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Study on the Effects of Pile Group for the Installation of an Oil Platform, Offshore Vietnam

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ABSTRACT

The paper presents the study results of the effects of pile group on the general performance of the offshore oil platform installed using skirt piles. Group of 3 piles per corner of the oil platform was installed close to each other with a spacing S/D less than 8 (the limit distance within which piles will interact with each other) and it was found that the capacity performance of the pile group was not necessarily the total of capacity of each individual pile. The pile group was installed in an offshore area with water depth of 115m and was driven to 112.4m below seabed. The pile diameter was 2134mm. The soil investigation work included 150m borehole and cone penetration testing with pore water pressure measurement also to 150m. The axial and lateral effects of pile group were analyzed using the method proposed by Poulos and the ultimate capacities of the pile group and the corresponding pile group efficiency factors were determined using the equivalent pier (block failure) concept and Poulos method. The results obtained would be necessary and very important for the determination of the available capacity that the pile group would be able to sustain and therefore, optimized design regarding technical and economic issues could be achieved.

Keywords: pile group effects, offshore platform, axial capacity, lateral capacity

1. Introduction

In the offshore oil industry, oil is prospected using drilling platforms. These platforms are built at onshore manufacturing facilities and installed in the middle of the sea. In order for those platforms to withstand environmental loads (storm loads, normal operating loads, etc.), they must be fixated to the seabed by piling activities (i.e using piles to stabilize the structure). Normally, the piles are installed at each corner of the drilling platform with each corner having at least 2 piles (also called skirt pile) to meet the axial and lateral capacity requirements from design step. However, the capacities of the pile group is not always equal to the total contribution of each pile because of an effect which is called pile group effect. This effect indicates that if the piles are installed in proximity to each other, each of the pile will influence on the behaviour of the other piles in the group (Focht et al, 1973; Poulos, 1980). Hence, it is important to know this effect to design the piles to have the required capacity to withstand the environmental loads during the structure's lifetime and ensure the safe and economical solution. In this paper, the pile group effect of a 03-pile group with each pile having the outer diameter of 2134mm will be analyzed and discussed.

2. Theoretical Background and Methodology

Pile group effect may be divided into lateral and axial effect on pile-soil deflection behavior and pile capacity. The pile group effect on shallow lateral pile-soil deflection behavior, i.e., p-y response, is more crucial and considered firstly in the following.

The lateral response of the pile group was analyzed by using the so-called "Combined Poulos P/Y Method" (Focht et al, 1973). In general, the method is a solution of

$$y_G = y_s + y_g \quad (1)$$

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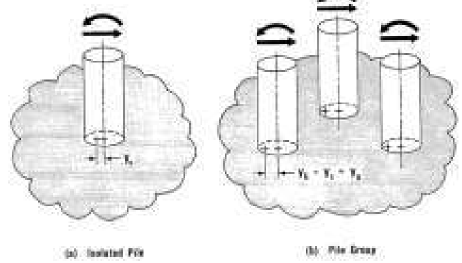

Figure 1. Lateral pile displacement

The added deflection is due to the superpositioning of elastic stresses in the soil mass from the lateral loads carried by other piles in the group. Increased deflections of a group result in bending stresses greater than in a single pile, which must be taken into account by the designer (Focht et al, 1973). By computing ys by a nonlinear p-y analysis for single pile and yg by a modification of elastic pile group analysis with lateral interaction factors proposed by Randolph (1981). This may be further written as:

$$y = y_F\left(\sum_{\substack{j=1\\ j\neq k}}^{m} H_j\alpha_{kj} + RH_k\right) \quad (2)$$

Where:

y is the displacement of pile k

y_F is the displacement of a single-pile under unit horizontal load

Hj is the load on pile j

α_{kj} is the lateral interaction factor between pile k and j (=ratio of additional deflection caused by adjacent pile deflection of pile under its own load).

