

Pile driving installation effects in low-to-medium density chalk

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This paper explores the effects of pile driving installation on low-to-medium density chalk. The damage developed around eight open and closed, steel and concrete, piles driven at the St Nicholas at Wade test site in Kent, UK, was investigated by carefully logging and micro-sampling chalk from around their shafts after long ageing in situ. The observations identified relatively thin annuli of de-structured ‘putty’ chalk left around the pile shafts. Related numerical studies have confirmed that, after re-consolidation in situ, the Zone A material largely controls the piles’ axial load–displacement behaviour. Measurements of the reduced Zone A water content profiles around piles with different geometries, scales and materials confirm that their thicknesses scale primarily with pile wall thickness t_w . A second, more extensive, annular Zone B was also identified, which manifests far more frequent fracturing than the natural chalk. Earlier numerical analyses have shown that its degraded properties largely control the piles’ lateral loading responses. The Zone B annular thicknesses, and degrees of damage within them, depend on both pile diameter D and t_w . These observations are crucial to both modelling piles driven in chalk and any lateral loading design calculations.

KEYWORDS: installation effects; site investigation; chalk; pile testing; piles and piling; piling and pile testing

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NOTATION

b	side length of square concrete pile
c_h	coefficient of radial consolidation
D	pile diameter
D^*	open-ended pile effective diameter
D_{50}	particle size for which 50% of the material is finer by mass
L_p	length of pile penetration in chalk after driving
N_{blows}	number of hammer blows required to install the pile
q_t	corrected cone resistance
R	radius of closed-ended pile
R_o	outside radius of open-ended pile
R^*	equivalent radius for open-ended non-circular piles
r	radial distance from the pile axis
S_r	degree of saturation
s_u	undrained shear strength
t_w	pile wall thickness
V	normalised velocity
v	velocity of pile
τ_{rzf}	local shear stress

INTRODUCTION

Percussive driving damages the fabric of soft rocks. Lord *et al.* (2002) reported that weak ‘putty’ annuli form around piles driven in low-to-medium density chalk, leaving

remarkably low shaft resistances. Lovera (2019) noted that de-structuration around 0.76 and 1.2 m diameter open steel piles driven in weak calcarenite led to annular crushed rock zones of similar thickness to the pile walls, and systems of vertical fissures that radiated out by several pile diameters into the rock. Muir Wood *et al.* (2015) report how piles and steel plates driven in low-to-medium density chalk developed putty over their surfaces and considered how such de-structuration might affect pile lateral loading behaviour.

Observations by Buckley *et al.* (2018) around two 139 mm OD open-steel piles driven at St Nicholas at Wade (SNW) in NE Kent, UK, noted post-driving shear strengths $s_u < 5$ kPa in annular putty regions, which they termed Zone A. This chalk subsequently re-hardened in situ. Buckley *et al.* (2018) also noted a second annular region they termed Zone B, which had a far higher frequency of fracturing and, therefore, reduced mass stiffness and shear strength (Clayton *et al.*, 2002; Jardine, 2023). Analyses by Jardine *et al.* (2024) and Wen *et al.* (2023) showed that Zone A dominates the piles’ non-linear behaviour under axial loading, while Pedone *et al.* (2023) and Kontoe *et al.* (2025) showed that Zone B has a similarly important influence on the lateral response. The outer undisturbed (Zone C) chalk has far less influence under working conditions. Characterising the extent and nature of the chalk in Zones A and B is essential to test interpretation, representative pile analysis and practical design.

The question of how to scale up to field conditions is important when considering, for example, 10 m diameter offshore wind-turbine monopiles. Buckley *et al.* (2018) hypothesised that the Zone A and B widths depended principally on pile wall thickness. Large displacement ‘GPFEM’ analyses of pile installation in structured weak rocks by Previtali *et al.* (2023) provide numerical predictions of the patterns of de-structuration and partial damage around driven piles. However, reliable field data is crucial to testing these assumptions and predictions.

