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FIELD STUDIES ON THE AXIAL CAPACITY OF SMALL DIAMETER PILES AND AGEING EFFECTS IN SANDS

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Abstract

Comprehensive series' of field pull-out tests have been carried out on small diameter (48 to 60mm outside diameter (OD)) open-ended steel driven piles at Larvik in Norway, Dunkirk in France and Blessington in Ireland to investigate the processes that affect the ageing of axially loaded piles in sand. This paper reports new investigations of the sites' geotechnical profiles and tension tests on corroded mild steel (MS) piles conducted up to 315 days after driving. The potential influences of: (i) pile diameter, (ii) ground water, (iii) steel type and (iv) installation method are assessed and comparisons made with the ageing responses established in earlier tension tests on larger diameter industrial scale steel driven pipe piles. Steel corrosion and bonding of soil particles are shown to be particularly important with the small diameter piles; the driving process is shown to be significant.

1. Introduction

The shaft capacities of industrial piles driven in sand increase over the weeks and months that follow installation; see Tavenas and Audy (1972), Astedt et al. (1992), Chow et al. (1998), Axelsson (2000), Jardine et al. (2006), Gavin et al. (2013), Karlsrud et al. (2014), Lim and Lehane (2014) or Gavin et al. (2015). Chow et al. (1998) proposed three possible causes:

i) Physiochemical processes around the shaft.
ii) Redistribution of radial effective stresses in the sand around the pile shafts
iii) Enhanced dilation at the sand-shaft interface under axial loading

Jardine et al. (2006) showed that the systematic ageing trends seen in 1st time tests on 'virgin' piles cannot be captured by testing single piles on multiple occasions. Gavin et al. (2013) attributed the ageing seen in their 1st time tests at Blessington (Ireland) to a combination of mechanisms i) to iii), including increased shaft roughness through bonding of sand particles. Jardine and Standing (2012) reported field tests (and Tsuha et al. (2012) reported calibration chamber experiments) in which low level cyclic axial loading also led to mild shaft capacity gains, while losses developed rapidly under high level cycling. Rimoy et al. (2015) related these cyclic phenomena to the re-distribution of radial stresses around the pile shafts and also concluded that (i) hard driving could cause lower initial capacities and greater set-up over time; (ii) ageing is independent of whether groundwater was fresh or salty and (iii) both concrete and steel piles can show marked set-up.

Rimoy et al. (2015) also demonstrated that both jacked and driven 36mm diameter stainless steel piles showed little shaft capacity growth over time in calibration chamber experiments. Noting the discrepancy with field behaviour, they concluded that ageing must depend on pile diameter and/or steel type. Lim and Lehane (2014) found similar trends with field tests on jacked model piles and remarked on possible installation effects: their jacked piles developed considerably less 'friction fatigue' and set-up than piles driven earlier at the same field location by Schneider (2007).

The crust of fractured sand noted by Yang et al. (2010) as forming around displacement piles installed in sands with CPT cone resistance (q_c) > 7 MPa offers a potential explanation as to why ageing trends might depend on pile diameter (D), Rimoy et al. (2015) noted that the crust thickness (t_{crust}) is independent of

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D and could become cemented by iron compounds in the field. They argue that higher t_{crust}/D ratios apply to small diameter piles that inevitably reduce shaft radial stress redistribution and so shaft capacity growth greatly over time.

Rimoy et al. (2015) also recognised that the interface dilation related component of shaft capacity (demonstrated in field tests by Lehane et al. (1993)) could become significantly more dominant for small diameter piles. Jardine et al. (2005) argue (after Foray and Boulon (1986)) that this component is directly proportional to pile (centre-line-average) surface roughness (R_{cla}) and sand shear stiffness (G), but is inversely related to D. These features are incorporated into the ICP-05 and UWA-05 design procedures which predict that, if other key parameters (q_c, angle of interface shearing resistance (δ), distance of shaft interface behind the pile tip/pile radius (h/R)), σ'_{vo}, G and R_{cla}) are constant, local shaft shear resistance should increase as D reduces.

Carroll et al. (2017) report new field experiments at Larvik (Norway), Dunkirk (France) and Blessington (Ireland) sand research sites that attempted to resolve the disparate trends of field and model piles outlined above. They investigated the influences on shaft capacity ageing trends of varying (i) pile diameter D, (ii) water table depth, (iii) pile steel type and (iv) installation method. This paper presents a summary of key results from experiments conducted on multiple 48 to 60mm Outside Diameter (OD) steel piles driven to embedded lengths between 1.7 and 2.4m before being subjected to carefully staged 1st time tension tests.

Strong and systematic shaft capacity ageing trends have been proven in earlier studies at the same sites through 1st time tension tests on industrial scale (340 to 504mm OD) mild steel driven pipe piles; see Rimoy et al. (2015). The larger piles, which had similar L/D ratios to the smaller diameter piles, showed the trends illustrated in Figure 1, where the shaft capacities are expressed as ratios of predictions made with the ICP-05 procedure to eliminate the effects of specific site conditions including the ground profiles, CPT traces and pile dimensions. The initial capacities corresponded to ≈0.75 times the 'medium-term' ICP-05 estimates and grew by an average factor of ≈2.7 over 80 days before tending to long term maxima ≈2.4 times the ICP estimates.