R is the ratio of single pile displacements calculated by nonlinear p-y analysis and Poulos' elastic analysis

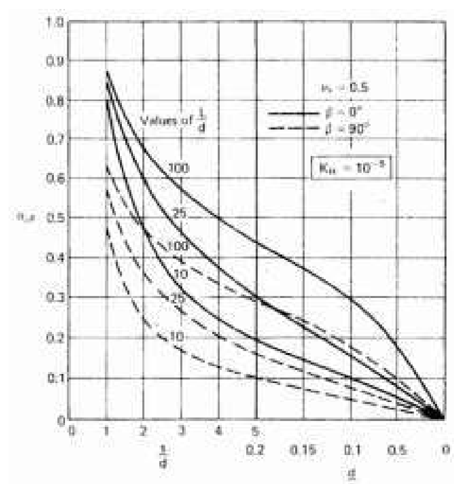

Figure 2. Graph for determination of α (Poulos, 1980)

3. Offshore project information

A comprehensive offshore geotechnical site investigation has recently been performed around the proposed platform site, including 150m sampling/PCPT borehole The subsoil conditions for the platform design comprise mixed CLAY and SAND layers to 150.0m depth. The CLAYs are mostly firm to stiff in consistency whereas the SANDs are medium dense to dense in state.

Axial pile capacity curves and pile-soil deflection data including T-z/Q-z/p-y were generated based on the API PR-2A WSD for the proposed 84-in. OD piles. The piles derive axial capacity from two sources:

i. Frictional soil resistance along the shaft length of pile;
ii. End bearing at the tip of pile.

Pile end bearing capacity was also modified for pile in transition penetrating from clay to sand and from sand to clay for 2D and 3D depth, respectively. These are consistent with the current industry practice. For the target penetration of 112.4m, the ultimate axial compressive pile capacities are summarized as below:

Table 1. Summary of Single Pile Capacities at 112.4m Penetration

Axial Pile Capacity	84-in. OD Pile
Skin Friction in CLAY (MN)	34
Skin Friction in SAND (MN)	25.1
Total Friction (MN)	59.1
End Bearing Capacity (MN) in SAND	42.9
Total Pile Capacity (MN) – Tip in SAND	102

The spacings (S) between pile centres for each 3-pile group are summarized in Table 2.

Table 2. Summary of pile spacing within a pile group

Pile Group	P1-P2	P2-P3	P1-P3	Average (around P1)
3-Pile Group	4.69m (S/D=2.20)	4.69m (S/D=2.20)	7.91m (S/D=3.71)	5.76m (S/D=2.70)

It can be seen that the ratios of pile spacing to diameter are well less than 4 for axial loading case (O'Neil, 1983) and less than 6 for lateral loading case (Poulous, 1980). Hence the group effect should be considered

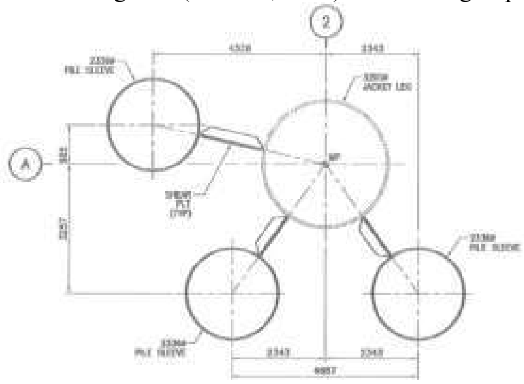

Figure 3. Details of pile spacing

The maximum load data are provided from the structural analysis as in Table 3.

Table 3. Max loads imposed on each pile

Pile Group	**Axial Force**		**Lateral Force**	
	Pile/Leg (Storm)	**Max Force (kN)**	**Pile/Leg (Storm)**	**Max Force (kN)**
3-Pile Group	P3/Leg B2	-39110	P9/Leg A2	5089

It may be concluded that due to a very small rotation angle at the pile-heads the pile groups could be considered as being fixed-head condition, though pile-head condition may be considered as restricted head condition with a small rotation.

The piles are designed to have a variable wall thickness and a penetration of 112.4m below mudline.

To derive appropriate y-factors for structural analysis, the calculation procedure specific to the subject location includes the following steps:

1) Calculation of the non-linear lateral response for a laterally loaded single pile under the given load and pile-head conditions, using the p-y data recommended by API RP 2A and the computer program LPILE;

2) Estimation of the pile interaction factors of the piles in the group, based on the geometry of the pile group, the soil stiffness/modulus and load direction, using the Randolph (1981);

3) Estimation of the lateral response of the pile group, using the simple calculation model presented in Equation [2] and the computer program PIGLET;

4) Calculation of pile displacement of the pile group using the results of Steps 2 and 3;

5) Calculation of y-factors for the cyclic p-y data using the results of Step 4.

Calculated results show that the lateral group response and corresponding y-factors are dependent on the group geometry, load magnitude, load direction and pile-head condition.

