results in expansive shrinkage cycles in soils with high clay content (Jebur et al., 2020). These piles have been used since their introduction in a large variety of civil and marine infrastructure works such as bridge abutments, transmission towers, submerged platforms, flood protection walls, dock-fendering systems, and marine dolphins. These constructions are often exposed to tensile (pullout) forces as a consequence of environmental forces, hydrodynamic forces, or working conditions (Sakr et al., 2020; Bilal et al., 2025).

The pull-out load-carrying capacity is even more problematic in seismically active areas, particularly in piles bearing tall or slender buildings, where both vertical and horizontal seismic excitations may develop tension forces. To overcome this, there have been innovative design solutions to alter the geometry of the piles most significantly through adding further enlargements, bulb or under-reams at given depths along the length of the pile shaft. The aim of such modifications is to mobilize more soil resistance by enhancing end bearing and side friction. Even the geometry of tapered or pyramidal piles has been studied to enhance the axial load performance in the past (El Naggar et al., 1999).

Jebur and Ahmed (2020) performed a numerical analysis based on finite element modeling (FEM) to assess the ultimate capacity (Q_u) of single-bulb under-reamed piles in various types of soil. Their findings led to an empirical equation to predict the base resistance (Q_b) of under-reamed piles in sandy soil that the enlarged sections of the piles greatly enhance the bearing capacity and shaft friction under different loading conditions.

Similarly, Ibrahim and Karkush (2025) stated that anchor piles that use winged or bulbous shapes are widely used to increase the stability of structures. These piles are capable of resisting both uplift and tension forces, but also compression, shear and overturning moments. Further to this, Mahdi and Jihad (2021) experimentally tested winged piles in collapsible soils and found that using winged piles has a positive impact on the factor of safety against bearing failure. Furthermore, they found that altering the location of the wings along the pile can reduce the post-construction settlement in collapsible soils from 26-61%, which highlights the importance of site-specific geometric parameters.

2 NUMERICAL MODELING

Numerical modeling techniques such as these are widely used to predict solutions to complex geotechnical engineering problems (Karkush et al., 2022; Ghrairi et al., 2022; Alani et al., 2023; Abbas et al., 2024). In this study, a three-dimensional finite element model has been developed using PLAXIS 3D to study the uplift response of a single winged pile in sandy soil under a pullout load (Ibrahim & Karkush, 2024). This represented the load carrying capacity of the pile-soil system, load-displacement behaviour of the system and failure mechanism. To provide accurate computations, the boundary of the domain (both lateral and bottom) was moved well away to avoid the boundary effects on the stress field and the pattern of deformation of the pile. The Mohr-Coulomb constitutive law was used to model the sandy soil in terms of its shear strength and dilatancy properties and the pile was represented as a linear elastic material that reflects the structural rigidity of the soil. Table 1 summarizes material properties employed in the analysis, and the soil is taken to be homogeneous to simplify the analysis.

Table 1. Description of the construction material properties used.

Parameter	Sandy soil	Pile	Unit
Modulus of elasticity, E	60000	25×106	kN/m^3
Unit weight, γ	17.15	24	(kN/m^3)
Relative density, Dr	40	-	(%)
Poisson's ratio, ν	0.3	0.15	-

Friction Angle, φ	39.4	-	(°)
Cohesion, c	5	-	(kN/m^2)

An interface element was added to the periphery of the piles, such as the wings to faithfully reproduce the behavior of frictional and adhesive contacts between the soil and piles. The under-reamed areas (wings) have been modeled specifically to determine its effect on uplift resistance and development of failure surfaces. Finite element analysis was done in PLAXIS 3D which automatically discretized the domain with the 10-node tetrahedral elements at their optimum accuracy of stress and deformation. A sensitivity analysis of mesh was carried out to identify the best trade-off between the computational efficiency and precision of the result. The analysis showed that a global coarseness setting of Fine was adequate enough to provide sufficient resolution without too much computation. The numerical model was run in four stepwise stages to emulate the real-life construction and loading environment:

- To determine the in-situ geostatic stresses under gravitational loading, the default K_0 -procedure was used.
- The volume of soil at the pile cluster was deactivated to imitate the borehole creation or the installation of the piles.
- The pile structure (with wings) was switched on inside the cavity and interface elements were on to simulate the soil-pile interaction.
- A defined displacement axial force was exerted on the head of the pile, to mimic pullout conditions and reaction forces were measured to identify uplift capacity.

The mesh arrangement with the fine discretization near the winged pile is presented in Figure 1.

