Ageing effects and CPT based design methods for driven piles in sands

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ABSTRACT: The offshore wind industry has traditionally relied on foundation and support structures that were developed for the oil and gas sector. As wind farms move into deeper water and thus more complex ground conditions, efficient foundation design will become increasingly more important. In water depths > 30 m jacket foundations become a viable economic method of supporting wind turbines. These structures rely on axially loaded piles to provide foundation support. Recent years have seen the emergence of CPT based design methods that use the CPT q_c profile to make more reliable predictions of the capacity of driven piles. These new design methods, including the ICP-05, Fugro-05, NGI-05 and UWA-05 have significantly improved the accuracy of predictions, proving the usefulness of site specific data, in this case CPT q_c data, for pile design. However, it is becoming clear through recent research that further factors need to be incorporated into the design codes to further improve the reliability of predictions. One such variable is the effect of ageing on the pile shaft capacity. Many researchers have shown that the capacity of driven piles in sand increases over time. This paper presents the results of a set of field tests in a dense silica sand site in Blessington, Ireland. A number of 340mm diameter open-ended steel piles were driven 7m into dense sand and load tested at different times after driving to obtain the pile's capacity. Predictions of the pile capacity using CPT design methods are compared with the measured capacities and it is shown that unless a time factor is included in the design method, the prediction ability of these design codes is confined to the short term capacity of piles, in the days after driving. Incorporating an Intact Ageing Characteristic, originally proposed for the ICP-05 design method, resulted in significantly improved predictions of the pile capacities at Blessington.

1 INTRODUCTION

1.1 *Axial Pile Design Methods*

Design methods for axially loaded driven piles in sands have evolved significantly over the past 20 years, mainly driven by the requirements of the offshore oil and gas industry. For fixed offshore structures, driven open-ended steel piles are the most common foundation solution, due to their relative ease of driveability and their ability to resist large moment loading (Schneider, 2007). The increasing demands of the offshore industry requires the continuing evolution of pile design methods to improve efficiency of design and to allow extrapolation of design methods to the extreme pile geometries now used in offshore renewables industry. Due to the large number of variables known to affect pile capacity in sand, existing theoretical methods for predicting the soil response during and after installation are generally considered inadequate (Randolph 2003). As a result a wide range of empirical approaches are currently in use. Traditional design methods for predicting the pile shaft capacity are based on the earth pressure approach which relates the local unit shaft friction, τ_f, to the in-situ vertical effective stress, σ'_{v0}. These earth pressure based approaches have been used successfully for over 50 years in the offshore industry and are included in the main text of the American Petroleum Institute (API) recommended practice for fixed offshore structures (RP2A) as follows:

$$\tau_f = \beta . \sigma'_{v0} \quad [1]$$

Where β is an empirical parameter based on the soil relative density, D_r, originally derived as the product of the coefficient of lateral earth pressure, K_f, and the tan of the interface friction angle. In recent editions of the guidelines API (2008), recommended values of β vary from 0.29 for medium dense sand-silts to 0.56 for very dense sand. The API methods poor predictive performance has been highlighted by several researchers (Toolan et al., 1990, Jardine et al., 2005, Lehane et al., 2005, Schneider et al., 2008, Gavin et al., 2011 and others) who compared the API capacity predictions to a database of static load tests. Significant bias in capacity predictions were noted with regards to the pile slenderness (ratio of pile length, L, to diameter, D) and soil relative density. The inherent bias evident in the API main text procedure has long been recognized and has driven research efforts to improve pile design methods.

