Simulation of Soil-Pile Interaction of Steel Batter Piles Penetrated in Sandy Soil Subjected to Pull-Out Loads

Ameer A. Jebur, William Atherton, Rafid M. Alkhaddar, Edward Loffill

***Abstract*—**Superstructures like offshore platforms, tall buildings, transition towers, skyscrapers and bridges are normally designed to resist compression, uplift and lateral forces from wind waves, negative skin friction, ship impact and other applied loads. Better understanding and the precise simulation of the response of batter piles under the action of independent uplift loads is a vital topic and an area of active research in the field of geotechnical engineering. This paper investigates the use of finite element code (FEC) to examine the behaviour of model batter piles penetrated in dense sand, subjected to pull-out pressure by means of numerical modelling. The concept of the Winkler Model (beam on elastic foundation) has been used in which the interaction between the pile embedded depth and adjacent soil in the bearing zone is simulated by nonlinear *p-y* curves. The analysis was conducted on different pile slenderness ratios *(lc/d)* ranging from 7.5, 15.22 and 30 respectively. In addition, the optimum batter angle for a model steel pile penetrated in dense sand has been chosen to be 20° as this is the best angle for this simulation as demonstrated by other researcher published in literature. In this numerical analysis, the soil response is idealized as elasto-plastic and the model piles are described as elastic materials for the purpose of simulation. The results revealed that the applied loads affect the pull-out pile capacity as well as the lateral pile response for dense sand together with varying shear strength parameters linked to the pile critical depth. Furthermore, the pile pull-out capacity increases with increasing the pile aspect ratios.

***Keywords*—**Slenderness ratio, soil-pile interaction, winkler model (beam on elastic foundation), pull-out capacity.

I. Introduction

STEEL pile foundations are slender structural elements, underneath massive building and the method has been used since 1800 as a load transferring system from shallow inadequate soil layers to deep bearing soil with a high degree of efficiency [1]-[4]. Steel open ended piles are normally used for facilitating installation in hard strata as well as saving energy required to achieve the design depth and to reduce excessive settlement [5]. It should be noted that pull-out pressure can be developed if superstructures such as basements and dams are built below the water table. Furthermore, skyscrapers, jetting buildings, mats and offshore platforms are normally designed to resist moments and lateral loads as a result of wave impacts, ship impacts earthquake loads etc. [7]-[9]. Additionally, pull-out forces may be induced on the deep foundations due to negative skin friction and swelling of the contact soil in the effective bearing zone [10], [11]. The numerical modelling of the steel model piles penetrated in sand and under the action of the independent pull-out loads are designed as shown in Fig. 1. The method of pile installation adopted in this research is bored pile (replacement pile).

Depending on the sand relative density and pile slenderness ratio, for all piles penetrated in soils the applied pull-out forces are basically transferred to the contacted soil layers by means of the skin friction resistance between soil-pile interaction in the effective radial zone [1]. Extensive research has been conducted on the soil-pile interaction in sandy soil while information on the behaviour of battered piles subjected to uplift load is scarce in the literature and it is not yet fully understood. It has been stressed by [6] that the shaft friction resistance of pile for both the compression and the pull-out is similar. In contrast, [7] has been demonstrated that the skin friction for pile subjected to compression load is higher than for shaft friction in tension by about 12% to 25% due to the reduction in shaft diameter as a result of the poisons' ratio influence. Moreover, a numerical study has also been conducted by [8] to simulate the behaviour of a $30m$ model batter pile at 10^0 subjected to vertical and horizontal loads. An elasto-plastic constitutive model has been implemented in the simulation. Additionally, the pile flexural stiffness and the poisons ratio were 625MNm2 and $\nu = 0.25$ respectively. The results revealed that the applied load had a major impact on the axial and lateral pile behaviour.

The objective of this research is to simulate the combined interaction between sand and model steel open-ended steel model piles by means of numerical modeling. In addition, we examined the concept of the critical pile length (lc) in the effective zone by taking into account the high non-linearity and the complex interaction between sand-pile. We determined the influence of the relevant parameters on the analyses such as soil shear strength parameters, modules of subgrade reaction (k), etc.