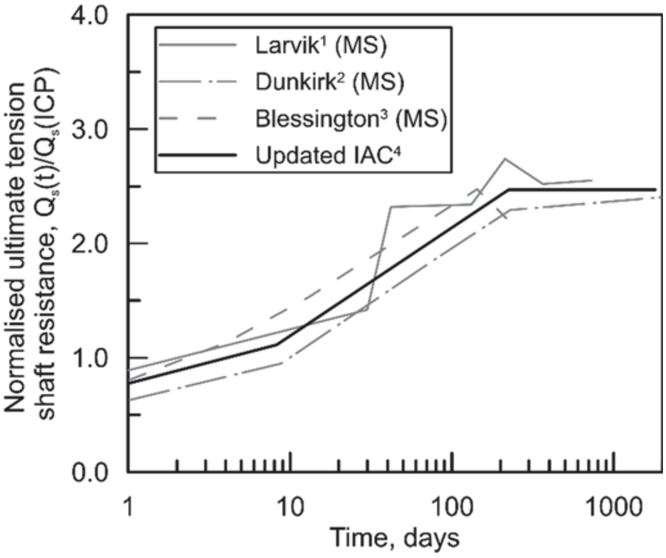

Figure 1: Ageing trends from industrial scale tests at Larvik, Dunkirk and Blessington by Karlsrud et al. (2014), Jardine et al. (2006) and Gavin et al. (2013), after Rimoy et al. (2015). Tension tests normalised by ICP-0 capacities.

Table 1 Properties of piles

		Larvik	Dunkirk	Blessington
R_{cla} roughness	µm	[1]8.5	NA	NA
Steel grade MS corroded	-	E220+CR2-S2	E470	NA
Outer diameter	mm	50	51	60
Wall thickness	mm	2	8	4
Contact length average	m	2.4	1.97	1.75
PLR, corroded pile	-	0.42	0.22	0.36

[1]Untested weathered pile. NA: Not available, PLR: soil plug length inside the pile to pile embedment ratio (plug length ratio).

One key research aim was to isolate the potential roles physiochemical processes play in ageing by testing stainless, galvanised, uncorroded (relatively smooth surface, referred to as 'fresh') mild and corroded (relatively rough corroded, referred to as 'corroded') mild steel piles. Carroll et al. (2017) show that the stainless and galvanised steel piles did not gain capacity over time at any site. They confirm Rimoy et al.'s (2015) conjecture that neither stress redistribution, nor dilation enhancement due to shear stiffness gains in the surrounding soil mass can, on their own, generate significant capacity gains over time with small model piles, regardless of their installation method. However, Carroll et al. (2017) found significant capacity growth over time with their mild steel (MS) 50mm OD piles.

This paper concentrates on reporting only the tests on corroded MS piles, whose characteristics are summarised in Table 1. Shaft roughness affects capacity significantly and measurements on a corroded Larvik pile indicated an R_{cla} value (8.5µm) close to the 10µm value suggested for steel piles by Jardine et al (2005). Qualitative checks indicate similar values for the Blessington and Dunkirk piles.

Table 2 Soil parameters and ground conditions for three site

	Unit	Larvik(1)	Dunkirk	Blessington
Water table BGL	m	2.2	4-4.7	6
Description		loose to medium dense silty sand with some silt layers	dense to very dense sand	dense, medium to fine sand
Unit weight (γ_{bulk})	kN/m^3	15.5	17.1	20(3)
Water content	%	26.5	5-7	10(3)
S_r	%	100*	25-40*	60*
D_{10}	mm	0.37-0.8	0.4	0.6
D_{50}	mm	0.16-0.38	0.26	0.1-0.15(3)
Fines content	%	6-20	0	5-10
Over consolidation ratio (OCR)		Normally consolidated	Normally consolidated	15 at 1m(6), 5 at 5m(6)
q_c average	MPa	2	40	15(7)
f_s average	MPa	0.02	0.15	0.16(7)

[1]NGI (2009), [2]Chow et al. (1998) direct shear box mild steel interface, [3]Gavin and O'Kelly (2007), [4]Tolooiyan and Gavin (2011), [5]Gavin et al. (2013) Bromhead ring shear sand interface, [6]Doherty et al. (2012), [7]Prendergast et al. (2015). *Suggested value as S_r varies with time and depth

2. Description of test sites

Table 2 summarises the soil parameters and ground conditions at the three sites. As described by Karlsrud et al. (2014), the Larvik test site is mostly fluvial and comprises loose to medium dense silty sand, with some silt layers, down to the investigated depth of 22m below ground level (BGL). The uppermost 2m of soil comprises Made Ground and the piles were embedded below the site's 2.2m deep water table. Three cone penetration tests (CPT) were conducted close to the test area in 2006 and a further six from 3.2m to 7m depth in 2016 for this study. Piezocone tests at Larvik show some pore water pressure spikes, however, the pore pressure parameter $B_q < 0.01$ while fines contents is in range of 5 to 20%. The effects on q_c of cleaning the bases of the cased initial CPT boreholes were assessed through comparison of the traces for CPT-3, which was advanced from the base of a cleaned borehole, with those from CPT-1 and 2 which were started at a higher level and were not from a cased BH; see Figure 2(a). The CPT q_c resistances range from 1 to 4 MPa and average around 2 MPa over the 3.5 to 7m depth interval of interest.

