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Prediction of Increase in Offshore Pile Shaft Capacity Following Installation using the Coefficient of Horizontal Consolidation (C_h)

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Abstract. During the offshore pile driving, the soils around the pile surface, particularly cohesive soils, lose strength because of an increase in pore water pressure and remolding. Following the installation of a driven pile, the excess pore pressure starts to dissipate, and thereby, the soils begin to regain the lost strength, which increases pile shaft capacity, a process known as pile setup. The time rate of increase in pile shaft capacity depends primarily on the coefficient of horizontal consolidation (C_h) besides pile diameter and pile wall thickness. This paper presents the results of a case study done on offshore driven open-ended steel pilesto a) predict the pile setup following the installation b) compare the predicted setup with the measured pile setup using pile driving monitoring data. A correlation between vertical and horizontal coefficients of consolidation (C_v and C_h) is suggested which may be consideredfor pile setup predictions in similar soils.

Keywords: Soil setup; Coefficient of horizontal consolidation (C_h); Coefficient of vertical consolidation (C_v); Offshore driven pile; Pile driving monitoring

1 Introduction

Offshore piles, in south Asia and southeast Asia, installed for supporting jacket structures are generally open-ended driven steel piles with deeper pile penetrations up to about 110m below the sea bed. For a given pile diameter, soil conditions and loadings, the geotechnical aspect of offshore pile design such as pile penetration, depends on static pile capacity estimated as per API RP-2A guidelines. During the pile driving, the soils around the pile surface, particularly cohesive soils, lose strength because of an increase in pore water pressure and remolding. Following the installation, the excess pore pressure starts to dissipate due to horizontal consolidation, and thereby, the soils begin to regain the lost strength, which increases pile shaft capacity, a process known as pile setup. It is often required to estimate the increase in pile shaft capacity with the time to be able to plan for the subsequent loading of the jacket structure.Also, it will help in optimizing the pile penetration in similar soils. This case study deals with the prediction of pile setup based on the models proposed by Ng et al. (2013), Randolph (2013), Dutt et al. (2009), and compare the same with the pile setup estimated using dynamic pile load testing data.

2 Pile Setup Phenomenon and Existing Methods of Estimation

The pile setup is expected to occur in three phases (Komurka et al., 2003), as shown in Fig. 1, with a pile capacity ratio defined as the ratio of pile capacity at any time to that at the end of driving.

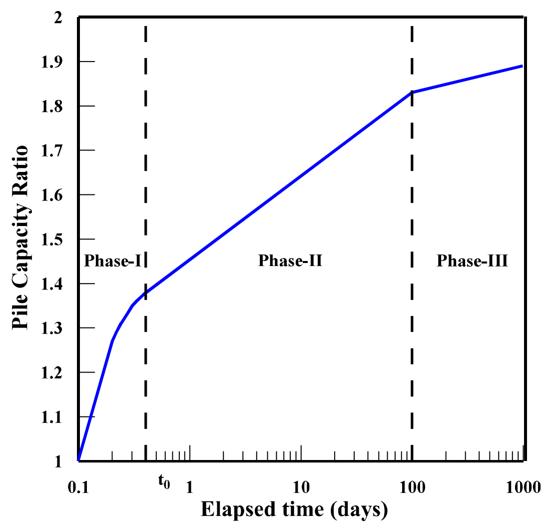

Fig. 1. Different phases of setup phenomenon (adapted from Komurka et al., 2003)

The three phases are described as below

(i) Phase 1: Logarithmically non-linear rate of excess pore pressure dissipation -difficult to model or predict
(ii) Phase 2: Logarithmically linear rate of excess pore pressure dissipation -can be modeled using soil and pile properties and pile testing
(iii) Phase 3: Aging, which is independent of effective stress - occurs at constant effective stress with no further dissipation of excess pore pressure (thixotropy)

Number of empirical/semi empirical models are available to predict phase-2 of pile setup, using

a) The pile capacity at end of driving and maximum static pile capacity (Pei and Wang (1986)
b) The pile capacity at reference time(t_o) after the end of driving at which pile setup becomes logarithmically linear with the time and setup factor (A), which describes the rate of increase in capacity with the time (Skov and Denver, 1988)
c) Soil sensitivity, S_t (Zhu, 1988), and
d) PI and OCR (Karlsrud et al., 2005)
e) Coefficient of horizontal consolidation (C_h), weighted average of SPT N values (Ng et al., 2013)

