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Setup of axial bearing capacity of open ended tubular steel piles driven in sand

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Abstract: This paper focuses on the setup of axial bearing capacity of open ended tubular steel piles that are used for offshore foundation systems such as those of wind turbines. A comparative evaluation of the most commonly used models for setup prediction shows an upper estimate bound and a lower estimate bound, which correspond approximately to a setup rate of 60% increase per log cycle of time and 20% increase per log cycle of time, respectively. This finding is validated with the results of case histories reported in literature, which show that the setup values of most case histories considered lie in the best estimate zone between the upper estimate zone and the lower estimate zone. The analysis results show a minimum setup factor of approximately 1.5 for 100 days following end of driving of open-ended tubular steel pile driven in sand.

Keywords: Setup, axial bearing capacity, driven open ended pile, granular soil, sand.

Highlights

- Detailed presentation of setup phenomenon in granular sand and contributing mechanisms
- Detailed presentation of setup prediction models in granular sand
- Demonstration of lower bound, best estimate bound and upper bound for setup prediction
- Compilation of case histories of setup for driven open ended pile in granular soil and validation of lower estimate, best estimate and upper estimate zone

List of Notations

A	setup factor according to Skov and Denver (1998) expressing the increase rate per log cycle of time
B	setup factor according to Svinkin et al. (1994)
CPT	cone penetration test
α	setup factor according to Long et al. (1999)
Q_t	axial pile bearing capacity at time t
Q_o	axial pile bearing capacity at time t_o
EOD	end of driving
EOID	end of initial driving
t	time elapsed after initial driving
t_o	reference time from which the increase in capacity is linear in logarithmic time scale
σ'_{rc}	local radial effective stress
$\Delta\sigma'_{rd}$	dilatant increase in local radial effective stress during pile loading
δ_{cv}	interface angle of friction at failure
τ_f	ultimate unit shaft friction

1 Introduction

Pile setup is defined as the increase of axial pile bearing capacity with time after its installation in soils. Pile setup is linked to some mechanisms such as the soil consolidation due to dissipation of excess pore water, soil ageing, corrosion or re-bonding and so on. Soil ageing is a process whereby recently disturbed or deposited soils gain stiffness and strength over time at constant effective stress. The ageing phenomenon often leads to an increase in the stiffness and strength of granular soils (Mitchell and Solymar (1984), Schmertmann (1991), Thomann and Hryciw (1992), Ng et al. (1998)). However, in a few cases, a reduction in pile capacity with time was reported (Bullock et al. (2005)). This reduction in pile capacity with time

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occurs primarily because of the dissipation of negative pore pressures due to pile driving. Chow et al. (1998) reported three soil profiles that may create this condition: strong soils that dilate during penetration, weak sediment and metamorphic rock, and sands confined by a cofferdam or closely spaced pile. The soil leading to a decrease in pile capacity with time is termed as sensitive by Mitchell and Solymar (1984), Mitchell (1986), York et al. (1994). The setup phenomenon linked to ageing and the increase of pile bearing capacity driven in granular soil has been observed in the field tests by Chow (1997), Skow and Denver (1998), Jardine and Standing (1999), Kirsch and von Bargen (2012); Ciavaglia et al. (2017). Pile axial capacities have been found to typically double over 6 months, although this effect is variable. The process of the setup has been found to continue for up to 5 years, long after pore pressures have dissipated (Browman and Soga (2005)).

This paper describes the setup phenomenon and the mechanisms that lead to setup in granular soils for better understanding of the setup phenomenon. Furthermore, a comparative study is carried out for the most common used models for setup prediction. The results obtained from this comparison study are validated with pile cases history.

2 Mechanism Of Setup In Granular Soil

When a pile is driven, a volume of soil approximately equal to the volume of pile is displaced during the installation. This soil displacement generally occurs in the direction of least resistance. For example, in normally consolidated or overconsolidated sand, the horizontal (radial) stress is generally lower than the vertical stress during the pile driving. Therefore, soil is displaced predominately radially along the pile shaft, and vertically and radially beneath the toe. However, some vertical displacement along the shaft may also occur. This displacement can significantly alter the stress in the soil. The soil below and adjacent to the pile undergoes a high degree of shearing, Bowman and Soga (2005), Jardine et al. (2006) and Chow et al. (1998). Randolph et al. (1979) states that in clay, pile driving can significantly alter the stress in the soil up to approximately 20 pile radii. As soil around and beneath the pile is displaced and disturbed, it forms an arching around the pile, thereby generating excess pore water pressures, thus decreasing the effective stress of the soil. As a result, the radial stress around the pile decreases. Hence, the pile shaft resistance also decreases. The ultimate unit shaft friction τ_f developed on a pile in sand follows the Coulomb failure criterion, Lehane et al. (1993), Jardine et al. (2005):