II. The Numerical Model

In this paper, FEC has been adopted to simulate the behaviour of the model steel open-ended piles penetrated in dense sand and subjected to independent uplift loads. The pile

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slenderness ratios varied as 7.5,15, 22.5 and 30. Fig. 1 shows the details of the model batter pile. The biggest advantage of the new model is that few predominant factors can be used as input parameters to build the numerical model pile and these factors can be easily determined by conducting quick and simple tests in the laboratory. The high nonlinearity induced from the modelling of the pile-soil interface is overcome by using acceptable levels of repeatability as well as using factors from sensitivity testing.

The Beam on Elastic Foundation model along with the application of the $p - y\ curves$ have been implemented to model the behaviour of the interaction between the pile and the sand. Winkler [9] reported that the elastic soil medium could be replaced by an independent narrowly spaced series of springs. Furthermore, the spring stiffness is equal to horizontal modules of subgrade reaction k_h as shown in (1):

$$k_h = \frac{p}{y} \tag{1}$$

where p is the lateral soil stiffness and y is the lateral pile deflection. The $\mathrm{p-y}$ curve model and the Winkler Model ($Beam\ on\ Elastic\ Foundation$) are defined in Figs. 2 and 3 respectively. The sand specimen is simulated as dry with Youngs Modulus ($\mathrm{E} = 19{,}500\mathrm{kPa}$) and Poissons Ratio ($\nu = 0.26$). The materials of the model piles are described as elastic for the purpose of simulation. For granular soils, k_h increases with increasing soil depth. While, for very dense sand and over consolidated clay $k_h$is remains constant with increasing profile of soil depth. The relationship of $k_h$with the ground depth becomes vital when trying to solve the differential equation that defines the behaviour of an elastic beam is explained in (2):

$$EI\frac{d^4y}{dz^4} + p = 0 \tag{2}$$

EI is the stiffness of the model pile, as mentioned in (1), $k_h * y = p$. Thus, (2) can be rewritten as:

$$\frac{d^4y}{dz^4} + \frac{k_h(z)*y}{EI} = 0 \tag{3}$$

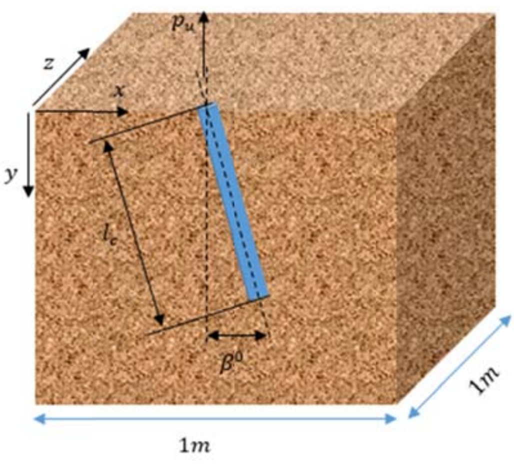

Fig. 1 Model of the batter pile subjected to pull-out load

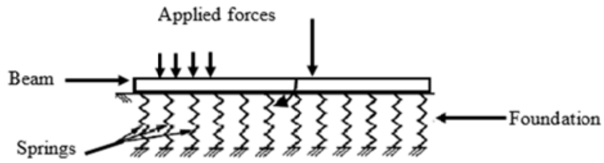

Fig. 2 Beam on Elastic foundation,(BEF), modified after [9]

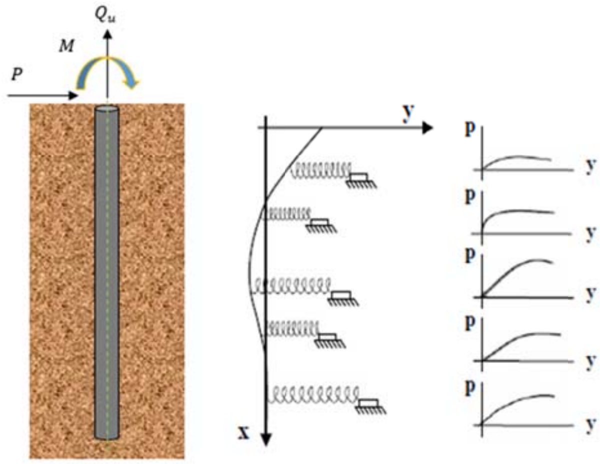

Fig. 3 Soil-pile interaction of a model batter pile subjected to independent uplift and lateral loading based on the p-y curves method, modified after [10]

