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Effect of Stress Level on Behavior of Bored Piles Embedded in Medium Sandy Soil

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ABSTRACT

In this paper investigation in the end bearing and shaft resistance of bored piles embedded in medium sand and subjected to axial load for wide rang of stress levels starting from laboratory dimensions and go toward field dimensions were made by utilizing the finite element method. The soil is modeled using hyperbolic soil model with empirical equation account for reduction of angle of internal friction Ø with increase in stress level while the bored pile assumed as a linear elastic material. It was found that the stress level has a significant effect on pile's behavior and the small scale model in laboratory dimension not represent the real behavior of pile in field dimensions and if the results from such dimensions are adopted, it will lead to overestimate of bearing capacity factor Nq. Also, the effect of embedment ratio (L/D) on pile's behavior is examined in this study and the results showed that the embedment ratio (L/D) increases the bearing capacity factor Nq up to a certain length beyond it the effect of embedment ratio (L/D) diminished.

Keywords: Bored Pile, Stress Level, Finite Element Method, Bearing Capacity Factor Nq, and Embedment Ratio.

تأثير مستوى الأجهاد على تصرف ركائز الحفر المغمورة في تربة رملية متوسط الكثافة

الخلاصة تم في هذا البحث التحري عن تحمل القاعدة و مقاومة الأحتكاك لركائز حفر مغمورة في رمل متوسط الكثافة و محملة تحميلاً محورياً لنطاق واسع لمستويات الأجهاد عن طريق الأبتداء بركائز بأبعاد مختبرية و زيادة الأبعاد الى حد الوصول الى الأبعاد الموقعية بأستخدام طريقة العناصر المحددة. تم تمثيل التربة بأستخدام نموذج القطع الزائد وتم اضافة معادلة له ذا النموذج تأخذ بنظر الأعتبار نقصان زاوية الأحتكاك الداخلي Ø بزيادة مستوى الأجهاد بينما تم فرض ركيزة الحفر كمادة خطية مرنة. وجد بأن

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مستوى ỷ5ừŨỸĸ لـه تـأثير كبير علـى تصـرف الركيـزة و أن النمـوذج المختبـري بالأبعـاد الصـغيرة لا يمثـل التصـرف الحقيقي للركائز في الأبعاد الحقلية و أن أستخدام نتائج الأبعـاد الصـغيرة علـى حالـة حقليـة سيؤدي الـى زيـادة فـي تقدير مقدار معامـل التحمـل Nq.تـم أيضـاً أختبـار تـأثير نسـبة الغمـر (L/D) علـى تصـرف الركائز حيث أظهرت النتائج أن زيادة نسبة الغمر (L/D) تؤدي الى الزيادة في معامل التحمل Nq الـى حد طول معين بعده يختفي تأثير نسبة الغمر (L/D).

INTODUCTION

The prediction of load carrying capacity of piles in sand is difficult due to misunderstanding for the response of sand under applied load and due to the reduction of angle of internal friction of sand as stress level increases as stated by many authors (e.g. Bolton, 1986, Salgado et al., 2000, Kumar et al., 2007, Chakraborty et al., 2010). This behavior of sandy soil makes a doubt about the validity of small scale models in representing the field problems for both shallow and deep foundations.

With the presence of finite element method and the acceptance of it in geotechnical engineering in analyzing simple and complex problems, the effect of stress level for wide range of bored piles length can be studied by simulation of reduction of angle of internal friction with stress by an empirical equation.

The objectives of this paper is to use finite element method to investigate in the effect of stress level in shaft resistance and end bearing of pile and check the validity of small model results in simulating real field problems for medium sand.

PROBLEMS CONSIDERED IN THIS STUDY

To achieve the objectives of this study, an attempt to pass through a wide range of stress levels starting from laboratory stresses (i.e. small scale model) towards field stresses was made. Five embedment ratios (L/D) used in this study which were (15, 20, 25, 30 and 40). The lengths and diameters of piles used are shown in Table (1).

PROGRAM USED IN THIS STUDY

The finite element computer program modified by Al-Shlash (1979) in FORTRAN language was used in the finite element analysis carried out during this study. Simple development was used by inserting empirical equation account for reduction of angle of internal friction with increasing mean stresses proposed by Bolton (1986). This equation correlates critical state friction angle (which is stress level independent), relative density, and mean effective stress with maximum friction angle by the following relation:

$$\boldsymbol{\varnothing_{mobilized} = \varnothing_{cv} + 3\ I_R} \text{ (in triaxial condition)} \qquad \textbf{... (1)}$$

$$\mathbf{I_R = R_D(Q - \ln(\sigma)) - R} \qquad \mathbf{0 \leq\ I_R \leq 4} \qquad \textbf{... (2)}$$

Where, $\phi_{c.v}$ angle of internal at constant volume, R_D relative density of sand, $Q\&R$ constants equal to 10 & 1 respectively (Bolton, 1986), and σ the mean effective stress.

