On the validity of classical beam theory for the analysis of thin-walled piles under lateral loading

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ABSTRACT: Open-ended steel piles connected by catenary mooring lines are one of the solutions for anchoring floating wind turbines. The piles are subjected to horizontal loading and the understanding of the pile behaviour in interaction with the foundation soil is essential for ensuring structural safety and optimizing design. To further understand this behaviour, an experimental campaign was conducted using a medium-scale model of a short open-ended pile (325 mm diameter, 2 m embedment) in dense sand, as part of the SAM-WT GEOLAB project. The pile was tested under monotonic lateral loading and instrumented with nine pile-head displacement sensors and 32 strain gauges along its length. The behaviour of a pile under lateral loading is usually analysed using the *p-y* curves method, which relates the soil lateral reaction on the pile shaft to the pile lateral displacement. Experimentally, the *p-y* curves can be derived from instrumentation of the pile shaft using strain gauges and the application of classical beam theories such as Euler-Bernoulli. However, this approach shows limitations when applied to thin-walled piles, as the simplified structural assumptions may not capture the real behaviour. This paper assesses the relevance and limitations of the classical approach to behaviour analysis. This is proposed here through analysis of experimental data and 3D finite element analyses of the pile, evaluating classical beam theory and the equivalent flexural rigidity approach. The results highlight that conventional modelling approaches fail to capture localized effects such as stress concentrations and cross-sectional ovalisation. These findings underscore the need for improved modelling strategies that can accurately represent the behaviour of thin-walled piles.

1 INTRODUCTION

Floating offshore wind turbines have emerged as a viable solution for deep-water renewable energy generation. Their anchoring systems, often consisting of open-ended steel piles, must withstand complex lateral loads induced by waves, wind and currents (Cerfontaine *et al.*, 2023).

A widely adopted approach for analysing laterally loaded piles is the *p*–*y* method: a semi-empirical model in which the pile is treated as a Winkler beam (Winkler, 1867), supported by a series of uncoupled, nonlinear springs simulating soil resistance (DNV, 2021, Reese *et al.*, 1974). Typically based on classical beam theories such as Euler–Bernoulli (EBB) or Timoshenko (TB), this method assumes uniform bending behaviour and neglects localized deformation mechanisms. While these simplifications reduce computational effort, they may be inadequate for thin-walled piles, which are more vulnerable to stress concentrations and cross-sectional ovalisation due to reduced flexural stiffness (Mittelstedt, 2024).

These theoretical limitations are intensified by the experimental complexity of capturing strain fields in thin-walled piles. As a result, most experimental post-processing assume classical beam theory and overlook localized responses (e.g. Rosquoët, 2004;

Puech and Garnier, 2017; Haouari and Bouafia, 2023). This is also the case of most simplified 1-D models, both *p-y* curve-type models and the PISA method (Burd et al., 2020).

The limitations of the current *p–y* method for short piles have been widely debated. Byrne *et al*. (2015) indicate that the method neglects base contribution, while Choo and Kim (2015) argue that it leads to an overprediction of lateral stiffness. Yet, the alternative models they propose continue to depend on classical beam assumptions.

In addition, some finite element and finite difference numerical models approximate thin-walled piles as solid piles with equivalent flexural rigidity (Chalhoub *et al.*, 2023; Wei *et al.*, 2025; Abdellatif *et al.*, 2025). These models typically adjust the Young's modulus while maintaining the geometry, yet still relying on classical beam theory; thus, inheriting its assumptions and limitations. Such simplifications risk omitting critical mechanical behaviours in the pile-soil system.

This paper investigates the influence of lateral loading on the bending response of thin-walled, open-ended steel piles. Drawing on high-resolution strain gauge data from the GEOLAB SAM-WT experimental campaign (Chalhoub *et al.*, 2024), this study examines localized structural behaviours, including stress concentrations and cross-sectional deformation, which are typically not captured by classical beam theory. Complementary numerical analyses assess key modelling assumptions, though without replicating the full experimental boundary conditions. This paper leads to recommendations for experimental data processing and simplified 1-D modelling are provided for future modelling of piles under lateral loading.

