

Influence of padeye depth on suction caisson anchor performance using 3DFE

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ABSTRACT: Suction caisson anchors are a widely used anchoring solution for floating offshore wind turbines, where inclined loading significantly affects their in-place performance. The depth of the padeye is a key geometric parameter influencing anchor capacity. This study employs the SANISAND-MS constitutive model in PLAXIS 3D to investigate how padeye depth impacts the capacity of suction caisson anchors embedded in sandy soils under inclined monotonic loading. A rigid caisson of diameter $D=5$ m is analysed in loose Dunkirk-type sand ($D_r \approx 30\%$), with padeye locations at $0.33L$, $0.5L$, and $0.67L$, aspect ratios $L/D=0.5-2.0$, and load angles from 0° to 90° . Capacity is taken as the maximum reaction developed at the padeye during a 0.2 m displacement-controlled loading step. The results show that capacity increases with aspect ratio for all padeye locations and decreases with load angle in an approximately linear manner. The influence of padeye depth depends on both aspect ratio and load angle: differences between $0.33L$ and $0.5L$ are small around $L/D=1$ and at near-vertical loading, whereas at $L/D \geq 1.5$ the deeper location ($L=0.67L$) tends to yield higher capacities over the angles examined.

KEYWORDS: Suction caisson anchors, padeye depth, offshore geotechnics, SANISAND-MS, 3DFE.

1 INTRODUCTION

The rapid expansion of the floating offshore wind sector has renewed interest in anchoring systems that are reliable, scalable, and economical to install. Suction caisson anchors (SCAs) are attractive in this context because they can be installed quickly, relatively quietly and with limited seabed disturbance, while providing significant resistance in tension, inclined and lateral loading. Despite their growing use, important aspects of in-place behaviour under inclined loading remain the subject of ongoing study.

Two geometric and loading parameters are particularly influential: padeye depth and load angle. Together with the anchor aspect ratio L/D , these parameters control the balance between lateral and axial components of resistance and influence the total capacity of the anchor.

This paper investigates SCAs in loose sand using three-dimensional finite-element analysis in PLAXIS 3D (Bentley Systems, Inc, 2024) with the SANISAND-MS constitutive model. The numerical campaign considers padeye depths at $0.33L$, $0.5L$, and $0.67L$, aspect ratios $L/D = 0.5-2.0$, and load angles from 0° to 90° . Capacity is quantified by the maximum reaction recorded at the padeye during displacement-controlled loading, allowing direct comparison across configurations.

The objective is to clarify how padeye depth interacts with L/D and load angle in determining capacity, and to provide a consistent dataset that highlights robust trends. The paper presents the modelling assumptions, key results and their interpretation, and discusses implications and limitations, including opportunities for future work.

2 METHODOLOGY

This study used three-dimensional finite-element (3D FE) analysis in PLAXIS 3D to investigate how padeye depth and load angle influence the capacity of an SCA embedded in loose sand. The model isolated soil-structure interaction effects by treating the caisson as a rigid body. All analyses were monotonic and drained.

2.1 Anchor Geometry and model setup

The caisson was modelled with a diameter (D) of 5 m. Aspect ratio effects were explored by varying the embedded length (L) in steps of 2.5 m, giving $L/D = 0.5, 1.0, 1.5$ and 2.0 . This range is representative of geometries commonly adopted in sand for SCAs.

The padeye was represented by modelling a load application point on the caisson centreline. Three depths were studied, expressed as a fraction of the embedment length: $z/L = 0.33, 0.5$ and 0.67 . Modelling the caisson as rigid focuses the analysis on soil response without structural effects. A schematic of the SCA is presented in Figure 1.

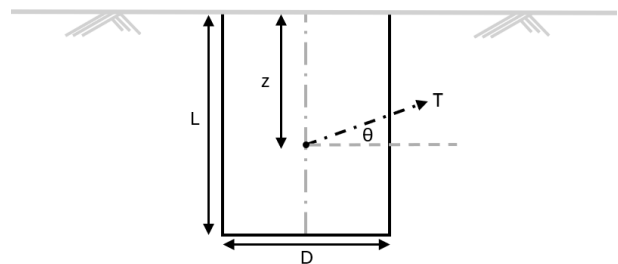


Figure 1. A schematic SCA illustrating the length (L) and diameter (D) of the caisson, depth to padeye (z), load angle (θ) and load (T).

Initial stresses were generated by self-weight. Installation was not simulated, with the caisson assumed to be in place at the start of loading, which was deemed to be acceptable for examining monotonic capacity trends.