The capabilities of the developed program and its validity are described in details in Akoobi (2012).

PROBLEMS GEOMETRY

All problems involved bored piles embedded in dry medium sandy soil with various diameters and lengths. The pile-soil system is treated as an axi-symmetric problem in two dimensional finite element analyses. Due to the symmetry of loading and geometry, only one radian of the pile-soil system is considered. Boundary of the soil in FEM depends on the diameters and the lengths of bored piles.

The effect of soil mass on pile response diminishes when the width is greater than $(20D)$ and the height of soil mass is $(L + 20D)$, in which, L is the length of pile and D is the diameter of pile (Chik et al., 2009). The boundaries are taken as $(20\ D)$ for width and $(L + 20D)$ for height of the soil. In order to use same mesh dimensions in different embedment ratios, the height of the mesh for all (L/D) ratios are taken on the basis of greater embedment ratio (i.e.$(L/D) = 40$). Five points isoparametric elements are used in forming finite element mesh to model the axi-symmetric soil-pile problem. The nodal points along the centerline and those on the far right vertical boundary are assumed to move only in vertical direction, while the nodal points in the bottom of the boundary are assumed to be fixed in vertical and horizontal directions. The finite element mesh for piles with embedment ratio (L/D)=40 is shown in Figure (1). In this Figure the mesh dimensions explained in term of lengths and diameters of piles.

Piles with other embedment ratios have same mesh dimensions shown in Figure (1); only the length of piles will be less than that of pile in Figure (1).

MATERIALS PROPERTIES

In this study the medium sand was used to study the effect of stress level. The soil is modeled using non-linear hyperbolic soil model (Duncan & Chang, 1970) while, bored pile is assumed to be linear elastic material. The nonlinear hyperbolic properties of medium sand and nonlinear soil – pile interface were adopted from Al-Kubaisy (2004) and shown in Table (2) and Table (3) respectively. It should be noted that the available data in literature from which the hyperbolic parameters were taken does not contain critical state friction angle of sand, for this causation this parameter was calculated by inverting Bolton's empirical equation (equation (1)) by knowing maximum mobilized friction angle and the relative density of sand. The linear elastic properties of the concrete bored pile are shown in Table (2).

ULTIMATE LOAD, SHAFT RESISTANCE AND END BEARING RESISTANCE

In this study, the failure criterion proposed by Terzaghi was used to predict the ultimate load that the pile can handle. The end bearing and shaft resistance were computed as follows:

1. The shaft resistance Q_S was computed by integrating the tangential shear τ in the interface elements. Thus:

$$Q_S = \sum_{i=1}^{tot} \tau_i \Delta L_i D_i \pi \quad \textbf{... (3)}$$

Where:
τ_i = shear stress in interface element.
ΔL_i = length of interface element.
D_i = diameter of pile, and
tot = total number of interface elements.

2. The finite element program used in this study calculates the stress at the centroid of the elements not in the edges of elements, due to this the end bearing resistance of pile Q_b was computed from equilibrium consideration by subtracting the shaft resistance obtained in step 1 from the total ultimate load from load - settlement curve. Thus:

$$Q_b = Q_T - Q_S \quad \textbf{... (4)}$$

A summary of ultimate load, ultimate shaft and end bearing resistance for all piles embedded in medium sand are shown in Table (4).

EFFECT OF STRESS LEVEL AND EMBEDMENT RATIO (L/D) ON BEARING CAPACITY FACTOR Nq

The bearing capacity factor N_q is obtained from the ultimate end bearing capacity for each pile by back calculation, thus N_q will be:

$$N_q = \frac{\text{Ultimate end bearing}}{\frac{\pi}{4} D^2 \gamma L} \quad \textbf{... (5)}$$

The values of the bearing capacity factor N_q computed from above equation are plotted against the lengths of piles in Figure (2). The mobilized angles of internal friction based on Bolton's equation at ultimate load $(10\% D)$ in the centroid of the element below pile tip for all lengths of piles are plotted in Figure (3).

Figure (2) shows a dramatic decrease of bearing capacity factor Nq as length of pile increase. This decrease can be justified by the reduction of mobilized angle of internal friction Ø with increasing stress level (i.e. length of pile). It can also be noticed that, this reduction is diminished beyond a length of 20 m and the bearing capaqcity factor Nq became independent of stress level. This independency can be justified by the followings:

1- The tendency of mobilized angle of internal friction to become almost constant or much less sensitive to increasing in applied stress on soil element in high stress range where its value approaches the critical state friction angle and as angle of internal friction becomes constant the bearing capacity factor N_q also tends to become constant.