For all the calculations, the following assumptions were made:

i. The group load was taken to be equal to the number of the piles in the group multiplied by the corresponding maximum lateral single pile load value

ii. Load direction on the pile group from in the most conservative direction, i.e. load direction is the same as the direction of pile-to-pile center line ($\beta = 0$)

iii. All pile heads of a group have the same lateral deflection with fixed-head conditions
iv. Due to the jacket superstructure restraints by employing top and bottom yoke plates and shear plates between piles and jacket leg.
v. Pile heads at seafloor level
vi. Local scour was considered to a depth of 1.0*D

Based on the analysis procedure, there are two parts of soil parameters involved, the nonlinear part related to the p-y data and linear part related to the averaged elastic Young's modulus E_s for the laterally loaded pile. The Young's modulus (E_s) for the lateral group displacement was estimated as the weighted average of Young's moduli of all layers up to a depth of about 1/3 of the pile length. The Young's modulus for each layer was calculated according to E_s = 225*Su for clay and E_s = 4.5*cone resistance (q_c) for normally consolidated sand. The q_c was taken from CPT data recorded. The Young's moduli are summarized in Table 4.

Table 4. Summary of Young's modulus at subject location

Layer	Depth (m)	Soil Type	S_u (kPa)/ q_c (MPa)	E_s (MPa)
1	2.1 – 3.9	Clay	16 - 30	5.2
2	3.9 – 27.8	Sand	6	27
3	27.8 – 36.7	Sand	5	22.5
4	36.7 – 44.8	Clay	50 – 60	12.4
			Weighted Average	**21.9**

3.1. Lateral Load-Deflection Behaviour of Pile Group

The lateral pile interaction effect is due to overlap of stress in the soil around the loaded piles. The lateral pile group effect can be assessed using the Combined PY-Poulos Method with the interaction factors (α) according to Poulos (1980).

The various parameters calculated for the proposed pile groups are summarized in Table 5. It should be noted that an average wall thickness for 1/3 pile length was used for these calculations though the piles have a variable wall thickness along pile length. However, the actual variable wall thickness was used for the single pile analysis with LPILE.

Table 5. Summary of parameters for lateral pile group analysis

Item	84-in. OD Pile
Pile Modulus E_p, kPa	$2.1\text{x}10^8$
Wall thickness t, mm	56
Moment of inertia I_p, m^4	0.197
Penetration to diameter ratio L/d	52.7
Pile flexibility factor K_r	$1.18\ \text{x}10^{-5}$
Influence factor I_{pH}	18
Pile flexibility P_f	$7.31\ \text{x}\ 10^{-6}$

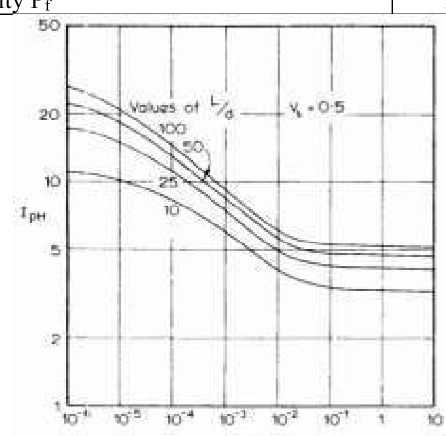

Figure 4. Graph for determination of I_{pH}

The pile head horizontal deflection under the maximum horizontal force by the Poulos elastic method is calculated as $D_{pou} = I_{pH}H/(E_sL)$.

The corresponding head deflections of single pile for site-specific p-y can be estimated by performing a single pile analysis routine in LPILE using the given maximum lateral forces as summarized in Table 7 below:

Table 6. Pile head deflection calculated

Item	3-Pile Group
Pile head force maximum (H_{max}), kN	5089
Deflection from single pile analysis LPILE (D_{sp}), m	0.039
Deflection by Poulos method (D_{pou}), m	0.037
Ratio R = D_{sp}/D_{pou}	1.05
Deflection from pile group (D_g), m	0.056

Note that due to the superstructure constraints the load distribution among the pile heads in the pile group is not even.

The group effect can be modeled by using a Y-factor for the p-y data. The Y-factor is a multiplication factor for all y values of the p-y data. The Y-factor was calculated by applying a range of y-factors to the non-linear soil resistance-deflection relationship (p-y data). The Y factor that matches the deflection of the pile group is the Y-factor that equals the group defection for the individual load on the pile. For each pile in the pile group a Y-factor was calculated. The resulting Y-factor of lateral pile group effect calculated is presented on Figure 5.