This paper addresses the question experimentally, considering eight steel and reinforced concrete piles, of various scales, driven at SNW. The study followed the ALPACA

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and ALPACA Plus JIP research programmes (Jardine *et al.*, 2024; Buckley *et al.*, 2024) and benefitted from their combined inventory of 41 pre-installed piles supported by intensive site characterisation (Vinck *et al.*, 2024) and related numerical analyses. The fully aged piles considered covered a wide range of scales and geometries and concentrated on those that had not experienced any prior lateral loading. The new dataset allows hypotheses to be tested and conclusions drawn for application in more representative modelling and design studies.

FIELD INVESTIGATIONS

Vinck *et al.* (2024) describe the investigations for the ALPACA JIPs by intensive in situ testing, wireline rotary coring, block sampling and comprehensive laboratory testing. The natural chalk has CIRIA Grade B3/B2 (Lord *et al.*, 2002) and the water table depth is $\approx 5.5\text{--}6\text{ m}$. Water contents are $29.5 \pm 2\%$ over the $0.75\text{--}3\text{ m}$ depth range of interest, where the average liquidity index is 0.91, dry densities are $1.43\text{--}1.53\text{ Mg/m}^3$ while mean unconfined compressive strength, triaxial s_u and CPTu q_t values are 4.1 ± 0.2 , 1.34 ± 0.35 and $13.3 \pm 4.5\text{ MPa}$, respectively.

The piles considered are summarised in Tables 1 and 2 and encompass a broad range of diameters and hammer types, with driving energies and rates detailed by Jardine *et al.* (2024) and Buckley *et al.* (2018). The observed damage patterns developed under markedly varied driving conditions, with non-dimensional velocity values $V = v \times D^*/c_h$ ranging from approximately 0.1 to 3.1.

Inspections were made at ages up to 426 days after driving from relatively shallow (maximum 1.8 m depth) approximately 1.5 m wide trenches cut radially out from the piles' axes. Most piles had experienced axial loading, which generated plastic deformation within relatively thin shaft shear zones in Zone A (Jardine *et al.*, 2024). However, we note that similar shear zone fabrics were observed around pile R2, which had not been taken to axial failure prior to exhumation. This supports the interpretation that the dominant shearing and de-structuration occurred during installation, rather than as a result of subsequent axial loading to failure. Only piles LD01 and LD09 had experienced lateral loading to failure and are included only to discuss their far more extensive damage regions, which were explored with a $7\text{ m} \times 10\text{ m}$ pit excavated to 4 m. As mechanical excavation increased the frequency of open fractures (Vinck, 2021), the inspection pit faces were carefully hand-trimmed before sampling and logging. Field checks confirmed that the fully de-structured (Zone A) 'putty' chalk hardened to give s_u greater than the deployed hand penetrometer's 250 kPa upper limit. Over 300 water content determinations were made immediately on site from small samples taken with sharp knives at a range of radial distances, r , from the pile axes along radial and vertical scanlines. Careful discontinuity logging was also undertaken around three open-ended piles.

WATER CONTENT PROFILES IN ZONE A

The variations of water content with radial distance from the pile axes are shown in Figs. 1(a)–1(d). The first combines Buckley *et al.*'s (2018) data from two 139 mm OD open steel piles, with equivalent measurements from a similar ALPACA pile (SD12). The new results confirm marked reductions within the de-structured Zone A annuli which extended out radially from each pile's shaft by 8–10 mm, matching the piles' average wall thickness t_w . The hypothesis that Zone A thicknesses depend on t_w (rather than D) was tested for open-ended piles by

considering the profiles from the 508 mm OD pile TP3 with 12.5 mm wall thickness; two 508 mm OD piles (LD01 and LD09, which had 20.6 mm walls); and Pile R2, which had a 1.22 m diameter and 24.6 mm t_w . Fig. 2 plots, at two scales, their water contents against radial distances normalised by t_w and confirms that Zone A was largely confined (over this depth range) to within an annular width $\approx t_w$. The Zone A water contents' minima range from $\approx 19.6\%$ to 24.9% with a 22.0% average, which matches that achieved after oedometer compression of putty to $\approx 20\text{ MPa}$ (Vinck, 2021). Despite the high near-shaft s_u and low water contents, the local shaft resistances τ_{zsf} mobilised over the sampling depths of the shafts all fell below 60 kPa under axial loading to failure (Jardine *et al.*, 2024). Interestingly, the lateral loading imposed on LD 01 and 09 had little effect on their Zone A thicknesses or water content profiles.