$$\tau_f = (\sigma'_{rc} + \Delta\sigma'_{rd}) \tan\delta_{cv} \tag{1}$$

σ'_{rc} = local radial effective stress; δ_{cv} = interface angle of friction at failure; $\Delta\sigma'_{rd}$ = dilatant increase in local radial effective stress during pile loading.

However, Boulon and Foray (1986) stated that changes in lateral stress during loading are quite uncertain, but appear to result from constrained dilation, which can be modelled using a cylindrical cavity expansion analogy.

The phenomenon of the setup in granular soil can be divided into four (4) time-dependent interrelated mechanisms, based on the results of Schmertmann (1991), Chow et al. (1996) and Axelson (2000), Jardine et al. (2013):

- Dissipation of excess pore water pressure during the primary consolidation
- Creep induced relaxation of the soil arch that leads to breakdown of the arching stress and increases in radial stress, hence gains in shaft capacity
- Soil ageing leading to an increase in dilatancy, strength and stiffness of the soil. This leads to large radial effective stresses acting to the pile shaft during loading.
- Chemical corrosion or re-bonding resulting in an increase in surface roughness and interface angle between pile material and soil (δ_{cv})
- Mechanical or thermal constrained dilatancy that leads to the increase of the radial effective stresses acting to the pile shaft during loading.

However, changes in stationary radial stress during set-up and enhanced dilation during loading appear to be the principal mechanisms controlling the pile ageing in sand (Gavin et al. (2015)). The setup is initiated by the dissipation of excess pore water pressure during the primary consolidation. The excess pore water pressure induced by pile installation can be dissipated in approximately 2 days after the end of driving in sand (Bullock et al. (2005)). The dissipation of excess pore pressure increases the radial effective stress, and therefore the ultimate unit shaft friction. The pile setup due to primary consolidation is termed as short-term setup (Axelsson (2000), Augustesen et al (2006)). The long-term setup is characterized by creep induced relaxation of soil arching, soil ageing and chemical corrosion of pile material. Creep-induced

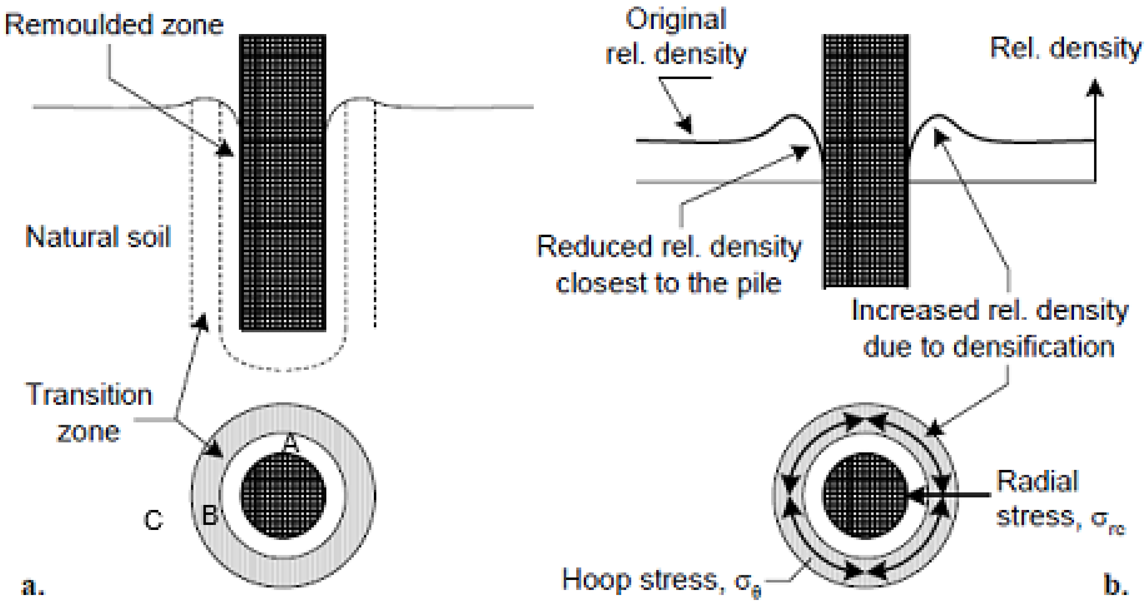

Figure 1: a) Zones created during pile driving, b) relative density in the soil and arching mechanisms around the pile shaft due to pile driving (Augustesen et al (2005))