Table 1. Summary of Existing Pile Setup Predictive Models (adapted from Ng et al., 2013)

Reference	Setup Model	Limitations
Pei and Wang (1986)	$R_t/R_{EOD} = 0.236[\log(t)+1][(R_{max}/R_{EOD})\text{-}1] + 1$	Purely empirical Site specific No Soil property Unknown or difficult to determine R_{max}
Zhu (1988)	$R_{14}/R_{EOD} = 0.375 S_t$	Only predicts pile resistance at 14th day
Skov and Denver (1988)	$R_t/R_0 = A\log(t/t_0)+1$	Require restrikes, Wide range and generic A value
Svinkin and Skov (2000)	$R_t/R_{EOD} = B[\log(t)+1]+1$	Requires restrikes, B value has not been extensively quantified, No clear relationship between B value and soil properties
Karslrud et al. (2005)	$R_t/R_{100} = A\log(t/t_0)+1$ $A = 0.1+0.4[1-(PI/50)]OCR^{-0.8}$	Assumed complete dissipation after 100 days is not accurate, Not practical to use R_{100}
Ng et al 2013	$R_t/R_{EOD} = [C\times\log(t/t_0)+1](L_t/L_{EOD})$ $C = f_c[C_{ha}/(N_a r_p^2)]+f_r$	Dependency on correlations if SPT N is not available

Note: R_t = pile resistance at any time t considered after EOD; R_{EOD} = pile resistance at EOD; R_{max} = maximum soil resistance assumed after complete soil consolidation; R_0 = reference pile resistance; R_{14} = pile resistance at 14 days after EOD; R_{100} = pile resistance at 100 days after EOD; S_t = soil sensitivity; C_{ha} = Weighted average of co-efficient of horizontal consolidation; N_a = weighted average of SPT N values; r_p = equivalent pile radius for given pile cross-sectional area ; *A*= pile setup factor defined by Skov and Denver (1988); *B* = pile setup factor defined by Svinkin and Skov (2000); *C* = pile setup factor defined by Ng et al (2013)

Ng et al. (2013), observed that (ΔR) is proportional to C_h and inversely related to undrained shear strength (S_u) and SPT *N* value. The equations for C_h , pile setup factor, *C*, and pile setup, based upon the dynamic pile tests conducted on five H piles driven into glacial clays, have been proposed

$$C_h(cm^2/min) = \frac{264.76}{(S_u)^{1.928}} \tag{1}$$

$$C_h(cm^2/min) = \frac{3.18}{(N)^{2.08}} \tag{2}$$

$$C = f_c\left[\frac{C_{ha}}{N_a r_p^2}\right] + f_r \tag{3}$$

$$\frac{R_t}{R_{EOD}} = \left[C \times log\left(\frac{t}{t_0}\right) + 1\right]\left(\frac{L_t}{L_{EOD}}\right) \tag{4}$$

Where f_c and f_r are taken from the Figure-2

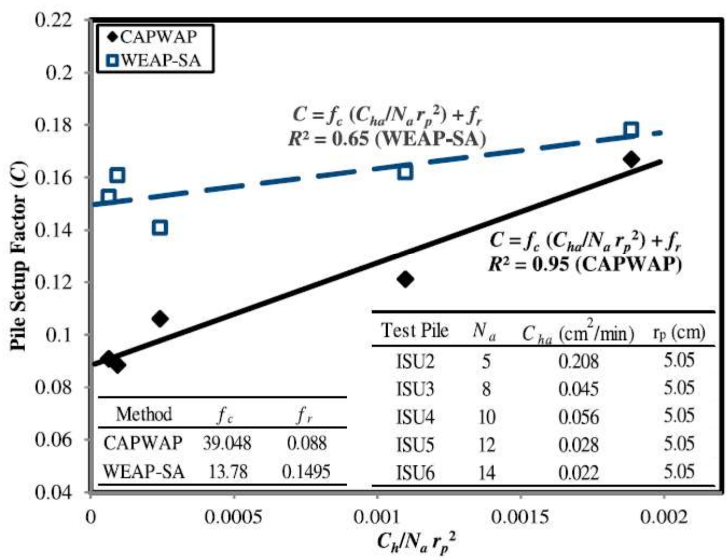

Fig. 2. Correlations between pile setup factor (C) for different ISU field tests and soils parameters, as well as equivalent pile radius (adapted from Ng et al., 2013)

