Contributing factors on soil setup and the effects on pile design parameters

Facteurs contribuant au durcissement du sol et leur effet sur les paramètres de conception des pieux

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ABSTRACT: Most of the pile setup studies in literature have focused on the variations of total capacityand/or tip and skin friction resistances. But it is of practical importance to propose realistic parameters for design applications such as pile shaft resistance β-parameter. Pile dynamic (PDA) and staticload test results are available for 5% of total of 6000 drivenpre stressed spun piles with OD of 450 mm at a petrochemical utility plant in southwest Iran.The range of β-parameter for each of the three layers along which the piles are embedded are determined for design applications in the regionwith back-calculationfromdynamic tests results at restrike. An axisymmetric finite element numerical model isused to simulate the cavity expansion developedduring pile driving and corresponding generation of excess pore water pressure (EPWP). The setup effects are evaluated allowing sufficient time for dissipation of EPWP and simultaneous increase in radial effective stresses along the pile shaft. The difference between shaft capacity obtained from the back-calculated β of the field data and that from the numerical model for EPWP dissipation analysisonly, is assumed to be attributed to aging effects. Increase in the interface shear strength between pile-soil with time isconsidered to account for the aging component of the soil setup. The results show that the dissipation of EPWP has been the dominant factor in soil setup corresponding to increase in the frictional resistance of the pile shaft of the study area in which 75% has been resulted from radial cosolidation (EPWP dissipation) and 25% from aging.

RÉSUMÉ : La plupart des études configuration de pieuxdans la littératureontmisl'accentsurles variations de la capacitétotale et / ou la pointe et les résistances de frottementlatéraldans le temps. Maisilestd'une importance pratique de proposer des paramètresréalistes pour les applications de conception telles le paramètre β décrivant la résistance de fût. Des essaisdynamiques (PDA) ainsique des résultatsd'essais de charge statiquesontdisponibles pour 5% des 6000 pieux de bétonpréfabriquésprécontraint d'un diamètreextérieur de 450 mm dansuneusinepétrochimique du sud-ouest de Iran. La plage des valeurs du paramètre β pour chacune des trois couches le long desquelles les pieuxsontenfoncésestdéterminée pour les applications de conception dans la région à partir de rétro-calculsd'après les résultatsd'essaisdynamiqueslors du rebattage. Un modèlenumérique par éléments finis axisymétrique estutilisé pour simulerl'expansion de la cavitédéveloppée au cours du battage de pieux et de la production correspondante de la pressiond'eauinterstitielle en excès (EPWP). Les effets de mise en place sontévaluées en permettant un temps suffisant pour la dissipation de l'augmentation de la pressiond'eau et l'accroissementsimultané des contraintes effectives radiales le long du fût du pieu. La différence entre la capacité de fûtobtenued'après les valeurs de β rétro-calculées à partir des données de terrain et cellesobtenues à partir du modèlenumériqued'analyse de dissipation de la pressiond'eauinterstitielle, estsupposéêtreattribués à des effets de vieillissement. L'augmentation de la résistance au cisaillementd'interface entre le pieu et le sol en fonction du temps supposétenircompte de la composante du vieillissement du durcissement du sol. Les résultatsmontrentque la dissipation de la pressioninterstitielle a été le facteur dominant dans le durcissement du sol correspondant à l'augmentation de la résistance de defûtdans la zone d'étudeoù 75% de l'augmentationestattribuable à la consolidation radiale (dissipation de la pressiond'eauinterstitielle) et 25% au vieillissement.

KEYWORDS: pile driving,numerical modelling,effective stress analysis, soil setup, aging, PDA test, cavity expansion

1 INTRODUCTION

Driven piles are frequently used in industrial projects in southern lowlands of Iran near Persian Gulf.One of the important issues in driven piles is variation of bearing capacity with time after the initial drive. This important issue is well-understood in literature and it is pointed out that depending on the soil type, either “soil setup” or “soil relaxation” may occur with time. Soil setup results in eventual increase in the pile capacity, whereas in the soil relaxation condition, the bearing capacity decreases with time.

Different reasons are stated for these phenomena and the types of soil in which either of the setup or relaxation may occur (Svinkin, 1996; Seidel and Kolinowski, 2000; Rausche et al., 2004; Bullock et al., 2005 and 2005b).In majority of reported cases however, the setup has occurred and relaxation has seldom been reported (Komurka et al., 2003; Axelsson, 2000). The bearing capacity variations are observed to be rapid with time initially, the rate of which substantially decreases with time elapse.