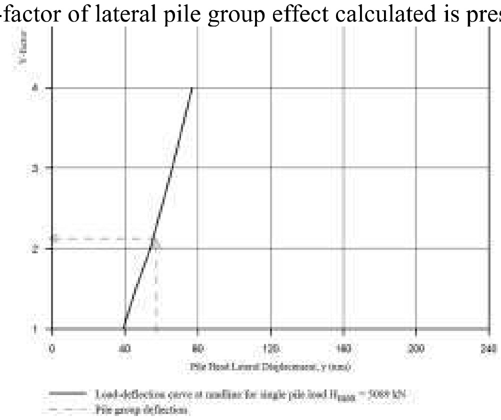

Figure 5. Results of lateral pile group effect analysis

3.2. Axial pile group effects

The axial pile group effect may include the effect on axial pile-soil deflection and on pile group capacity, though such effect may not be substantial for offshore long piles. The axial response of the pile group was analyzed by also using the so-called "Combined Poulos-P/Y Method" (Focht, 1973). In this case the p-y data was certainly replaced by the t-z data.

The Young's modulus for each layer was calculated according to E_s = 450*Su for clay and E_s = 4.5*cone resistance (q_c) for normally consolidated sand. Table summarize the moduli for axial pile group analysis.

Table 7. Summary of Soil Modulus Estimated for Axially Loaded Pile

Layer	Depth (m)	Soil Type	S_u (kPa)/ q_c (MPa)	E_s (MPa)
2	2.1 – 3.9	Clay	16 - 30	10.4
3	3.9 – 27.8	Sand	6	27
4	27.8 – 36.7	Sand	5	22.5
5	36.7 – 44.8	Clay	50 – 60	24.8
6	44.8 – 53.9	Clay	60 – 80	31.6
7	53.9 – 80.0	Clay	80 – 130	47.3
			Weighted Average	**32.9**

The pile head deflection/settlement (S_{pou}) under the maximum vertical force (V_{max}) by the Poulos elastic method is calculated as

$$S_{pou} = \frac{VI}{E_S D} \quad (3)$$

Where:

I is the combined correction factor = $I_0 R_k R_h R_v$

I_0 is the settlement-influence factor for incompressible pile in semi-infinite mass

R_k is the correction factor for pile compressibility
R_h is the correction factor for finite depth of layer on a rigid base
R_v is the correction for soil Poisson's ratio

Table 8. Pile Head Deflections/Settlements Calculated

Item	3-Pile Group
Pile head force (V_{max}), kN	39110
Settlement from single pile analysis APILE (S_{sp}), m	0.036
Settlement by Poulos method (S_{pou}), m	0.019
Ratio $R = S_{sp}/S_{pou}$	1.92
Deflection from pile group (S_g), m	0.047

The group effect can be modeled by using a z-factor for the t-z data while keeping the same q-z data. The Z-factor is a multiplication factor for all z values of the t-z data. The Z-factor was calculated by applying a range of Z-factors to the non-linear soil resistance-deflection relationship (t-z data). The Z-factor that matches the deflection of the pile group is the Z-factor that equals the group deflection for the individual load on the pile. For each pile in the pile group a Z-factor was calculated. The resulting Z-factor is presented in Figure 6.

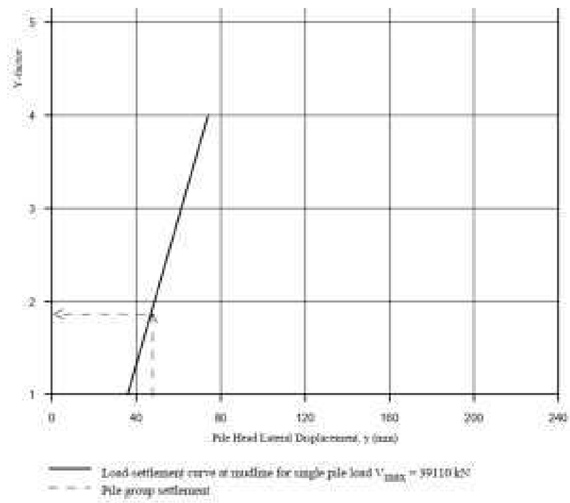

Figure 6. Results of axial pile group effect analysis

3.3. Load Capacity of Pile Group

For assessment of pile group load capacity for a pile group with a spacing ratio of 3 to 8 due to overlap of stresses among the loaded piles, a group efficiency factor may be used to compare the ultimate axial capacity of a pile group comprising n piles and the ultimate capacity of n single piles. Depending on the pile group configuration, embedment depth and the soil strata, the group capacity may not be the same as a single isolated pile capacity multiplied by the number of piles in the group.