3 Case Study

A case study was done on pile setup estimation based on the pile driving data obtained during 5nos of offshore jacket structures installation in an offshore field in the west coast of India. All jackets have been founded on open-ended piles driven underwater through skirt sleeves. The piles, 2.13m in diameter with wall thickness varying from 85mm (pile shoe) to 55mm, have been driven to their respective final penetrations ranging from 109m to 120m below the seabed.

The soils in this field are predominantly stiff to very stiff silty clays of high compressibility (CH) up to the final penetration depths with intermittent medium dense siliceous carbonate sand layers of thicknesses not exceeding 3m. The clays are generally highly plastic and normally to slightly over consolidated with maximum OCR values not exceeding 1.5. The CPT tip resistance ranged from 0.1MPa near seabed to about 0.5MPa at about 30m depth, and 1.2MPa to 3.8MPa near the final pile penetration depths. The PI of soils ranged from 32% to 63%.The sensitivity, which was measured for soils only up to 30m, ranged from 2 to 4. A generic shear strength profile, based on S_u values at all the five locations is shown in Figure-3.

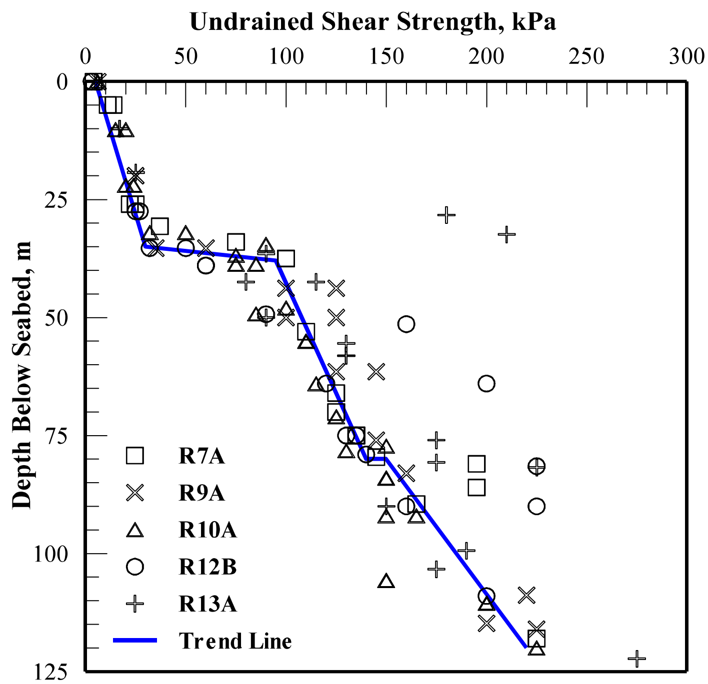

Fig. 3. Undrained shear strength vs Depth

3.1 Dynamic pile load testing

Dynamic pile monitoring was done during the driving of four piles at each of the five locations. The force and velocity signatures were captured and processed by Pile Driving Analyzer (PDA) for every hammer blow. The data was then analyzed using CAPWAP (Case Pile Wave Analysis for Piles) for estimating the available pile shaft resistance at the time of end of driving (EOD), R_{EOD}, for each pile and at an elapsed time after the end of driving during restrike, R_t. Analyses were also done on the data at penetrations shallower than final penetrations, where driving was stopped and re-sumed after a time delay. The summary of CAPWAP analyses at final penetrations where restrike test was performed is provided in Table –2

Table 2. Summary of Pile Setup estimated from Dynamic pile load test (CAPWAP)

Platform location	Pile Name	Penetration, m	Pile Shaft Capacity, MN (CAPWAP)		Restrike time after EOD	Pile Setup (CAPWAP)
			R_{EOD}	R_t	t, days	R_t/R_{EOD}