The stated reasons for setup can be summarized as: (1) generation of excessive pore water pressure during pile driving and subsequent dissipation with time, (2) aging. Most of the studies available in literature, however, have focused on pile capacity variation with time and it is stated that (for example by Svinkin, 2000) the most portion of setup is related to dissipation of effective pore water pressure. Little attention has been paid on distinguishing between the contribution of dissipation of EPWP and aging.

The main objective of this study is a numerical approach to study the setup effects on a single pile embedded in layered strata on the basis of back-calculated parameters from an industrial unit in southwest Iran. An axisymmetric nonlinear finite element scheme is adopted to simulate the cavity expansion as a result of pile driving and its subsequent dissipation of EPWP and aging effects. A case in fajr II utility have been carried out at End of Initial Drive (EOID) and, after 13 days, at Beggining of Resrtike (BOR) condition is selected to study the different components contributing to the setup effects.

2 CONSTRUCTION SITE AND TESTS

Fajr II is a 32-hectar utility plant in PetZone of Mahshahr, located in southwes Iran near Persian Gulf. The site accommodates a power plant, pre-treatment and treatment water units and air unit. Different types of precast and prestressed driven concrete piles at a total of nearly 7000 points have been constructed within the past three years. About 6000 points include 450 mm outside diameter prestressed spun piles with a wall thickness of 80 mm and closed-toe. The spun piles have been driven with Kobe-35 and Kobe-45 diesel hammers, or equivalents, down to embedment depths ranging between 14 through 22 m. The dominant soil layering across the construction site is a very soft to stiff silty clay, average of 15 m thick (layers I & II), overlain a medium dense to dense sand, 4 to 8 m thick (layer III). The pile tips are mostly embedded within the sandy layer. Table 1 shows the geotechnical parameters for construction site layers.

Nearly 5000 spun piles, 450 mm OD were driven to support 12 water tanks. Pile dynamic tests (PDA) and static load tests were carried out on 30 test piles & 221 construction piles, including, respectively, 54 & 251 PDA tests and 4 & 32 compressive static load tests. Static and PDA tests procedure comply with general guidelines and specification of ASTM D1143 and D4945, respectively. Some of the comparisons between static and dynamic load tests are presented in Fakharian et al. (2012). In fact about 5% of the construction piles were PDA tested and average of 2 piles were static load tested at each tank. With support of the test program, the factor of safety was lowered to about 2 to 2.2 and sometimes as low as 1.8, that resulted in considerable savings compared to previous projects in the region. The construction challenges and cost savings are presented in more details by Fakharian et al. (2012).

Further information about tank details, test piles and borehole location, pile arrangement and No. of construction pile tests can be found in Sarrafzadeh et al. (2012).

The dominant soil layering in the 32-hectar site is highly variable but classified in three layers, from top to bottom respectively, layer 1 with 8 m thickness as soft clay, layer 2, 7 m thick as medium stiff to stiff clay, and layer 3, sand down to 20 m. The incremental and cumulative shaft capacities from CAPWAP analysis are available, from which, β-factor versus depth is back-calculated. All the data points of five tanks were put together and the results are presented in Fig. 1.

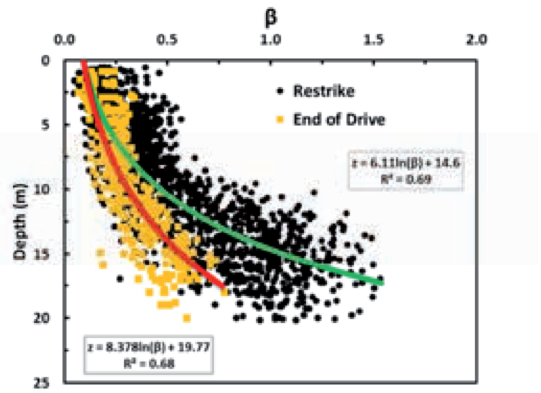

Figure 1.β variation with depth at EOD and Restrike for all tanks.

The lower and upper bounds of β-values and the average trend lines are plotted in Fig.2. The average trend line can be represented by empirical Eq. (1):

$$\beta = e^{\frac{z-14.6}{6.11}} \qquad (\beta < 1.5) \qquad (1)$$

in which, z (in m) is depth from ground surface.