2 METHODOLOGY

The study detailed in this paper aims to provide insights and analysis of the lateral response of piles for offshore wind applications. An experimental campaign was first carried out to observe the physical response of a model thin-walled pile under controlled loading conditions. The results serve as an impetus for the development of 3D finite element (FE) models to evaluate the validity of Euler-Bernoulli Beam (EBB) theory for piles subjected to unidirectional lateral loading.

2.1 Experimental campaign

A reduced-scale physical experiment was conducted to investigate the behaviour of laterally loaded piles under complex loading conditions. The setup, instrumentation, and procedures are summarized here, while a more extensive description of the test set-up is provided in in Chalhoub *et al.* (2025b).

The test campaign was performed in the geotechnical testing pit of the Technical University of Darmstadt between March and June 2024. A hollow open-ended steel pile, internally filled with sand (i.e. unplugged or cored), was embedded 2.0 m into dry Darmstadt sand within a 5.44 m × 5.00 m × 2.60 m test pit. The model pile, designed at a 1:5 scale based on Jenck *et al.* (2021), had an outer diameter of 324.9 mm, a wall thickness of 5.25 mm and a total length of 3.00 m (with 2.00 m embedded in the sand sample). The steel used (grade S235) ensured linear-elastic behaviour during load application, even at high loads.

In the experimental test campaign, the pile was subjected to different loading conditions of increasing complexity. This paper solely focuses the results of the unidirectional monotonic load, referred to as Test 0 (Chalhoub *et al.*, 2025b). In this test, the load was applied by a 100 kN hydraulic actuator at 0.58 m above the sand surface via a rod connected to the geometric centre of the pile cross-section (Figure 1).

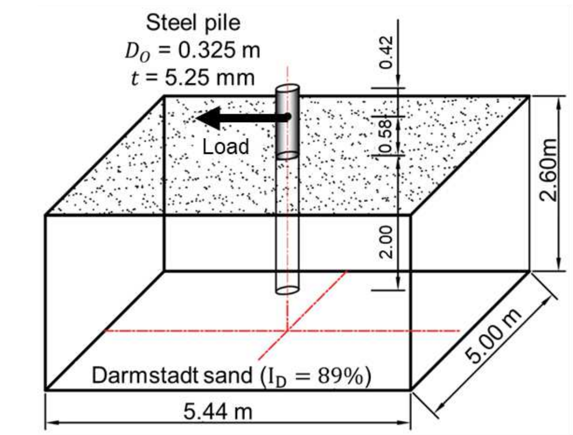

Figure 1. Experimental setup, from Kochnev et al. (2025).

The test pit was filled with Darmstadt sand in 13 layers of 0.2 m, which was compacted using a vibratory plate with the pile maintained in the centre of the soil pit. This "wished-in-place" pile installation method was adopted to preserve undisturbed conditions and ensure consistency with planned numerical modelling. Seven Cone Penetration Tests (CPT) confirmed accurate horizontal and vertical uniformity of the sand sample, and the achieved relative density was equal to I_D = 89 %.

The model pile was instrumented with 32 quarter-bridge strain gauges (SG), arranged in four lines of diametrically opposed pairs to measure longitudinal strain in all directions, as illustrated in Figure 2. Four lines of strain gauges were needed for the overall test campaign, involving multi-directional loading. Additionally, nine Linear Variable Differential Transducers (LVDTs), mounted on a rigid tetrahedral frame, measured the displacements and rotations of an aluminium box rigidly affixed to the pile head. This instrumentation permitted to track the displacements and rotations at the pile loading point and provide a refined analysis of both strain localization and cross-sectional deformation along the pile shaft.

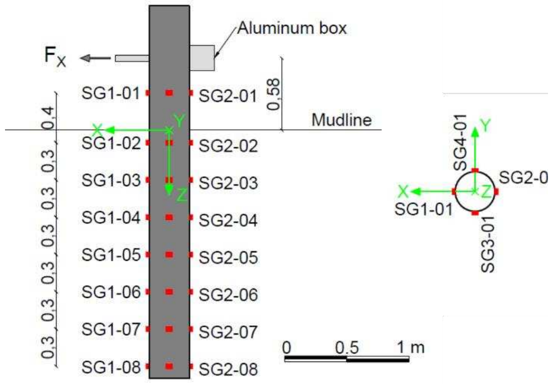

Figure 2. Instrumentation distribution of the pile in the experimental setup.