2- The less sensitivity of bearing capacity factor Nq to change in mobilized angle of internal friction as its value starts to approach critical state friction angle.

From the previous disscution it can be conclude that, extrapolation of bearing capacity factor Nq for medium sand from small scale model to field scale is not valid due to the effect of stress level in reduction of angle of internal friction and the dependency of bearing capacity factor Nq on it. It can be seen also from Figure (2) that, as embedment ratio (L/D) increases the bearing capacity factor Nq increases until 20 m length beyond this length, the embedment ratio (L/D) effect will be approximately vanished and all embedment ratios will give the same value for the bearing capacity factor N_q.

EFFECT OF STRESS LEVEL ON BEHAVIOR OF BORED PILES

To study the effect of stress level on the behavior of piles, the end bearing, shaft resistance, and total capacities of piles in ultimate conditions (i.e. 10% D) are plotted against the lengths of piles for all diameters considered in this study. For better understanding for the piles behavior for a specific diameter and a specific range of stresses (i.e. lab or field), each diameter is drawn separately and will be discussed in this section.

Figures (4) to (10) show the relationship between end bearing, shaft resistance, and total capacities for piles embedded in medium sand with pile lengths for all diameters of piles under study.

In Figure (4) the relations mentioned above were drawn for pile with diameter (2 cm), it can be seen that the end bearing capacity is much higher than the shaft resistance in laboratory dimensions and the shafts resistances contribution in the total capacities for piles are very low. Also, when lengths of piles increase the end bearing, shaft, and total capacities are increased. The increase in end bearing with length is attributed to the increase in bearing capacity factor Nq as embedment ratio increase and the increase in shaft resistance of pile with increasing shaft length. The reason that the mobilized end bearing capacity is much higher than shaft resistance may be attributed to high friction angle mobilized in such low stresses and the dependency of end bearing capacity of piles on angle of internal friction. As stress level increase (i.e. doubling the dimensions) as shown in Figures (5) and (6), the end bearing capacities for piles still higher than the shaft resistance but the difference between them decreases due to decrease of angle of internal friction which leds to decrease end bearing capacity for piles. In case of higher stresses range (Figure (7) to (10)), the mobilized end bearing capacity start to become less than shaft resistance and the difference between them increases as lengths of piles increase. This behavior also attributed to the reduction of internal friction angle due to increasing the stress level in such dimensions. It can also be noticed that, there is no limiting value for pile capacity is reached for all diameters and stresses. One exception that the end bearing for the piles with length higher than (18 m) is no longer increases as length increases, but the total piles capacities increase due to increase in shaft resistance as shown in Figure (10). This can be explained by the tendency of the bearing capacity factor N_q to decrease due to decrease in the angle of internal friction and this decrease will make unsignificant effect for increase in overburden pressure in increasing end bearing capacity for pile according to static end bearing design equation. From these observations, it can be concluded that the stress level has a significant effect on end bearing capacity and unsignificant effect on shaft resistance and care should be taken in extrapolating the results from a model pile in small scale dimensions (low stress level) to field dimensions (high stress level) and for such extrapolating a stress level factor should be used for safe and economical design for pile in sand.

EFFECT OF EMBEDMENT RATIO (L/D) ON RATE OF INCREASE IN PILE CAPACITY

Increasing the pile length means more stress generated at the pile interface along its length and will lead to increase pile capacity. Also, increasing the diameter of pile means increasing in the surface area of the shaft contact with the surrounding soil which in turn will lead to increase in the shaft resistance. In addition, increasing the diameter of pile means more end bearing resistance area of pile.

Figure (11) shows the relation between embedment ratio and rate of increase for piles capacities from pile's capacity with embedment ratio 15 for all diameters. It can be concluded that increasing embedment ratio increases the bearing capacity of pile with approximately constant rate for all stress range and that there is no limiting value reached for high embedment ratio. This observation gives a conclusion about the fallacy of critical depth for all stress ranges, since the critical depth assume that there is a limiting value reached for both end bearing and shaft resistance as assumed by many authors (e.g. Vesic, 1967; Venkatramaiah, 2006; Reese et al., 2006). Also, This observation gives aid for site engineers who wants to predict the effect of increasing embedment ratio for piles in the site depending upon results of load test they conduct previously on any pile in that site.