Similarly, Eqs. (2) and (3) represent the upper bound, β_u, and lower bound, β_l, respectively. The β parameter variation with depth value is limited to 1.5 in all equations.

$$\beta_u = e^{\frac{z-11}{7.5}} \qquad (\beta < 1.5) \qquad (2)$$

$$\beta_l = e^{\frac{z-20}{5.5}} \qquad (\beta < 1.5) \qquad (3)$$

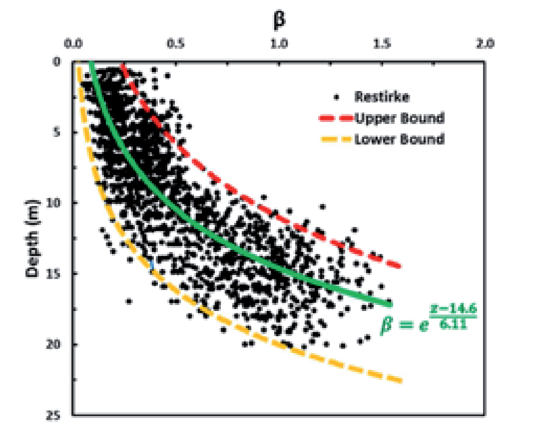

Figure 2. Mean β and lower and upper bounds at restrike.

3 NUMERICAL MODEL AND VALIDATION

Test pile No. 11 with 15.4 m embedment length is selected for modeling, PDA test was performed at End of Initial Drive (EOID) and, after 13 days, at Beggining of Resrtike (BOR) condition. an elastic isotropic cylindrical pile with radius of 225.5 mm and 15.4 m length has been generated using the FEM numerical package ABAQUS, in 2D axisymmetric condition. Elasto-perfectly plastic model has been considered for the soil material. Therefore, the required parameters for the elastic part include elastic modulus, E, and Poisson's ratio, ν, and Mohr-coloumb strength parameters for the shear failure. The soil surrounds the pile shaft with a radius of 5 m and length of 15.4 m. The brick soil elements have been generated 2.5x2.5cm adjacent to the pile skin with gradual increase in size to reach a maximum dimension of 2.5x12.5cm at the vertical boundary. The pile shaft is simulated by 2.5x2.5cm solid elements. Table 1shows the specified parameters for both pile and soil material.

Table 1. Soil and pile parameters in numerical model (for TP 11)

Layer #	Soil type	Depth (m)	γ' (kN/m³)	E (MPa)	K (m/s)	C (kPa)	φ'
I	Soft clay	0-7.4	10	20	1×10^{-9}	27	0
II	Medium to stiff clay	7.4-12.4	10	20-50	1×10^{-9}	27	0
III	Medium dense to dense sand	12.4-15.4	10	50	1×10^{-8}	1	30
Pile	Concrete	15.4	14	20,000	-	-	-

The solid element CAX4RP has been used for which simultaneous measurements of PWP and stress-strain are possible. It is assumed that drainage is possible from the ground surface only. Therefore, the top horizontal boundary was specified as a zero pressure surface. Interface elements were specified at the pile-soil contact surface. The interface parameters were specified as tangential interface.

The pile installation process has been simplified to an eventual expansion of the soil from a zero radius up to the 225.5 mm. In other words, cavity expansion has been simulated in axisymmetric condition, therefor effects of eventual pile shaft penetration are not considered in this study. The PWP at the end of cavity expansion (U_0) has the maximum magnitude, corresponding to t=0 in the presented results.

Validation of the numerical model was done by comparing the numerical model results with the results of instrumented case that is reported by Konrad and Roy (1987).It is noticed that the numerical model predictions compare reasonably well with measurements.For example, Figs. 3 representthe dissipation of EPWP resulted from driving at depth 6.1 m with time. The EPWP at any time t (U_t) is normalized with U_0 and expressed in percentage. Therefore U_t/U_0 at t=0 is 100% and supposed to approach 0 at sufficiently long periods of time, depending on the permeability of the soil material. More details of verification process may be found in Haddad et al. (2012).