A	B1	116	9.66	25.53	2.4	2.64
	A2	112	7.72	24.61	4.9	3.19
B	A2	108	11.28	32.24	3.5	2.81
C	A1	120	7.95	24.60	1.7	3.09
	A2	115	10.81	29.06	3.2	2.69
	B2	115	12.25	29.87	2.8	2.44
D	A1	109	11.29	27.29	2.3	2.42
	B2	103	7.15	24.17	3.9	3.38
E	A1	118	11.31	32.34	1.7	2.86
	B2	120	11.21	34.34	3.6	3.11

3.2 Pile setup prediction

Three predictive pile setup models- Ng et at (2013), Randolph (2013) and Dutt et al (2009)- which have been developed based on soil properties C_h, S_u, SPT N value and hindcast wave equation analysis- were used to predict the pile setup. The predicted pile setup was compared against the estimated pile setup from CAPWAP pile capaci-ty.

Consolidation tests: The laboratory testing programme included one-dimensional consolidation tests as required by Randolph (2013) predictive pile setup model.
The vertical consolidation tests were performedas per ASTM D 2435, on the undis-trubed samples available at penetrations 11m, 27.6m, 45m and 70.6m at their corre-sponding effective overburden pressure values of 100kPa, 200kPa, 400kPa and 600kPa respectively and $C_v$values were determined. Deformation vs Time plots are provided in Figures – 4 to 7.