CONCLUSIONS

From finite element simulation for a bored piles embedded in medium sand in wide range of stress levels, the following conclusions can be established:

1- Using small scale model to study the behavior of piles embedded in medium sand are not correct if the stress level effect is neglected. So, the stress level effect should be incorporated and taken with care in such stress level dependent soils.
2- The bearing capacity factor N_q decreases with the increase of length of pile until it reaches approximately a constant value beyond a (20 m) depth.
3- The embedment ratio (L/D) increases the bearing capacity factor Nq till a length of 20 m beyond this length, there is not effect for embedment ratio (L/D).
4- For piles with same embedment ratio (L/D), the end bearing in small-scale dimensions is larger than shaft resistance, while in field dimension, the shaft resistance is larger than end bearing.
5- For piles embedded in medium sand, the stress level has a significant effect on end bearing but this effect is not significant on shaft resistance of these piles.
6- No sign of critical depth is noticed for all stresses studied in this paper.

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Table (1) Bored piles dimensions used in the F.E. analysis.

Diameter (cm)	L/D =15	L/D =20	L/D =25	L/D =30	L/D =40
	Length (m)	Length (m)	Length (m)	Length (m)	Length (m)
2	0.3	0.4	0.5	0.6	0.8
4	0.6	0.8	1	1.2	1.6
8	1.2	1.6	2	2.4	3.2
16	2.4	3.2	4	4.8	6.4
30	4.5	6	7.5	9	12
60	9	12	15	18	-----
120	18	24	30	-----	-----

Table (2) Non-linear hyperbolic properties of medium Sand. (After Al-Kubaisy, 2004).

Parameters	Soil	Pile
Unit weight γ (kN/m3)	14.5	24
Coefficient of at rest earth pressure, k_o	0.463	----
Cohesion intercept c (KPa)	0	----
Max.Angle of internal friction Ø	32.5	----
Poisson's ratio υ	0.3	0.2
Modulus of elasticity (Kpa)	Variable	25000000
K	250	----
n	0.6	----
R_f	0.8	----
E_f (kPa)	0.1 of prefailure ratio	----
$Ø_{c.s}$	23.86	----
R D (%)	39	----

Table (3) Non-linear interface parameters for Medium Sand-pile interface (after Al-Kubaisy, 2004).

Material	δ	K_I	n	R_f
Soil-pile interface	33.5	23300	0.27	0.9

Table (4) Summary of ultimate load, ultimate shaft resistance and end bearing resistance for piles embedded in medium sand.

D (cm)	L (m)	L/D	Ultimate load (kN)	Ultimate shaft resistance (kN)	Ultimate end bearing (kN)
2.0	0.3	15	0.04075	0.0104	0.03035
4.0	0.6	15	0.2757	0.0823	0.1934
8.0	1.2	15	1.8905	0.6908	1.1997
16.0	2.4	15	12.285	5.586	6.699
30.0	4.5	15	76.751	37.975	38.776
60.0	9	15	504.117	305.207	198.91
120.0	18	15	3653.15	2450	1203.15
2.0	0.4	20	0.06	0.0144	0.0455
4.0	0.8	20	0.3912	0.10	0.2912
8.0	1.6	20	2.905	1.078	1.827
16.0	3.2	20	18.958	9.74	9.218
30.0	6	20	120.034	63.726	56.308
60.0	12	20	813.37	513.09	300.28
120.0	24	20	5408.72	4282.52	1126.198
2.0	0.5	25	0.0835	0.021	0.067
4.0	1	25	0.5561	0.1561	0.400
8.0	2	25	4.268	2.015	2.253
16.0	4	25	28.426	17.28	11.146
30.0	7.5	25	174.386	110.51	63.876
60.0	15	25	1134.14	863.28	270.86
120.0	30	25	7000.24	5741.33	1258.91
2.0	0.6	30	0.1089	0.0323	0.0766
4.0	1.2	30	0.807	0.304	0.503
8.0	2.4	30	5.422	2.162	3.260
16.0	4.8	30	38.65	22.66	15.99
30.0	9	30	231.51	144.77	86.74
60.0	18	30	1545.55	1112.14	433.41
2.0	0.8	40	0.1825	0.0735	0.109
4.0	1.6	40	1.309	0.554	0.755
8.0	3.2	40	9.467	4.736	4.731
16.0	6.4	40	61.41	40.24	21.17
30.0	12	40	364.21	248.11	116.10