The strains imposed close to pile tips during installation are sufficiently large to fully de-structure the chalk left on the shaft out to $\approx t_w$, irrespective of the total number (from <100 to >2000) of blows applied to drive the various piles to depth. It is interesting to note that thicknesses recorded by Lovera (2019) of the crushed rock annuli formed around open steel piles driven in weak calcarenite were similarly comparable to those piles' wall thicknesses.

Table 1 refers to three closed-ended cases: (i) SD07, a closed-ended 139 mm dia. steel pile, (ii) SD19, a 200 mm square reinforced concrete pile, and (iii) SD10, a steel sheet pile. It was postulated that these piles' 'effective wall widths' could be considered as $\approx R = D/2 = 69.5\text{ mm}$ for the cylindrical closed pile and $\approx R^* = 112.8\text{ mm}$ for the square pile where $R^* = [\text{Section area}/\pi]^{0.5}$ and the thickness t (12.2 mm) of the sheet pile, which might resemble a very large diameter open pipe pile wall. The results, normalised by the above 'width' dimensions, are plotted at two scales in Fig. 3, where they are compared with the mean 'open-pile' trend from Fig. 2. While the two closed piles' shafts indicated lower average minimum water contents (of 20.2%) than the open and sheet piles' average minima of 22.0% and 21.2% , respectively, a general trend of extending out to the equivalent 'widths' is clear. Jardine *et al.* (2024) show the closed-ended piles all developed significantly higher average τ_{zsf} values under axial testing than equivalent open piles.

DISCONTINUITY OBSERVATIONS IN ZONE B

The patterns of Zone B chalk fracturing induced by driving and ageing were also recorded around the 508 mm dia. TP3 and 1.22 m diameter R2 piles, adding to Buckley *et al.*'s (2018) observations around piles DP1 and DP7. These piles had significantly different histories of driving under a range of hammers. While R2 required 1220 blows to reach target depth, TP3 experienced 694 blows and DP1/DP7 needed only ≈ 100 blows each. The chalk discontinuities were characterised by measuring spacings at $\approx 0.75\text{ m}$ depth along radial scan lines. Vertical scanlines were also logged 100 mm either side of both piles and at the mid-point between them. Figure 4 summarises the observations and provides photographs of the TP3 and R2 pit faces where the 'natural undisturbed' chalk vertical fissure spacings observed at points far from the piles were $\approx 200\text{ mm}$, and the horizontal fissure spacings were $\approx 80\text{ mm}$. While the sporadic and discontinuous nature of the chalk fracturing makes it hard to define the affected widths precisely, the frequency of sub-vertical fissuring was around four times greater within the Zone B annuli, extending out radially to 300 mm from R2's shaft. On average, the frequency of sub-vertical fissuring doubled within a 200 mm radial distance of TP3's shaft. The

