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A revised Broms' theory to estimate the ultimate capacity of laterally loaded piles driven in chalk

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ABSTRACT: Chalk is often encountered at onshore and offshore sites in Northwest Europe, where it poses challenges for projects that rely on driven piles. Percussive driving causes significant damage in chalk and similar weak rocks, severely affecting their axial and lateral bearing behaviour, as proven through extensive testing conducted under the recent ALPACA research projects. Lateral loading field tests at the ALPACA test site in Southeast England and associated advanced 3D finite element analyses helped to identify the physical factors and mechanical parameters that dominate the lateral behaviour of piles driven in chalk. The present paper introduces a further analytical advance: an evolution of the classical theory proposed by Broms that considers the ultimate capacity of laterally loaded piles driven in media such as chalk. The extended approach accounts for the gaps that open on the active side of piles under monotonic lateral loading and generates profiles of the ultimate soil reactions mobilised at the soil-pile interface. The approach was tested successfully against some of the ALPACA field data, delivering good predictions of the ultimate capacities, failure mechanisms, rotation point depths (for relatively rigid piles) and maximum pile bending moments.

KEYWORDS: Driven piles, chalk, lateral loading, Broms' theory, ultimate capacity.

1 INTRODUCTION

Chalk is often encountered at onshore and offshore sites in Northwest Europe (Mortimore, 2012), posing several challenges to designers, especially when projects rely on driven piles (Carotenuto et al., 2018). Percussive driving causes significant damage in chalk and similar weak rocks, severely affecting axial and lateral pile bearing behaviour, as proven through extensive testing conducted under the recent ALPACA projects (Jardine et al., 2024; McAdam et al., 2024).

As part of these recent research projects, 38 tubular steel piles were driven in chalk and subsequently subjected to axial and lateral loading, under either monotonic or cyclic conditions. These pile tests were conducted at St. Nicholas at Wade (Kent, UK) in structured, low-to-medium density, B2/B3 chalk following Lord's et al. (2002) CIRIA classification scheme (B2/B3 grade signifies that the chalk contains macro-discontinuities with <3 mm aperture and 60-600 mm spacing).

Buckley et al. (2018) and Vinck et al. (2025) report that the percussion driving of the steel tubular piles at St. Nicholas at Wade (i) led to the formation of a de-structured chalk annulus close to the pile shaft and (ii) induced additional fracturing in the chalk in a second, more extensive, annular region around the piles. Given that these damaged areas significantly affect both axial and lateral pile load-displacement behaviour, the properties of both fully de-structured and intact chalk have been characterised through extensive laboratory and field testing (Liu et al., 2023; Liu et al., 2024; Vinck et al., 2024).

The ALPACA lateral pile loading tests were modelled by Pedone et al. (2023) and Kontoe et al. (2025) through advanced 3D finite element analyses. Pedone et al. (2023) simulated a pair of high-yield stress (X80 grade) steel piles with an embedded Length-to-Diameter ratio, L/D=6, imposing fully drained analyses that reflected the relatively high mass permeability of highly fractured chalk (Lord et al., 2002).

The numerical simulations presented by Pedone et al. (2023) captured the pile-chalk interaction well, providing lateral capacities and bending moment profiles close to those measured on site. The analyses also showed that the brittle intact chalk's post-rupture properties are broadly representative of the average shear strength that can be mobilised by fractured chalk, following similar experimental findings reported by Millar (2000) and discussed by Clayton et al. (2002).

The piles modelled by Pedone et al. (2023) exhibited what Broms (1964a; 1964b) defined as "short pile" failure, with a rotation point set at around 2/3 of the embedded length. This implied that pile-chalk interaction induced chalk passive loading in the areas located: (i) in front of the pile, above the rotation point; (ii) at the back of the pile, below the rotation point. The analyses also indicated gap opening in the active regions, confirming field observations (McAdam et al., 2024).

The methodology described in this paper offers a tool that should be particularly useful in the design of offshore windfarms located at sites where chalk is encountered. The recently developed PISA methodology (Burd et al., 2020; Byrne et al., 2020) offers the current industry standard for designing monopiles for such projects, with specific reference to sand- and clay-dominated sites. This design methodology typically involves undertaking a limited number of advanced 3D FE analyses at selected locations, as described by Taborda et al. (2020) and Zdravkovic et al. (2020). The numerical outputs obtained inform the far larger numbers of 1D p-y analyses that are required to achieve optimal designs for each individual turbine location.