The Dunkirk site described by Jardine et al. (2006) has been employed recently for the PISA project experiments reported by Byrne et al. (2015). The key layer for the tests described herein is a mostly clean sand hydraulic fill derived from nearby fine marine sand, which was placed in the early 1970s. It overlies a dense to very dense marine sand. The small diameter piles are located above the water table. Recent CPT tests conducted for the PISA project are shown in Figure 2(b) together with four CPT tests carried out in March 2017 for the present project at the small pile test locations. The q_c profile rises steeply with depth to maxima around 40 MPa before declining. The average q_c values employed pile capacity calculations were derived from the latter test set, excluding CPT-02 after quality control.

The University College Dublin Blessington experimental site is located 25 km southwest of the city. As documented by Gavin and O'Kelly (2007), Gavin et al. (2009) and Doherty et al. (2012), the medium-to-fine clean sand is dense. The water table is relatively deep and the piles were installed above the water table. The eight CPT tests performed and reported by Prendergast et al. (2015) are summarised in Figure 2(c). The average q_c values increased from 10 MPa just below the ground surface to 15 MPa at 3m depth.

3. Experimental programme at test sites

3.1 Piles and embedment

The multiple small diameter open-ended piles installed at Larvik were driven into position from the bottom of cased starter holes in order to bypass the upper made ground, casing was extended to 3.8m BGL. Short soil plugs (≈0.08m long) were measured inside the casings prior to pile installation. The piles were installed at the base of the cleaned BH's and this was the start of the contact length for each pile. Tests are reported in this paper on seven 50mm OD corroded mild steel (MS) piles which were driven to tip depths of 6.13m BGL and embedment's of ≈ 2.4m at Larvik by a 63.5kg mass that could fall between 0.2 and 0.35m. The driving energy could be varied between 125 and 218 Joules (assuming Efficiency Ratio ER ≈ 60%).

The MS piles were corroded before use at NGI's Oslo laboratory for some weeks before transport to Larvik. No pile roughness measurements were made prior to driving. Pile 2 was installed within a week of arrival on site, while the remaining piles were exposed to the coastal atmospheric conditions for three months. After which time all but one of the MS piles were driven. The latter MS pile, that was not driven, remained at the site for one year, laying on the ground surface. After one year this pile was returned to the

NGI laboratory for surface roughness measurements using a Mitutoyo Surftest-SJ-210-Series-178 device. Centre line average roughness's (R_{cla}) were measured at 16 locations along a 4 mm length of the pile. Table 1 presents the average values of these measurements. No pile was extracted after testing at Larvik. Driving started at Larvik with drop heights of 0.2m that typically increased to 0.35m over the final 0.4m of penetration. Blow counts were monitored over 0.2m to 0.5m penetration intervals. All piles plugged to some extent with an average final Plug Length Ratio (PLR) of 0.42 for the corroded MS piles, see Table 1. Driving was consistent for most piles and the average total number of blows required to achieve full penetration was 160. Slightly higher blow counts were required for pile P12.

At Dunkirk, as described by Carroll et al. (2017), many 51mm OD piles were driven from ground level by a Sol Solution Grizzly® machine that could apply variable driving energy. The maximum setting of the machine is equivalent to the standard SPT energy (475 Joules) and it delivers a similar Energy Ratio (ER) to a trip SPT hammer system (60 to 70%). The 'Grizzly' machine's energy ratings were adjusted to achieve consistent pile penetration rates. The corroded Dunkirk piles described in Table 1 were recycled from previous tests and were relatively rough on both their outer and inner surfaces as it was not possible to remove all the sand that adhered to the insides of the piles. Driving was consistent for the piles, although the corroded MS piles' had a lower average PLR (0.22, see Table 1) than at the other two sites, probably due to small patches of fine sand adhering to the piles' interiors.

Testing at Blessington commenced by driving corroded MS open-ended piles. These piles were visibly oxidised and considered rough on a quantitative basis. The upper 1m of soil was hand augured and removed before driving commenced. A handheld metal post driver was then used to drive the piles to 0.5-0.7m penetrations with up to 90 blows being applied before the piles effectively refused to advance any further with this lightweight driving system. The first pile, MS1, was damaged by hammering and had to be abandoned. An over-sized 4 tonne mechanical drop hammer was then deployed that advanced the piles easily to tip depths 2.75m BGL. Only 25 or so additional blows were required to advance the tip over the remaining 1.25m. The blow counts, of 2-5 blows per 0.25m, are very low and arguably led to a response that might resemble a pile jacked rapidly in 50 to 125mm stroke lengths as closely as any industrially driven pile.