III. Sand Properties and Sample Preparation

As mentioned previously, one of the advantages of FEC is that few input parameters required and that they can be found from simple laboratory tests. Therefore, some experimental tests were performed on the dry pre-prepared sand. A number of experimental tests were performed on the dried sand and according to the unified soil classification system (USCS) the sand specimen adopted in this research is classified as SP. The ratio between the adopted pile diameter to the minimum medium diameter of the sand (d_{50}) must be at least 45 [11]. While, it has been proposed by [12] that the ratio must be at least 60 times pile diameter. In this research study, the ratio between pile diameters to minimum medium diameter (d/d_{50}) is about (83) matching the above criteria. Fig. 4 illustrates the sieve analysis test for the sand specimen adopted in this constitutive model. The results of the sand-sand direct shear test (the shear stress versus the normal stress and shear displacement) of the dense dry sand specimen are drawn in Figs. 5 (a) and (b) respectively. It can be seen that the maximum shear $14.9kPa$ occurs at displacement equal to $1.25mm$. Furthermore, the chemical, physical properties and the sand morphology are shown in Table I following the procedure listed in the ASTM [13] and Fig. 6.

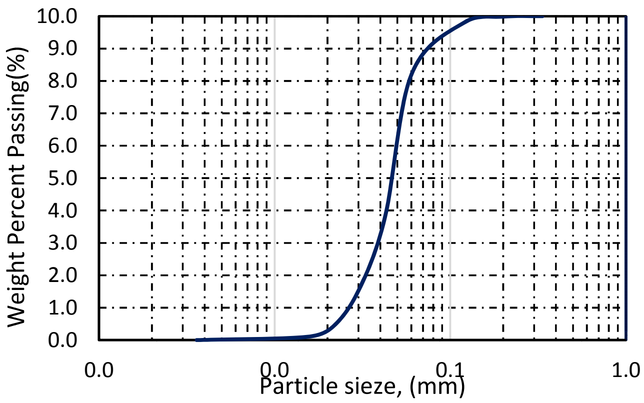

Fig. 4 Particle size distribution curve of the sand sample

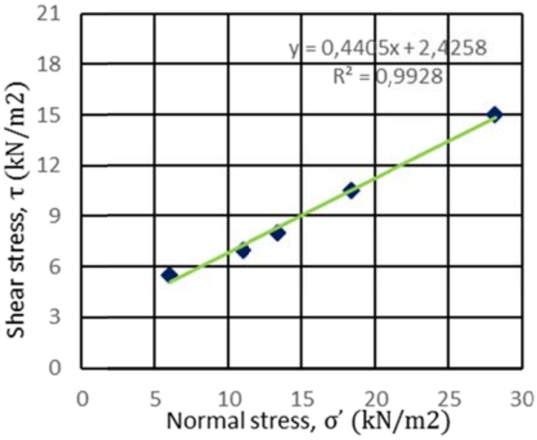

Fig. 5 (a) Sand-sand direct shear box test results

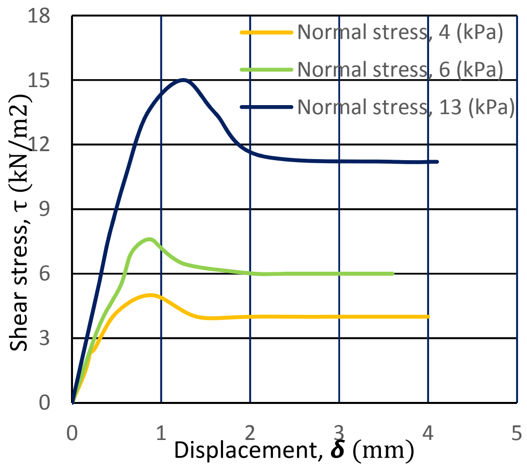

Fig. 5 (b) Shear-displacement test results

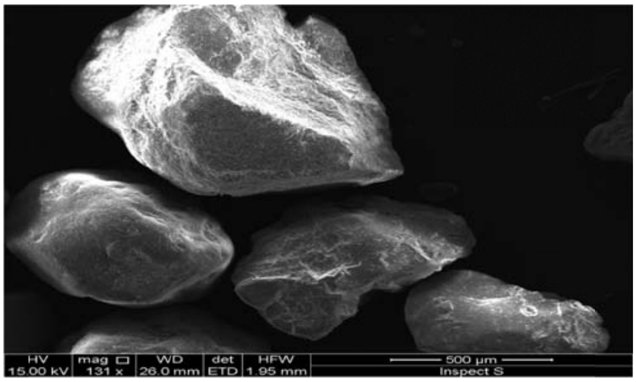

Fig. 6 SEM of a sand sample

TABLE I
SAND PROPERTIES

Soil Property	Value	Reference
Coefficient of Uniformity, Cu	1.786	D-2487
Specific Gravity, G_S	2.65	D -891
Coefficient of Curvature, Cc	1.142%	D -6913
Effective Grain Size, D_{10} (mm)	0.28	D -6913
Moisture Content, Mc (%)	< 0.2%	D -1558
Specific Surface Area, (cm^2/ml)	900.3	C -1069
Maximum Dry Unit Weight, $\gamma_{d\ max}$ (kN/m^3)	17.5	D -7382
Minimum Dry Unit Weight, $\gamma_{d\ min}$ (kN/m^3)	14.1	D -7382
pH	5.7	D -1293
Sand Classification, (USCS)	*SP*	D -2487
Maximum Index Void Ratio, e_{max}	0.81%	D -7382
Minimum Index Void Ratio, e_{min}	0.46%	D -7382
