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# Pull-out performance of finned suction anchors in sand considering torsional effect

Min-Hao Zhang
*Department of Ocean Science and Engineering, Southern University of Science and Technology, Shenzhen, 518055, China; State Key Laboratory of Intelligent Construction and Healthy Operation and Maintenance of Deep Underground Engineering; Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hong Kong, China*

Yong Fu*
*Department of Ocean Science and Engineering, Southern University of Science and Technology, Shenzhen, 518055, China; State Key Laboratory of Intelligent Construction and Healthy Operation and Maintenance of Deep Underground Engineering*

Zhen-Yu Yin
*Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hong Kong, China*

**fuy3@sustech.edu.cn (corresponding author)*

**ABSTRACT:** When the suction anchor is subjected to torsional load due to imprecise installation or deviations of mooring line caused by current forces, it significantly reduces the pull-out capacity, thereby posing potential risks to floating structures. However, there is a dearth of relevant studies investigating scenarios involving torsional load and anti-torsion solutions. Therefore, this paper aims to enhance the anti-torsion pull-out performance in sandy seabed through a novel design incorporating finned suction anchors. Three-dimensional finite element analyses are conducted using the advanced SIMSAND model for sand constitutive behaviour. A comprehensive parametric study is performed to examine the influence of fin number, width, length, and length-width ratio on pull-out capacity and failure mechanisms. Based on these analyses, optimal fin configurations are discussed considering material costs, and a case study is presented illustrating the process of configuration optimization. These findings can contribute towards addressing issues related to torsional loads in research and design practices.

**Keywords:** finned suction anchor; torsion; SIMSAND model; pull-out capacity; failure mechanism

## 1 INTRODUCTION

Suction anchors are increasingly utilized as foundations for mooring systems due to their facile installation and removal, cost effectiveness, dependable pull-out capacity, and reusability. These anchors establish a connection with floating structures through mooring lines, providing essential resistance against environmental forces such as wind and waves. Widely employed for spar platforms and deep-sea floating wind turbines, the pull-out capacity of suction anchors has emerged as a focal point in both scientific research and engineering applications (Zhang et al., 2023).

Historically, research on the suction anchor pull-out capacity has encompassed a range of methods, including field tests, centrifuge tests, 1g physical model tests, and numerical simulations. However, the influence of torsional loading induced by mooring line eccentricity has been largely overlooked in most studies. Torsion can arise from misalignment during installation or deviations caused by current forces. The presence of torsional loads significantly diminishes the pull-out capacity of suction anchors and poses a risk to fixed floating structures. Furthermore, there is relatively limited research focused on enhancing both the pull-out capacity and anti-torsion performance through the incorporation of anchor fins. The augmentation of lateral response for suction piles through fin or wing additions near the pile head was initially investigated in the early 2000s by Newcastle University in the UK and Hamburg University in Germany. Existing studies (i.e., Castillo Garcia and Panayides, 2021) have primarily concentrated on improving lateral capacity while neglecting comprehensive exploration into enhancing anti-torsion pull-out capability.

Therefore, this paper presents a numerical investigation of the pull-out performance of innovative finned suction anchors in sand, with a specific focus on torsional impacts. Utilizing the advanced SIMSAND model to simulate soil behaviour, this study systematically examines the influence of fin quantity, width, length, and length-to-width ratio on pull-out capacity and failure mechanisms. Subsequently, a case study is provided to demonstrate how anchor design can be optimized for enhanced pull-out capacity under both torsion-free and torsional conditions based on the analysis results.

## 2 MODEL SET-UP

A three-dimensional finite element model is created using ABAQUS/EXPLICIT. The finned suction anchor is treated as "wish-in-place" and modelled as a rigid body with the following dimensions: a diameter $D$, a skirt length $L$, a wall thickness $t$, a fin width $w$ and a fin length $l$. For this study, the dimensions of the anchor shaft are adopted from Bang et al. (2011) and Ahmed and Hawlader (2015), with values of $D$ = 3 m, $L$ = 6 m and $t$ = 0.1 m. Properties of steel are selected for the anchor, with a unit weight of $\gamma_a$ = 78 kN/m$^3$ and a Young's modulus of $E_a = 2.1\times10^8$ kPa. The soil domain has a diameter of $7D + 14w$ and a height of $3L$, ensuring it is large enough to minimize boundary effects. Velocity boundaries are restricted perpendicular to the bottom and side surfaces of the soil domain. The minimum mesh size of the soil adjacent to the suction anchor is set as $1.5t$ based on mesh convergence analyses which can ensure both computational efficiency and accuracy. For the soil-anchor interface, the Coulomb friction model is used, represented as $\tau = k\phi_c$. In this study, the parameter $k$, which typically ranges from 0.5 to 0.7 in sand (Tiwari and Al-Adhadh, 2014), is set to 0.5. The pull-out of the suction anchor is achieved by applying a concentrated force $P$ at the padeye (the padeye is located at the anchor skirt with a depth $z_p$) with a loading angle $\theta$ and a torsion angle $\beta$. Figure. 1 illustrates the general model sketch and definitions of the angles.