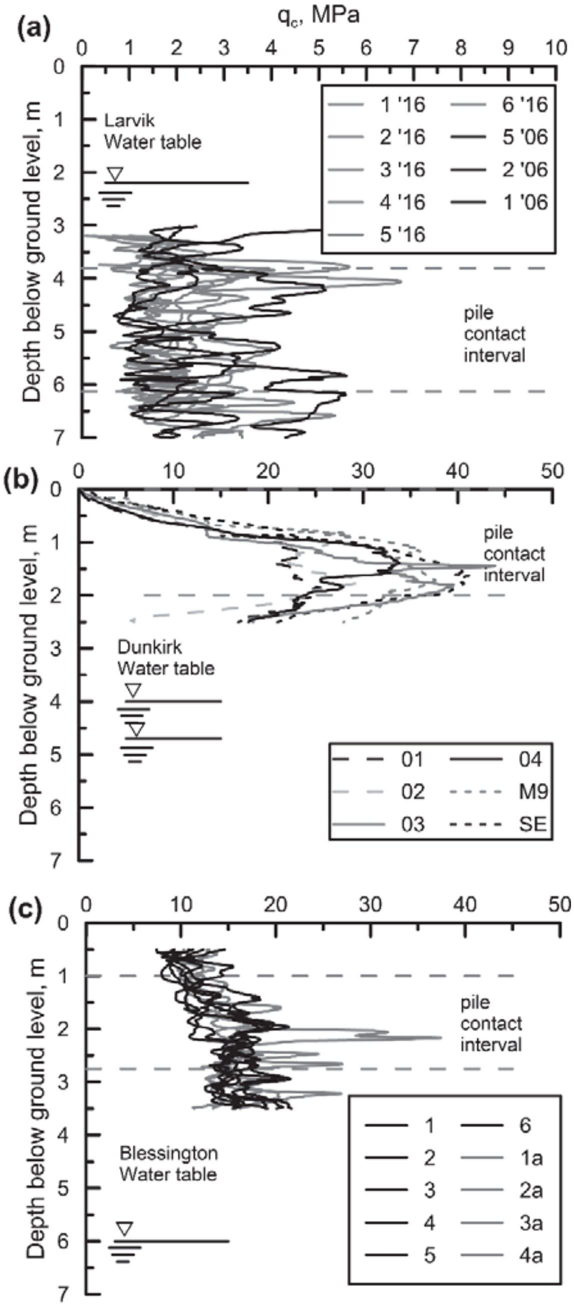

Figure 2: Variation of CPT q_c with depth (a) Larvik, (b) Dunkirk and (c) Blessington

The average PLR recorded at Blessington was 0.36.

3.2 Tension testing procedures

The corroded piles driven at all three sites were subjected to first time static tension load testing at ages of up to 315 days after driving. The equipment and procedures varied between the three sites. The Larvik tension loads were applied in ≈0.5 kN increments that were held for 20 minutes, employing a lightweight tripod set-up that reacted against surface pad foundations and used the casing of the pre-installed boreholes drilled through the fill layers as a displacement datum. The static tests were terminated once a clear load displacement plateau developed and displacements had exceeded 7 mm (14% of the pile OD).

A steel beam system was employed to react against surface pad foundations at Dunkirk. The initial load increments were ≈10% of estimated initial capacity. The load increments, which reduced as failure approached, were each maintained for ≈15 minutes and tests were terminated after 15 to 30mm of displacement. The displacement ratios at failure (0.30 to 0.6, relative to pile OD) were ten times those required for the 456mm OD Dunkirk piles referred to in Figure 1. Similar systems were employed at Blessington, where ≈10 load increments were applied to reach failure. Load steps were held for 30 seconds and the total times to failure (around 20 minutes) were shorter than at Dunkirk or Larvik. Tests terminated when the hydraulic jack could no longer maintain the desired load due to excessive displacement rates. Failure was associated relatively large (10 to 15mm) displacements which amounted to 20% or more of the piles' ODs.

4. Results

4.1 Static load testing: load versus displacement

Examples of the tension load-displacement curves recorded at the three sites are presented in Figure 3. Pile capacity was defined as the peak load, assuming no reverse end bearing capacity (q_{base}) could develop. At Larvik the weight of the pile and plug and adjustment for buoyancy were subtracted, these corrections were not applied to Dunkirk or Blessington where capacities were considerably greater than these components. The conventional definition of capacity as the load required to give a displacement equal to 10% of pile diameter could be applied reasonably to the Larvik piles, but was not considered appropriate for the other two denser sand sites, which required far greater displacement to reach any clear failure. It is clear from Figure 3 that:

(i) The capacities of the Dunkirk and Blessington corroded MS piles were an order of magnitude higher than those measured in the looser and more silty Larvik sand

(ii) The Larvik and Dunkirk piles' responses were mainly ductile, while the Blessington piles showed some post-peak reductions

(iii) Shaft capacities increased markedly over time at Larvik and Dunkirk, but not at Blessington.

