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Shaft capacity ageing trends of onshore and offshore piles driven in sand

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ABSTRACT: The enhancement of driven piles' axial capacities over time, or set-up, involves a series of complex processes. This paper considers evidence from onshore and offshore site studies into pile ageing at sand sites, considering the potential for ageing gains to enable more economic pile design for offshore wind turbines and other structures. Results from recent onshore tests at Cuxhaven in Germany are contrasted with earlier onshore studies and tests on large offshore piles collated under the recent PAGE JIP. The paper demonstrates that ageing can vary markedly with pile scale, slenderness ratio and geochemical conditions and explores potential geotechnical explanations for the range of behaviours observed. The conclusions drawn have implications for ensuring reliable axial pile design in a range of onshore and offshore environments.

Keywords: Driven piles, capacity, ageing, sand

1 INTRODUCTION

Predicting axial capacity reliably is central to ensuring safe and economical offshore pile design. While it is well known that shaft capacities grow with time after driving in sand (Chow et al., 1998, Jardine et al., 2006, Gavin et al., 2015, Bittar and Lehane 2024) design guidance does not yet cover ages greater than the ≈25-day mean applying to the ICP-05 (Jardine et al., 2005) or ≈14-day median age of the Unified (Lehane et al., 2020) methods' databases. Furthermore, such databases are dominated by relatively small piles driven with onshore equipment at freshwater sites and include only one test set on open steel piles with outside diameters D > 0.81m.

While static offshore testing is only feasible under exceptional circumstances, key insights into offshore pile ageing have been gained from cases where dynamic pile strains and accelerations were monitored during driving and later re-strike tests. Signal matching analyses can then provide end-of-drive (EoD) and beginning-of-restrike (BoR) soil resistance profiles that can be compared with design capacities; Overy (2007) and Jardine (2015). Cathie et al., (2022), (2023) report the Pile Ageing (PAGE) Joint Industry Project (JIP) which examined paired stress-wave analyses of EoD and BoR blows applied, after ageing, in high-quality tests conducted at well-characterised offshore sites on 25 large piles. These were complemented by re-analyses of tests on open-ended steel piles at onshore sites that facilitated comparisons between dynamic and static testing. The offshore piles' (with a mean diameter D of 2.8m) dynamically measured shaft capacities grew after driving to give set-up factors that reached a plateau of ≈2 within a month of driving, while the onshore piles (with a mean D of 0.81m) showed set-up continuing to grow over a year, or more. Jardine (2023) considered the potential physical processes that contributed to such set-up and reviewed the evidence regarding the contributions of:

- Local radial shaft stresses σ'_{rc} rising through a weakening of the circumferential arching that forms around pile shafts during driving.
- Corrosion reactions raising local radial shaft effective stresses σ'_{rc} in tandem with increases in shaft centreline roughnesses R_{CLA} and interface shear angles δ.
- Enhanced interface dilation and possibly gains in sand shear stiffness G boosting the $\Delta\sigma'_{\underline{rd}}$ increments in σ'_r developed during loading.

Jardine (2023) reviewed recent advanced FEM and DEM analyses of pile installation effects, as well