relaxation of the arching may additionally decrease the excess pore water pressure. *Figure 1* is taken from the paper by Augustesen et al. (2005) and annotated with additional points A, B and C by the authors of the present paper:

(i) Zone A represents the remoulded soil adjacent to the pile (Ciavaglia et al. (2017)). In this zone, the soil is altered by the pile driving process that leads to the accumulation of excess pore water pressure. As a result, the radial effective stress is lower in comparison to the original natural soil in zone C, which is not disturbed by the pile driving process.

(ii) Zone B represents a transition zone with arching soils developed during the pile driving process (Chow et al. (1998), Browman and Soga (2005)). Some soil blocks show hoop stresses and form soil arching in this zone. Creep induced relaxation leads to breakdown of soil arching. As a result, the effective radial stress increases.

(iii) Zone C is not disturbed by the pile driving process.

3 Setup Prediction Models And Comparison

Adequate time to assess the setup after the end of the driving depends on the soil type, the degree of the soil disturbance, the ability of the soil to dissipate the excess pore water pressure (hydraulic conductivity), the coefficient of radial (horizontal) consolidation, the pile diameter, and the soil layering. Therefore, there is no general agreement regarding the adequate time to assess the setup.

In engineering practice, particularly in offshore industry, long delays between end-of-driving and restrike testing are not always possible or practicable. Therefore, some empirical, semi-empirical, and analytical models have been proposed by researchers to predict pile setup with time (Skov and Denver (1988), Svinkin et al. (1994) and Long et al. (1999), Svinkin and Skov (2000)). Most of these empirical equations were developed based on a limited database, and therefore, site specific (or local) calibration may be essential for best prediction. **Table 1** presents a summary of the commonly used models for the prediction of the setup in sand. The value *A, B and α* are assumed to be dependent only on the soil type. Based on the different mechanisms of the set-up phenomenon described in *section 2*, it can be believed that the value of *A* would depend also on the pile type, the pile geometry, the driving method, the overconsolidation ratio of the soil, and other soil properties.

Figure 2 presents a comparison of the setup prediction models. It can be seen that the results of these prediction models show the best estimate zone lying between the upper estimate zone and the lower estimate zone. The upper estimate bound represents a setup rate of approximately 60% increase per log cycle of time,