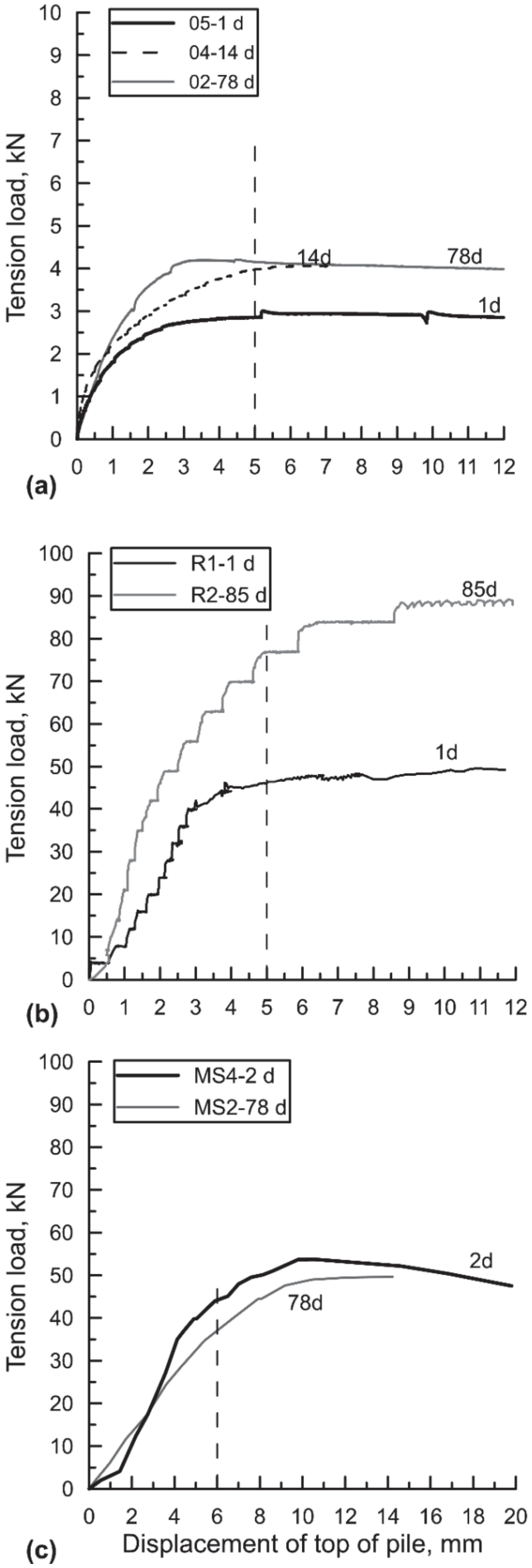

Figure 3: Tension load versus displacement for selected tests at (a) Larvik, (b) Dunkirk and (c) Blessington

Considering the piles' stiffness trends, we note first that the 456mm OD industrial pile tests conducted earlier at Dunkirk showed initial stiffness remaining practically constant over time, irrespective of their large increases in shaft capacity; Jardine et al. (2006). The smaller, corroded MS Dunkirk piles showed gains of up to 100% over 85 days at the 1mm displacement level, although other Dunkirk tests reported by Carroll et al. (2017) showed less systematic stiffness trends. The Larvik piles indicated stiffness gains of around 30% over 80 days at the 1mm axial displacement levels, while the Blessington tests did not show any clear overall stiffness-time trend.

4.2 Shaft capacity time trends, normalized by early age capacity

The corroded MS piles' shaft capacity-time trends are presented first in Figure 4, where the peak tension shaft resistances are normalised by the tension capacities developed shortly after driving. Nominal ratios of Q_t/Q_t at 1 day were defined by applying reference capacity values defined from tension tests conducted within two days of driving.

Figures 4(a) and 4(b) confirm significant capacity growth in the Larvik and Dunkirk MS piles. Noting that stainless steel piles showed no such gains (see Carroll et al. 2017), these trends can only be related to ongoing physiochemical processes that occurred:

(i) Below the water table at Larvik, leading to capacity increasing by more than 100% over 315 days.
(ii) Above the water table at Dunkirk where gains of around 30% to 80% developed over 315 days.

It is important to note that while significant, these gains in capacity are far less marked than those proven for the larger piles tested at the same sites. As remarked earlier and shown in Figure 1, the ≈500mm OD piles' 80 day capacities were on average 2.7 times those interpreted within a day of the end of driving. Figure 4c) confirms that the small piles driven at Blessington showed, if anything, capacity losses over time, contrasting sharply with the marked set-up of the 340mm OD piles tested previously at the same site (see Figure 1). This is despite the water table depth (well below the pile tips) leading to partly saturated conditions that should promote pile corrosion.

The lack of capacity growth at Blessington might relate to the unusually large penetrations (50 to 125mm) achieved per blow with the four tonne hammer employed for the final drives. In addition the driving behaviour of the 60mm OD piles' contrasts strongly with earlier tests reported by Gavin et al. (2003) on 75 to 114mm OD open pipe piles installed to 1.7m with an SPT hammer. These piles had a high total blow counts and cored during installation giving higher final PLRs than the 60mm OD piles. Lim and Lehane (2014) postulate that upper limits apply to the pile capacity available after all ageing processes have been completed. If such a limit was reached prematurely due to the installation method adopted for the 60mm OD piles, there would be no scope for further ageing benefits to develop over time.