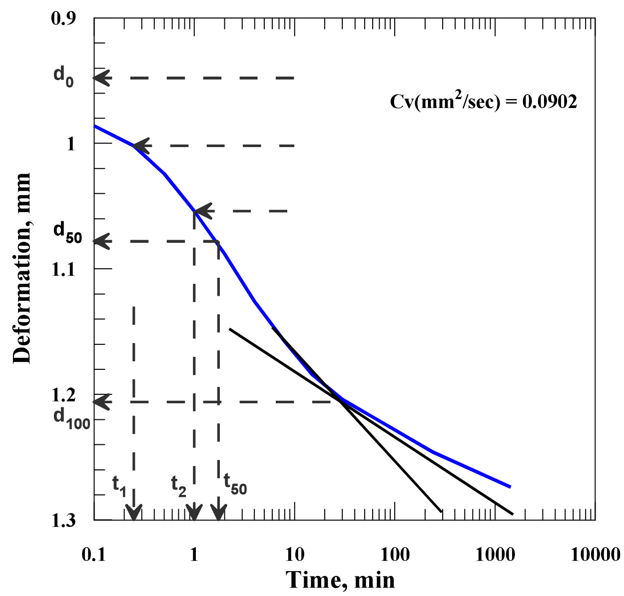

Fig. 4. Deformation vs Time, 11m, 50kPa

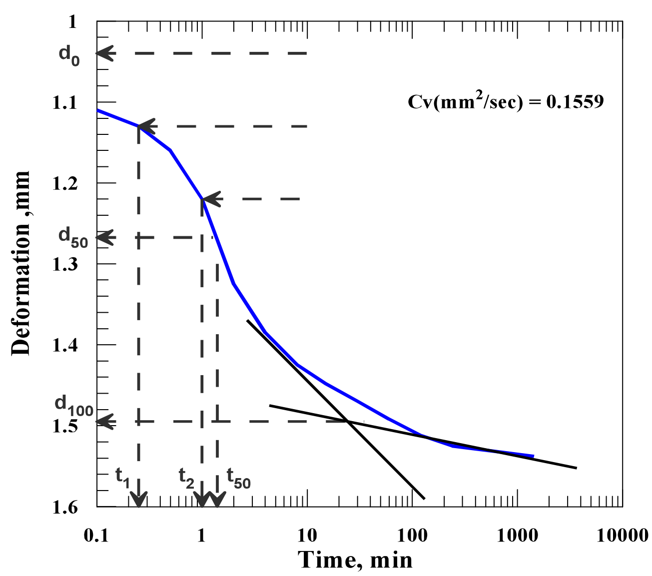

Fig. 5. Deformation vs Time, 27.6m, 100kPa

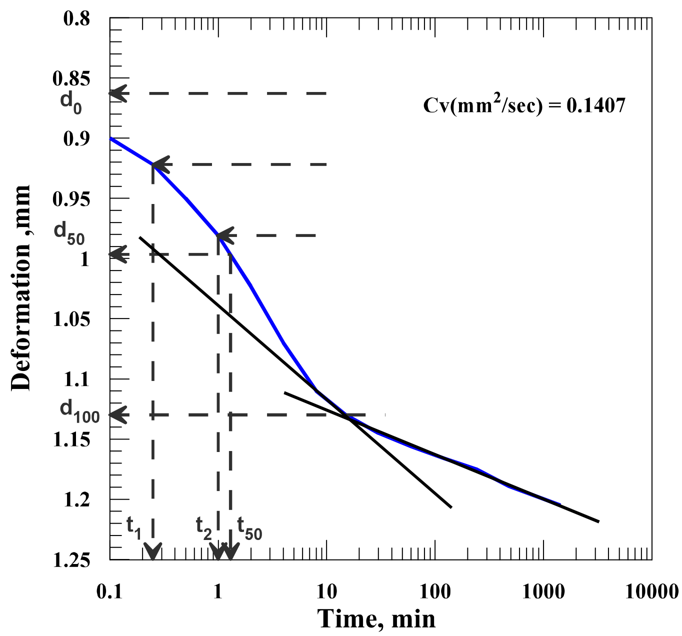

Fig. 6. Deformation vs Time, 45m, 200kPa

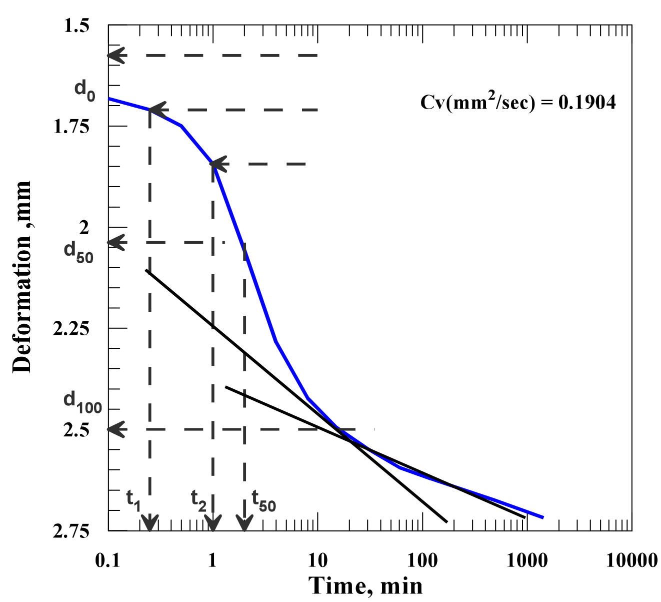

Fig. 7. Deformation vs Time, 70m, 600kPa

Ng et al. (2013). The weighted average of SPT 'N' values, N_a, was calculated from CPT tip resistance values using the correlation between normalized tip resistance vs mean particle size, D50 (Robertson and Campanella, 1988). The D_{50} of the soils at the subject field was generally found to be less than 0.001; therefore, the ratio of normalized CPT tip resistance, (q_c/P_a) , and the SPT 'N' value was considered to be equal to 1.0. The C_h and C values were calculated using Equations-2 and 3. The pile setup was then calculated using Equation-4.

The weighted average of Su, interpreted N_a values and the predicted setup factors are summarized in the Table-3

Table 3. Weighted average soil properties and estimated setup factor

Platform location	Pile Name	S_u	SPT Value	C_{ha}	Setup factor, C	Pile Setup (Ng et al, 2013)
		(kPa)	N_a	*(cm²/min)*	$f_c\left[\frac{C_{ha}}{N_a r_p^2}\right]+f_r$	R_t/R_{EOD}
A	B1	108.2	16	0.0099	0.088	1.31
	A2				0.088	1.34
B	A2	104.3	17	0.0087	0.088	1.33
C	A1	103.0	18	0.0077	0.088	1.30
	A2				0.088	1.32
	B2				0.088	1.32
D	A1	106.8	22	0.0051	0.088	1.31
	B2				0.088	1.33
E	A1	132.5	31	0.0025	0.088	1.30
	B2				0.088	1.31

The pile setup predicted did not match the setup estimated by CAPWAP. The maximum setup factor proposed for relatively stiff clays (i.e., N_a of 12) is 0.088. Therefore, for any N_a value of more than 12, the setup factor to be considered is 0.088. At the subject field with N_a range of 16-31, the pile setup estimated never exceeded 1.3. The maximum setup that can be expected is only about 1.5 in one year after EOD. The reason for such low prediction of setup, comparing to measured setup, could be mainly due to the difference in pile size, the depth of pile embedment, and the sensitivity of soil. The maximum pile dimension (width or diameter) of the external data used by Ng et al. (2013) for validation ranged from 244 to 750mm with area ratio, AR (i.e., the ratio between pile embedded surface area and pile tip area) ranged from 115 to 278. In contrast, the pile diameter and AR of the piles at the subject field were 2130mm and 1226, respectively.