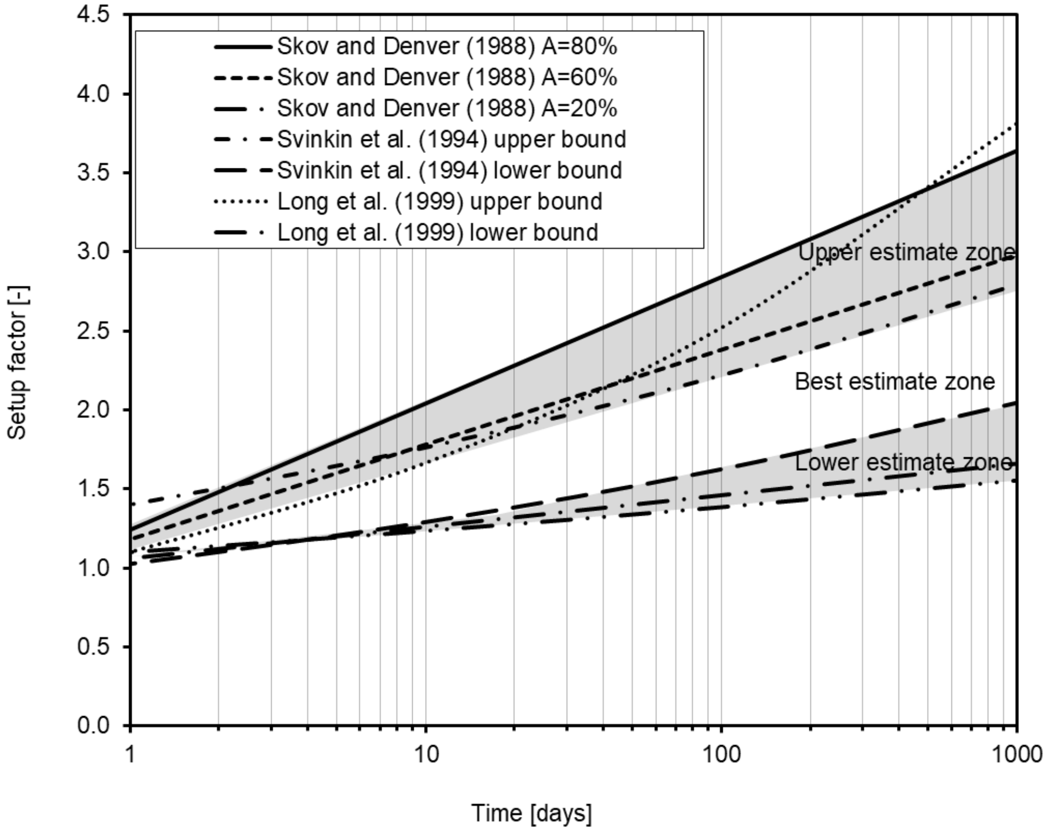

Figure 2: Comparison of results of setup prediction models in sand

Table 1: Empirical models for predicting increase in bearing with time

References	Equation	Comments
Skov and Denver (1998)	$Q_t = Q_0(1 + A \log t/t_0)$	$t_0 = 0.5$ and $A = 0.2$ for sand
Svinkin et al. (1994)	$Q_t = BQ_{EOD}t^{0.1}$	$B = 1.4$ upper bound $B = 1.025$ lower bound
Long et al. (1999)	$Q_t = 1.1Q_{EOD}t^{\alpha}$	$\alpha = 0.18$ for upper bound value $\alpha = 0.13$ for average value $\alpha = 0.05$ for lower bound value

while the lower estimate bound represents a step rate of approximately 20% increase per log cycle of time.

The results of case histories of open ended tubular piles driven in sand have been compiled in **Table 2**. Data obtained from offshore pile driving is scarce as most researches are carried onshore for practical reasons. However, Bowman and Soga (2005), Rimoy et al. (2015) stated that water has little influence on pile setup, especially in sands, since pore water pressures dissipate almost immediately and effective stresses govern pile capacity (Gavin et al. (2015)). Therefore, results of onshore and offshore tests should be comparable. Nevertheless, it should be noted that cycling of the water table (in onshore tests) may increase set-up rates (Bowman and Soga (2005), White and Zhao (2006)).

The results of these case histories are plotted in the semi-logarithmic setup time diagram.

Figure 3 shows that the most case histories lie within the best estimate zone. Therefore, the upper estimate, lower estimate and the best estimate zones obtained from the comparative evaluation can be assumed to be validated by the results of case histories considered. However, few results of case histories lie out of the lower and upper estimate zones that can be explained by the quality of pile testing results or the non-consideration of the pile geometry, pile material, particle shape, particle strength, overconsolidation ratio, relative density of sand etc.

Figure 3 shows a minimum setup factor of approximately 1.5 for 100 days following end of driving of open ended tubular steel pile driven in sand. That is valid for pile subjected to predominantly axial loading. Results of model tests by Ciavaglia (2017) showed that the ultimate shaft resistance can be affected by previous lateral loading. While the application of lateral loads up to

Table 2: Compilation of case histories for open-ended tubular piles driven in sand