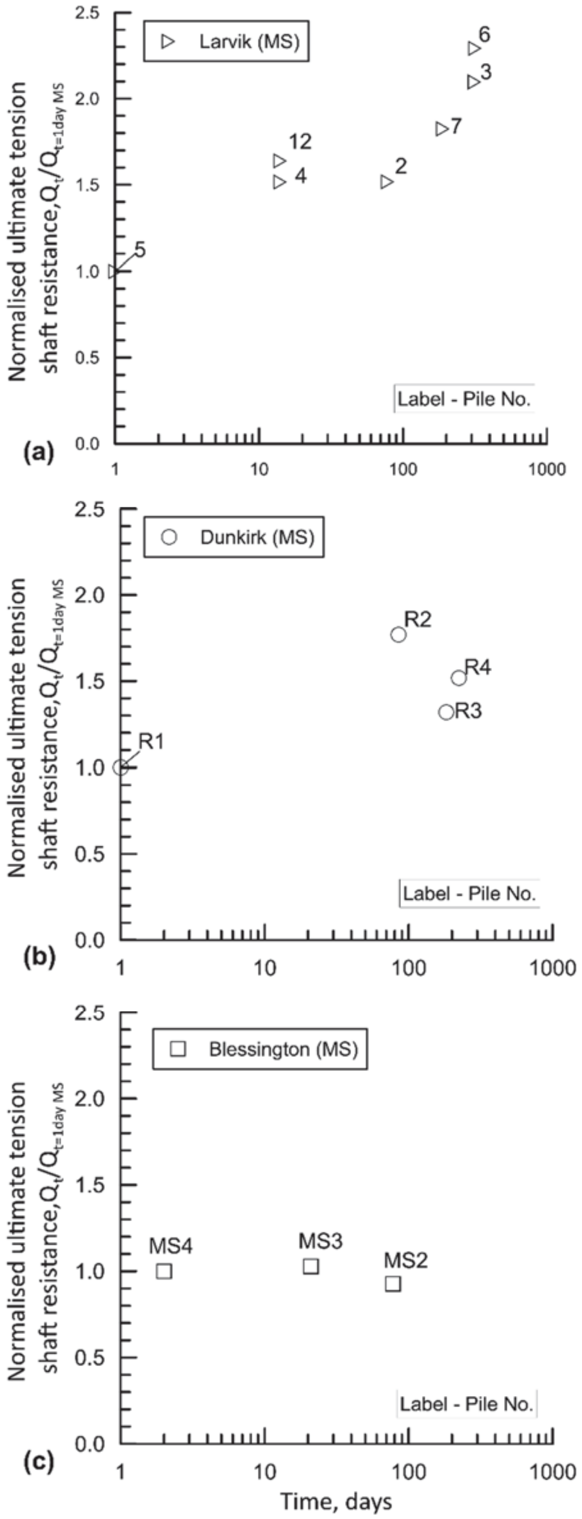

Figure 4: Normalised ultimate tension shaft resistance based on peak capacity ($Q_t/Q_{t=1\ day\ MS}$) at (a) Larvik, (b) Dunkirk and (c) Blessington

4.3 Shaft shear resistances related to predictive design methods

It is instructive to compare the tension capacities of the small diameter piles driven and tested at the three sites with predictions from five approaches that are routinely employed to design large offshore piles: the API Main Text, Fugro-05, ICP-05, NGI-05 and UWA-05 methods. As illustrated by the ICP calculations shown in Figure 1, such methods aim to match the capacities developed by industrial piles in tests conducted a modest number of days after driving. The methods do not address time-dependency and so tend to over-predict shaft resistance immediately after driving and under-predict long-term, aged, capacities.

Table 3 presents an assessment of how the methods apply to the small diameter pile tests. It compares the field measurements made 1 to 2 days after driving the corroded MS piles with tension capacities predicted by the average CPT profile for each site.

The ICP-05 and UWA-05 approaches include shaft friction components that derive from dilation at the pile-to-soil interface. As explained earlier, these terms depend inversely on OD and are proportional to the piles' centre line average roughness. R_{cla} values of 8.5 µm were taken for Larvik and 10 µm for Blessington and Dunkirk.

The first points to note from Table 3 are the (i) very low measured average shaft friction for the loose, silty, Larvik sand case and (ii) broad range of predictions made for Larvik by the five methods, which vary by a factor of ≈10. While the Fugro and NGI approaches under-predict the short term capacity, the API and 'diameter dependent' ICP-05 and UWA-05 approaches give substantial over-predictions. The longer term gains in shaft capacities shown in Figure 3a) lead to the capacity discrepancies reducing with time. But the long term capacities still fall far below the values expected by the ICP or UWA methods.