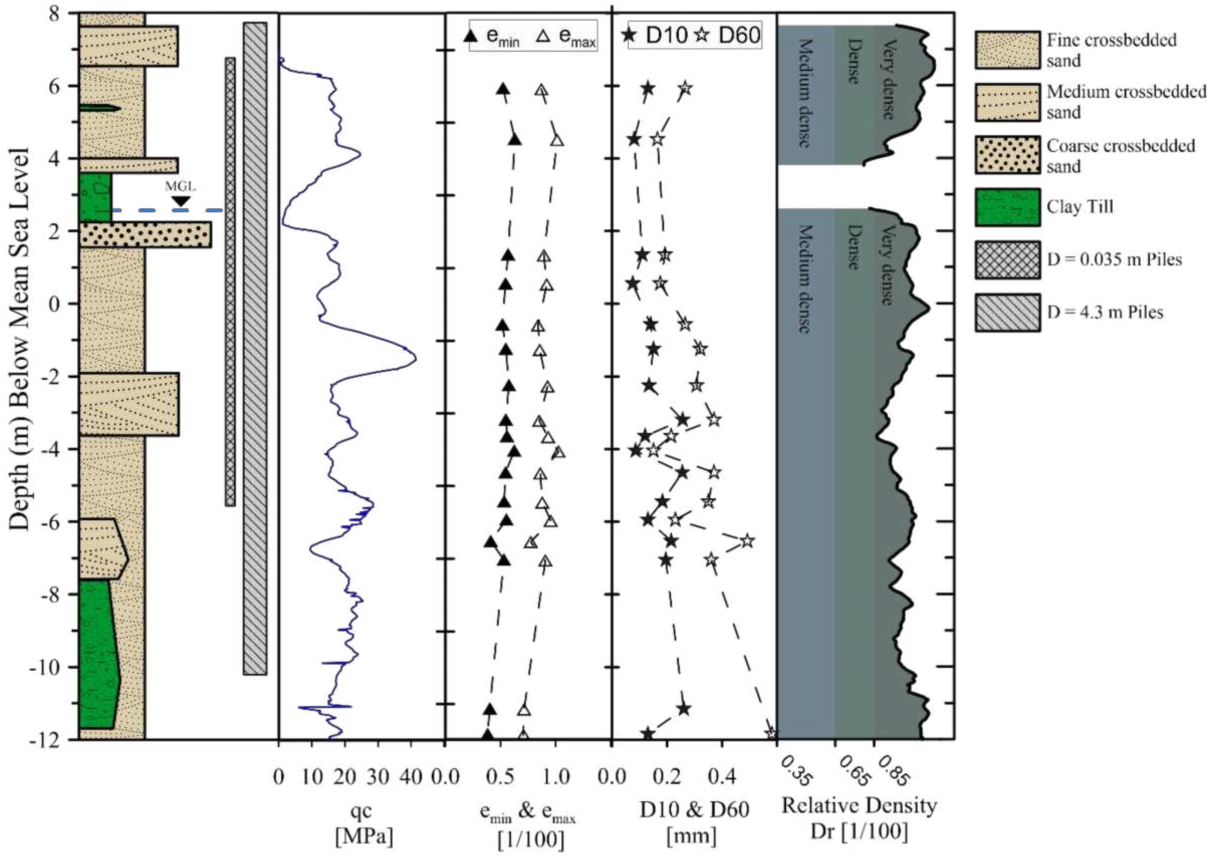

Figure 1: Cuxhaven Soil Profile. MGL: Mean Groundwater Level

as model and field pile tests including experiments by Carroll et al., (2020) on tens of 50 to 60 mm diameter, mild-steel and stainless/galvanised steel, open-ended, micro-piles driven at three sand sites. The finding that small diameter stainless-steel micro-piles showed negligible tension capacity gains after driving, while most mild steel micro-piles showed significant set-up underscored the importance of corrosion. Corrosion products gradually encrust the crushed sand zones found around mild steel piles (see Chow 1997, Osaki 1982, Kolk et al. 2005 or Yang et al., 2010). Jardine (2023) reconciled the disparate trends given by a range of field tests by invoking to a diameter-dependent interface dilation mechanism and identifying cavity expansion limits which, for the range of L/D values considered, capped the aged shaft capacities of piles with D < 0.5m to multiples of ≈ 2 to 3 times the ICP-05 shaft capacities.

Busch et al. (2022) report further pile ageing studies conducted at Cuxhaven, near the North German coast for which Figure 1 summarises the typical ground conditions. Noting the range of processes summarised in Figure 2, the programme included dynamic tests on 3 large (D = 4.3 m, L_{emb} = 18.5–19.1 m) open-ended monopiles with L/D ≈ 4.4 and multiple, static tension tests on 44 small (D = 0.035 m, L_{emb} = 12.1 m) closed-ended mild and stainless steel micro-piles with L/D ratios (≈ 346) that are far higher than are usually adopted offshore. The small piles were subjected to tension testing immediately after driving, and then only once again after specified ageing periods. This paper extends the interpretation of the Cuxhaven piles' shaft capacity trends, as measured at ages up to 1000 days after driving. It explores the test results within the 'PAGE' JIP's interpretative framework to offer new insights into the piles' ageing behaviour and considers a far wider range of outside diameters and L/D ratios than earlier published studies.