Reference	Test location	Soil description	CPT cone resistance qc (MPa)	Pile diameter	Pile	Wall	Static / dynamic	Max	Results
				(m)	Length (m)	thickness (mm)	testing	time (d)	
Skov and	Südkai, Hamburg,	alternating layers of fine,	-	0.762	33.7	12.7	dynamic and	30	42% increase in total capacity,
Denver (1988)	Germany	medium and coarse sand, locally with fine gravel					static testing		derived from CAPWAP analysis of initial driving and a restrike test after 30 days
Shioi et al. (1992)	Trans Tokyo Bay	alternating layers of	40	2	62	31–34	dynamic and	50	set-up factor of approx. 2 on
	Highway, Japan	cohesive soil and very dense sand					static testing		total resistance was measured
York et al. (1994)	JFK Airport, New	medium dense, medium-	-	0.355 and	20	5.3–6.1	dynamic and	49	increase in pile capacity of 40-
	York, USA	fine glacial sand; ~2m thick clay and peat layer near surface		0.2			static testing		75% occurred because of set- up
				(tapered monotube piles)					
Fellenius and	North Shore,	2 m of sand and gravel fill	-	0.324 and	16.5	12.5 and 9	dynamic testing	71	total pile capacity
Altaee (2002)	Vancouver, Canada	on top of silty sand, sandy silt and dense “till like” silt and sand		0.457					approximately doubled between 1 and 30 days after driving
Bhushan (2004)	LAXT wharf, Los	medium dense to very		0.91 and 1.37	33.5 - 41.5	16–25	dynamic testing	139	a set-up of 1.2 to 1.5 for
	Angeles, USA	dense sands inter-layered with clay and silt layers	1 in clayey silts, 7 to 33 in sands						periods of 1 to 10 days and 1.6

Continued **Table 2:** Compilation of case histories for open-ended tubular piles driven in sand

Reference	**Test location**	**Soil description**	**CPT cone resistance qc (MPa)**	**Pile diameter**	**Pile**	**Wall**	**Static / dynamic**	**Max**	**Results**
									to 2 for periods from 14 to 139 days
Kolk et al. (2005)	Eemshaven,	silty to very silty, medium to	40 to 80	0.76	up to 47 m	36–42	dynamic (during	533	total capacity increase of at
	Netherlands (EURIPIDES JIP)	very dense, fine to medium sands					driving) and static testing		least 1.5 after 533 days, compared to capacity after 6 days
Jardine et al. (2006)	Dunkirk test piles,	dense to very dense marine	10 to 20	0.324 and	Nov 22	13–20	static and	1991	100% increase in shaft
and Chow et al. (1998)	France	sand		0.457			dynamic		capacity 8 months after driving. 85% increase between 6 months and 5 years.
Rücker et al. (2012)	BAM Horstwalde	sand	16	0.711	18	-	dynamic testing	30	between 11 - 14% gain in
	test site, Germany								capacity after 10 - 30 days
Kirsch and	Nordsee Ost	Predominantly dense sand,	-	2.438	35	-	dynamic testing	31	reported set-up factor of 1.5
von Bargen (2012)	offshore wind farm, North Sea	(silty) sand with thin clay layers above 26m							after 31 days of ageing
Gavin et al. (2013)	Blessington,	very dense, glacially	10 to 20	0.34	7	14	Static tension test	220	pile capacity increased by
	Ireland	deposited fine sand							185% over 220 days
Reddy and	Puget Sound Lowlands		-	0.36	8.7		dynamic testing	0.23	reported set-up factor of 1.0 to 4.0
Stuedlein (2014)		Silt, Till		0.91	48.8			13	