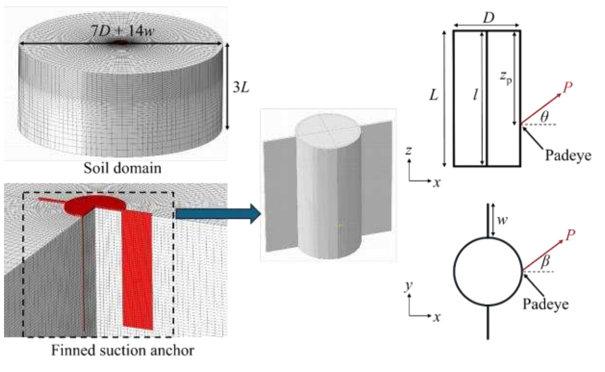



*Figure 1. General model sketch and definitions of the angles.*

The advanced SIMSAND model proposed by Yin et al. (2017) is used to describe the soil's constitutive behaviour in this study. This model is a critical state-based nonlinear Mohr-Coulomb framework, enhanced with nonlinear elasticity, plastic hardening, and stress-dilatancy effects. It is implemented via the VUMAT subroutine in ABAQUS/Explicit. The parameters for this study following Jin (2019) shown in Table 1, have been calibrated using experimental results from drained triaxial tests on Baskarp sand (Aalborg University Sand No. 0), as reported by Houlsby and Byrne (2005).

*Table 1. Model parameters adopted in this study.*

| Parameters | Symbols | Value |
|---|---|---|
| Referential bulk modulus (dimensionless) | $K_0$ | 344 |
| Poisson's ratio | $\upsilon$ | 0.25 |
| Elastic constant controlling the nonlinear stiffness | $n$ | 0.58 |
| Critical state friction angle | $\phi_c$ | 35.1 (°) |
| Initial critical state void ratio | $e_{ref}$ | 0.9 |
| First constant controlling the nonlinearity of CSL | $\lambda$ | 0.38 |
| Second constant controlling the nonlinearity of CSL | $\xi$ | 0.11 |
| Constant of magnitude of the stress-dilatancy | $A_d$ | 0.45 |
| Plastic modulus related constant | $k_p$ | 0.0034 |
| Peak friction angle related constant | $n_p$ | 1.6 |
| Phase transformation angle related constant | $n_d$ | 4.4 |

## 3 RESULTS AND ANALYSES

A series of cases is conducted to investigate the pull-out capacity and failure mechanism of finned suction anchors in sand, taking into account the torsional effect. The loading angle is maintained at 0° throughout the analyses because the torsion angle has the greatest impact on the 0° loading angle (Zhang et al., 2023). Factors such as the number of fins and fin dimensions (including fin width, length, and length-width ratio) are analyzed. In terms of naming conventions for the modelled anchors, for example, "$N2w0.5l1$" refers to a 2-fin anchor, with fins having a width of $0.5D$ and a length of $1L$. The pull-out capacity is defined as the pull-out force when the anchor padeye displacement reaches approximately $0.1D$, in line with previous studies (e.g., Ahmed and Hawlader, 2015).

## 3.1 Effect of fin number

Figure. 2(a) illustrates the pull-out capacity of suction anchors with different numbers of fins as the torsion angle varies from 0° to 90° (the pull-out capacity is normalized by the pull-out capacity of finless anchor $P_u/P_{u,N0}$). When the torsion angle is small (between 0° and 15°), the pull-out capacity of the 2-fin anchor exceeds that of the 3-fin and 4-fin anchors (~7% higher than 3-fin anchors and ~2% higher than 4-fin anchors). Adding more fins (from 4 to 8) results in only a limited increase in pull-out capacity (~13% increase of pull-out capacity). As the torsion angle increases, the pull-out capacity demonstrates a growth trend characterized by a rapid increase with 0 to 3 fins, followed by a slower increase with 4 to 8 fins. These findings can be interpreted by the mobilized failure zone displayed in Tables 1 and 2.