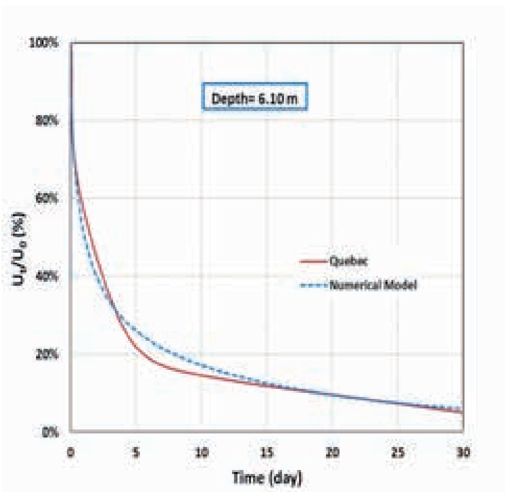

Figure 3.Dissipation of EPWP with time resulted from pile driving at depth 6.1 m.

4 ANALYSIS RESULTS

The main focus of this study is effect of setup on skin friction. The important factors contributing to variation of skin friction with time are radial effective stress and PWP adjacent to the pile shaft, as far as the effect of dissipation of EPWP is concerned. To account for aging effects, the interface shear strength parameters have been considered. The interface strength parameters have been specified applying the β′ reduction factor introduced by Fakharian and Iraji (2010) as:

$\tau_{int} = \beta'(c' + \sigma \tan\varphi')$
in which:
τ_{int}: shear strength at interface
c′: effective cohesion of adjacent soil
φ′: effective angle of internal friction of adjacent soil

Figure 4 shows the contour lines of effective radial stress along the pile shaft and up to the boundaries both at the end of initial drive (4a) and after 13 days (4b). It is observed that the radial stress has substantially increased as a result of dissipation of EPWP. Similarly, Fig. 5 presents the PWP at the end of initial drive (5a) and after 13 days (5b).Pore water pressure significantly increased due to the compressibility of the soft soil, except close to the ground surface that the dissipation has occurred rapidly due to short distance to the open boundary.

Comparing the results of Figs. 3 and 4 indicate that in zones that higher PWP has been generated at EOID, higher radial effective stress is developed after 13 days that about60% of EPWP has dissipated. Figure 6 presents the variation of effective radial stress with time between initial *in situ*condition up to end of EPWP dissipation along the pile shaft. It is of importance to note that the effective radial stress at EOID is considerably greater than initial *in situ* condition. This could be attributed to passive stress path outside the expanded cavity zone, indicating compaction of the soil. This requires further investigation with more advanced constitutional models and field measurements. The change in variations at depths of 7.4 and 12.4 m is because of soil layer differences.

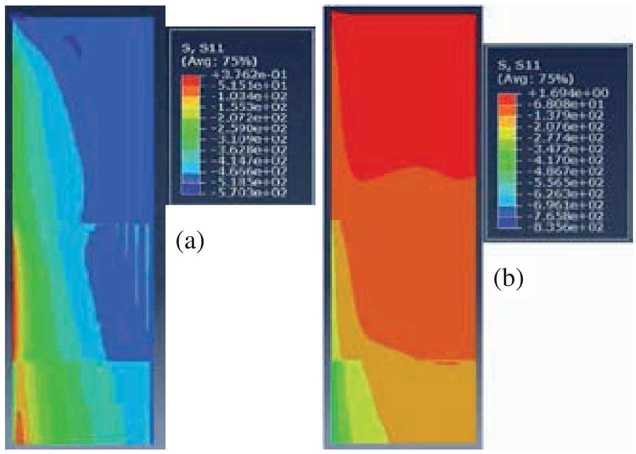

Figure 4.Radial effective stress distribution innumerical model: (a) EOID, (b) BOR after 13 days.

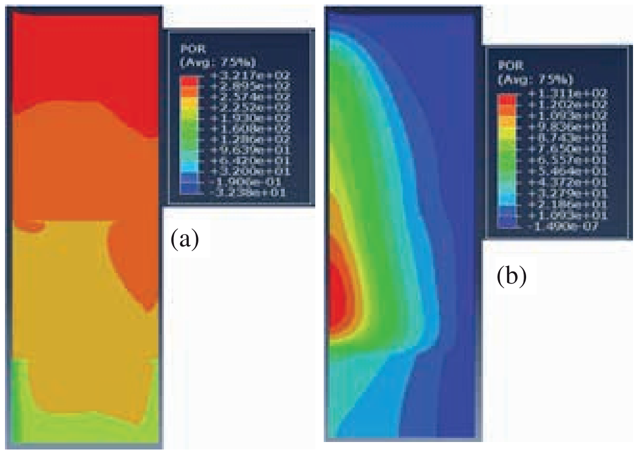

Figure 5.Excess pore water pressure distribution in numerical model: (a) EOID, (b) BOR after 13 days.