Table 1. Summary of the pile geometry and pile testing history

Pit	Pile	$R, R^* (\dagger \ddagger); \text{m}$	$L_p; \text{m}$	$t_w; \text{mm}$	D/t_w	Pile type	Pile shaft material	Driving date	Test date	Prior loading type	Exhumation date
1	DP1	0.0333	5.5	8.5	16	Open pipe	API 5CT Grade L80/N80	19/10/2015	28/06/2016	Axial monotonic and cyclic	19/07/2016
1	DP7	0.0333	5.5	8.5	16	Open pipe	API 5CT Grade L80/N80	19/10/2015	22/06/2016	Axial monotonic and cyclic	19/07/2016
2	SD12	0.0362	5.35	10.2	14	Open pipe	Drill casing steel	15/05/2018	01/03/2019	Axial tension to failure	05/06/2019
3	TP3	0.0787	18.00	12.5	41	Open pipe	S355 steel	12/10/2020	27/10/2021	Axial tension to failure	07/12/2021
4	LD01	0.100	10.16	20.6	25	Open pipe	X80 steel	22/11/2017	01/08/2018–10/09/2018	Axial and lateral, monotonic and cyclic	5–15/11/2018
4	LD09	0.100	10.16	20.6	25	Open pipe	X80 steel	21/11/2017	04/08/2018–10/09/2018	Axial and lateral, monotonic and cyclic	5–15/11/2018
3	R2	0.1715	18.00	24.6	50	Open pipe	S460 steel	07/10/2020	21/10/2021	Unfailed axial compression	07/12/2021
2	SD07	0.0695	5.40	69.5	N.A.	Closed pipe	Drill casing steel	14/05/2018	26/02/2019	Axial tension to failure	05/06/2019
5	SD19	0.1128	5.40	112.8	N.A.	Solid square	PC concrete	23/10/2018	29/03/2019	Axial tension to failure	05/06/2019
2	SD10	0.058	5.42	12.2	24	Corrugated sheet	S355 steel	14/05/2018	27/02/2019	Axial tension to failure	05/06/2019

Notes: $\dagger R^* = (R^2_{\text{outer}} - R^2_{\text{inner}})^{0.5}$ (for all open-ended piles); $\ddagger R^* = (b^2/\pi)^{0.5}$ (for solid square pile SD19)

Table 2. Summary of pile installation

Pit	Pile	$R, R^* (\dagger \ddagger); \text{m}$	$L_p; \text{m}$	$t_w; \text{mm}$	D/t_w	Pile type	Pile shaft material	Normalised $\bar{V}$	Upper bound $t_{95}; \text{min}$	Hydraulic hammer (ram mass)	N_{blows}
1	DP1	0.0333	5.5	8.5	16	Open pipe	API 5CT Grade L80/N80	0.25–3.07	3.1	Junttan SHK-4 (4 t)	53–119 [§]
1	DP7	0.0333	5.5	8.5	16	Open pipe	API 5CT Grade L80/N80	0.25–3.07	3.1	Junttan SHK-4 (4 t)	53–119 [§]
2	SD12	0.0362	5.35	10.2	14	Open pipe	Drill casing steel	0.52–1.50	3.4	Delmag (1.4 t)	172
3	TP3	0.0787	18.00	12.5	41	Open pipe	S355 steel	0.50	17.2	BSP CX110 (9 t)	694
4	LD01	0.100	10.16	20.6	25	Open pipe	X80 steel	0.79–2.09	27.9	Junttan SHK-4 (4 t)	1041
4	LD09	0.100	10.16	20.6	25	Open pipe	X80 steel	0.79–2.09	27.9	Junttan SHK-4 (4 t)	890
3	R2	0.1715	18.00	24.6	50	Open pipe	S460 steel	1.64–2.48	81.8	BSP CX110 (9 t)	1220
2	SD07	0.0695	5.40	69.5	N.A.	Closed pipe	Drill casing steel	0.36–1.20	13.4	Delmag (1.4 t)	235
5	SD19	0.1128	5.40	112.8	N.A.	Solid square	PC concrete	0.10–0.16	35.5	Delmag (1.4 t)	1703
2	SD10	0.058	5.42	12.2	24	Corrugated sheet	S355 steel	0.24	9.0	Delmag (1.4 t)	982

Notes: $\dagger R^* = (R^2_{\text{outer}} - R^2_{\text{inner}})^{0.5}$ (for all open-ended piles); $\ddagger R^* = (b^2/\pi)^{0.5}$ (for solid square pile SD19); [§]Range for the DP1–DP7 series after Buckley *et al.* (2018)