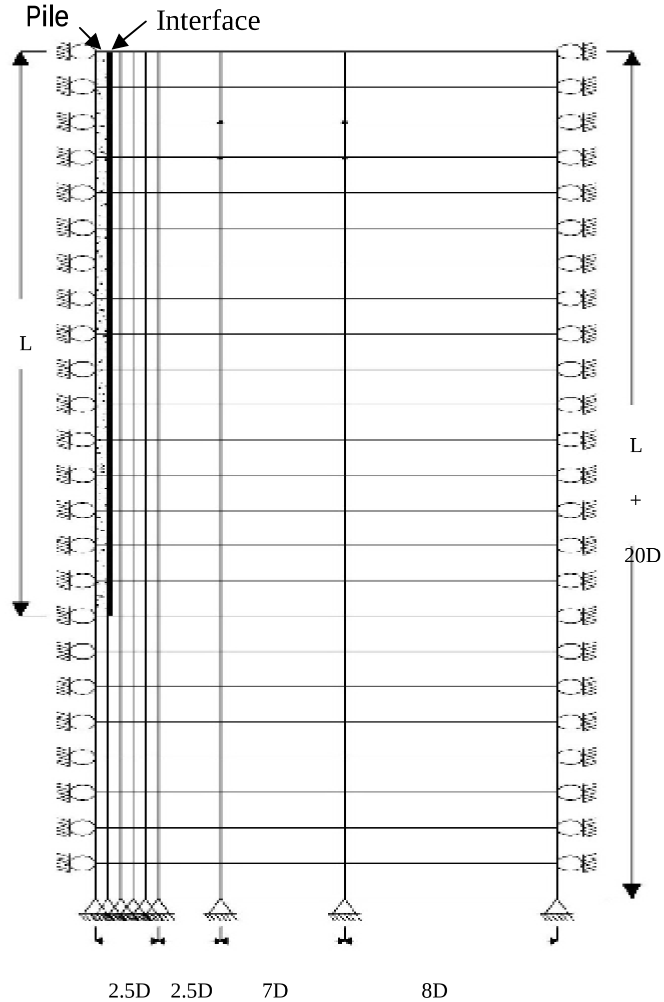

Figure (1) the finite element mesh for piles With $(L/D) = 40$.

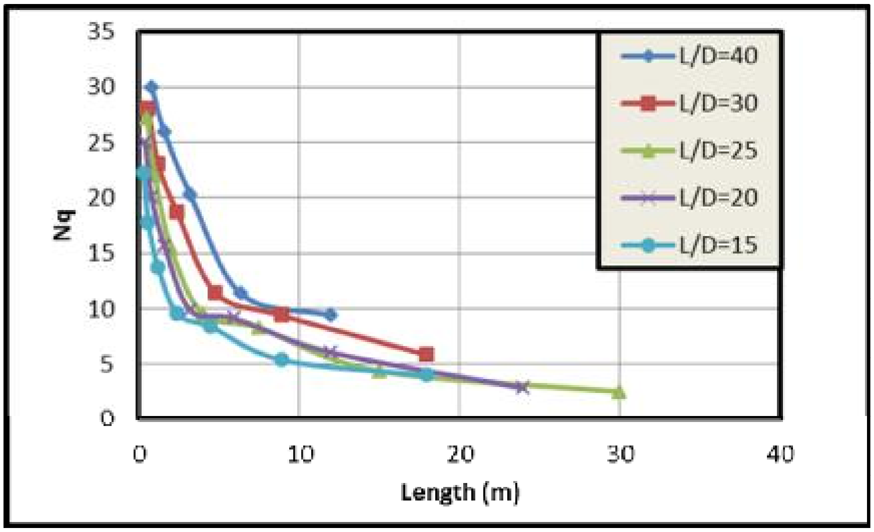

Figure (2) Bearing capacity factor N_q vs. length for all pile embedded in medium sand.

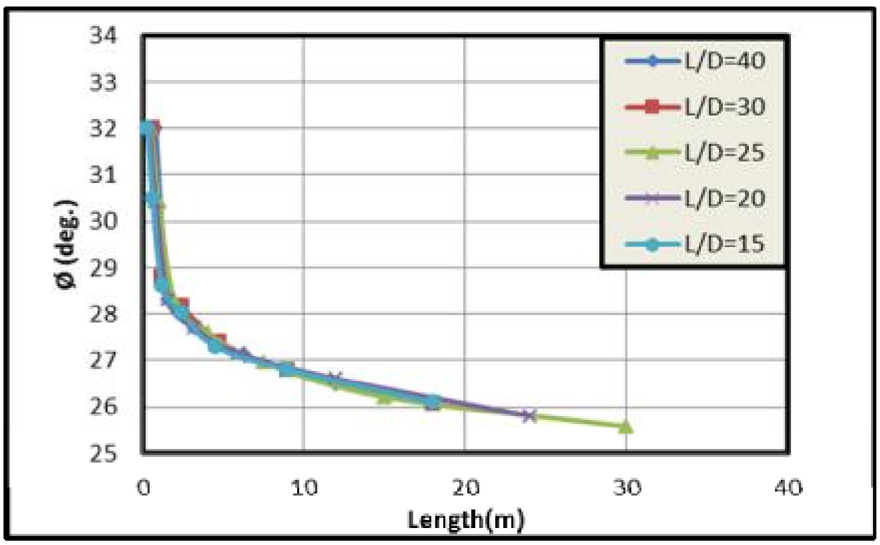

Figure (3) Mobilized angle of internal friction in the element Below pile tip vs. length for piles embedded in medium Sand estimated at a settlement of $(10\%\,D)$.