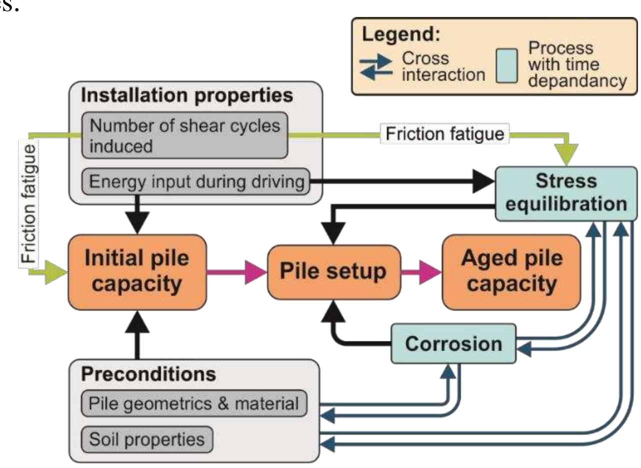

Figure 2: A summary of the processes that lead to pile ageing; after Busch (2022)

2 SHAFT CAPACITY AGEING TRENDS

Busch (2022) gives a full description of the Cuxhaven site conditions, as well as pile and laboratory testing programmes. The water table fluctuates seasonally between 4 and 6.5 m below the ground surface. The site, composed primarily of dense sand with occasional layers of glacial clay tills, is known to replicate conditions typical of the German North Sea. These and other geotechnical laboratory tests enabled case-specific ICP-05 (Jardine et al 2005) and Unified (Lehane et al 2017) sand shaft capacity calculations that are employed below to help interpret the tests. These CPT methods incorporate similar interface dilation terms that vary inversely with pile diameter and become systematically more important as pile L/D ratios grow. The methods default settings lead to interface dilation making up ≈ 67 to 82% of the shaft capacities predicted at medium-term ages for the 35mm diameter (L/D = 346) Cuxhaven piles, but offering less than 1% of the shaft capacities expected for the relatively short (L/D = 4.3) 4.3m diameter monopiles.

The shaft capacities reported by Busch et al (2022) are reassessed below following the PAGE (Cathie et al. 2022, 2023) framework, which allows comparison with the latter JIP‘s onshore and offshore tests. Hyperbolic tangent functions (see Equation 1) are employed to fit the shaft capacity ageing trends with pile age t (in days) after the end of driving (EoD).

$$y = A + B \times \tanh\left(C \times (t - 3)\right) \quad (1)$$

$$Setup = \frac{R_s(t)}{R_{s\,initial}} \quad (2)$$

Parameter A defines the y-axis value at t=3, while B sets the maximum increase of the y-value at t >> 3 and C controls the slope of the function at t=3. Figure 3 presents the trends for set-up (as defined in Equation 2) with pile age, while Figures 4 and 5 consider shaft capacity as multiples of estimates made with the ICP-05 and Unified approaches. To keep compatibility with PAGE, the clay layers' contributions were estimated for both cases by applying the UWA-13 CPT based approach. The fitting parameters found by least squares fitting for the mild-steel PAGE and Cuxhaven piles are listed in Table 1. Parameters were chosen by eye to fit the stainless-steel piles far more gently varying set-up curves. The 80% confidence intervals calculated for the PAGE cases are also plotted in Figures 3 to 5.

3 DISCUSSION

Considering the set-up data plotted in Figure 3, the very high L/D mild steel 35mm Cuxhaven piles showed modest (around 20%) shaft capacity gains over the first two weeks before developing more marked long-term set-up factors (2.8 to 3.6) over the following three months that exceeded those seen with larger diameter piles in both the onshore and offshore PAGE datasets. The equivalent stainless steel Cuxhaven piles showed no measurable tension capacity gains over the first two weeks and a modest mean set-up factor of ≈ 1.2 after 100 days. These features attest to long-term corrosion being very active around the mild steel piles, whose upper shaft lengths are positioned above the water table, while some other process, such as creep, led to the modest gains shown by the stainless-steel piles.

The mild steel, 4.3m D, Cuxhaven monopiles showed intermediate trends with set-up ratios of ≈1.35 during their first restrikes after around 2 weeks, which fall below the PAGE trends for both industrial-scale onshore piles (D=0.46m-2.0m) and larger offshore piles. Second re-strikes applied at 1000 day ages, after the three monopiles had also experienced lateral loading tests at ages of 60 to 90 days, suggested higher set-up factors of 2.6 to 3.3, which plot around the mean PAGE onshore pile trend line. While intermediate re-strike tests involving limited permanent displacements may not always affect the outcomes of later re-strikes (Shonberg et al 2023), the 4.3m D piles' 1000 day capacities were probably influenced by their prior lateral loading to failure. Such tests induce high radial stress gains in the passive regions developed near the rotating piles' heads and toes, along with reductions in the corresponding active regions.