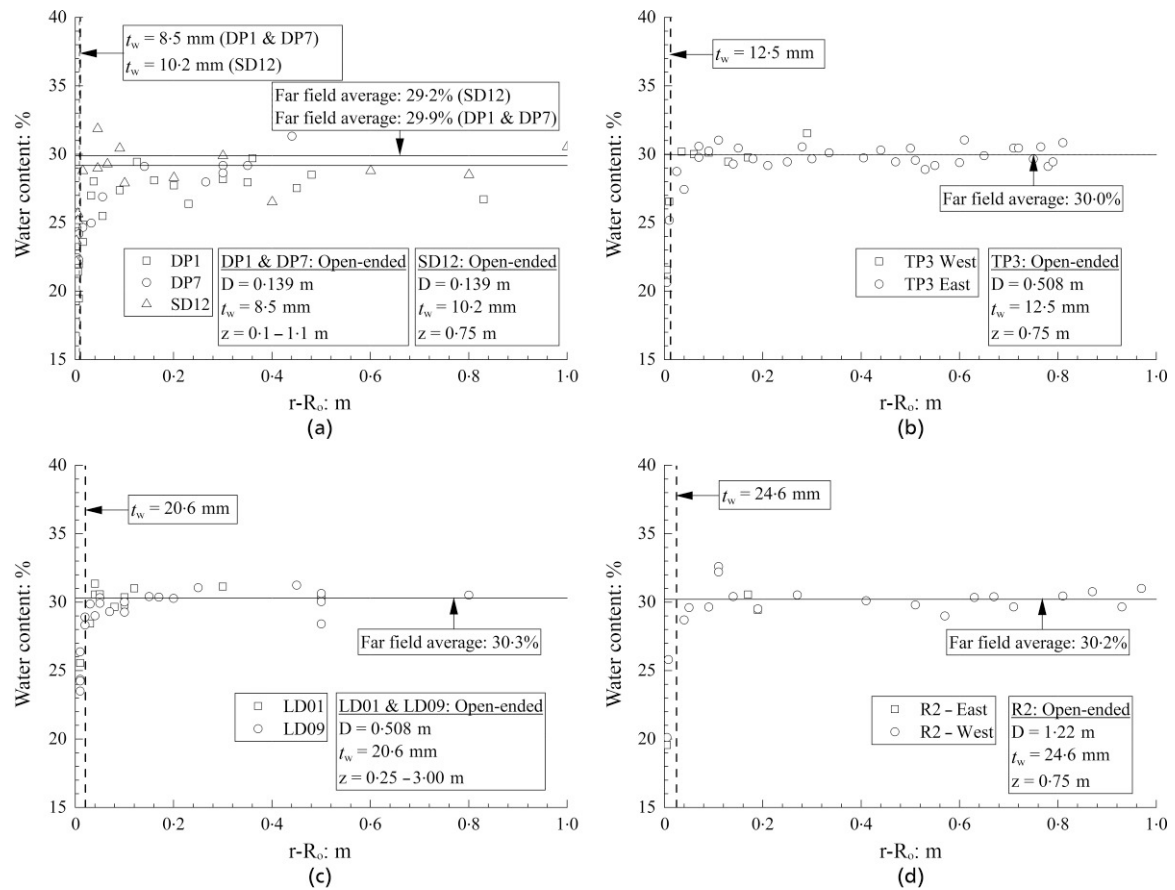


Fig. 1. Water content profiles with radial distance from the pile wall for open-ended piles: (a) DP1, DP7 and SD12, (b) TP3, (c) LD01 and LD09, and (d) R2