Table 2 summarizes the development of the plastic zone (where SDV18 refers to the equivalent plastic strain) for suction anchors with varying numbers of fins, measured under no torsion ($\beta = 0°$) at the moment when padeye displacement reaches 0.1D. It can be seen that at low torsion angles, the plastic zone primarily takes on a wedged shape on the active side and a strip shape at the bottom, with interconnected plastic zones surrounding the anchor fins on the active side. The pull-out capacity of the 2-fin anchor exceeds that of the 3-fin and 4-fin anchors because the fins are perpendicular to the loading direction, resulting in a larger projected contact area. The limited increase in pull-out capacity when adding more fins (from 4 to 8) is due to the minimal effect these additional fins have on the size of the failure wedge on the active side. There is only a small area of concentrated plastic zone surrounding anchor fins on the passive side. In conditions with torsion (see Table 3, $\beta = 90°$), the plastic zone primarily exhibits an arc-shaped distribution on the side opposite the loading direction. This zone is connected near the anchor fins close to the padeye, while an isolated failure zone surrounds the fins farther away from the padeye. The pull-out capacity shows a growth trend characterized by a rapid increase with the addition of 0 to 3 fins, followed by a slower increase with 4 to 8 fins. This pattern occurs because, as the number of fins increases from none to two, the failure mode shifts from "soil-skirt friction" to "soil-fin interaction," resulting in a significant improvement in pull-out capacity. However, the subsequent addition of fins, particularly from 4 to 8, has a relatively minor impact on the size of the arc-shaped plastic zone.

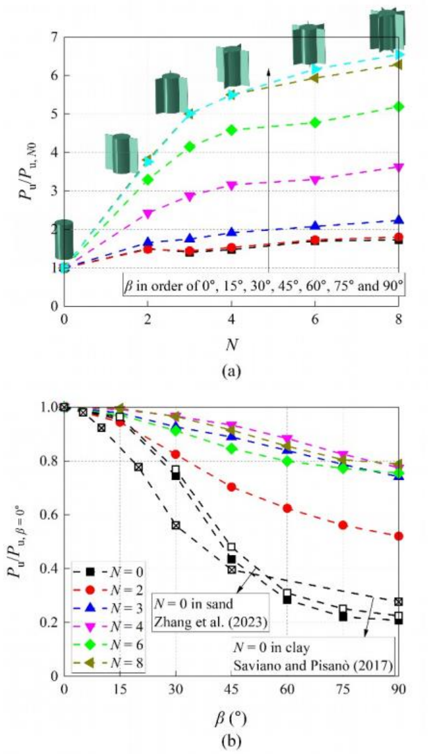



*Figure 2. Effect of fin number on the (a) pull-out capacity and (b) decay curves of pull-out capacity with varying torsion angles.*

Figure. 2(b) shows the decay curves of pull-out capacity due to torsion for suction anchor with different number of fins (the pull-out capacity is normalized by the pull-out capacity without torsion, $P_u/P_{u,\beta=0°}$). Overall, for both finless and finned anchors, the pull-out capacity decreases with increasing torsion angle, exhibiting a three-stage trend of "slow-rapid-slow" (Saviano and Pisanò, 2017; Zhang et al., 2023) These stages correspond to three types of pull-out behaviors: “pure translational”, “mixed translational and torsional” and “pure torsional”.

*Table 2. Plastic zone development for anchors with various fin numbers (β = 0°).*