2.2 Loading Conditions

Loading was applied at the padeye by displacement control, representing the mooring-line action on the anchor. The load angle was measured from the horizontal and takes the values $0^\circ, 40^\circ, 45^\circ$ and 90° .

For each angle, a prescribed displacement of 0.2 m was imposed at the padeye reference point. This magnitude was

sufficient to capture both the initial stiffness and the approach to ultimate reaction.

2.3 Soil Model

The constitutive model used for the soil surrounding the caisson was the SANISAND-MS model, developed by Liu et al. (2019). This model was chosen as it was specifically developed to capture the key behaviours of sandy soils, including dilatancy, cyclic loading effects and strain softening.

The model was calibrated to Dunkirk sand at a relative density of 30%, following the parameters published by Pisano et al. (2024) and presented in Table 1. This calibration provides a realistic response for loose sand under drained monotonic loading and is adopted without modification.

Table 1. Dunkirk SANISAND-MS Parameters (Pisano, et al., 2024)

Parameter	Value
G_0	451
ν	0.17
M_c	1.28
c	0.7188
λ_c	0.135
e_0	0.91
ξ	0.179
m	0.065
h_0	3.5
c_h	1.0
n_b	1.9
A_0	1.3
n_d	0.75
μ_0	260
ζ	$10^{-4}, 10^3$
β	1

The Mohr-Coulomb constitutive model was adopted for the soil-steel interface, with a stiffness (E_{ref}), of 100,000kPa, interface angle of 32° and Poisson's ratio (ν) of 0.17.

2.4 3DFE Analysis

A fine mesh with a localised mesh refinement zone around the caisson was applied to ensure accurate stress and strain gradients within the critical region around the caisson, whilst maintaining computational efficiency.

The mesh geometry and boundary extents were selected to minimize boundary effects on the results, with the lateral and bottom boundaries extending at least three times the anchor diameter distance away from the anchor centreline. Figure 2 shows a representative model setup for this analysis.

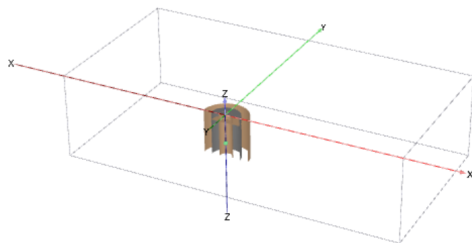


Figure 2. Example model setup for this analysis.

3 RESULTS AND DISCUSSION

Results from the numerical analysis were obtained by applying an incremental displacement to the padeye point for each combination of anchor length, padeye depth and load angle. At each stage, the resultant reaction force was obtained to

determine the anchor capacity, whilst anchor displacements were recorded to identify the deformation behaviour of the anchor (an example output is presented in Figure 3). This approach was adopted to enable a comprehensive evaluation of the governing variables influencing the anchor's performance in this study.

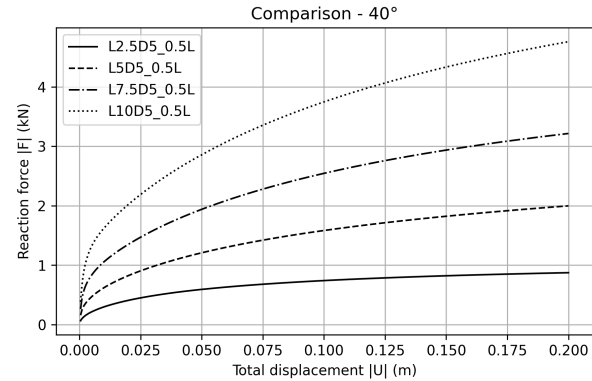


Figure 3. Example set of force-displacement results for a load angle of 40°, padeye depth of $z/L = 0.5$, and for aspect ratios of $L/D = 0.5, 1.0, 1.5$ and 2.0 .

3.1 Influence of load angle

As shown in Figure 4, the capacity decreases approximately linearly with load angle for all padeye locations. The 0.5L and 0.33L curves overlap, which is why only one trace is visible, and as such, they can be treated as equivalent at this aspect ratio of $L/D=0.5$. At 0°, the 0.67L location is slightly higher, whereas at 40° and 90°, the overlapping 0.33L/0.5L case is marginally above 0.67L. The differences are small overall, indicating limited depth sensitivity when $L/D=0.5$.