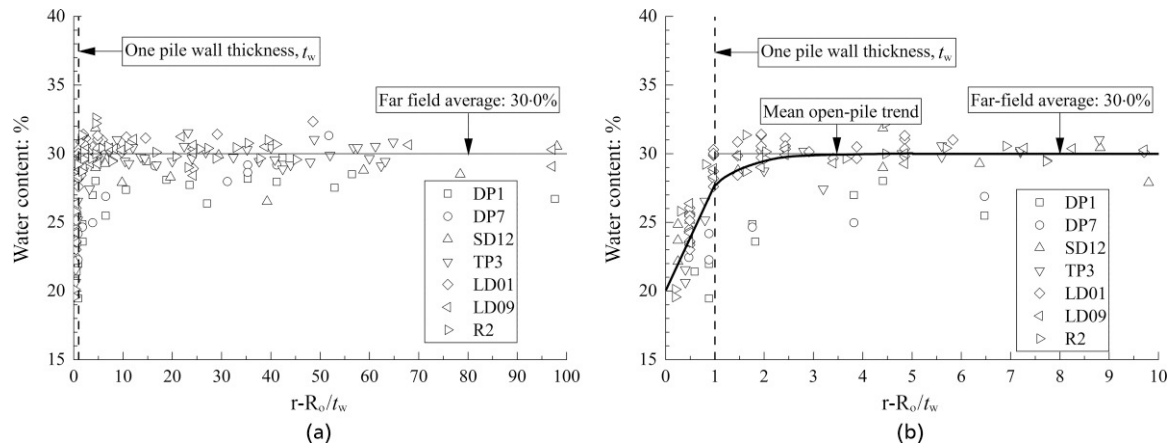


Fig. 2. Water content profiles with radial distance from the pile wall normalised by pile wall thickness for open-ended piles, plotted at two scales: (a) 1–100 and (b) 1–10

vertical scan lines considered at 100 mm radial distances from both piles' vertical shafts showed the frequency of sub-horizontal fracturing similarly doubling within the Zone B volumes and remaining consistent over the 1.25 m depths investigated.

The piles considered had diameters from 0.139 to 1.22 m and wall thicknesses of 8.5–24.6 mm. The radial distances (r_B) from the pile shaft to the outer Zone B regions are plotted against D in Fig. 5(a) and diameter t_w in Fig. 5(b). Recalling the piles' different driving histories, and that the radial widths of the fractured regions cannot be defined to less than half their 20–40 mm fracture spacings, significant scatter appears unavoidable. Both parameters appear

influential with trend lines passing through the respective origins indicating either $r_B \approx 0.27D$ or $r_B \approx 12.4t_w$, with the latter trend showing greater scatter. Considering both variables suggests $r_B \approx 0.14D + 6.2t_w$ for this small dataset, with a mean scatter of $\pm 23\%$.

Figure 6 summarises the key field observations. The new finding that Zone B scales radially with D as well as t_w has important implications for predicting how large diameter-driven piles behave under lateral loading. It is also important to recall that the intensity of fracturing, and therefore chalk stiffness loss, was twice as great within the Zone B region around pile R2 (with 25.4 mm wall thickness) than around TP3, whose t_w was 12.5 mm. The additional

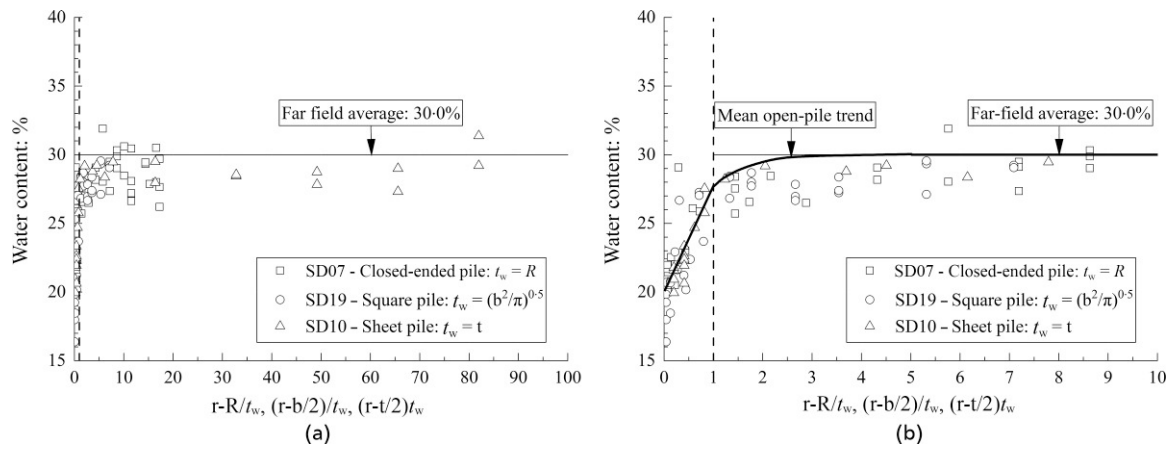


Fig. 3. Water content profiles with radial distance from the pile wall normalised by pile wall thickness for closed-ended piles, plotted at two scales: (a) 1–100 and (b) 1–10