Moving to consider the Cuxhaven piles' shaft 'End of Driving' (EoD) resistances, normalised by ICP-05 'medium-term' predictions, the EoD results for the 35mm diameter piles presented in Figure 4, amount to 0.3 to 0.4 of the predicted medium-term capacity values. Set-up leads to the mild steel piles only reaching or surpassing their ICP-05 capacities after ≈100 days, rather the 25-day period at which this was achieved, on average, in the ICP-05 database of first-time static tests on driven piles. The mild-steel piles' longer term shaft capacity trends were not recorded but appear likely to have grown as corrosion continued until, perhaps, they met the upper limits associated with the cavity expansion limit mechanism postulated by Jardine (2003) based on dozens of field micro-pile tests, supported by advanced PFEM numerical analyses that accounted for pile installation effects.

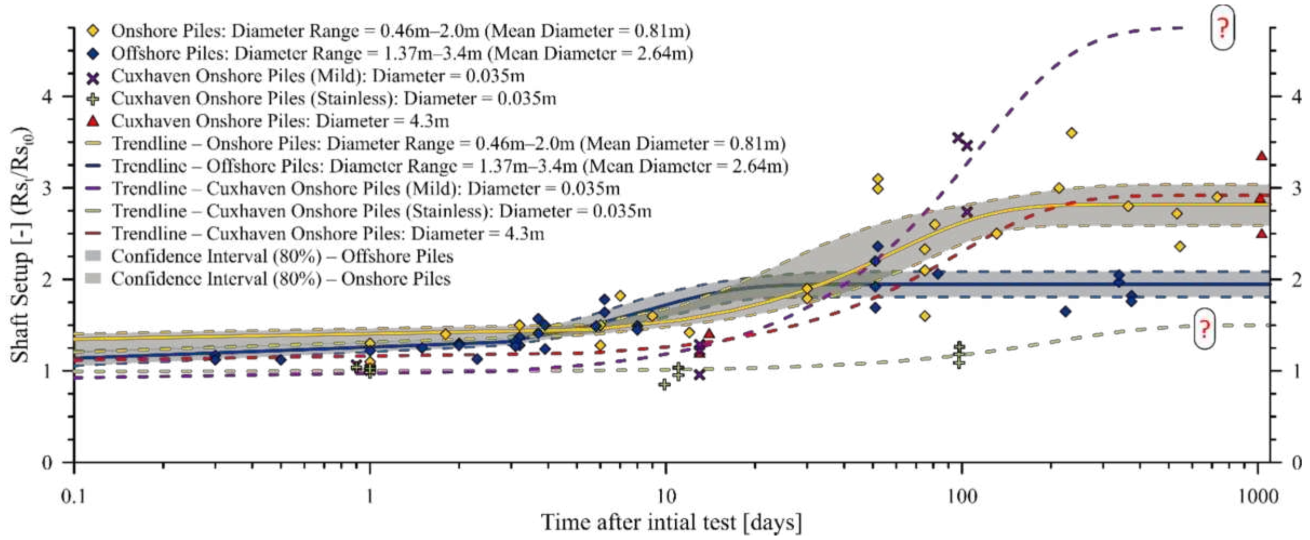

Figure 3: Pile Shaft Setup with Fitted Trend Lines

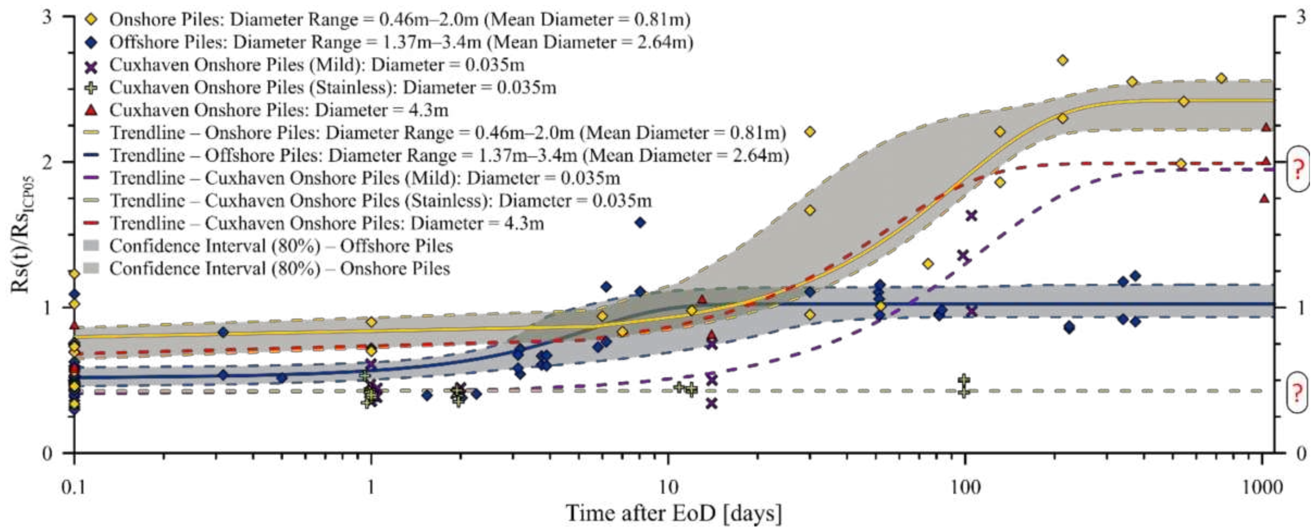

Figure 4: ICP05 normalized Shaft Capacities