The group efficiency factor (η) of a pile group is defined as:

$$\eta = \frac{Q_g}{nQ_s} \quad (4)$$

Where: Q_g is the axial capacity of the group; n is number of piles in a group and Q_s is the capacity of a single pile.

Based on considerations that the offshore driven piles are open ended and less interactive than for close ended driven piles and these piles have to be installed or embedded in the deep sand layer as well as the conservatism adopted in the study and Figure 7 as proposed by O'Neil (1983), a design global pile group efficiency factor, $\eta = 1.0$ (no reduction in pile capacity), can be reasonably recommended to be applied for the 3-pile group. Alternatively, zero reduction factor may be applied to t values in t-z data for the 3-pile group.

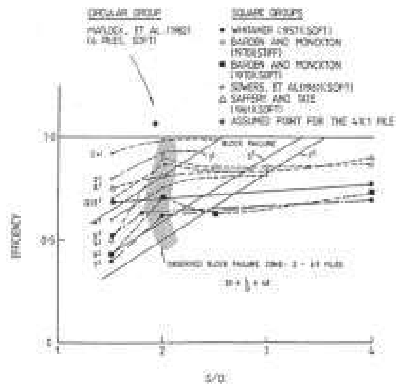

Figure 7. Vertical efficiency for model groups (O'Neil, 1983)

4. Conclusions

It is found from the study in this paper that it is recommended to take into account the effects of pile group when the piles are installed in close proximity with the average spacing ratio (S/D) less than 4 and 6 for the vertical loading case and lateral loading case, respectively, to better predict the actual field behavior and pile performance. The y-factor and z-factor play an important role in facilitating safe and economic design of oil platform structure regarding installation and serviceability purpose. The y-factor and z-factor of 2.07 and 1.87 shall be applied respectively in the structural analyses to have a conservative and safe design of piled foundation.

However, the analyses in this study are applicable to one location only and it is recommended to carry out appropriate survey as well as to derive suitable soil's elastic modulus specific to an installation site to best predict the actual behavior of the pile group. In addition, the results obtained are valid for a certain target penetration depth, it should be re-assessed for the group effects if there are changes in installation depths.

The cases analyzed in the paper are for vertical piles only. For battered piles, there should be further research to study group effects.

Acknowledgements

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TÓM TẮT

Nghiên cứu ảnh hưởng của nhóm cọc cho lắp đặt giàn khoan dầu khí ngoài khơi Việt Nam

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Bài báo trình bày kết quả nghiên cứu về ảnh hưởng của nhóm cọc đến hiệu suất tổng thể của giàn khoan dầu ngoài khơi được lắp đặt bằng cọc váy. Một nhóm gồm 3 cọc tại mỗi góc của giàn khoan dầu được lắp đặt gần nhau với khoảng cách S/D nhỏ hơn 8 (giới hạn khoảng cách mà cọc có thể tương tác với nhau). Kết quả cho thấy khả năng chịu lực tổng thể của nhóm cọc không bằng tổng của từng cọc riêng lẻ. Nhóm cọc được lắp đặt ở khu vực ngoài khơi có độ sâu nước 115m và được đóng sâu 112,4m dưới đáy biển. Đường kính cọc là 2134mm. Công tác khảo sát địa chất bao gồm các hố khoan và thí nghiệm xuyên tĩnh có đo áp lực nước lỗ rỗng tới độ sâu 150m. Ảnh hưởng về khả năng chịu tải dọc trục và phương ngang của nhóm cọc được phân tích bằng phương pháp do Poulos đề xuất, và sức chịu tải giới hạn của nhóm cọc cùng với các hệ số ảnh hưởng nhóm cọc được xác định bằng phương pháp khối tương đương (phá hủy khối) và phương pháp Poulos. Các kết quả thu được sẽ là cần thiết và rất quan trọng để xác định khả năng chịu lực khả dụng mà nhóm cọc có thể duy trì và do đó, có thể đạt được thiết kế tối ưu về các vấn đề kỹ thuật và kinh tế.

Từ khóa: nhóm cọc, giàn khoan ngoài khơi, sức chịu tải dọc trục, sức chịu tải ngang.

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