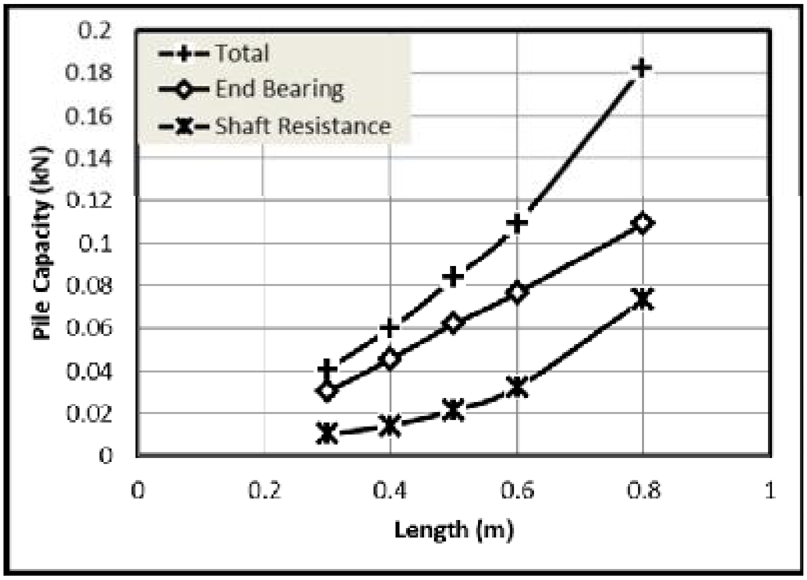

Figure (4) Load capacity vs. length for pile embedded in medium sand & D= 2 cm.

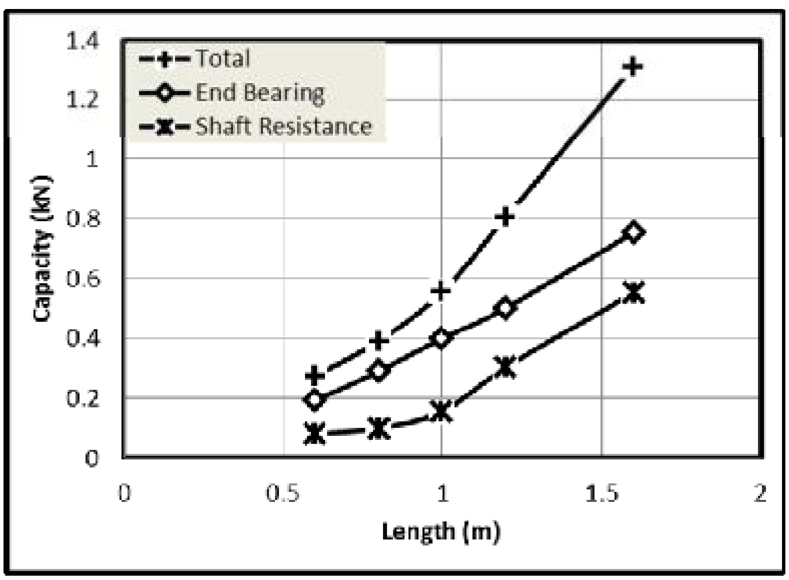

Figure (5) Load capacity vs. length for pile embedded in medium sand & D= 4 cm.