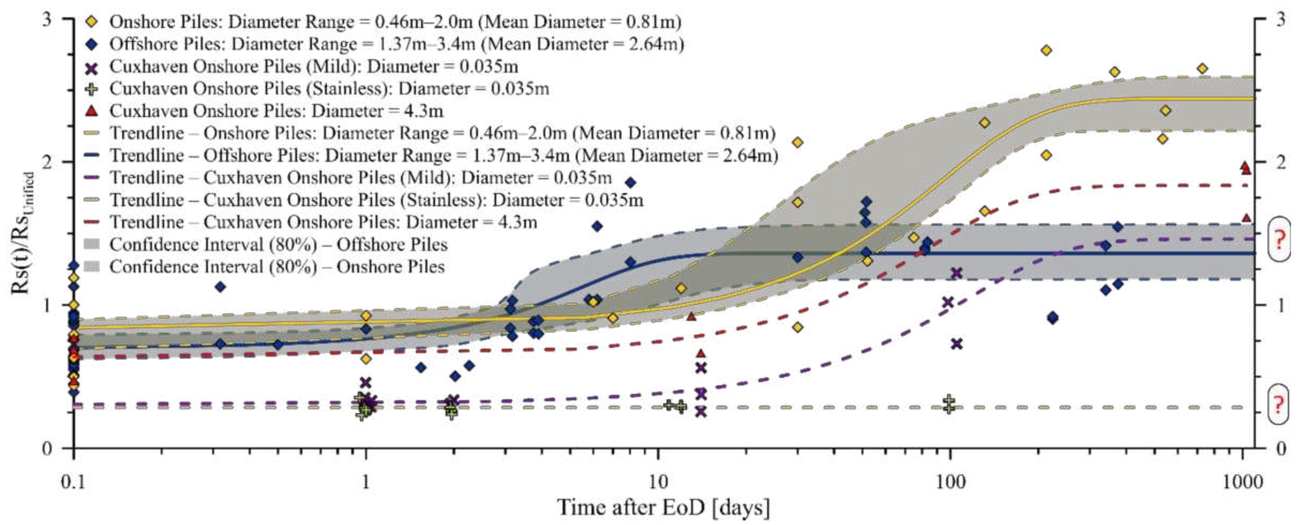

Figure 5: Unified normalized Shaft Capacities

Table 1: Fitted ageing hyperbolic set-up function parameters. R2 = coefficient of determination

	Pile category	A	B	C	R2
Shaft resistance setup	0.46m-2.0m D Onshore Piles	1.402	1.416	0.013	0.85
	1.37m-3.4m D Offshore Piles	1.326	0.62	0.108	0.89
	4.3m D Cuxhaven Piles	1.159	1.759	0.008	0.89
	0.035m D Cuxhaven mild steel Piles	1.002	3.737	0.007	0.97
	0.035m D Cuxhaven stainless steel Piles	1 (fixed)	0.5 (fixed)	0.004	0.79
ICP05 normal-ised setup	0.46m-2.0m D Onshore Piles	0.835	1.588	0.008	0.79
	1.37m-3.4m D Offshore Piles	0.702	0.329	0.232	0.76
	4.3m D Cuxhaven Piles	0.734	1.256	0.014	0.93
	0.035m D Cuxhaven mild steel Piles	0.438	1.51	0.007	0.84
	0.035m D Cuxhaven stainless steel Piles	0.427	0.0	0.0	
Unified normal-ised setup	0.46m-2.0m D Onshore Piles	0.879	1.562	0.0082	0.80
	1.37m-3.4m D Offshore Piles	0.927	0.434	0.197	0.62
	4.3m D Cuxhaven Piles	0.668	1.166	0.009	0.93
	0.035m D Cuxhaven mild steel Piles	0.328	1.323	0.007	0.84
	0.035m D Cuxhaven stainless steel Piles	0.285	0.0	0.0	