The Cone Penetration Test (CPT) can provide a large amount of repeatable information on the vertical variability of the soil strength and compressibility (Schneider et al. 2008) and the penetration of a cone into the soil can be seen as somewhat analogous to closed-ended pile installation. A campaign of field tests using a highly instrumented closed-ended model pile was started by Imperial College in the early 1990s. The Imperial College Pile (ICP) was jacked into a medium-dense sand site at Labenne (Lehane, 1992) and into dense marine sand at Dunkirk (Chow, 1997). Several key findings stemmed from this research as follows:

a) The local shear stress during failure was seen to follow a Mohr – Coulomb failure criterion and was dependent on the equalised radial effective stress, σ'_{rc}; a component related to the increase in radial stress as a result of dilation, $\Delta\sigma'_{rd}$; and the tan of the interface friction angle at failure, δ_f:

$$\tau_f = (\sigma'_{rc} + \Delta\sigma'_{rd}) . tan\delta_f \quad [2]$$

b) Both the local shear stress, τ_f, and the equalised radial effective stress, σ'_{rc}, at any location on the pile shaft were seen to closely mirror the CPT cone resistance, q_c, profile.
c) The ratio of σ'_{rc}/q_c or (τ_f / q_c) was similar at both sites, despite the largely different CPT q_c profiles, and reduced as the distance from the pile tip, h, increased. This phenomenon is known as friction fatigue.

The findings of the Imperial College Pile tests, and an assessment of several other model scale and large scale pile tests, provided the impetus for the development of a number of different CPT based design methods at several research centres around the world, namely the ICP-05 (Jardine et al. 2005), Fugro-05 (Kolk et al. 2005) and UWA-05 (Lehane et al. 2005) pile design methods. An entirely separate campaign of field tests conducted by the Norwegian Geotechnical Institute (NGI) resulted in the development of the NGI-05 (Clausen et al. 2005) CPT based pile design method. A summary table of the design formulations of the four new methods for tension loading of steel open-ended piles is shown in Table 1.

Table 1: Recent CPT-Based Design Methods for Shaft Friction of Driven Piles in Siliceous Sand

Method	Design Equations (for tension loading of open-ended steel piles)
ICP-05	$\tau_f = 0.9\left[0.023\ q_c \left(\frac{\sigma'_{v0}}{p_{ref}}\right)^{0.13} \left[\max(\frac{h}{R^*}, 8)\right]^{-0.38} + \Delta\sigma'_{rd}\right] tan\delta_f$
Fugro-05	$\tau_f = \left[0.045\ q_c \left(\frac{\sigma'_{v0}}{p_{ref}}\right)^{0.15} \left[\max(\frac{h}{R^*}, 4)\right]^{-0.85}\right]$
UWA-05	$\tau_f = 0.75\left[0.03\ q_c\ A_{r,eff}{}^{0.3} \left[\max(\frac{h}{D}, 2)\right]^{-0.5} + \Delta\sigma'_{rd}\right] tan\delta_f$ Where $A_{r,eff}$ = 1-IFR $(D_i / D)^2$ IFR = $\Delta L_{plug} / \Delta L$ (incremental change in plug length with respect to penetration)
NGI-05	$\tau_f = \frac{z}{L}\ p_{ref}\ \left[2.1(0.4\ln(\frac{q_{c1N}}{22}) - 0.1)^{0.7}\right] \left(\frac{\sigma'_{v0}}{p_{ref}}\right)^{0.25} \geq 0.1\ \sigma'_{v0}$

Note: $\Delta\sigma'_{rd} \approx 4G\Delta y/D$; p_{ref} = 100kPa; R^*=equivalent pile radius = $(R^2 - R_i^2)^{0.5}$, R and R_i is the external & internal pile radius = $D_i/2$; $q_{c1N} = (q_c/p_{ref})/(\sigma'_{v0}/p_{ref})^{0.5}$

Lehane et al. (2005) performed an assessment of the reliability of the four new CPT design methods and noted considerable improvement in the predictive performance of the CPT methods when compared with the traditional API main text approach. As a result the four CPT based methods were included in the commentary of the API design guidelines and were suggested to be "*fundamentally better and show statistically closer predictions of pile load test results*" than the API main text approach. The API commentary suggests that the new CPT methods are preferred to the main text approach but stipulated that "*more experience is required with all these new methods before any single one can be recommended for routine design instead of the Main Text method*".