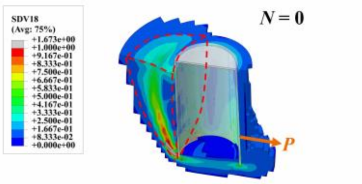
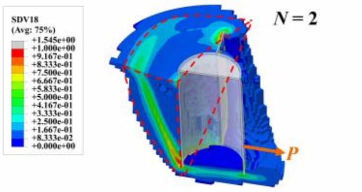
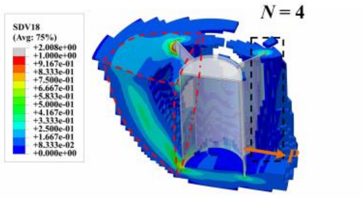
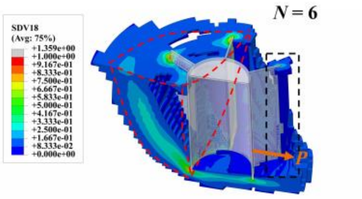
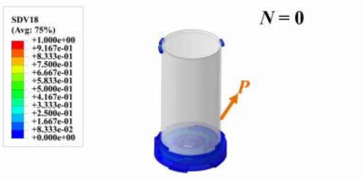
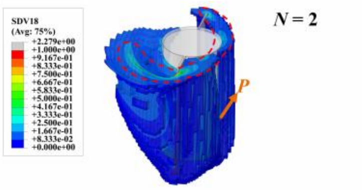
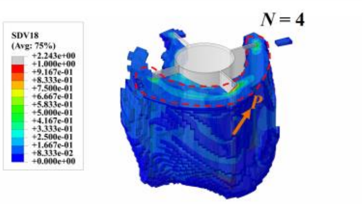
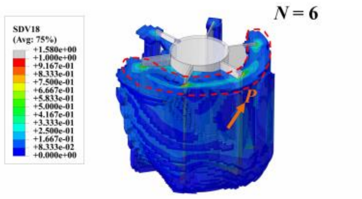
| Plastic zone development |
|---|
|  |
|  |
|  |
|  |

*Table 3. Plastic zone development for anchors with various fin numbers (β = 90°).*

| Plastic zone development |
|---|
|  |
|  |
|  |
|  |

As the number of anchor fins increases from 0 to 4, there is a significant enhancement in anti-torsion performance. However, when the number of fins is further increased from 4 to 8, the anti-torsion performance slightly declines. This indicates that the optimal solution for anti-torsion performance will appear when the number of fins is around 4. The 2-fin anchor manages to limit the maximum reduction in pull-out capacity (at a torsion angle of 90°) to approximately 50%, while the anchors with 3 to 8 fins experience a reduction of around 20%.

## 3.2 Effect of fin dimension

### 3.2.1 Effect of fin width and length

The pull-out capacity shows a nearly linear increase with the widening of the fins, as illustrated in Figure. 3(a). This trend is intuitive, as a greater fin width substantially enlarges the failure wedge on the active side. However, the enhancement in anti-torsion performance diminishes as fin width increases (see Figure. 3(b)), with anchor fins of 0.3$D$ and 0.5$D$ displaying similar anti-torsion capabilities.

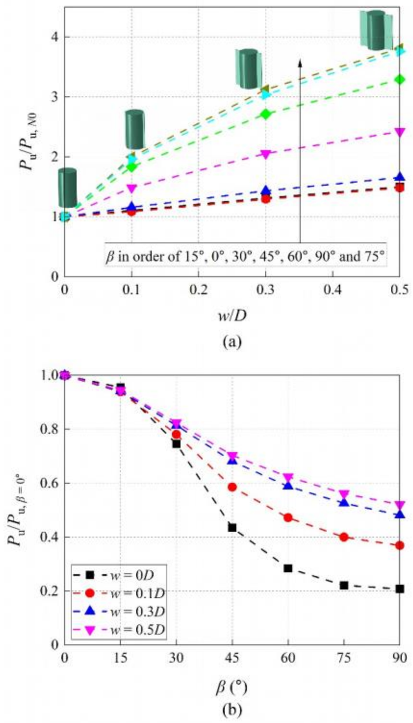



*Figure 3. Effect of fin width on the (a) pull-out capacity and (b) decay curves of pull-out capacity with varying torsion angles.*

In contrast, the pull-out capacity initially increases rapidly with fin length before gradually converging (Figure. 4(a)). Beyond a fin length of 0.5$L$, further increases have little effect on the pull-out capacity. This occurs because the increase in fin length has a minimal effect on the plastic zone, regardless of whether the torsion angle is low or high. The slight variation in pull-out capacity is primarily attributed to changes in the length of the concentrated plastic zone surrounding the fin as the fin length increases. Additionally, the length of the fin has minimal impact on anti-torsion performance (Figure. 4(b)).