The most likely cause of the 35mm piles' ICP-05 shaft capacity over-estimation is likely to be found in the interface dilation terms, which as noted earlier dominated the predictions for these small D, very high L/D piles. The nominal 20μm radial dilation expected by the method implies a relatively large cavity strain $\varepsilon_c \approx 0.11\%$ for these small piles. At this strain level, the average 'pressuremeter' shear stiffness mobilized in the surrounding non-linear sand mass is likely to be far less than the G_{max} assumed in the ICP-05 calculations, where it is related to CPT resistance q_t. A potentially credible ≈2/3 reduction in G is required to match the medium-term (25 day age) mild-steel field results; a more significant reduction is required to match the medium term capacities of the uncorroded stainless steel piles.

Moving to consider the 4.3m diameter Cuxhaven monopiles, their EoD shaft capacities were around 0.75 of the ICP predictions, a higher ratio than the 0.5 average found for the PAGE offshore piles. The monopiles were able to mobilise average dynamic shaft capacities approaching the ICP-05 predictions after about two-weeks of ageing, as expected from the ICP-05 database and the PAGE onshore and offshore tests. Jardine (2023) concluded that such early ageing was due to a short-term creep mechanism applying before corrosion becomes the dominant long-term set-up process. The 4.3m D Cuxhaven piles showed long-term (1000 day age) re-strike shaft resistances of between 1.75 and 2.25 times the ICP-05 predictions, falling below the PAGE mean trend for 0.46m-2.0m diameter onshore piles, but far above the PAGE offshore pile mean trend. Taking the results at face value suggests more marked set-up occurs around large diameter piles at onshore rather than offshore sites. This might be explained by corrosion reactions being slower under relatively cold and anoxic, although saline, offshore conditions; Jardine (2023). As noted earlier, the large piles' long-term shaft capacities are likely to have been affected by their prior lateral testing. However, it is reassuring that the lateral loading did not appear to reduce shaft capacity.

The corresponding Unified method plots in Figure 5, show broadly similar trends to Figure 4. The main differences are: (i) the Unified method trends show less dispersion between the 35mm (L/D = 346) and 4.3m (L/D = 4.3) Cuxhaven cases and (ii) the Unified method shaft capacity predictions are lower (by around 18 and 13% respectively) than those from ICP-05. Scarfone et al (2023) explore the potential sources of dispersion between the two methods noting from Cathie et al (2023) that the Unified method led to capacity predictions around 25% lower than ICP-05 for the PAGE offshore pile dataset, which had a mean D of 2.8m and L/D of ≈16.

4 CONCLUSIONS

Five main conclusions flow from the axial shaft capacity ageing trends of the piles driven at Cuxhaven:

1. Shaft capacity growth through ageing varies strongly with pile shaft material, diameter, L/D ratio and, probably, geochemical conditions.
2. Corrosion was the main cause of the marked set-up of the 35mm diameter mild-steel Cuxhaven piles.
3. The initial set-up trends of the 4.3m D Cuxhaven monopiles were slower and more compatible with those shown by the PAGE (onshore and offshore), ICP-05 and Unified databases.
4. The 1000-day Cuxhaven re-strikes on 4.3m diameter piles indicated more marked set-up, and larger

multiples of the ICP-05 or Unified method predicted capacities, than the PAGE offshore piles. While this may reflect the different geochemical conditions applying onshore and offshore, the monopiles' long-term capacities may have also been affected by their complex loading histories.

5. Overall, it appears unwise to assume that ageing trends established from relatively small onshore piles apply equally to large diameter offshore piles.

AUTHOR CONTRIBUTION STATEMENT

A. Busch: Conceptualization; Investigation; Analysis; Methodology; Visualization; Writing. **R. Jardine**: Conceptualization; Investigation; Analysis; Methodology; Writing. **R. Silvano**: Data curation; Investigation; Methodology; Validation;

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