2.2 3D Finite Element modelling

This study employed two complementary numerical modelling approaches to investigate the behaviour of short piles under lateral loading, with a particular focus on the limitations of classical beam theory when applied to thin-walled sections. In this initial approach, only the pile is subjected to localised loading. This corresponds to an extreme case where the soil reaction and soil plug do not come into play, in order to highlight the behaviour of the pile alone. All simulations were carried out using the commercial finite element (FE) software Abaqus (Dassault Systèmes Simulia, 2024). Solid elements were consistently used to capture full 3D stress and strain states, including through-thickness effects.

2.2.1 Flexural rigidity and cross-section influence

To assess the influence of flexural rigidity and cross-sectional geometry on pile behaviour, a 3D FE analysis was conducted based on a previously validated model, originally developed by Zachert *et al.* (2023) to analyse a three-point bending test performed on the 3m-long pile used subsequently in the SAM-WT experimental campaign presented in Chalhoub *et al.* (2024, 2025a, b) and Kochnev *et al.* (2025) and in this paper. The model was adapted to simulate short piles under lateral loading with a cantilever-type boundary condition, fully fixed against displacement and rotation.

Two pile geometries were investigated:

- A **Solid Pile (SP)**, and
- A **Thin-walled Pile (TP)**, with the same outer diameter as the SP (324.9 mm), but a wall thickness of 5.25 mm.

Both models, illustrated in Figure 3 and Figure 4, were discretized using solid elements to ensure accurate capture of local 3D stress states and avoid numerical artefacts, particularly around zones of stress concentration. A minimum of three elements were used across the pile thickness to support accurate strain/stress recovery. The final meshes consisted of 108,540 nodes with 8-node linear brick elements (C3D8R) for the solid pile and 67,028 nodes with 20-node quadratic brick elements (C3D20R) for the thin-walled pile. A mesh sensitivity was rigorously performed prior this study and is presented in Coelho (2025).

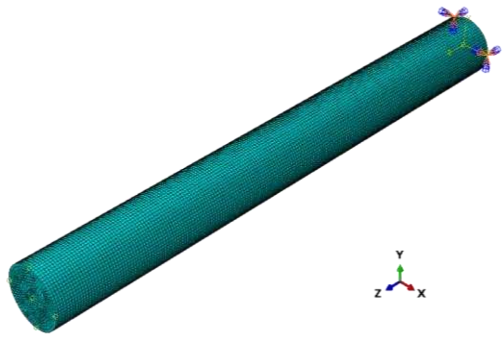

Figure 3. 3D FE model for the solid pile (SP).

Figure 4. 3D FE model for the thin-walled pile (TP).

Three loading scenarios were applied to each pile:

- **CL**: A concentrated load applied at the centre of the cross-section, 3.0 m from the fixed end (i.e. at pile other end).
- **FL**: A concentrated load applied at the free end of the pile, at the topmost point of its outer surface, i.e, at 0° as indicated in Figure 5.
- **DL**: A distributed load of 2.33 MPa applied along the upper half circumference, between 2.642 and 2.758 m from the fixed end, using a clamp.

In all cases, the resultant lateral load was 70 kN, acting in the negative Y-direction and no sand was considered in the simulations. It is worth noting that only for the DL load a clamp with 115 mm thickness was used in both piles to be able to distribute the load across their surface. This clamp is represented in the solid pile depicted in Figure 5.

These loading configurations were chosen to explore stress localization and deformation modes representative of real soil-structure interaction. The quadratic moments for the solid and thin-walled piles, I_{SP} and I_{TP}, were 5.5 × 10⁻⁴ and 6.7 × 10⁻⁵ m⁴, respectively. The material behaviour was assumed linear elastic with a Young's modulus of 210 GPa and Poisson's ratio of 0.3, for both models.

The complete stress and strain tensors were extracted at five locations along the pile: 0.1 m, 1.0 m, 1.5 m, 2.0 m, and 2.9 m from the fixed end. For each location, points were evaluated at the pile surface, i.e. pile shaft, at four different angles, as shown in Figure 5.