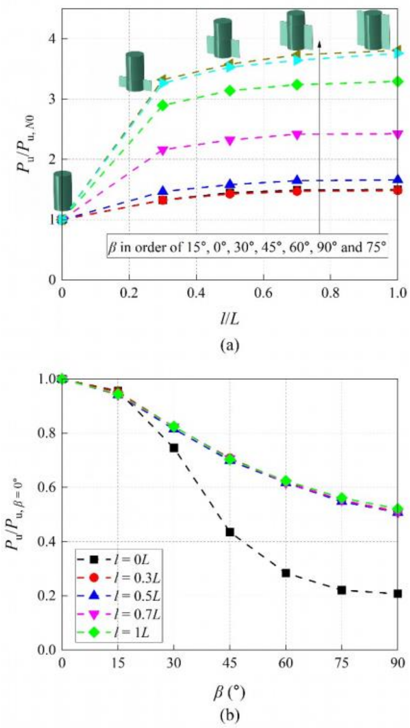



*Figure 4. Effect of fin length on the (a) pull-out capacity and (b) decay curves of pull-out capacity with varying torsion angles.*

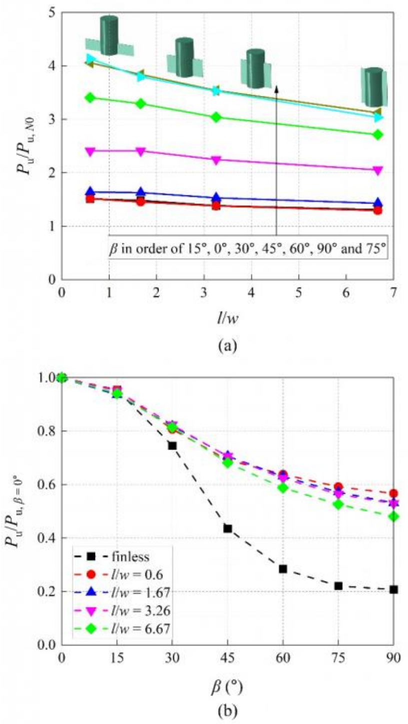



*Figure 5. Effect of fin length-width ratio on the (a) pull-out capacity and (b) decay curves of pull-out capacity with varying torsion angles.*

### 3.2.2 Effect of fin length-width ratio

Figure. 5 shows that the pull-out capacity decreases as the fin length-width ratio increases, with the effect becoming more pronounced at higher torsion angles (Figure. 5(a)). It is found that at high torsion angles ($\beta$ = 90°), anchor fins with small aspect ratios (short and wide) produce a continuous plastic zone surrounding the entire anchor. In contrast, anchor fins with large aspect ratios (long and narrow) result in an arc-shaped discontinuous plastic zone. Anchor fins with smaller aspect ratios demonstrate better anti-torsion performance; however, the effect is not significant when the aspect ratio is below approximately 3 (Figure. 5(b)).

## 4 DISCUSSIONS ON CONFIGURATION OPTIMIZATION CONSIDERING MATERIAL COST

Figure. 6 illustrates the normalized pull-out capacities (normalized by the pull-out capacity of *N*0, $P_u/P_{u,N0}$) under conditions with and without torsion ($\beta$= 0° and 90°), plotted against the normalized material cost (normalized by the anchor weight of *N*0, $W/W_{N0}$). The plots also include comparisons of the relevant increases in length (at constant diameter) and diameter (at constant length) for finless anchors. It is clear that increasing the length is a more effective approach for enhancing the pull-out capacity than increasing the diameter, regardless of whether torsion exists. At relatively small torsion angles (see Figure. 6(a)), it is notable that many configurations involving additional anchor fins are less effective than simply increasing the length of finless anchors (points below the solid line). In summary, the use of anchor fins is primarily beneficial when employing a small number of fins with a low length-to-width ratio (points above the solid line). At large torsion angles (see Figure. 6(b)), adding anchor fins significantly improves the pull-out capacity compared to merely increasing its length or diameter (with all points above the solid and dashed lines).

Based on these findings, a case study is presented to demonstrate configuration optimization in the anchor design process considering material cost. The original anchor has the dimension of $D$ = 4.5 m, $L$ = 7.5 m and $t$ = 0.1 m following the prototype scale adopted in the centrifuge tests by Allersma at al. (2000). Two design approaches are considered to enhance the anchor's pull-out capacity: increasing the length ($D$ = 4 m, $L$ = 8.7 m) or adding 2 fins ($D$ = 4 m, $L$ = 7.5 m, $w$ = 2 m and $l$ = 3.75 m). Both designs maintain the same total material cost. Figure. 7 summarizes the comparisons of pull-out capacity without and with torsion. From Figure. 7(a) it can be seen that the two optimization methods mainly enhance the pull-out capacity under relatively small loading angles when the torsion angle is 0°. Increasing the length and adding 2 fins can bring a maximum improvement of 14% and 35%, respectively. When considering torsion (Figure. 7(b)), increasing the length no longer has a significant advantage, and adding anchor fins can significantly improve the pull-out capacity under torsional loads. Even at a 90° torsion angle, the pull-out capacity of the 2-fin anchor can reach 70% of the original anchor's pull-out capacity.