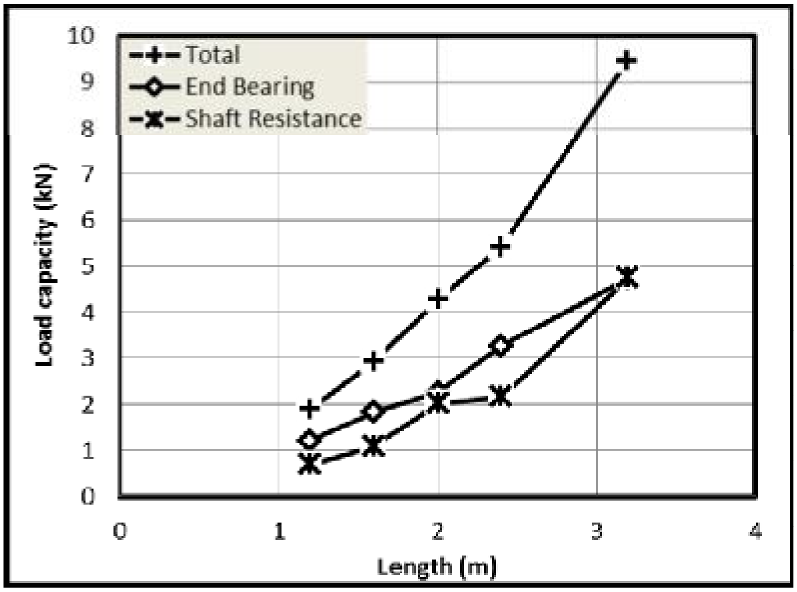

Figure (6) Load capacity vs. length for pile embedded in medium sand & D= 8 cm.

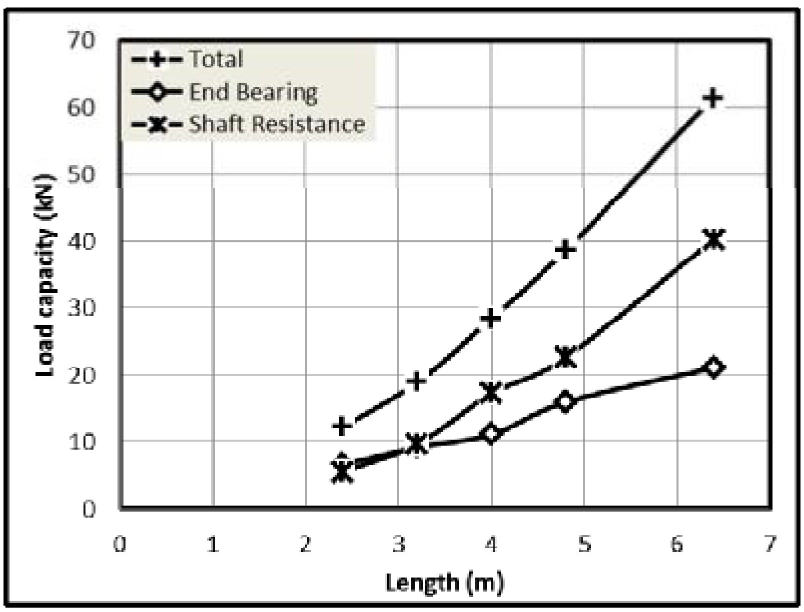

Figure (7) Load capacity vs. length for pile embedded in medium sand & D= 16 cm.

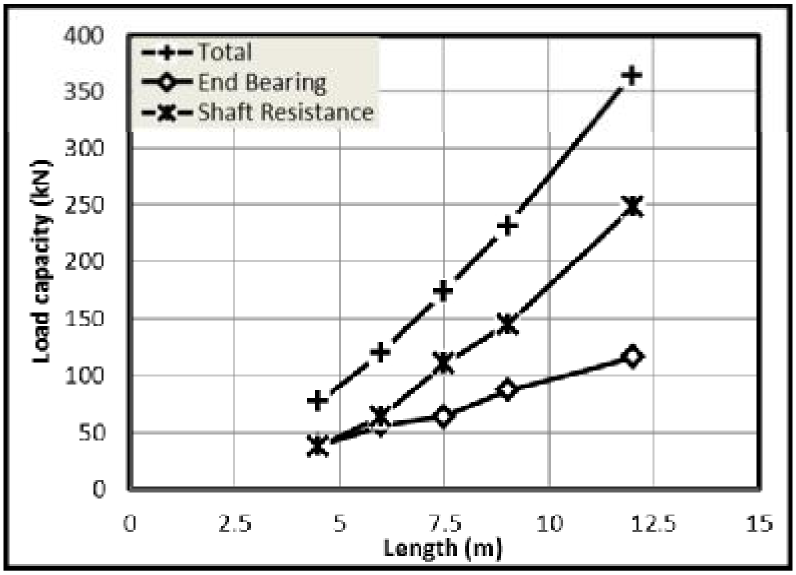

Figure (8) Load capacity vs. length for pile embedded in medium sand & D= 30 cm.