Silicon dioxide, SiO2	> 96%	C -114
Aluminium oxide, Al2O3	*Max* 2%	C -114
Sodium oxide, Na2O	0.33%	C -114
Calcium oxide, CaO	0.38%	C -114
Ferric oxide, Fe2O3	0.25%	C -114
Potassium oxide ,K2O	0.86%	C -114
Magnesium oxide, MgO	0.27%	C -114
Loss of ignition, LOI (%)	0.22	C -114
Angle of internal friction, φ	41.1^0	D -7891
Soil-pile interface friction, δ	31.89^0	D -7891

IV. LOADING STATUS AND PROPOSED PILE FORMULATION

Cylindrical mild steel model piles subjected to uplift load are adopted in the research study, considering four different slenderness ratios to simulate the behaviour of short or rigid piles and long or flexible piles. During the simulation, the static uplift load is applied at the pile tip of the steel pile plus an extra length of about 5mm to limit the contact applied load with the sand surface. To minimize the effective radial stress at depth, it has been advised by [14] that the minimum distance between the piles and the sand varies between 3 and 5 times the diameter of the pile. Additionally, the pile diameter used in this research is $2.5cm$ and the sand specimen size is $(1x1x1)m$ to avoid the failure wedge around the pile model in the effective radial stress zone. The material properties of the mild steel pile are adopted from [15]. Table II lists the material properties and the test ID for each model pile.

TABLE II
TESTING ID AND MODEL PILES INPUT PARAMETERS

Test ID	Poisson's Ratio, υ	Slenderness Ratio, l/d	Sand Mass Relative Density, Dr %	Modulus of Elasticity, E, GPa	Test Depth (mm)
T SC1-1	0.28	7.5	80 %	200	18.75
T SC1-2	0.28	15	80 %	200	37.5
T SC1-3	0.28	22.5	80 %	200	56.25
T SC1-4	0.28	30	80 %	200	75

V. RESULTS AND DISCUSSION

The results of the numerical analysis for the behaviour of the steel model piles subjected to pull-out loading are presented in this section. For slenderness ratios ranging as 7.5, 15, 22.5 and 30, the ground reaction verses depth has been presented. Furthermore, the shear force, pile head displacement and the moment profile against the sand depth have also presented and discussed in detail. It can be seen that the pile response to uplift load and the soil-pile interaction are highly non-linear. Therefore, the advantages of the finite element approach are the accurate prediction of the interaction between the soil and the pile.