Randolph (2013). Analytical solutions for radial consolidation, following insertion of a solid object such as pile or piezocone, give the normalized excess pore pressure, $\boldsymbol{U = \Delta u/\Delta u_{initial}}$, as a function of a non-dimensional time $\boldsymbol{T = C_h t/D^2}$, where C_h is the consolidation coefficient (Randolph and Wroth, 1979). For rigidity index (I_r) (the ratio between shear modulus and undrained shear strength) of 100, the relationship between U and T may be approximated by

$$U = \frac{1}{1 + \left(\frac{T}{T_{50}}\right)^{0.75}} \tag{5}$$

Where T_{50} is the time for 50% dissipation and is about 0.6. The corresponding value of T_{90} is about 12. For an open-ended pile, the outer diameter, D, should be replaced by the equivalent diameter, D_{eq}, so that T_{50} is defined as

$$T = \frac{C_h t}{D_{eq}^2} \tag{6}$$

The average R_{EOD} at final pile penetration was about 20% of the long-term static capacity as per API RP-2A. Therefore, the equation for predicting the percentage of the ultimate pile capacity at any time after EOD, R_t and pile setup can be written as

$$\frac{R_t}{R_{ult}} = 0.2 + 0.8(1 - U) \times 100 \tag{7}$$

The C_v values from consolidation tests for the subject field varied from 0.0009cm^2/sec to 0.0019cm^2/sec. No pore pressure dissipation tests were available for estimating C_h. The value of C_h is generally higher than C_v. The ratio between C_h and C_v at which the predicted setup was found to be matching the estimated setup from CAPWAP was 3.0, with an average C_v of 0.001cm^2/sec. The degree of consolidation with the time was predicted from equation-5, as shown in Figure-8. The predicted setup using equation-7 was compared with CAPWAP estimated setup as shown in Figure-9