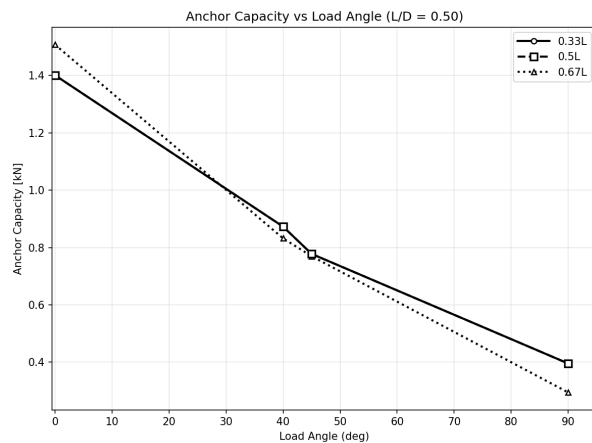


Figure 4. Anchor capacity with respect to load angle, $L/D=0.5$

The capacity again reduces monotonically with angle for the aspect ratio of 1.0, as shown in Figure 5. At 0°, the 0.33L location produced the highest capacity. At 40°, the 0.67L location becomes comparable to, or slightly above, the others. By 90°, all three locations are close, suggesting that depth choice is less influential for near-vertical loading at this aspect ratio.

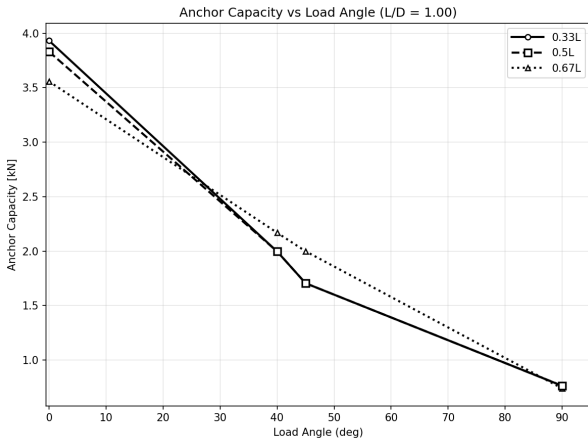


Figure 5. Anchor capacity with respect to load angle, $L/D=1.00$

From Figure 6, it is evident that the influence of padeye depth is more pronounced at an aspect ratio of 1.50. The 0.67L location provides the greatest capacity across the angles shown, with a clear separation from the 0.33L and 0.5L cases, and an overall angle-to-capacity trend remains near-linear. The 0.33L and 0.5L cases do not always overlap, their curves are similar but remain distinct, with small angle-dependent differences. At intermediate angles (e.g., around 40°), the 0.5L case is slightly lower than 0.33L, while near 90° , the two are more similar.

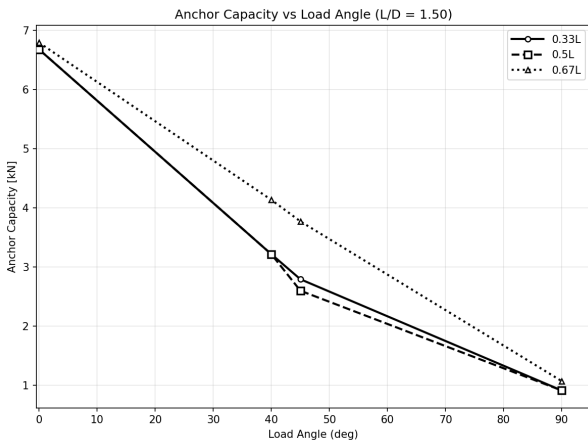


Figure 6. Anchor capacity with respect to load angle, $L/D=1.5$

At an aspect ratio of 2.0 (see Figure 7), the influence of padeye depth is strongest. Locating the padeye at 0.67L yields the highest capacity at all load angles, with a clear separation from the other cases at 0° and 40° . The 0.33L and 0.5L series form a tight lower band: 0.33L is marginally higher at 0° , and the difference between them diminishes toward 90° . For all padeye locations, capacity decreases with angle in an approximately linear manner.

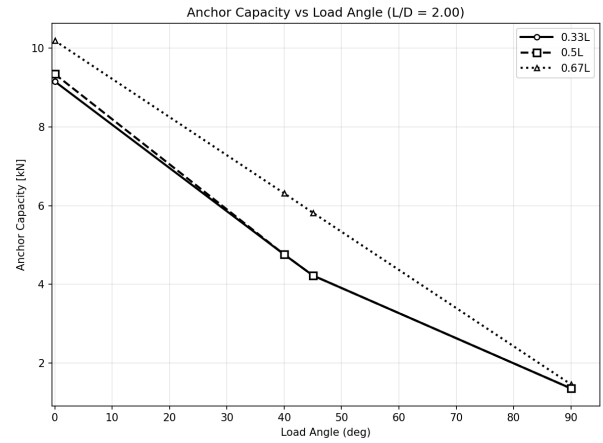


Figure 7. Anchor capacity with respect to load angle, $L/D=2.00$

3.2 Aspect Ratio

As shown in Figure 8, at a load angle of 0° , which yields the highest capacities, the padeye location of 0.33L and 0.5L exhibit broadly similar performances across the aspect-ratio range considered. At $L/D = 1$, placing the padeye at 0.33L gives a slightly higher capacity, whereas at $L/D = 2$ placing it at 0.5L is marginally higher. When the padeye is located at 0.67L, capacity is lower than the 0.33L and 0.5L cases at $L/D = 1$, but at $L/D = 2$ it surpasses both and provides the greatest capacity.