Closer analysis of calculations made with the latter two methods' shows that their dilatancy components contribute around 80% of the predicted shaft capacities at Larvik, so much less dilatancy must be developing in the field than expected in both the short and long term tests. The dilatancy terms decline as diameter increases and the ICP method gives far better agreement with the short term tests on 504mm OD piles at Larvik, as illustrated in Figure 1. Field experiments by Lehane et al. (1993) with 102mm OD highly instrumented piles in comparably loose, but clean, Labenne dune sand gave direct evidence of more significant dilatancy under loading. The development of less-than-expected dilation at Larvik probably reflects the sands' relatively high (5 to 20%) fines contents and silt sub-layers. The design methods' implicit simplifying assumption of a linear operational sand shear stiffness G controlling the normal stiffness at the pile-soil interface may also contribute to the mismatch. Suitable adjustments could be made with micro-piles to account for non-linear, diameter dependent, sand stiffness.

Table 3. Measured and design method predictions for one-day tension capacities.

1 day results	Unit	Larvik	Dunkirk	Blessington
Measured tension capacity, Q_m	kN	2.6	50.4	54.5
Mean shaft stress, τ_{rzf}	kPa	6.9	160	165
API-00 Q_c/Q_m	-	2.35	0.06	0.10
Fugro-05 Q_c/Q_m	-	0.46	0.35	0.19
ICP-05 Q_c/Q_m	-	4.50	0.55	0.46
NGI-05 Q_c/Q_m	-	0.85	0.57	0.52
UWA-05 Q_c/Q_m	-	4.00	0.59	0.51

In contrast, the short-term shaft resistances of the corroded Dunkirk and Blessington piles are remarkably high, indicating average shear stresses $\tau_{average}$ of 160 to 165 kPa and associated radial effective stresses in excess of 300 kPa at failure (found by dividing $\tau_{average}$ by tan δ), that exceed the predictions given by all five methods, particularly the API Main Text approach, which under-predicts the early age capacities by factors of 10 to 14. The Q_c/Q_m ratios applying to the ICP-05, NGI-05 and UWA-05 methods fall in the 0.45 to 0.60 range, while the Fugro-05 method gives more significant under-predictions for the observed '1-day' capacities.

It appears that one or more factors is causing systematic under-prediction of the capacity of the 51 to 60mm OD piles at the two dense sand sites. Possible contributing factors include:

(i) The piles were driven above the water tables at both sites. Pore water suctions are indicated by piezocone tests at Dunkirk above the water table at the pile depths that could have raised the field shaft capacity. The ≈ 20 kPa average recorded suctions would have added around 7% to the average radial effective stresses (>300kPa) applying at failure.

(ii) The low number of blow-counts during driving at Blessington may have led to higher initial shaft capacities than typical industrial pile driving, with the pile acting more like a jacked rather than driven pile.

(iii) The low plug length ratios (PLRs) developed in the Dunkirk piles due to their rough interiors may also have contributed to capacity. However, checks run with the closed-ended form of the ICP suggest that this would have added only 5% to capacity.

Recalling the better match shown in Figure 1 when applying the ICP approach to the 465mm OD Dunkirk and 340mm OD Blessington piles, it appears probable that the major part of the discrepancy between predictions and measurements originates in the dilatancy developed by the small piles being greater-than-expected by the ICP and UWA methods. The exceptionally large displacement-to-diameter ratios (0.2 to 0.6, see Figure 2) required to reach tension failure at Dunkirk and Blessington are consistent with dilation playing a more important role in the dense sand tests than in the loose and silty Larvik sand, where shaft failure was reached after displacement ≈14% of the piles' OD.

It is interesting that the lower degrees of shaft capacity ageing gain seen with the 51 and 60mm OD Dunkirk and Blessington piles led to their long term capacities converging towards similar multiples (2 to 3.2) of the ICP estimates as the larger 340 to 456mm OD piles, which showed an average ratio of ≈2.4. An upper limit may apply to the shaft failure radial effective stresses that can be developed compared to those found from the ICP-05 or UWA-05 calculations, irrespective of any continuing physiochemical process.

5. Ageing mechanisms

Two of the three possible mechanisms for pile capacity growth over time proposed in the introduction are considered below.

5.1 Physiochemical effects

Carroll et al (2017) found differences between aging of fresh and corroded piles which show that physiochemical process was clearly important in contributing to the set-up trends of the corroded 50mm OD MS piles tested at Larvik and Dunkirk. Active corrosion could lead to:

(i) Roughening of the pile surface and bonding with sand grains promoting interface friction angles, δ that may rise towards the sands' soil-soil critical state φ'_{cs}. This shift could contribute a proportional increase equal to [$\tan \varphi'_{cs} / \tan \delta$], which could amount to around 25% in many silica sands shearing against industrial pile shafts

(ii) Additional dilative radial displacements due to the higher roughness and hence effective stress increases developing at the shaft under shear loading

(iii) Outward expansion of the solid phase corrosion products formed as the iron takes on oxygen, hydroxyl and other molecules from the groundwater. Any such expansion would generate radial effective stress gains over the shaft

(iv) Possible increases in the stiffness of the surrounding sand due to any migrating soluble corrosion products depositing in pore spaces and forming interparticle bonds.