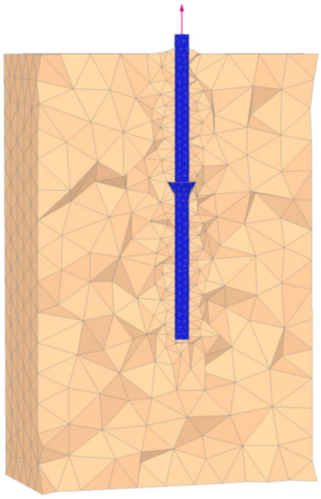

Figure 1. PLAXIS 3D software of pile wing 3D meshing.

To be reliable the numerical model was checked against experimental pullout test data of Kurian and Srilakshmi (2010). Good correspondence between the simulated and measured responses of load-displacement proved the correctness of the:

- Constitutive models (MohrCoulomb of soil, linear elasticity of pile)
- Interface parameters, and
- Boundary condition assumptions.

The table 2 indicates the adopted soil properties in the validation analysis in which the under-reamed pile has a total length of 4.5 m. The performance of the numerical model was assessed by comparing the simulated response of the load and set up with the experimental results. As shown in figure 2, there is a high degree of correlation between the curve of the pile head displacement calculated in the PLAXIS-3D analysis and that of the experiment in reference 2 by Kurian and Srilakshmi (2010), thus validating the usefulness of the numerical method to predict the behavior of under-reamed piles under uplift loading.

Table 2. Soil properties by (Kurian and Srilakshmi, 2010).

Parameter	Symbol	Value	Unit
Young's modulus	E	8×10^3	kN/m^2
Unit weight	γ	17	(kN/m^3)
Poisson's ratio	ν	0.3	-
Friction Angle	φ	10	(°)
Cohesion	c	50	kN/m^2

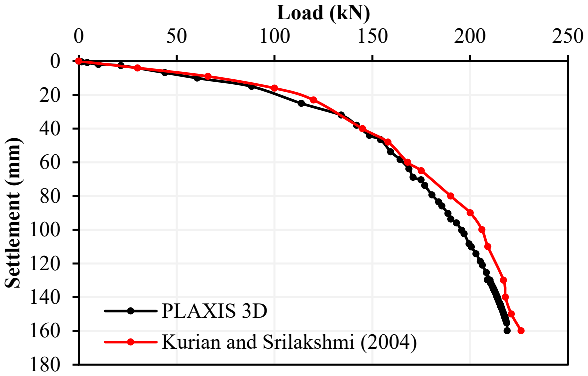

Figure 2. Confirming the proposed model with the results mentioned in (Kurian and Srilakshmi 2010).

3 BEHAVIORS OF PILES SUBJECTED TO UPLIFT LOAD

The main aim of integrating pile wings is to increase the pull out resistance of many types of structures which include transmission towers, retaining walls, sheet piles, dry docks and submerged pipelines. In this numerical study, the five pile configurations considered were a standard pile and four winged piles whose wing positions were at depths of L, 0.75L, 0.5L and 0.25L along the pile stem. The diameter of the pile (d) was 0.45 m, the wing diameter (dw) was 1.0 m and the overall length of the pile (L) was 12 m as illustrated in Figure 3. This is necessary to understand the soil behavior in the vicinity of the piles and the related failure mechanisms to assess soil-pile interaction when axial loading occurs. It also involves the study of the amount of soil that is mobilized during the failure of the wing piles and the deformation profiles of the pile stem and wing bulbs, which lead to the heightened friction or cohesion (George and Hari, 2015).

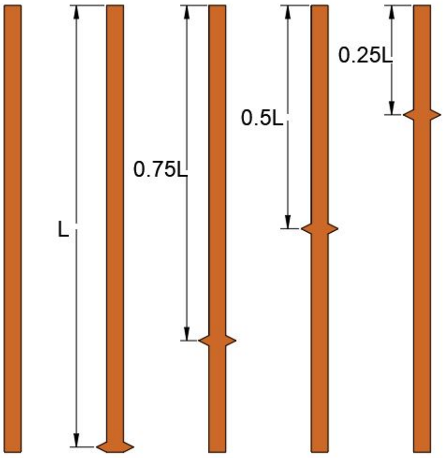

Figure 3. Geometrical position of pile wings.

4 NUMERICAL RESULTS AND OBSERVATIONS

Figure 4 represents the finite element model (FEM) created in this study that models the pile and wing-pile interfaces. This model is the most accurate in terms of geometric representation of the piles, the wing attachments at various depths, and the domain of soil around the piles. With this arrangement, a thorough simulation of soil-structure interaction under axial tensile loading conditions can be provided.