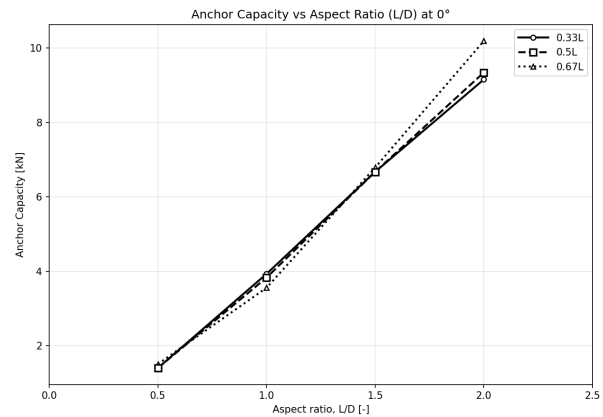


Figure 8. Influence of aspect ratio on anchor capacity (at load angle of 0°).

The influence of padeye location is more pronounced during inclined loading, with the example of a 45° load angle presented in Figure 9. The 0.67L location provides higher capacity than the 0.33L and 0.5L locations at most aspect ratios. The separation between the three series is limited at $L/D = 0.5$, increases at $L/D = 1.5$, and is most evident at $L/D = 2.0$. The 0.33L and 0.5L cases remain close to each other throughout, indicating that the primary change at 45° is associated with moving the padeye deeper to 0.67L.

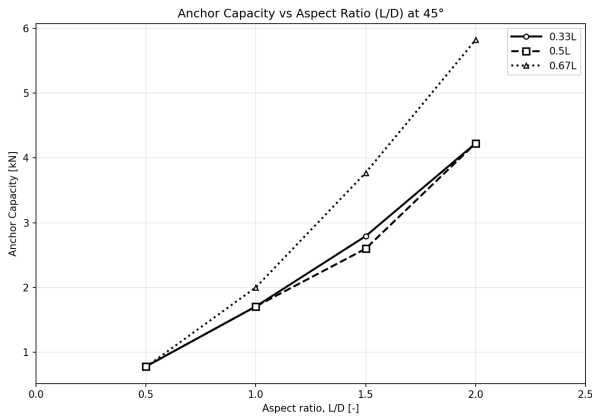


Figure 9. Influence of aspect ratio on anchor capacity (at load angle of 45°).

4 CONCLUSIONS

This paper presents the numerical investigation into the influence of padeye depth, aspect ratio and load angle on the capacity of a suction caisson anchor in loose sand. Using PLAXIS 3D with SANISAND-MS, capacity was defined as the maximum reaction force achieved at the padeye under a displacement of 0.2m. The results clarify the main trends and the conditions under which padeye depth becomes influential. The key conclusions can be summarised as follows:

1. Capacity increases with aspect ratio across all padeye locations, however, the influence of padeye depth depends on aspect ratio. At $L/D=1$, locating the padeye at 0.33L–0.5L yields slightly higher capacity, whereas at $L/D=2$ locating it at 0.67L provides the highest capacity.
2. Across this dataset, capacity increases with aspect ratio (L/D) and decreases with load angle; the influence of padeye depth depends on L/D and angle differences are small for $L/D \leq 1$ and near-vertical loading, whereas for $L/D = 1.5-2.0$, the padeye located at 0.67L gives higher capacities across the angles examined.
3. Differences between the 0.33L and 0.5L locations are consistently small across the study, and in several cases the curves overlap, indicating similar performance for these two padeye depths.

These conclusions are specific to the modelling assumptions adopted (rigid caisson, monotonic drained loading, Dunkirk-type loose sand, and the chosen interface properties). The study provides a consistent numerical dataset and clarifies the interplay between padeye depth, aspect ratio and load angle, offering a basis for future experimental validation and for extending the analysis to cyclic loading and installation history. This aims to advance the understanding of suction caisson anchor behaviour, offering insights into developing efficient and reliable anchoring systems for floating offshore wind turbines.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

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