Pile head displacement versus depth is clearly presented in Fig. 7. The figure indicates that the maximum pile head displacement occurs for a short model pile (lc/d=7.5) which is about $12.6mm$. In addition, the behaviour of the model pile (lc/d=15) is quite similar for the model pile (lc/d=7.5) with a pile head deflection equal to 10mm. On the other hand, the displacement of the model pile (lc/d=22.5) is about $7mm$. Moreover, for a long pile (lc/d=30) the pile head deflection is about $4.5mm$. It should be noted that the pile head deflection decreases with increasing the pile slenderness ratio along with increase in the pile skin friction. Additionally, the variation of the shear force profile with pile depth is illustrated in Fig. 8. It can be seen that the distribution of the shear force is highly non-linear ranging from about $-2.2N$ for all model piles to reach a maximum value of about $1.42N$ for short piles and about $0.95N$ for long model piles.

The profile of the moment distribution and the net ground response versus soil depth has also been generated in Figs. 9 and 10. It can be seen from Fig. 9 that the moment distribution with depth is non-linear. For a short pile (lc/d=7.5), the moment distribution is very small reaching a maximum value of about $2Nm$, while for short rigid pile (lc/d=15), the maximum moment distribution is about $10.3Nm$ at depth of about 20cm in the effective stress depth. Additionally, for long piles (lc/d more than 22), the maximum moment distribution of about $40.6Nm$ induced at a depth of about 30cm from the point of the applied load. It is observed that for long pile, the net moment profile is quite similar at early stages of the loading up until reaching a value of about $39.3Nm$ but afterwards they vary by about $3Nm$. Furthermore, the ground reaction profile versus pile depth is presented in Fig. 10. It can be seen that for short model piles (lc/d less than 22), the ground reactions are similar reaching a maximum value of about $400N/m^2$. Moreover, at the beginning stages from the applied load, the ground distribution with depth is comparable until a depth of around 28cm and then changes to a ground reaction of about$1{,}500\ N/m^2$. Additionally, for pile slenderness ratio lc/d=30, the maximum ground reaction is around $2{,}000N/m^2$ at a depth of 37cm from the direction of the applied pull-out load.

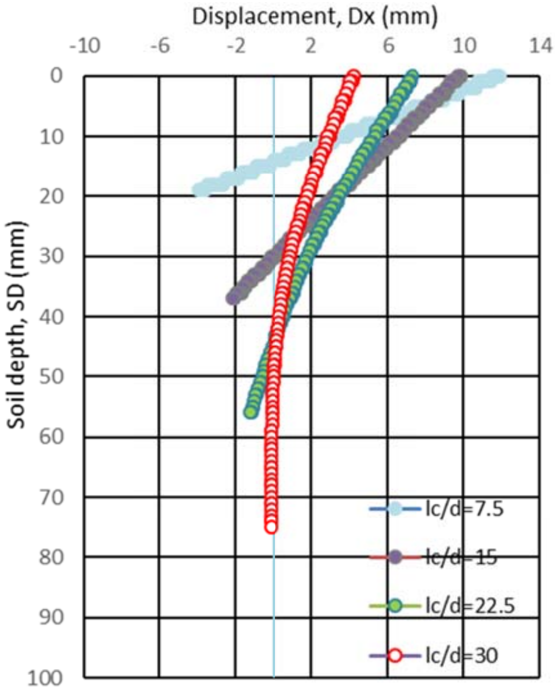

Fig. 7 Displacement versus pile depth

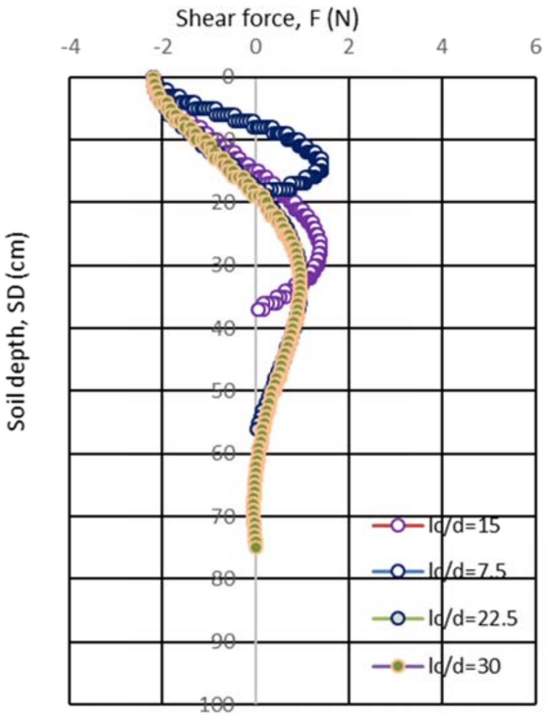

Fig. 8 Shear force versus pile depth

A sharp variation in curvature of the ground reaction and moment distribution can be noticed in the profile along with the pile distribution depths for flexible and rigid piles. This is highly influenced by the pile slenderness ratio in the effective stress zone and also the sand relative density. This is due to an increase in the lateral earth pressure and the pile bearing capacity from the skin friction with the contacted soil in the radial effective diameter.