1.2 *Pile Ageing*

The positive effects of ageing on pile capacity have been noted by York et al. (1994), Axelsson (2000), Bullock et al. (2005), Jardine et al. (2006), Gavin et al. (2013) and others. Axelsson (2000) and others have shown that the beneficial effects of ageing relate primarily to increases in shaft friction, with the base resistance remaining relatively unaffected by age. Chow et al. (1997) described reload tests on piles driven in Dunkirk. The piles, which had a relatively complicated loading history involving multiple re-load tests exhibited an 85% increase in capacity over 5 years. Based on equation 2, Chow suggested three possible mechanisms for the ageing which occurred at Dunkirk:

1) Changes in the stress regime around the pile which led to an increase in the equalised radial effective stress, σ'_{rc}
2) The effect of ageing on soil properties resulting in enhanced constrained interface dilation and an increase in $\Delta\sigma'_{rd}$
3) Chemical corrosion resulting in an increase in surface roughness and thus a higher mobilised interface friction angle

Following on from the findings of Chow et al. (1997) at Dunkirk, Jardine and Standing (2000) and Jardine et al. (2006) presented data from a program of large scale, 457mm diameter, pile tests specifically investigating pile ageing. The load test program included multiple tension static load tests on previously untested ‘virgin’ piles at different time intervals after driving. The results from the virgin static load tests are plotted in Figure 1a and show a 2.3 fold increase in capacity between 9 and 235 days after driving. Based on these findings Jardine et al. (2005) suggested an Intact Ageing Characteristic (IAC) for previously unfailed ‘virgin’ piles in the ICP-05 design procedures as seen in Figure 1b. The original ICP-05 shaft capacity prediction, $Q_{p\text{-}ICP}$, was suggested to predict the medium term (approximately 10-day) capacity, with the end of driving (1-day) capacity tentatively suggested to equate to 0.7 times the ICP prediction (i.e. 0.7 $Q_{p\text{-}ICP}$). Another finding of the Dunkirk experiments was that testing and failing piles resulted in significant disruption of the ageing process, with re-tested aged piles showing substantially lower capacity increases due to ageing.

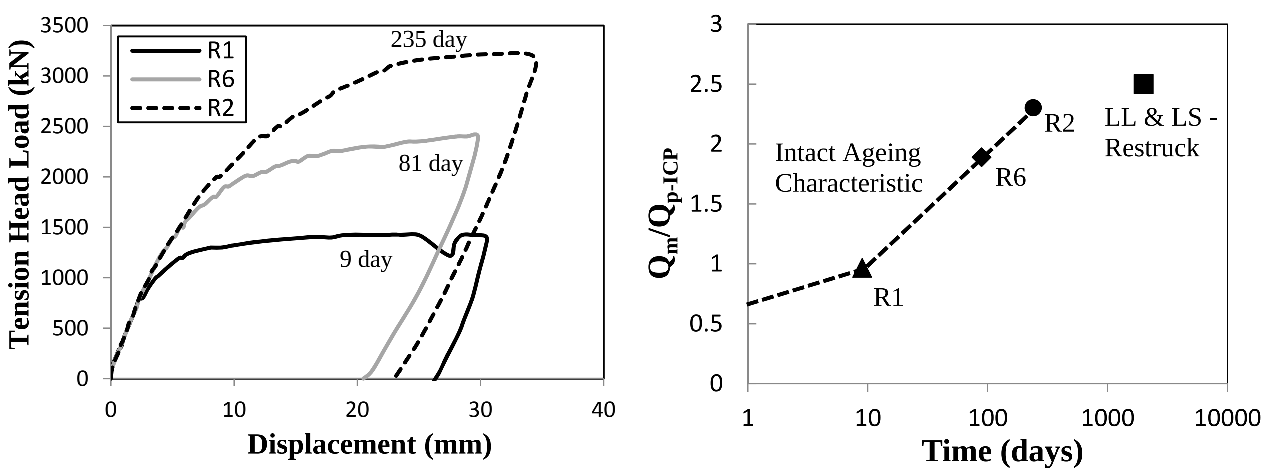

Figure 1 (a) Virgin Tension Tests from Dunkirk and (b) Intact Ageing Characteristic from Dunkirk (after Jardine et al. 2006)