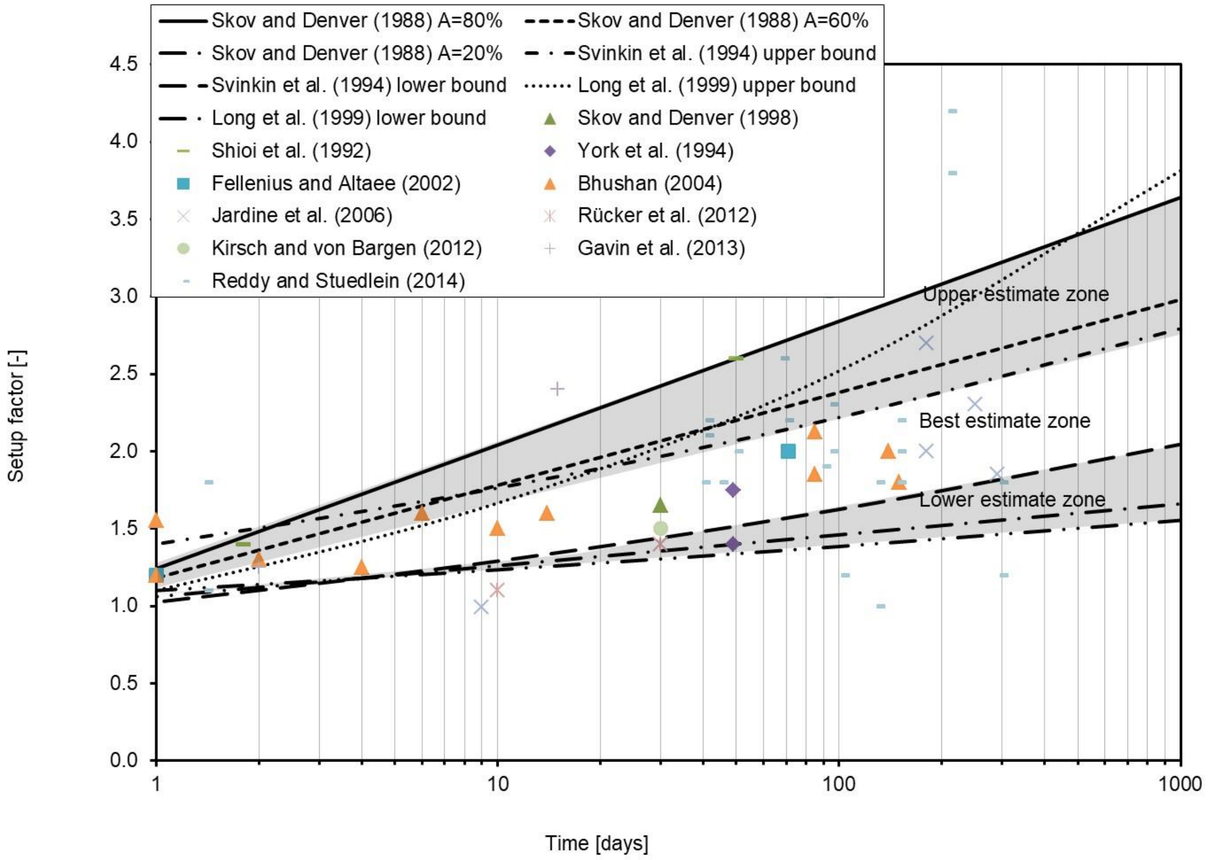

Figure 3: Compilation of pile cases history in predominately sand layer

10% of the ultimate lateral resistance did not affect axial pile resistance, lateral loads reaching 50% of the ultimate lateral pile resistance resulted in a 65% reduction in ultimate shaft resistance relative to a pile that experienced no previous lateral loading (Ciavaglia (2017)). The increase of the axial pile capacity in the first hours after the end of driving is mainly controlled by the dissipation of the excess pore induced by the driving process. Therefore, it can be deduced that this short-term increase of pile capacity decreases with increasing pile diameter, since the degree of the pore water accumulation and the rate of the radial consolidation (pore water dissipation) are expected to be increased with increasing pile diameter. However, some of the mechanisms that contribute to long-term setup (e.g., soil creep and dilation, and soil stiffness increase with ageing) do not depend on the pile diameter (Bowman and Soga (2005); Rimoy and Jardine (2015)). Therefore, it can be concluded that the pile diameter influences particularly the short-term setup characterized by the dissipation of excess pore water pressure due to primary consolidation. The larger the pile diameter, the larger the driving induced excess pore water pressure will be.

It was found that low amplitude cyclic loading could accelerate axial pile capacity at a greater rate than no cyclic loading (White and Zhao (2006)). Jardine et al. (2006) also observed this phenomenon and it is confirmed by the creep tests performed by Bowman and Soga (2005). The increase of setup rate at low cyclic loading can be explained by accelerated, kinematically restrained dilatant of the soil surrounding the pile under compression creep (Bowman and Soga (2005)). Therefore, it can be recommended to drive the offshore pile in summer mainly characterized by low cyclic amplitude of waves in order to accelerate the rate of pile setup.

4 Conclusions

This paper described the mechanisms behind the setup of open-ended tubular piles driven in granular soils.

A comparative evaluation of the most commonly used models shows that the results of the setup prediction provide an upper estimate bound and a lower estimate bound, which correspond approximately to a setup rate of

60% increase per log cycle of time and 20% increase per log cycle per time, respectively. This finding is validated with the results of case histories reported in literature, which shows that the setup values of the most case histories lie in the best estimate zone between the upper estimate zone and the lower estimate bound zone. The analysis results show a minimum setup factor of approximately 1.5 after a delay of 100 days from the end of driving of open ended tubular steel pile driven in sand.

It is recommended to drive the offshore piles in summer because of the beneficial effect of the less cyclic wave loading that can accelerate the setup. Significant cost reductions in projects involving pile foundations in sand can be realized by taking pile setup into account.

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