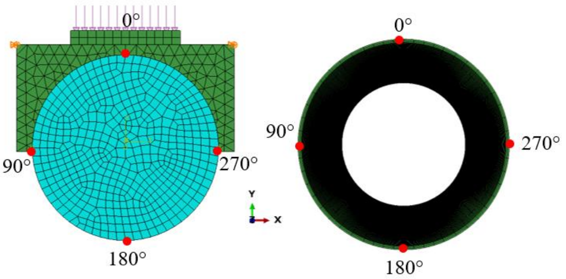

Figure 5. Schematic representation of the analysed points for each section.

2.2.2 Equivalent flexural rigidity approach

In the second numerical analysis, the concept of equivalent flexural rigidity was tested to determine whether the behaviour of a thin-walled pile could be replicated using a solid pile with an adjusted Young's modulus. According to EBB theory, the transverse displacement of a beam under bending arises solely from its curvature, which is controlled by the flexural rigidity, EI, as follows:

$$M_x(z) = EI_x \frac{\partial^2 y}{\partial z^2} \quad (1)$$

where M_x (kN·m) is the bending moment at depth z (m), E (GPa) is the Young's modulus, I_x (m⁴) is the quadratic moment along the X-direction, and y (m) is the transverse displacement.

Therefore, identical transverse displacements are expected if the SP and the TP modelled piles have the same EI value. In this study, the SP pile was assigned a reduced Young's modulus of 25.9 GPa to match the EI of the TP pile, thereby ensuring equivalent flexural rigidity.

Both piles were 3.0 m long with an outer diameter of 324.9 mm. The thin-walled pile had a wall thickness of 5.25 mm, while the solid pile was fully solid. Both were modelled using solid elements and subjected to a 70 kN vertical load applied at the outer surface at the free end (i.e. FL loading scenario). Cantilever-type boundary conditions were applied at the fixed end.

The FE meshes and the locations at which stresses and strains were evaluated were identical to those described in Section 2.2.1.

Results from both models were compared to evaluate the effectiveness of the equivalent EI modelling approach in capturing not only displacement fields but also localized deformation phenomena, such as ovalisation and hoop stress, characteristic of thin-walled structures.

3 RESULTS AND DISCUSSION

3.1 Experimental results

Figure 6 depicts the axial strain measurements on the four profiles (SG1 to 4) for a monotonic unidirectional lateral loading up to 70 kN (value to achieve a lateral displacement at the loading point at the top of the pile of 0.2 D_0, where D_0 is the pile outer diameter).

According to EBB theory, unidirectional lateral loading of the pile would cause the axial strain to have the same magnitude in the tension and compression zones along the loading direction. Simultaneously, the axial strain along the neutral axis (orthogonal to the loading direction) should be zero. However, such behaviour represents an idealised case; for real piles in sand, the strain distribution is affected by soil-pile (shear) interaction, which can lead to marked deviations from the classical pattern.

Nonetheless, Figure 6 shows that the measured axial strain relative to the loaded direction (SG1 and SG2) have highly different magnitudes and profile shapes, and the strain along the neutral axis (SG3 and SG4) is non-zero. Notably, the strain in this direction also changes sign with depth, but is almost equal on both sides, indicating complex deformation patterns, which cannot be entirely attributed to shear at the soil-pile interface.

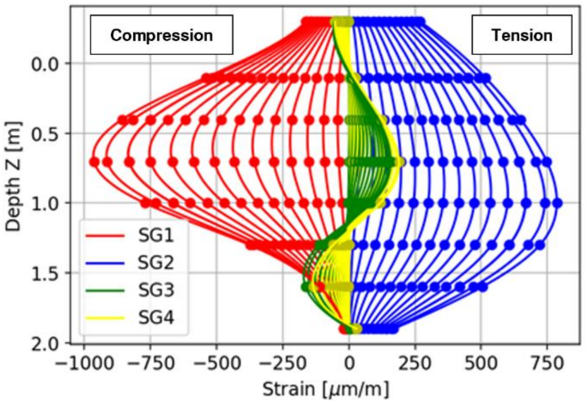

Figure 6. Axial strain measurements on the pile shaft at various depths and various loading stages up to F_x = 70kN in increment of 5kN, for monotonic Test 0.