With the exception of the ICP method, none of the other three CPT methods account for the significant effects of ageing in their calculation procedures. The CPT design method calculations are considered to be representative of the short to medium term pile capacities (typically less than 50 days), with database study reviews of the design methods thus far ignoring ageing effects or excluding aged piles altogether. The database of tension pile tests compiled by Gavin et al. (2011), which had significant commonality with the UWA database described by Schneider et al. (2008) and previous databases, is reinterpreted with respect to pile ageing in Figure 2. The database is limited to piles where siliceous sands contributed more than 75% of the shaft capacity. The piles in the database are separated into 'virgin' previously untested piles and re-tested piles and the normalised predicted capacities using the API and ICP calculation procedures are plotted against time. Taking the overall dataset as a whole, it is clear that the ICP method shows much less scatter than that of the API suggesting significantly improved predictive reliability. Another notable feature when considering the database as a whole is the lack of any strong ageing trend with time, contrary to what one might expect in light of the Dunkirk tests. However when considering the virgin pile tests only (closed symbols), there appears to be a strong trend for both the API and ICP design methods to over-predict the capacity of recently installed piles (<10 days) and under-predict the capacities of older piles. In the database compiled by Gavin et al. (2011) the oldest virgin pile test was test 28 days after driving. The retested piles (open symbols) appear to be unaffected by ageing, which follows from the conclusions of Jardine et al. (2006) who suggest that pre-failed or re-tested piles exhibited substantially less ageing effects. Therefore, as the database consists of mainly relatively un-aged 'virgin' piles and older pile re-tests, no significant conclusions regarding ageing effects can be drawn. This paper presents results of pile field tests conducted by University College Dublin at the Blessington sand research site. The pile tests followed a testing program specifically designed to investigate the effects of pile ageing and cyclic loading.

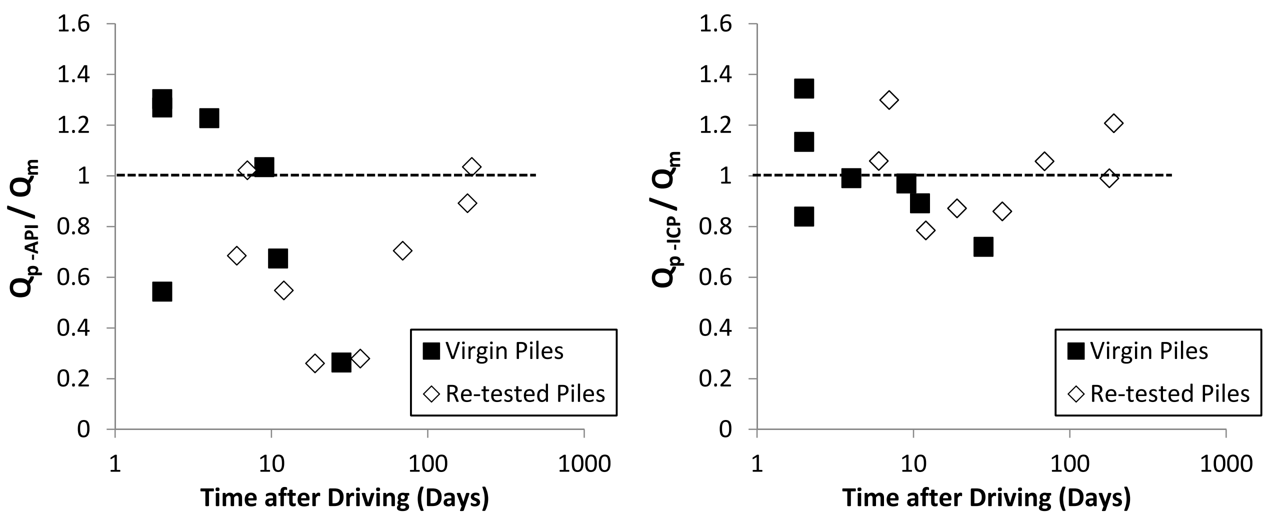

Figure 2 Normalised predicted over measured pile capacities with time for (a) the API and (b) the ICP calculation procedures