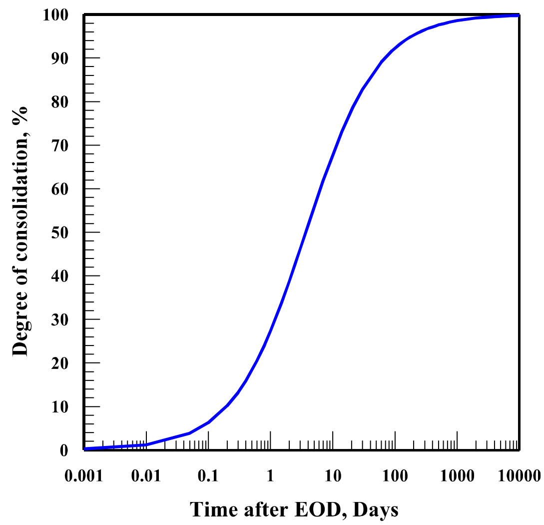

Fig. 8. Degree of consolidation vs Time

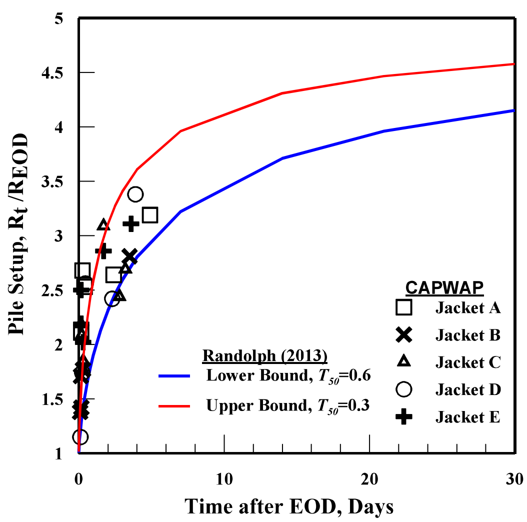

Fig. 9. Predicted vs CAPWAP Estimated setup

The C_h value of 0.003 cm^2/sec used in the above setup prediction was less than the range of 0.006-0.03 cm^2/sec used by Randolph (2013) to match the setup data measured on bigger diameter piles of 2.1 to 2.7m driven into high plasticity clays (Dutt et al., 2009) in the Gulf of Mexico and offshore West Africa. The T_{50} value of 0.6, proposed by Randolph (2009) for I_r of 100 is more than the range of 0.2 to 0.3 suggested by Teh and Houlsby (1991) for I_r range 25 to 500. The CAPWAP estimated setup values for the subject field were found to be falling within the predicted setup curves with T_{50} = 0.6 (Lower bound) and T_{50} = 0.3 (Upper bound)

Dutt et al. (2009). Based on hindcast wave equation analyses of the pile driving data of large diameter offshore piles driven into high plasticity clays, Dutt et al. (2009) proposed predictive setup curves and, concluded that the observed increased rates of setup suggest that the radial extent of soil disturbance for large diameter piles is confined to the soil very near the pile wall, so that the pile diameter does not influence the geometry of excess pore pressure field and the rate of pore pressure dissipation. Thus, the soil behavior approaches that observed to flat plates of equivalent thickness. About 60 to 80% of ultimate capacity was reported in 7 days with 100% setup in about 60days.

The CAPWAP estimated setupvalues for the subject field were found to be falling within the predicted setup curves as presented in Figure-10

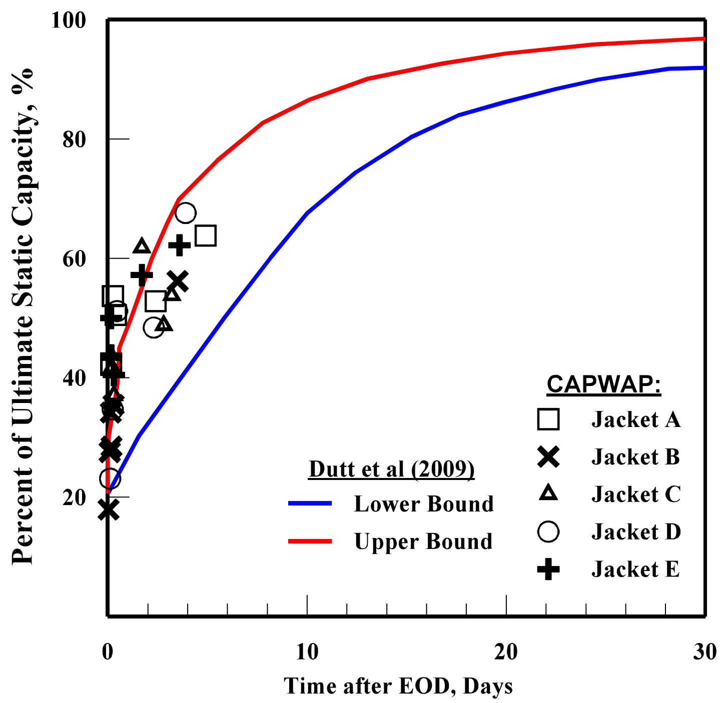

Fig. 10. Predicted Setup vs CAPWAP Estimated Setup

4 Conclusions

The maximum pile setup that can be predicted for stiff to very stiff clays using Ng et al. (2013) is 1.5 in one year after EOD. The proposed method is not valid for large diameter piles driven into stiff to very stiff high plasticity clays with sensitivity more than 1.5.

The predicted setup using Randolph (2013) matched the estimated setup from CAPWAP with the back-calculated C_h/C_v value of 3 and T_{50}range of 0.3 to 0.6.

The predicted setup using Dutt et al. (2009) matched the estimated setup from CAPWAP.

Authors would believe that either predictive setup models, Randolph (2013), Dutt et al (2009,) may be considered for predicting pile setup for large offshore pipe piles installed in soils similar to the field studied. More comparative studies, by using C_h and C_v determined either from pore-pressure dissipation tests in the field or consolidation tests in the laboratory, will improve confidence in using these predictive setup models

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