The main objective of this study has been attempting to distinguish between dissipation of EPWP and aging. As an example, variation of shaft capacity with respect to time are plotted in Fig. 7, resulted both from the back-calculation of field PDA tests and model predictions. The PDA test results are available for EOID and 13 days, depicted in Fig. 7 by for four solid square symbols.

In the numerical model, adopting a β′ of 0.235 has resulted in a good match between the EOID ofPDA test and model prediction. In other words, after the simulation of initial drive (cavity expansion), as an EOID condition, β′ was adjusted till the predicted and measured capacities have a good correlation. Then dissipation was allowed for 1, 4, 13 and 50 days (with the same β′) and the shaft capacity is calculated. The shaft capacity results from this procedure are plotted with green solid line (circled symbols) betweenEOID to 50 days. Considerably lower capacities are resulted compared to the measured capacities. This difference is thought to be attributed to the so-called aging effects.

To account for the aging setup effects, the interface frictional resistance coefficient, expressed by β′ factor in this study, has been increased until correlations are obtained between predicted and field measurements. This has been shown by the blue line in Fig. 7. The difference between the two green and blue lines in figure is assumed to be representing all the contributing factors to soil setup that are not effective-stress related. Such factors are referred to as "aging" in this study, and as explained, the β′ factor is assumed to account for it. Figure 7 shows that the contribution of dissipation of EPWP is 75% while the contribution of aging is 25%.

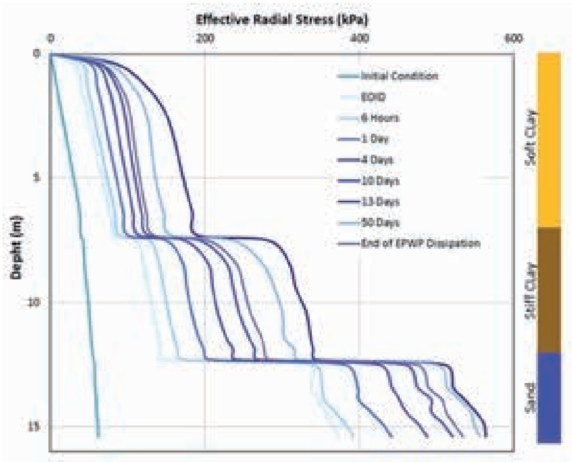

Figure 6.Radial effective stress changes with timealong the pile shaft.

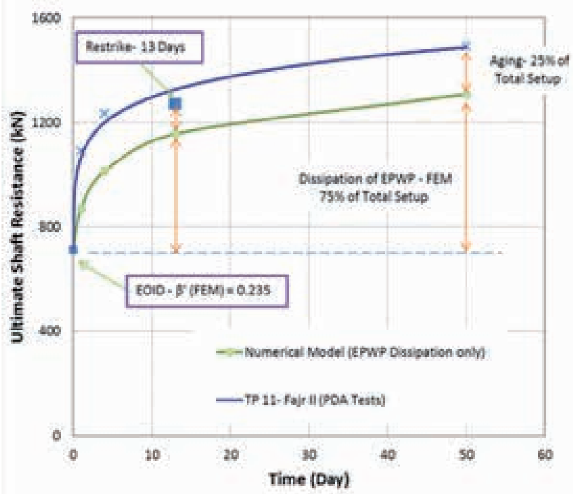

Figure 7.Increase in pile shaft capacity in numerical model.

5 CONCLUSION

The construction site ofFajr II utility plant,Mahshahr, Iranis selected to study the different components contributing to the setup effects using an elasto-perfectly plastic axisymmetric FEM model. Theadopted FEM model is capable of effective stress analysis and consideration of PWP effects and has been used to simulate the cavity expansion resulted from pile driving and subsequent dissipation of EPWP. The focus of study was to distinguish the effective stress-dependent and independent factors influencing the setup in layered strata. The findings of the study are listed below:

-An empirical equation for calculation of shaft capacity after setup is presented for the study area.Two equations also are proposed as upper and lower bounds.

- The numerical model predictions compare well with field measurements.

-The generation of EPWP as a result of cavity expansion and subsequent dissipation with time has been predicted reasonably well.

-The variation of interface shear strength reduction factor, β′is considered to represent the setup component attributed to aging.

-In the layered media of the study site, the contribution of dissipation of EPWP and aging to soil setup has been estimated 75% and 25%, respectively, at about 50 days after initial drive.

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