2 BLESSINGTON AGEING TESTS

2.1 *Experimental Details*

The pile testing program described in this paper involved driving five open-ended steel piles, designated S2 – S6 into dense sand. The 340 mm diameter piles were driven to 7m depth using a Junntan PM-16 drop hammer piling rig. Pile driving was paused every 1m to take internal soil plug length measurements. After installation the piles were load tested in tension at various time intervals after driving. The tests were scheduled primarily to capture the ageing effects on previously untested 'virgin' piles over the first few weeks and months after driving. With this in mind, piles S2, S3, S4, S5 and S6 were scheduled for first time load testing 1 day, 10 days, 30 days, 220 days and 144 days after driving respectively. Further static tension tests and cyclic tests were performed after these first time tests. Full details of the experimental testing programme are given in Igoe et al. (2014). The tension load tests were conducted using a 5m long loading frame which transferred the load through reaction beams into the ground. A metal top cap, welded onto the piles after installation, allowed the piles to be pulled using a 45mm threaded bar. The static tension tests were loaded in 40 kN increments using a fully automated load controlled hydraulic system which maintained each target load level for a 10 minute period before ramping up to the next load level.

2.2 *Site Description*

The pile tests were performed at the University College Dublin (UCD) sand test site situated in Blessington, 25 km southwest of Dublin city. The ground conditions at the site and the sand properties have been reported in Gavin et al. (2009) and Doherty et al. (2012) amongst others. In summary, the ground conditions comprise of a very dense, glacially deposited fine sand with a relative density close to 100%, CPT q_c resistance in the range of 15 to 20 MPa, and a small strain stiffness (G_0) in the range 100 to 150 MPa. A total of 10 CPTs were conducted on the site with two CPTs each conducted 1.5m either side of piles S2 – S5 (Figure 3). In general the CPTs showed very good repeatability although the CPT profiles adjacent pile S4 show a slightly lower q_c value from 6 – 7 m depth compared with those adjacent piles S2, S3 and S5. Dilatometers conducted at the site indicated a lift off pressure, P_0 of between 800 – 1000 kPa with limit pressures, P_L, approaching 3500 kPa at depth. Particle size distribution analyses performed on samples taken from depths ranging from 0.7 m to 2 m below ground level (bgl) indicated the mean particle size, D_{50}, varied between 0.1 and 0.2 mm. The sand had a fines content (percentage of clay and silt particles) of between 5 and 15 %. Samples typically had less than 10% coarse grained particles (> 0.6 mm). The water table was approximately 13 m bgl.