Comparable behaviour has been reported from large-scale field studies on a range of laterally loaded rigid piles conducted in dense sand in Dublin by Doherty et al., (2015) and in Dunkirk marine sand (McAdam et al., 2020). In the Dublin tests, the reduced compressive strains were attributed to a migration of the neutral axis toward the compression side of the pile cross-section. In contrast, the pronounced asymmetry between tensile and compressive strains observed in the Dunkirk sand tests was identified as atypical, although no definitive explanation was proposed by the authors.

This was further understood by Li et al. (2021) and Blanc (2024) through centrifuge tests on a 5 m diameter pile (L/D = 5) installed in dense sand at the University Gustave Eiffel. Near the ground surface, lateral pile displacement induces strong opposing soil reactions that restrain forward movement, enhancing soil–pile contact and increasing tangential and frictional stresses. As a result, compressive strains on the front face of the pile intensify and can exceed tensile strains for short embedment ratios, such as L/D = 3 and 5. At greater depths, tensile strains consistently dominate due to stronger soil reactions, increased shaft friction, and base shear.

Importantly, a deviation from the expected behaviour is also observed in Figure 6 in the segment of the pile located above the sand, where soil influence is absent. This suggests that the discrepancies cannot be attributed solely to soil–pile interaction. Rather, they point to limitations in classical beam formulations when applied for short thin-walled piles, like EBB, which assume negligible transverse stresses, no cross-sectional warping and uniform bending behaviour. Therefore, to investigate the structural mechanisms responsible for this unexpected response, numerical modelling was employed.

3.2 Numerical results

Numerical simulations were conducted to further investigate the influence of pile geometry, particularly the comparison between thin-walled and solid cross-sections, on structural response. This analysis considered both the flexural rigidity and the point of load application.

One key parameter evaluated was cross-sectional ovalisation, defined by Eq. (2), where α (%) is the ovalisation and D_i(m) and D_f (m) are, respectively, the initial and the final (deformed) outer diameter of the pile in the Y-direction, respectively.

$$\alpha = \frac{D_i - D_f}{D_i} \times 100 \quad (2)$$

Unsurprisingly, the results depicted in Figure 7 show significant ovalisation for thin-walled piles, especially when the load is applied at the outer surface (Case FL), while solid-section piles with the same outer diameter and Young's modulus exhibit practically no transverse deformations.

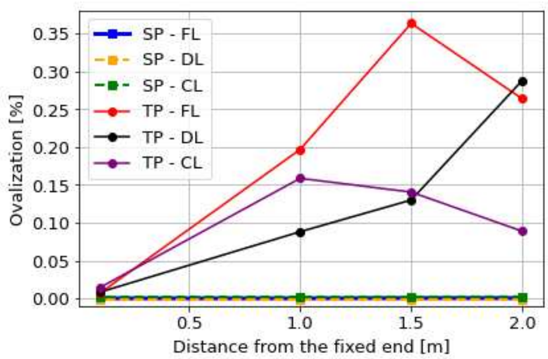

Figure 7. Ovalisation comparison between thin-walled (TP) and solid section piles (SP) at selected positions along the pile. Results beyond 2 m are omitted for clarity.

A similar trend is observed when analysing the normalized hoop stress, defined as the ratio between hoop (or circumferential, $\sigma_{\theta\theta}$) and axial stresses σ_{zz} at the same angular position θ indicated at Figure 5 (Figure 8). In thin-walled piles, circumferential stresses are significantly larger, contradicting EBB theory assumptions, which consider these stresses negligible. Furthermore, axial stress concentration is evident on the loaded side of the pile especially for the FL case (Figure 9). The high stress values, exceeding the steel elastic limit, are related to the embedment condition of the pile at its fixed end in this modelling and would not occur experimentally.

These localized effects can be attributed to the lower flexural rigidity, i.e. EI product, of thin-walled sections. This violates a core assumption of EBB theory, which assumes that the cross-section rigidity is infinitely high. Consequently, this study highlights the limitations of using EBB theory for short rigid piles, where boundary conditions induce complex behaviour that cannot dissipate over the limited pile length. These findings therefore challenge the suitability of EBB theory for pile modelling.