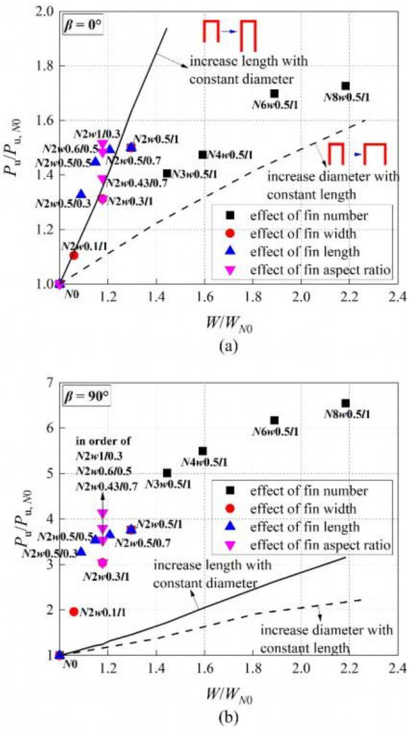



*Figure 6. Summary of pull-out capacities considering material cost: (a) β = 0°, (b) β = 90°.*

## 5 CONCLUSIONS

In this paper, three-dimensional finite element analyses were conducted to investigate the pull-out capacity and failure mechanism of finned suction anchors in sand considering torsional effects. The key findings regarding the influence on the pull-out capacity are as follows: (a) under low torsion, the 2-fin anchor exhibits a significant advantage in terms of capacity. As the torsion angle increases, the pull-out capacity initially rises rapidly (0-3 fins), followed by a more gradual increase (4-8 fins) with an increasing number of fins; (b) there is a nearly linear increase in pull-out capacity with widening of the fins, while for fin length, there is an initial rapid increase before gradually converging (over 0.5*L*); (c) as the fin length-to-width ratio increases, the pull-out capacity decreases, particularly at higher torsion angles. In terms of anti-torsion performance, among different configurations tested, it was found that the 4-fin anchor demonstrates superior effectiveness. Furthermore, increasing fin width significantly enhances anti-torsion performance, especially when it is below 0.3*D*. Based on our analysis results, we conclude that to improve the pull-out capacity of finless anchors while considering material consumption constraints, optimal strategies include increasing skirt length or adding anchor fins with smaller aspect ratios and fewer quantities; notably, adding anchor fins can significantly enhance pull-out capacity under torsional loading conditions. A case study is presented to illustrate how anchor configuration optimization can be incorporated into design processes.

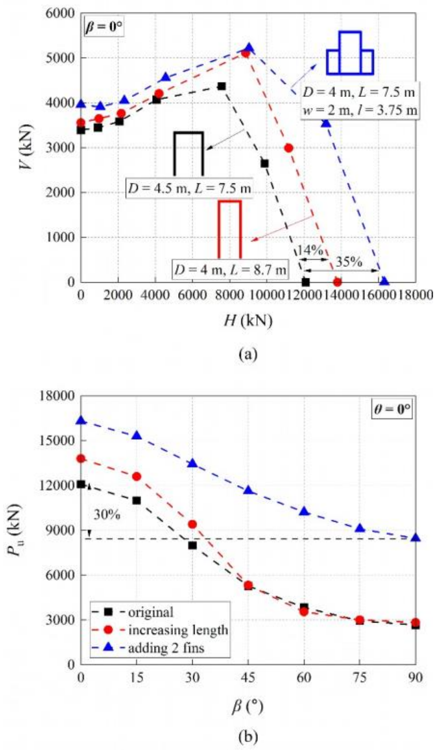



*Figure 7. Configuration optimization: (a) H-V envelopes (β = 0°), (b) decay curves of pull-out capacity (θ = 0°).*

## AUTHOR CONTRIBUTION STATEMENT

**Min-Hao Zhang**: Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Yong Fu**: Writing – review & editing, Supervision, Funding acquisition. **Zhen-Yu Yin**: Conceptualization, Software, Resources, Supervision.

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