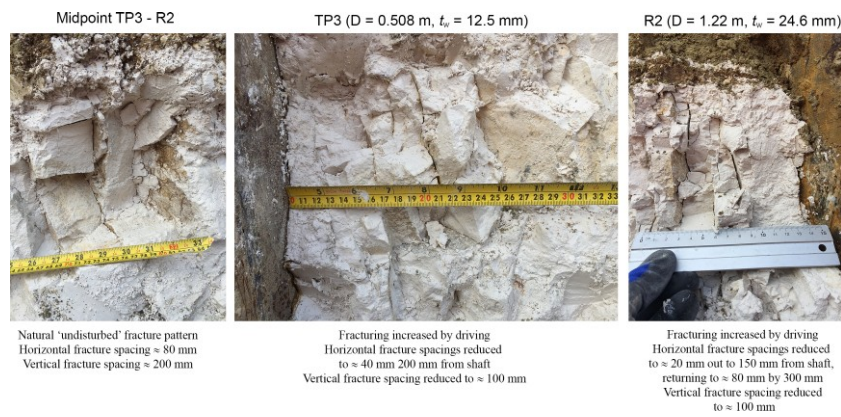


Fig. 4. Chalk discontinuity observations around piles R2 and TP3

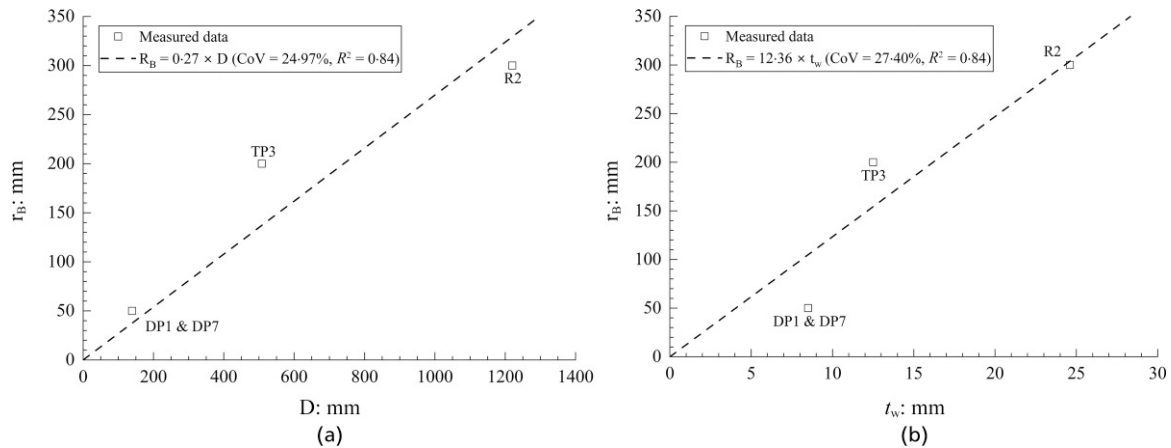


Fig. 5. Correlations of radial distances r_B from the shaft to the outer boundaries of damage Zone B, with (a) outside diameter D and (b) wall thickness t_w , for three open-ended SNW pile configurations

logging of 508 mm dia. open-piles LD01 and 09 identified that their prior lateral loading had led to fracturing extending out $\approx 1.7D$ further in the direction of loading after their eventual (progressive) failures (Vinck, 2021). The observed increase in Zone B extent after monotonic lateral loading indicates that cyclic loading – such as from offshore wind turbine operation – is likely to further degrade the lateral stiffness of chalk. McAdam *et al.* (2025) observed progressive accumulation of permanent displacements and extension of fractured zones during field cyclic lateral loading tests. Similar to findings from the PISA project in other

geomaterials, shaft-adjacent gaps may develop and influence the cyclic response. These mechanisms, which build upon the initial installation-induced fabric changes, highlight the importance of considering long-term evolution of chalk properties in offshore foundation design.