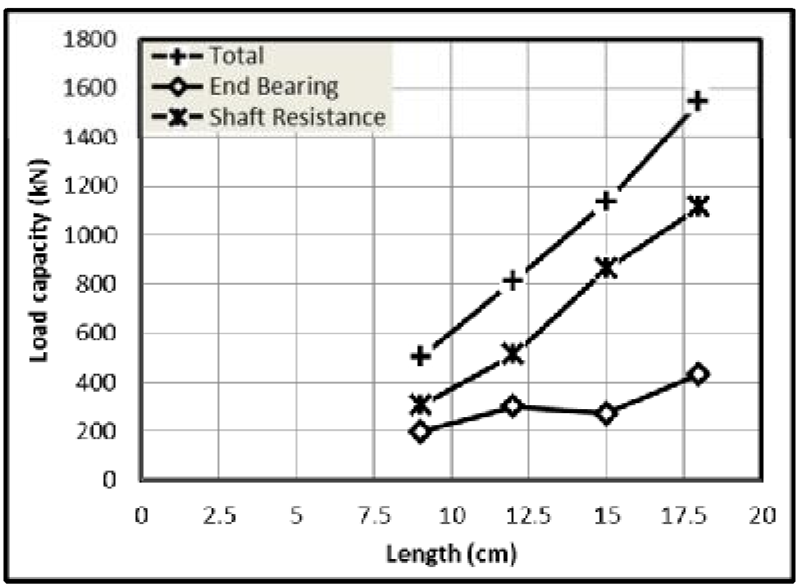

Figure (9) Load capacity vs. length for pile embedded in medium sand & D= 60 cm.

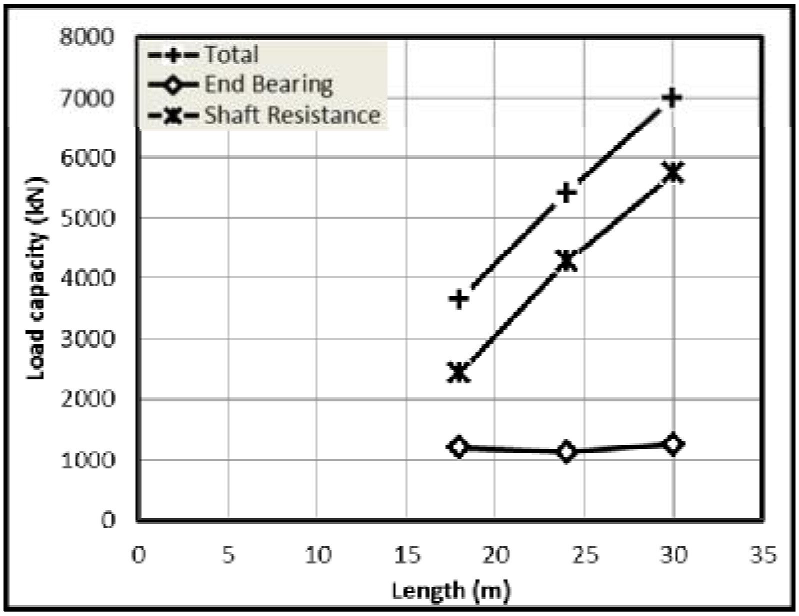

Figure (10) Load capacity vs. length for pile embedded in medium sand & D= 120 cm.

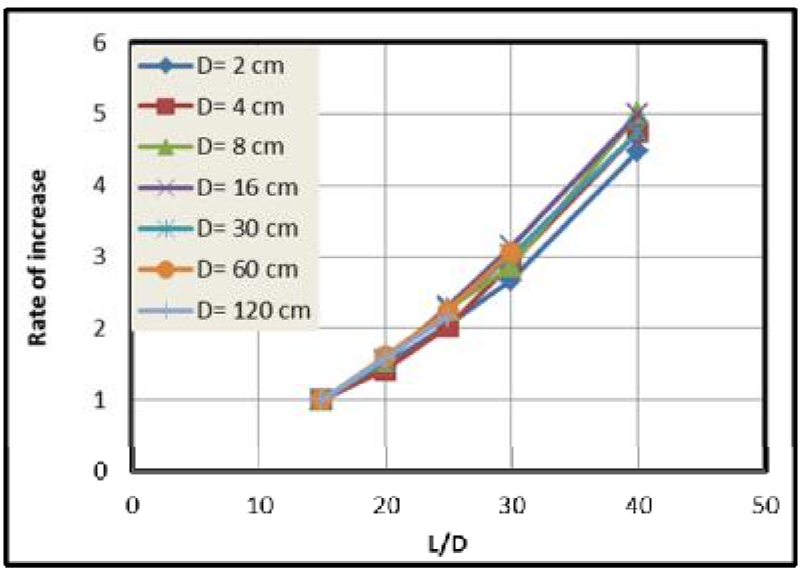

Figure (11) L/D relation with rate of increase for all stresses range.