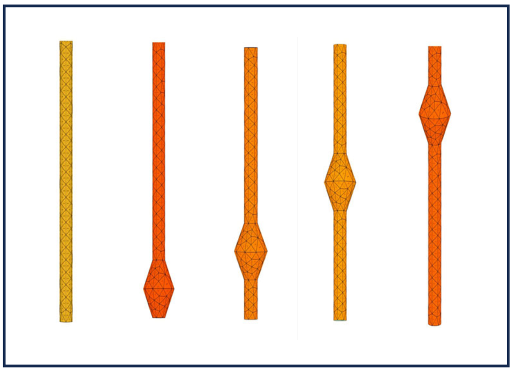

Figure 4. Interface modelling of pile wings.

The contour for uplift displacement for different types of piles are shown in Figures 5-9, which are generated from PLAXIS 3D numerical simulations. These numbers compare the behaviour of a conventional straight-shaft pile (no wings) with single-winged piles with wings at four depths (relative to the length of the pile) at L (pile head), 0.75L, 0.5L and 0.25L (measured from pile head). The contours provide a somewhat closer look at the vertical soil deformations around the pile and where the maximum deformations occur, and the effect of wing location on the size and shape of the mobilised soil mass. These can be used to draw several conclusions:

- Highly displaced soil lends significant importance to the wing that alters the distribution of stresses and reduces localized deformation of the soil.
- Winged piles are known to have significantly smaller vertical movements at the pile-soil interface than conventional piles, which implies enhanced load transfer and mobilization of binding soil.
- Wing positioning, in turn, alters the geometry of the mobilized soil mass, influences the depth of the maximum soil deformation, and the formation of possible shear planes.
- With much more soil being involved, strategically positioned wings enhance the effective anchorage depth of the pile, leading to enhanced tensile capacity.

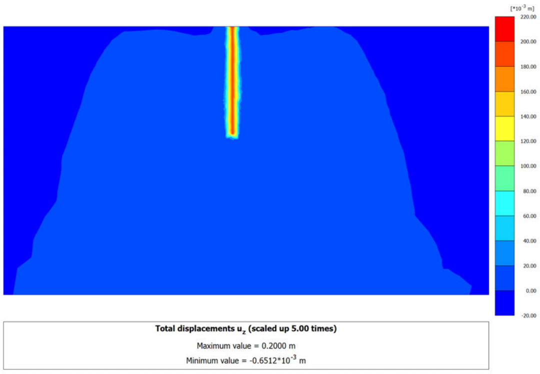

Figure 5. The vertical displacement distribution of pile of uniform cross-sectional area.

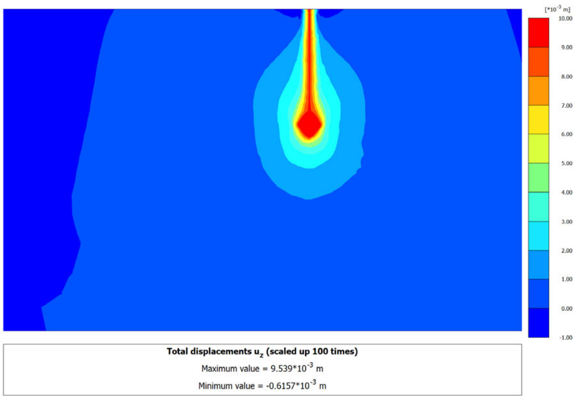

Figure 6. The uplift displacement distribution of pile wings at L.

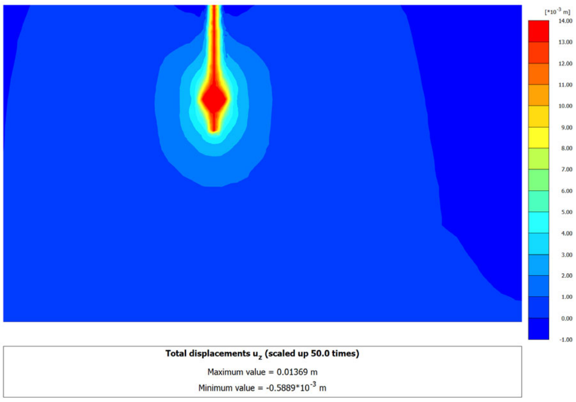

Figure 7. The uplift displacement distribution of pile wings at 0.75 L.

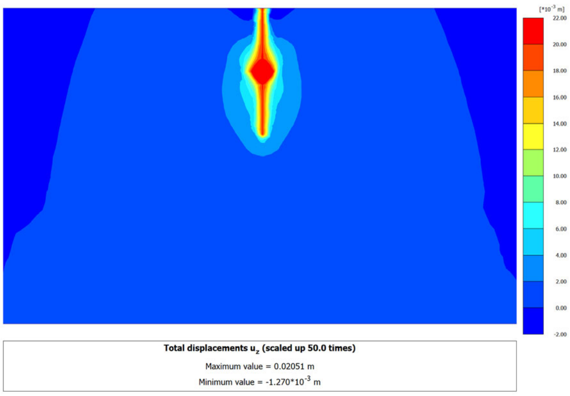

Figure 8. The uplift displacement distribution of pile wings at 0.5 L.