SUMMARY AND CONCLUSIONS

Five main conclusions flow from the study that have important implications when modelling or designing piles driven in low-to-medium density chalk:

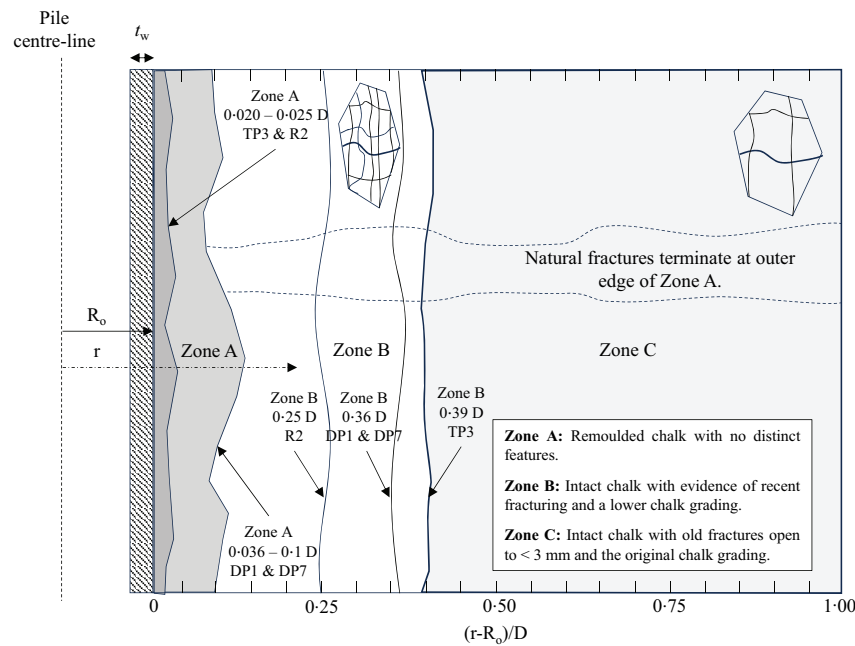


Fig. 6. Schematic diagram of conditions in chalk surrounding 139, 508 and 1220 mm OD open-ended piles, expressed as radial distances normalised by outside diameter D for three open pile configurations (Adapted from Buckley *et al.*, 2018)

1. Impact driving causes considerable damage. Relatively thin annuli of de-structured 'putty' chalk form around the shafts, which, after re-consolidation in situ, leave a relatively low void ratio and strong calcareous silt layer shear zone, which largely controls the piles' subsequent axial load-displacement behaviour. Similar shear zones were found around piles irrespective of whether axial failure had been imposed before excavation, indicating that installation is the dominant cause of their formation.
2. Water content profiles around open-ended piles driven with different geometries, scales and materials confirm that Zone A's annular thicknesses scale primarily with wall thickness t_w . With closed-steel pipe and prefabricated square reinforced concrete-driven piles, the thicknesses are approximately equal to their effective radii, R^* .
3. A second, more extensive, annular damage, Zone B, develops around open piles during driving, where fracturing was two to four times more frequent than in the natural chalk. Zone B extends out to radial distance r_B from the pile shaft of approximately $0.14D + 6.2t_w$ ($\pm 23\%$).
4. The fabric within Zone B leads to degraded properties that largely control the piles' lateral loading responses. There is limited evidence that the frequency of fracturing within Zone B increases with pile wall thicknesses.
5. The extent of the fractured chalk grows in the direction of any significant level of applied lateral loading. It extended out radially by an additional $\approx 1.7D$ after lateral pile failure had been achieved in the ALPACA tests at SNW.

The authors acknowledge that variability in chalk properties could affect the precise dimensions and intensity of damage zones around piles. However, the very soft putty-like behaviour and low-to-medium density chalk encountered at SNW is consistent with descriptions at other sites of comparable CIRIA Grades (Lord *et al.*, 2002; Buckley *et al.*, 2018). While trends such as the scaling of Zone A with wall thickness and the dual influence of pile diameter

and wall thickness on Zone B appear robust across the piles studied, further work is required to assess whether these relationships hold in denser, more structured chalks or at sites with different fracture patterns.

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