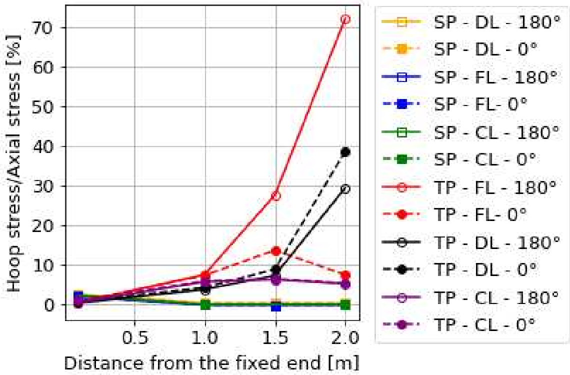

Figure 8. Comparison of normalized hoop stress in thin-walled (TP) vs. solid-section piles (SP). Results beyond 2 m are omitted for clarity.

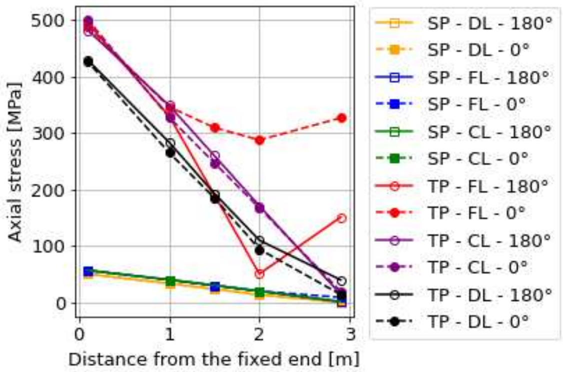

Figure 9. Absolute value of axial stress in thin-walled (TP) vs. solid-section piles (SP).

The simulations also revealed that loading at the outer surface (through, for example, a pad-eye mooring connection) induces more critical stress conditions than centred loading (CL case), highlighting the importance of accurately modelling the point of force application in future experimental setups.

To further examine modelling approaches, the thin-walled pile was approximated using an equivalent solid section model (as described in Section 2.2.2). The vertical displacement profiles (Figure 10) were nearly identical for both models, except near the load application point.

However, substantial differences were found in the ovalisation (Figure 11) and hoop stress distributions (Figure 12). These differences can be explained by the scaling relationship derived from EBB theory.

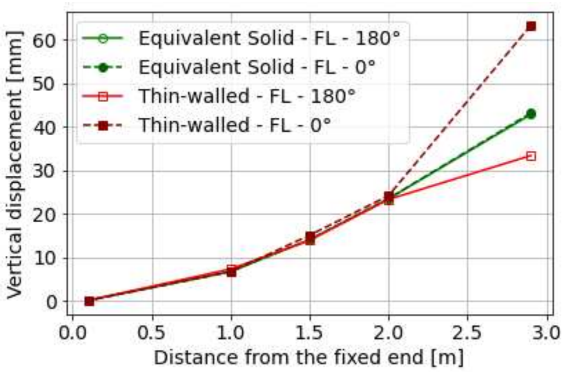

Figure 10. Vertical displacement comparison for thin-walled and equivalent solid-section piles. Both piles were subjected to a vertical load applied at the outer surface at the free end.

The governing equation for the axial stress in simple bending is written as follows:

$$\sigma_{zz}(z) = \frac{-M_x(z)}{I_x}\nu \rightarrow \sigma_{zz}^* \propto \frac{1}{I_x^*} \qquad (3)$$

where σ_{zz} (MPa) and M_x (kN.m) are, respectively, the axial stress and the bending moment at depth z (m), I_x (m^4) is the quadratic moment of inertia, ν (m) is the distance from the neutral axis and σ_{zz}^*(-) and I_x^*(-) are, respectively, the axial stress and the quadratic moment scaling factors.

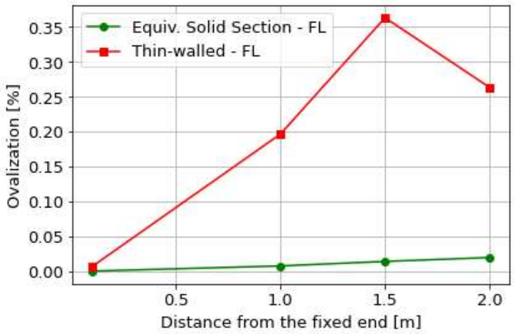

Figure 11. Ovalisation comparison between thin-walled and equivalent solid-section piles. Results beyond 2 m are omitted for clarity.