Large North Sea windfarms may involve over 100 turbines set in farms with areas of several hundred km^2 and the approach proposed herein offers a simple way of undertaking rapid checks on the piles' ultimate lateral capacities. This tool should prove valuable when designing multiple installations for variable ground conditions. In particular, the paper sets out an extension to Broms's theory (1964a, 1964b) that aims to provide a simple and reliable estimate of the ultimate lateral pile capacity available at chalk-dominated sites. The approach herein proposed, adopted in combination with the classical solutions introduced by Broms, can be extended further to deal with sites where both soil and chalk units are encountered at foundation level.

2 METHODOLOGY

2.1 *Broms' theory*

The approach proposed by Broms (1964a; 1964b) allows to estimate the lateral capacity of piles interacting with (i) purely frictional soils (effective angle of shearing resistance, $\phi' \neq 0$, and effective cohesion intercept, $c'=0$) or (ii) purely cohesive soils in undrained conditions (undrained shear strength, $c_u \neq 0$). Broms assumed rigid-perfectly plastic behaviour for the pile and the soil, with the ultimate soil resistance corresponding, respectively, to (i) $3K_p \cdot \gamma z \cdot d$ and (ii) $9c_u \cdot d$, where K_p is the Rankine passive earth pressure coefficient, γ is the soil unit weight, z is the generic depth below ground level, and d is the pile external diameter (in case of circular piles).

In Broms' theory, the soil resistance varies with depth following the schemes shown in Figure 1. The soil resistance profile for undrained, purely cohesive materials, starts from a $z=1.5 \cdot d$ in order to fit, in a simplified manner, a more complex soil resistance distribution based on experimental data.

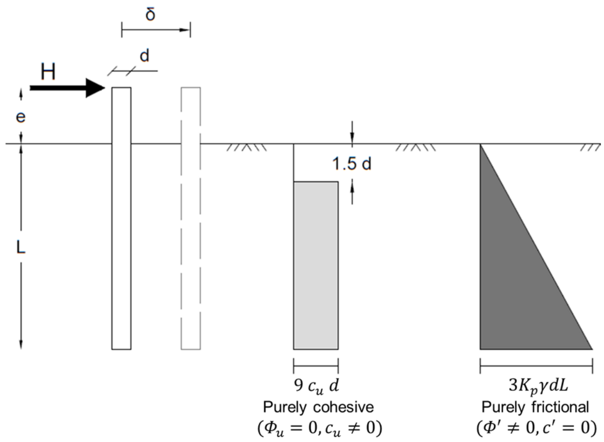

Figure 1. Profiles of soil resistance according to Broms (1964a; 1964b) for cohesive (undrained) and cohesionless (drained) soils.

The ultimate resistance, p_{lim}, for fully drained frictional materials is taken as three times the Rankine passive pressure, to account, in an approximate way, for three-dimensional effects. As observed by Cecconi et al. (2019), Broms' assumption transforms a 2D plane strain solution given by:

$$p_{lim}/d = \sigma_{h,p} - \sigma_{h,a} = \gamma z \cdot (K_p - K_a) \quad (1)$$

into a 3D expression corresponding to:

$$p_{lim}/d = \gamma z \cdot 3K_p \quad (2)$$

so 3D effects are accounted by a coefficient, α_ϕ:

$$\alpha_\phi = 3K_p / (K_p - K_a) \quad (3)$$

The 2D plane strain solution considers the lateral capacity as being provided by the difference between passive and active pressures generated in front of and behind the pile, referred to as $\sigma_{h,p}$ and $\sigma_{h,a}$, respectively, and is calculated as a function of the passive and active earth pressure coefficients, K_p and K_a.

Cecconi et al. (2019) noted that a constant value of $\alpha_\phi=3.35$ leads to a very close approximation of the solution provided by Broms for purely frictional fully drained soils. Based on this observation, they extended the following 2D plane strain solution for c'-ϕ' soils:

$$p_{lim}/d = \gamma z \cdot (K_p - K_a) + 2c' \cdot \left(\sqrt{K_p} + \sqrt{K_a}\right) \quad (4)$$

into the corresponding 3D solution:

$$p_{lim}/d = \alpha_\phi \cdot \gamma z \cdot (K_p - K_a) + \alpha_c \cdot 2c' \cdot \left(\sqrt{K_p} + \sqrt{K_a}\right) \quad (5)$$

again expressed as the difference between passive and active earth pressures, conveniently multiplied by the frictional and cohesive coefficients α_ϕ and α_c, whose values are taken as:

$$\alpha_\phi = \alpha_c = \alpha = 3.35 \quad (6)$$

A further approximation is provided by Cecconi et al. (2019), leading to the following final expression for c'-ϕ' soils:

$$p_{lim}/d = \gamma z \cdot 3K_p + 9c' \cdot \sqrt{K_p} \quad (7)$$

Assuming either free-head or restrained-head piles, Equation (7) leads to the equilibrium equations under different horizontal loading failure mechanisms. For example, Figure 2 shows the free-head pile failure mechanisms proposed by Cecconi et al. (2019) and the corresponding forces and soil resistances acting on the piles.