The redox reactions that drive the above processes can be expected to develop at rates that depend on specific site details including the ground temperature, pile and water chemistry, pile surface condition and oxygen supply levels. The crushed sand zone formed around the pile shafts in the high q_c Dunkirk and Blessington cases may also have influenced the physiochemical processes.

The first of the above processes should develop independently of pile diameter. However, as argued by Rimoy et al. (2015), processes (ii) to (iv) all involve local changes that apply to zones of restricted radial extent. Consequently, their impact on the shaft radial effective stresses at failure can be expected to fall inversely with pile diameter and to be expected to be more marked with small diameter piles. Noting that the 340 to 504mm OD piles showed far larger rates of gain in capacity over time at all three sites than the 48 to 60mm OD piles, indicates that steel corrosion cannot be the sole or even major mechanism governing the ageing of the larger piles. Further observations that support this assertion are:

(i) Concrete industrial piles driven in sand also show shaft capacity set-up over time; Rimoy et al. (2015)

(ii) Significant capacity gains have been identified over relatively short set up periods with large offshore steel pipe piles driven to depths where little oxygen is available to promote the same redox reactions; Jardine et al. (2015).

5.2 Radial stress redistribution in the sand around the pile shafts

The ageing tests on stainless and galvanised piles reported by Carroll et al. (2017) showed no tension capacity growth over time at any of the three sites. It is therefore clear that the purely mechanical stress redistribution mechanism postulated by Chow et al. (1998) does not develop to any significant extent around the small diameter piles. This finding reinforces the conclusions drawn by Rimoy et al. (2015) from model pile tests in a well instrumented calibration chamber.

However, the ageing behaviour of the larger piles does not appear to be explicable by physiochemical effects alone and radial stress redistribution may play a more significant role with larger piles. As noted earlier, the crust of fractured sand observed around the shafts of piles driven in dense sand and characterised by Yang et al. (2010) has a thickness t_{crust} that is independent of diameter, Rimoy et al. (2015) argue that higher t_{crust}/D ratios apply to small diameter piles that reduce the degree of local stress concentrations and so limit the scope for radial stress redistribution and shaft capacity growth over time.

It was also argued earlier that the lack of set-up shown by the 60mm OD Blessington piles could be related to their installation process, which differed from the other piles of various diameters driven earlier at the same site. Other general differences between the small and large diameter piles include their lower:

(i) Total blow counts
(ii) Ratios D/t of diameter D to wall thickness, t
(iii) Penetration depths and average initial in-situ stress levels
(iv) Lower PLRs.

The above factors may also play a role in defining the post-driving stress conditions and limiting the extent of radial stress re-distribution over time around small driven piles.

6. Summary and conclusions

This paper describes an investigation into the ageing of piles driven at three sand research sites. Fourteen pull-out tests on 48 to 60mm OD open-ended corroded mild steel piles at ages between 1 and 315 days at three sites covering loose to dense conditions, along with supporting site investigations have been presented. Integration with parallel larger diameter pile tests allowed the potential influence of several factors on ageing to be investigated. The key conclusions are:

1. Corrosion and physiochemical processes had a dominant influence on the set-up of the small diameter corroded MS piles driven at Larvik and Dunkirk in both loose and dense sands, above and below the water table.
2. The physiochemical processes are likely to have involved: pile surface roughness increasing and potential bonding between sand grains and pile shaft resulting in higher effective diameter and increased interface shear angles through both radial expansion of the corroding steel causing static radial stress increases and enhanced dilation at the pile-sand interface under loading.
3. However, no ageing benefit was seen in the 60mm OD piles installed at Blessington, despite the piles corroding *in situ* after driving. These piles appeared to have reached a 'limit capacity' during installation as a result of driving with a massively oversized pile hammer.
4. While corrosion of the pile shaft was highly significant with the small MS piles, the processes' impact on shaft capacity are diameter-dependent.
5. Observed increases in the axial capacity of larger diameter piles cannot be explained by corrosion alone. Other ageing mechanisms must apply to larger piles which are probably affected more significantly by the re-distribution of highly non-uniform radial stresses set up by driving.
6. Checks with five commonly employed axial capacity predictive methods showed a range of outcomes for the small diameter piles. All under-estimated even the short term capacities available in the dense sands at Dunkirk at Blessington, while a spread of under and over-predictions was found for the loose and silty sand Larvik.
7. The discrepancies between the 50 to 60mm OD field tests and medium term ICP-05 and UWA-05 capacity estimates are thought to relate principally to the interface dilation factors, which are highly significant over the investigated diameter range.
8. The ICP and UWA approaches appear to greatly over-predict the dilatant response seen in loose silty sand and these terms should be downgraded or even eliminated when applied at sites where the piezocone response indicates loose silty sand and partially draining conditions.
9. The final long term capacities developed by small (50 to 60mm OD) and larger (340 to 456mm OD) piles tested at the two dense sand sites far exceeded the ICP-05 estimates, with all the measured ratios falling in the 2 to 3.2 range.

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