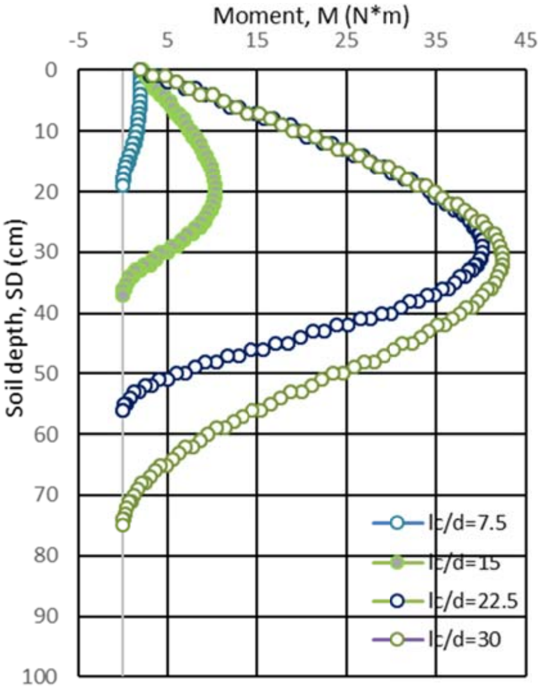

Fig. 9 Moment against pile depth

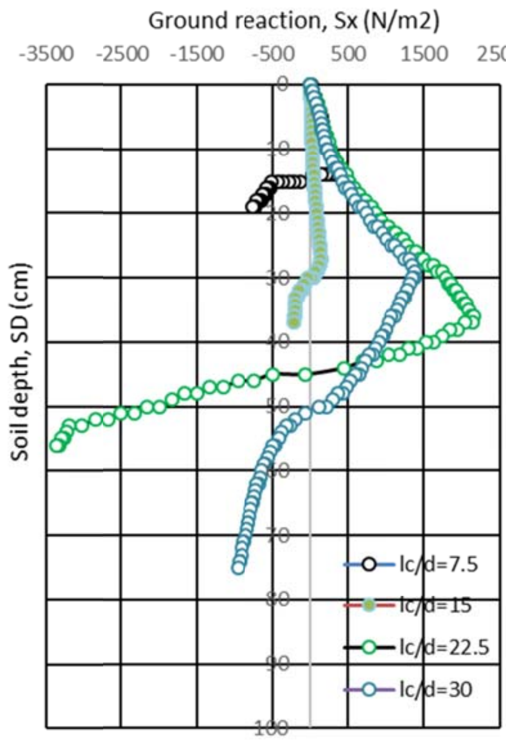

Fig. 10 Ground reactions versus pile depth

VI. Conclusion

A developed FEC has been adopted to analyse the response of mild steel model piles with outside diameter equal to 2.5 cm and 1.5 mm thickness, the model pile slenderness ratios have been varied from 7.5,15, 22.5 and 30 respectively. The piles were subjected to a pull-out loading system of $1kN$. The numerical simulation adopted in this paper takes the advantages of appropriate constitutive models for the predominant elements that have the greatest effect on the simulation procedure e.g. the model pile length, diameter and the sand type. In the numerical model, pile dimensions and the batter angle were properly scaled down. To limit the effect of the pile stress zone, the analysis setup of the mild steel pile and the size of the sand bed were carefully designed. It has been seen that the pile bearing capacity subjected to uplift load increases with increased pile length due to an increase in the shaft resistance and the lateral earth pressure. Moreover, it is observed that at a specific pile depth called "$critical\ depth$" the percentage increase in the moment distribution, shear profile and pile head displacement start to be influenced. The position of the critical depth is determined to be at around 34cm from the point of the applied load.

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