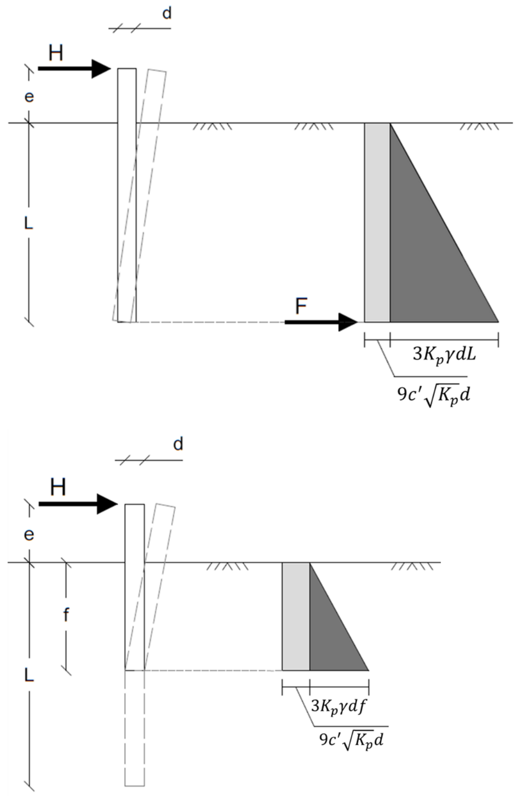

Figure 2. Free-head pile failure mechanisms according to Cecconi et al. (2019, modified).

Following Broms, only two failure mechanisms are considered for the free-head pile case: (i) short-pile failure and (ii) long-pile failure. The short-pile failure takes place if the bending moments along the pile do not exceed the yielding moment of the pile section, M_y. Otherwise, it is assumed that a plastic hinge will form at a given section and that only the soil located above it will react to lateral loading.

With reference to the short-pile failure case, it is worth highlighting that Cecconi et al. (2019), in keeping with Broms' solution for purely frictional materials, derived the soil resistance assuming a rotation point at the pile base. Consequently, they considered a force, F, acting at the base of the pile, as representing, in a simple way, the soil resistance developed over the back of the pile below the rotation point.

2.2 *Revised Broms' theory*

Following the Broms' theory extension proposed by Cecconi et al. (2019), the present paper introduces a methodology aimed at estimating the lateral capacity of piles interacting with weak fractured rocks, whose mechanical response can be assumed to be (i) fully drained and (ii) dominated by post-peak properties, as shown by Pedone et al. (2023) for piles driven in chalk.

As observed during the ALPACA field testing campaign, lateral loading of piles driven in chalk caused gap opening next to ground level, suggesting that the critical pile-chalk interaction takes place in the passively loaded areas. Based on this assumption, Equation (5) can be rearranged to provide, in combination with Equation (6), the following revised soil resistance expression:

$$p_{lim}/d = 3.35 \cdot \gamma z \cdot K_p + 3.35 \cdot 2c' \cdot \sqrt{K_p} \qquad (8)$$

The present study targets cases, such as monopiles supporting offshore wind turbines, where free-head pile failure mechanisms apply, as shown in Figure 2. However, for the short pile failure mechanism, the proposed approach does not include any additional force, F, acting at the base of the pile. Instead, it allows for the rotation of the pile to take place at a given section, whose location is assumed to be unknown, as shown in Figure 3.

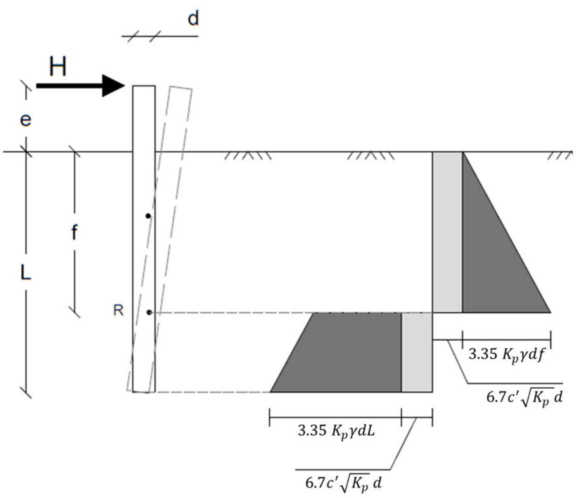

Figure 3. Proposed free-head pile failure mechanism.