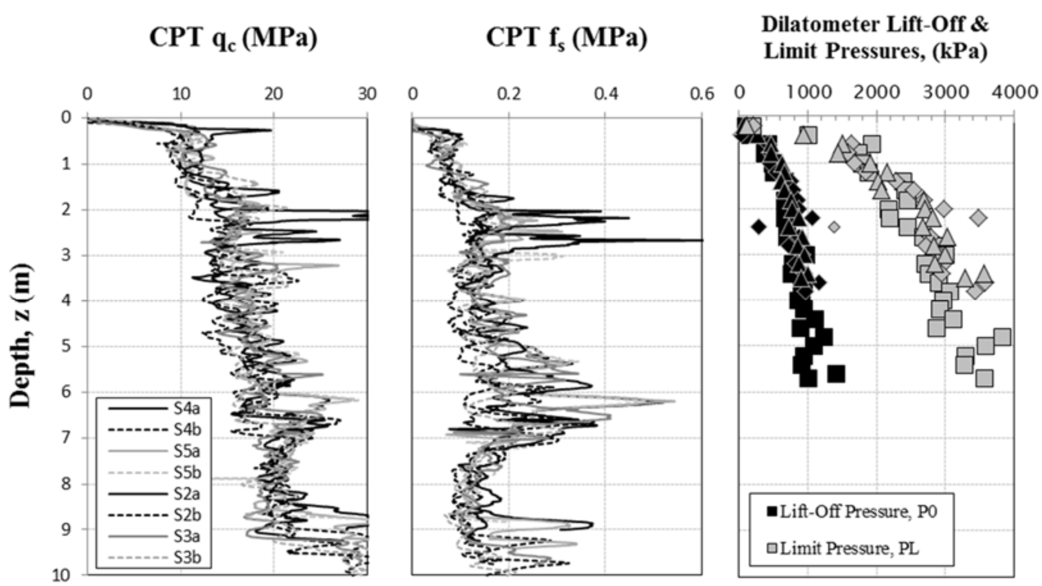

Figure 3 (a) CPT cone resistance, (b) Sleeve Friction and (c) Dilatometer Lift-off and Limit Pressures

2.3 *Load Test Results*

The virgin static load test results for piles S2 – S5 have previously been reported by Gavin et al. (2013). Additional virgin static load –displacement test data from pile S6 is shown in Figure 4a. With the exception of pile S4 it is evident there is a strong trend for capacity to increase with time. The ultimate pile tension capacities are plotted against the log of time in Figure 4b. The capacity of the piles appears to increase linearly with the log of time except capacity of pile S4 plotting well below the general trend line. Gavin et al. (2013) noted that pile S4 had a lower CPT resistance over the bottom 1m of the pile, exhibited notably less plugging during installation and had a significantly lower blow-count during driving then the other piles. This would indicate that pile S4 may have a substantially lower end of driving capacity and hence does not match the ageing trendline exhibited by the other 4 piles. This pile was described as a normal irregularity and further investigation is underway to determine the cause.

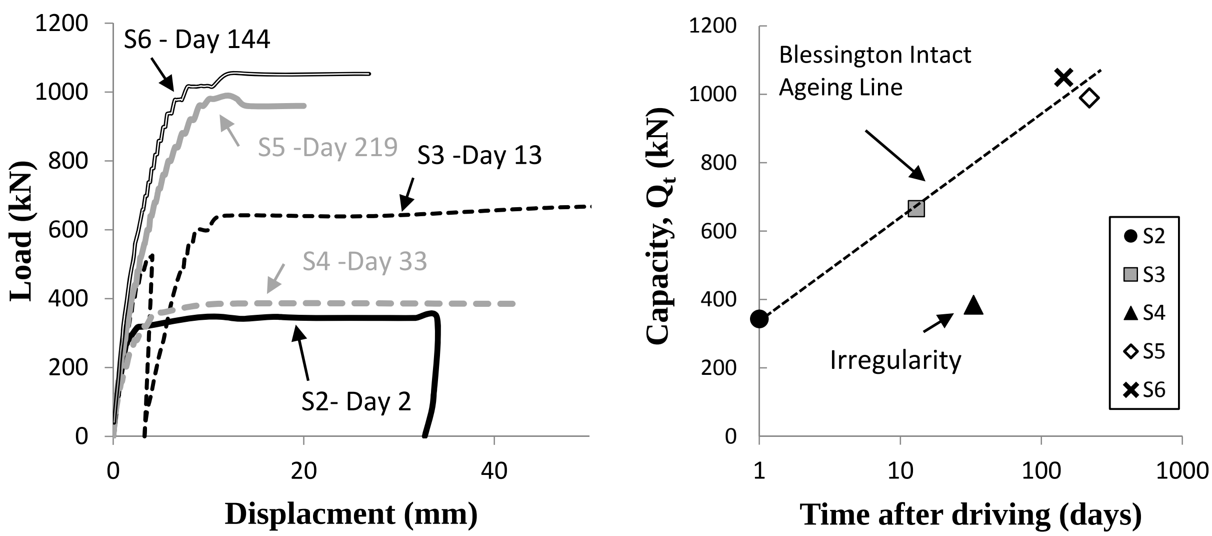

Figure 4 Blessington Pile Test (a) Static Load Displacement curves and (b) Capacity Variation with Time