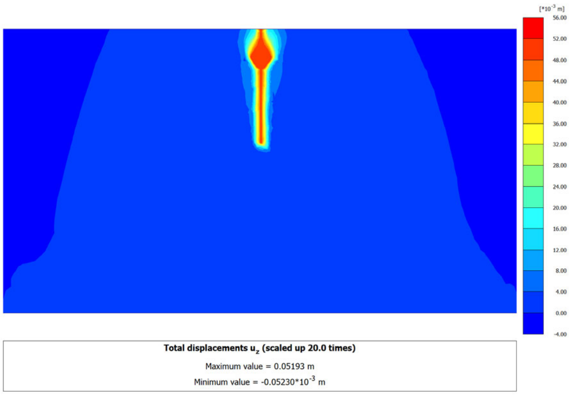

Figure 9. The uplift displacement distribution of pile wings at 0.24 L.

Of the configurations considered, wings located at 0.5L (about half the pile length) showed the best results as they achieved the optimal anchorage depth and the highest soil mobilization, leading to lower uplift displacements than the other wing configurations. The findings show that the wings of the pile, if properly designed and positioned, can significantly improve the pullout capacity, the interaction between the soil and pile and decrease the uplift settlement of the pile. Figures 5-9 aid in understanding the influence of the wing position on the uplift characteristics of the piles. For the bare pile (pile with a uniform cross-section, without wings), the uplift displacement of the soil was the largest (approximately 0.20 m) for the applied uplift load. But the displacements were much smaller for the piles with wings, in relation to the position of wings on the pile shaft. Specifically, the recorded displacements were 0.009 m for wings positioned at L (the pile tip), 0.013 m for 0.75L, 0.020 m for 0.5L, and 0.051 m for 0.25L. The results indicate that the use of wings greatly improves the uplift capacity of the pile due to the increased contact area between the pile and soil and mobilisation of higher skin friction. The wings induce a "bulb" effect in the soil mass to prevent the formation of potential slip planes to mobilise a larger mass of soil during uplift, and hence increase the uplift resistance.

The load-displacement response of the numerical simulations is also shown in Figure 10. The pile with wings at depth L offers the greatest improvement, resulting in an increase of about 95% in the uplift capacity relative to the conventional pile at the same displacement. This type of pile achieved the maximum pullout capacity by engaging the maximum confining stress zone in the soil. Furthermore, these findings also show that the geometry and location of the bulbs affect the gradient and shape of the load-settlement curve, which means a change in the stiffness and ultimate load capacity. The bulbs enhance both the load-bearing capacity and uniformity of the displacement, resulting in a more efficient load transfer and improved structural response under uplift loads.

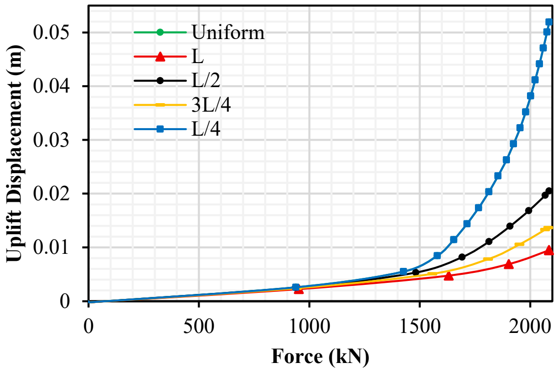

Figure 10. Load–displacement curves of different winged pile.

5 CONCLUSIONS

A numerical testing program is used to assess the uplift capacity (Q_{up}) of vertical piles with wings in sand with different soil densities. The main goal is to evaluate the effects of the winged enhancements on the uplift capacity and displacement of the pile, comparing their performance with plain (non-winged) piles.

- Placing wings on a pile considerably minimises uplift-induced settlement (74% to 95%) with variations depending on the pile's geometric shape and embedment depth of the wings.
- The optimum position of wing improves load distribution and confinement of soil, thereby reducing vertical displacement.
- For a certain geometry of pile and soil density, the Q_{up} of winged pile increases linearly with increasing embedment depth of the wings.
- Wings increase the shear resistance on the surface, and enhance anchorage.
- Even with 95% less settlement, the wings exhibit nonlinear response with increasing embedment, with a diminishing effect at deeper embedment depths.
- Wings enhance the uplift capacity and settlement of winged piles compared to conventional piles, especially in medium-dense to dense sands.
- Observations from the numerical results agree with theoretical failure mechanisms in which the wings change the shape of the slip surface, mobilizing more soil.

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