3 PRELIMINARY RESULTS

The revised Broms' theory introduced above has been applied in calculations that consider the two ALPACA lateral pile tests described by McAdam et al. (2024) and analysed numerically by Pedone et al. (2023).

Two tubular high-yield stress (X80 grade) steel piles were considered, which had embedded Lengths, L=3.05m, outer Diameters, D=0.508m, pile wall thicknesses, t=20.6mm, load eccentricities, e=0.95m, and yield stresses, σ_y=550MPa. A total unit weight γ=19.5kN/m^3 was considered, together with the (above the water table) pore pressure distribution measured in the field by Vinck et al. (2024) and the post-peak mechanical properties ϕ'=29° and c'=159kPa reported by Pedone et al. (2023).

Based on the soil resistance distributions proposed in Figure 3, horizontal force and bending moment equilibrium equations can be derived, providing an estimate of the ultimate lateral pile capacities and the bending moments acting at different pile sections. Maximum bending moments smaller than the yielding moment of the pile section, M_y=2032kNm, were estimated, indicating that a short pile failure mechanism would apply. This was confirmed by the field tests and predicted through the 3D FE analyses of Pedone et al. (2023). A rotation point close to 2/3 of the embedded length is inferred through the revised Broms' theory introduced here, similar to that found by means of 3D FE analyses (Pedone et al., 2023).

The soil resistance distribution shown in Figure 3 gives rise to an ultimate lateral pile capacity, H_{lim}=1020kN, which is encouragingly close to that observed in the field, as illustrated in Figure 4, where the in-situ measured lateral pile capacities are plotted against ground level displacements. The results of a 3D FE analysis conducted by Pedone et al. (2023) with a perfectly-plastic Mohr-Coulomb model employing the same post-peak strength properties herein adopted (i.e. ϕ'=29° and c'=159kPa) are also shown.

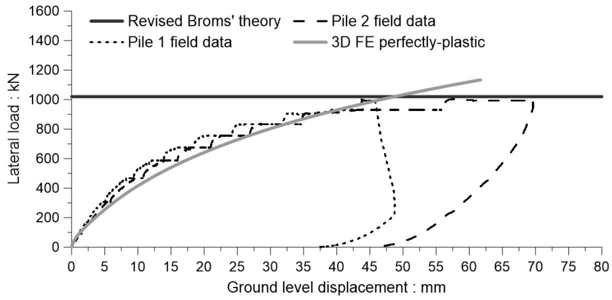

Figure 4. Experimental and numerical load-displacement curves (Pedone et al., 2023) compared with the lateral pile capacity estimate.

Figure 5 shows the experimental field and numerically predicted bending moments against the corresponding rotations at ground level, along with the ultimate bending moment at ground level obtained with the proposed analytical solution, showing excellent agreement.

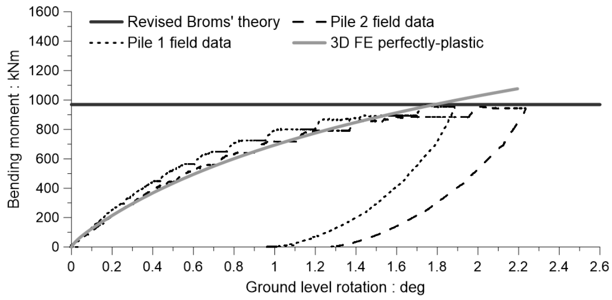

Figure 5. Experimental and numerical moment-rotation curves (Pedone et al., 2023) compared with the lateral pile capacity estimate.

4 CONCLUSIONS

The present paper introduces an analytical solution, developed from the theory proposed by Broms, that considers the ultimate capacity of laterally loaded piles driven in soft brittle rocks such as chalk. The approach accounts for the gaps that open on the active side of piles under lateral loading and generates profiles of the ultimate soil reactions mobilised at the soil-pile interface.

The approach has been demonstrated by comparing its results with experimental data obtained from two ALPACA field tests and more sophisticated 3D FE analyses, delivering good predictions of the ultimate capacities, failure mechanisms, rotation point depths and pile bending moments. These results encourage further examination of the proposed approach's ability to match cases involving long pile failure mechanisms, piles driven in other weak rocks, and layered profiles of soils and rocks.

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