When the thin-walled pile is replaced with an equivalent solid section that has the same flexural rigidity, the displacement remains consistent because the overall flexural rigidity is preserved, as shown in Eq. (1). However, the stress level in the pile is lower. This is because the scale factor for axial stress is inversely proportional to the scale factor of the moment of inertia, as indicated by Eq. (3). Since the equivalent solid section typically has a higher quadratic moment than the thin-walled one, the resulting stress level, and therefore the local deformation, decreases.

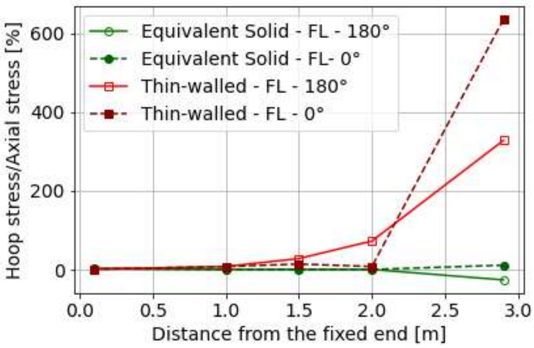

Figure 12. Normalized hoop stress comparison between thin-walled and equivalent solid-section piles.

As a result, localized effects, such as stress concentrations and cross-sectional ovalisation are not captured by the Equivalent Flexural Rigidity approach. This confirms that, while the flexural rigidity-based equivalence can serve as a preliminary tool for estimating global displacements, it is insufficient for capturing the actual stress distribution and deformation mechanisms occurring in thin-walled piles. For precise analysis of internal force transmission, it is necessary to apply advanced beam theories or conduct detailed numerical simulations using the actual pile geometry.

4 CONCLUSIONS AND DISCUSSION

4.1 Key observations from this paper

This study is based on experimental observations to develop a 3D finite element (FE) model to evaluate the applicability of classical beam theories, such as Euler-Bernoulli (EBB) beam theory, to thin-walled piles subjected to unidirectional lateral loading. An extreme case where the soil reaction is not taken into account and the pile is embedded at its base is considered in order to highlight its behaviour under lateral load. The findings indicate that, while solid piles exhibit minimal local deformation, thin-walled piles undergo significant stress concentrations at the loading zone and cross-sectional ovalisation of the shaft along most of the pile length. These localized effects challenge the foundational assumptions of classical beam theory and highlight the limitations of widely used design approaches, such as the current experimental derivation of *p–y* curves, which fail to capture these complex behaviours present by short piles.

The numerical simulations further suggest that for thin-walled piles, classical beam theories may not provide accurate predictions. Furthermore, the Equivalent Flexural Rigidity approach cannot capture the localized phenomena that develop in thin-walled piles, even though the resultant displacement is similar. In this manner, to be able to observe how internal stresses are transmitted in the pile, it is necessary to model its full geometry, considering the thin-walled section.

However, these numerical conclusions are based on idealized boundary conditions, namely a fully fixed cantilever base and the exclusion of surrounding and internal sand, which limit the generalizability of the results. A more comprehensive 3D model that incorporates realistic soil-structure interaction is necessary to simulate pile behaviour more accurately, particularly with respect to ovalisation and localized stress response.

4.2 Discussion for instrumented pile experimental analysis and 1-D modelling

The results suggest that axial strain measurements in short thin-walled piles would not only be affected by global bending but also by transverse stresses and cross-sectional ovalisation. To further this analysis, a similar numerical study on a pile model interacting with the surrounding soil is required.

This limitation implies that *p–y* curves derived from instrumented thin-walled piles using conventional post-processing techniques may incorporate structural effects that are unrelated to soil–pile interaction. This insight underscores the need for future experimental work to include measurements of both axial and hoop strains to capture the full stress state of thin-walled piles under lateral loading and then be able to isolate the deformation caused only by global deformation modes.

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