3 COMPARISON OF CPT METHOD PREDICTIVE PERFORMANCE

Predictions of the capacities of piles S2 – S6 were made using the four recent CPT methods. The predicted capacity, Q_p, normalised by the measured capacity, Q_m, for each method is plotted against time in Figure 5. Figure 5a shows the design methods where standard design predictions with no ageing factor are applied. The ageing trend is quite clear with all four CPT methods over-predicting the 1-day capacity of pile S2 but under-predicting the capacity of all other piles (with the exception of pile S4 which is thought to be an irregularity as mentioned previously). When the Intact Ageing Characteristic described in the ICP-05 design method is applied to all the design methods, their predictive performance is improved significantly with all the predictions matching the measured capacities closely (except pile S4). It is clear that using ageing factors, such as the Imperial College Intact Ageing Characteristic can lead to notably better capacity predictions with time. The authors are currently investigating the mechanisms controlling pile ageing and are reinterpreting the original pile test database to assess the effect of ageing on piles of varying sizes and geometries.

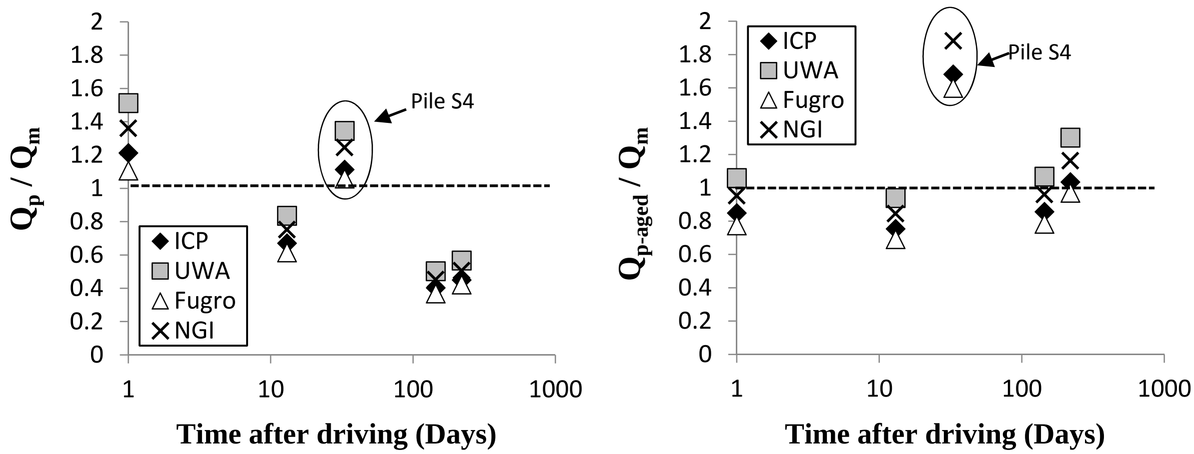

Figure 5 Normalised Predicted Capacity for the four recent CPT design methods (a) with no ageing factor and (b) using the Imperial College Intact Ageing Characteristic

4 CONCLUSIONS

This paper presents new field test data from a series of large scale pile tests investigating pile ageing. The piles, which were driven at the University College Dublin, research sand test site at Blessington, were tested sequentially to assess the effects of ageing on the tension capacity of open-ended steel piles in sand. The data from the field tests indicate that pile capacity can increase 300% over the 5 months following driving. A reassessment of a pile test database compiled by Gavin et al. (2011) indicates that there is dearth of previously unfailed 'virgin' tests on aged piles. Four recent offshore CPT based design methods, which are included in offshore design guidelines, are discussed and their predictive performance is assessed against the measure pile capacities at Blessington. All four methods offer reasonable predictions of the short to medium term pile capacities but significantly under-estimate the capacities of aged piles. When an ageing factor, the Intact Ageing Characteristic proposed by Imperial College, was applied to the calculations to account for ageing effects, significantly improved predictive performance was noted for all four design methods. Further research is currently underway to investigate the mechanisms controlling pile ageing and to assess if these ageing factors can be extropolated to different pile sizes and geometries and be used routinely and safely in design practice.

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